Comparing selected kinematic parameters of the late swing phase during a sprint, isokinetic strength, and flexibility in male soccer players with and without anterior pelvic tilt

Dissertation

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List of Abbreviations

EC	Euler Characteristic
EMG	Electromyography
F_c	Cut-off Frequency
F_{ext}	External Force
F_{ib}	Biceps Femoris Force
F_s	Sampling Frequency
F_{sm}	Semimembranosus Force
F_{st}	Semitendinosus Force
F_{total}	Total Force
GTO	Golgi Tendon Organ
H_{con}	Hamstring Concentric Peak Torque
H_{con}:Q_{con}	Convetional Hamstring to Quadricpes Ratio
H_{ecc}	Hamstring Eccentric Peak Torque
H_{ecc}:Q_{con}	Functional Hamstring to Quadricpes Ratio
HE_{con}	Hip Extensors’ Concentric Peak Torque
HF_{con}	Hip Flexors’ Concentric Peak Torque
HF_{con}:HE_{con}	Convetional Hip Flexors to Hip Extensors Ratio
HF_{ecc}	Hip Flexors’ Eccentric Peak Torque
HF_{ecc}:HE_{con}	Functional Hip Flexors to Hip Extensors Ratio
ITB	Iliotibial Band
MVC	Maximum Voluntary Contraction
NASM	National Academy of Sport Medicine
Q_{con}	Quadriceps Concentric Peak Torque
$SAFT^{90}$	90-minutes Soccer-specific Aerobic Field Test
SnPM	Statistical non-Parametric Mapping
SPM	Statistical Parametric Mapping
SSC	Stretch-shortening cycle
TFL	Tensor Fascia Lata
VMO	Vastus Medialis Oblique

Abstract

Introduction and theoretical background

Soccer is a competitive sport in which the players suffer a high amount of injury specifically muscle strain i.e. hamstring strain. Hamstring strain can be a categorized into two forms: contact or non-contact. The non-contact has been studied and the late swing phase has been proposed as the time point where the muscle is likely to suffer from an injury due to the lengthening occurring with regards to is normal length when standing upright. The literature suggests that the anterior tilt of the pelvis increases the risk of sustaining a hamstring injury while performing a sprint at the late swing phase. It is justified that the increase of the pelvis angle would lead to an increase in the musculotendon tension, which can eventually predispose the hamstring to sustain an injury. However, the kinematics and muscular activity of the pelvis, hip and knee region while performing a sprint at the late swing phase in soccer players with and without anterior pelvic tilt has yet to be fully understood.

Furthermore, risk factors such as flexibility and strength has been extensively studied, but a controversy yet remains as to if a deficiency in these parameters could predict the outcome of an injury, specifically hamstring strain. The previous studies did not however, incorporated the amount of pelvic tilt into their measurements, in order to analyse its relationship with the outcome of flexibility and strength results. The aim of this study was to theoretically and empirically analyze the association of pelvic tilt with hip and hamstring muscle flexibility, the EMG and kinematics of late swing phase while sprinting, and maximum isokinetic eccentric and concentric strength of the knee and hip muscles as well as the conventional and functional ratios.

Hypotheses

Hamstring flexibility differs between soccer players with and without anterior pelvic tilt.

Hip flexors' flexibility differs between soccer players with and without anterior pelvic tilt.

Sagittal kinematic parameters i.e. knee, hip and pelvis angle differ at the late swing phase in a sprint between soccer players with and without anterior pelvic tilt.

Neuromuscular activities of the gluteus maximus, rectus femoris, vastus medialis, and hamstring biceps femoris at the late swing phase during a sprint differ between soccer players with and without anterior pelvic tilt.

Abstract

Maximum concentric and eccentric isokinetic strength for knee flexors, knee extensors, hip flexors and hip extensors and their ratio differ between soccer players with and without anterior pelvic tilt

Methods

A cross sectional, single measurement under lab conditions was conducted for the purpose of this research. Initially a total number of 38 soccer players were recruited from the Hamburg league, but due to the drop out during the measurements the number of participants reduced to 34. After a general warmup the players had their measurements taken for the spinal alignment, and hamstring and hip flexors' flexibility. Hamstring flexibility was assessed using the 90:90 active knee extension clinical test. For the hip flexor flexibility the modified Thomas test was used. The measurements were taken using a photographic camera with reflective markers attached on the great trochanter, knee, and lateral malleolus. The pictures were taken from the sagittal plane and latter analysed using the Kinovea software. Next they proceeded to a sprint test in which the neuromuscular activity and the kinematic angles were recorded. The players performed three sprints at the speed of 6.9 m/s on a motorized treadmill. Using the template for the lower extremity, 40 markers were applied to the athletes in addition to the electrodes to record the electrical activity of their muscles. The average of 5 late swing phases for each player was extracted for both kinematic and EMG values for statistical analysis. Finally maximum isokinetic strength test was measured for the knee and hip joint. Peak torque values were taken for knee flexion and extension, and hip flexion and extension at 120 °/s concentrically and eccentrically. Conventional and functional strength ratios were also calculated for statistical analysis. The players were grouped using the Diers Formetric device into players with and without anterior pelvic tilt.

All data were assessed for their normality using Shapiro-Wilk normality test. Independent t-test was used for flexibility, peak torque, and pelvic tilt angle for comparison. For EMG and kinematic analysis a time series analysis was conducted using the SPM package. Since the kinematic data were normally distributed the parametric t-test was used and for the EMG the non-parametric t-test equivalent was used. All alpha levels were set to 0.05 and adjusted for using the Bonferroni correction.

Results

The results show that the amount of pelvic tilt between two groups of players was significantly different ($p < 0.001$). The amount of hamstring flexibility showed significant difference between players with and without anterior pelvic tilt ($p = 0.05$) with an effect size of 0.79 which is considered a large effect size. No significant difference was indicated for the hip flexors flexibility between the players with and without anterior pelvic tilt ($p > 0.05$). For kinematic only hip flexion depicted significant difference ($p < 0.05$) at the late swing phase (85.2% - 100%) while sprint; with the players without anterior pelvic tilt demonstrating a higher hip flexion in comparison to those with anterior pelvic tilt. The effect size was calculated for this range to be 0.90-0.98 which is considered to be a large effect size. No other significant difference was found for other kinematic and EMG parameters. No significant difference was determined for maximum isokinetic strength test for knee and hip joints ($p > 0.05$). There was no significant difference for the conventional and functional strength ratio for knee and hip joint between the two groups ($p > 0.05$).

Discussion

Soccer players with anterior pelvic tilt demonstrated a higher hamstring flexibility and less extended hip flexion during the late stages of late swing phase while sprinting in comparison with players without anterior pelvic tilt. It should be noted that while measuring the hamstring flexibility the initial pelvic tilt angle can contribute to the amount of flexibility displayed by the athletes and thus should be taken into consideration. Furthermore smaller amount of hip flexion prior to ground contact can be analyzed performance-wise due to the fact that it would reduce the amount of stride length. However further research is needed to understand the effect of smaller hip flexion on different aspects of sprinting.

Conclusion

When assessing the hamstring flexibility the amount of pelvic tilt should be taken into account as it is associated with amount of hamstring flexibility. Anterior pelvic tilt should also be noted as it reduces the amount of hip flexion at the end stages of the late swing phase which may have performance and injury implications during sprint.

1 Introduction

Soccer is believed to be one of the most popular sports in the entire world with an estimate of 256 million people playing the game by the year 2007 (Kunz, 2007). With a vast amount of participants in this sport, athletes strive to achieve better performance and simultaneously avoid injury. Soccer athletes incorporate various techniques to achieve their top performance. One technique that soccer players are constantly trying to master is sprinting. Better sprinting allows the players to outmanoeuvre the opponent giving them the advantage by increasing the chances of ball possession and even the possibility to determine the outcome of a game. Improving one's sprinting performance entails persistent training, controlled diet, excelling techniques, lifestyle changes, and a various other factors. In the lifestyle category, adopted posture (Hennessey & Watson, 1993) is considered to be one of the contributing factors influencing an athlete's performance.

Human posture has an influence on the way we precede with our daily activities. If the posture deviates from normal conditions, our body compensates for it by adopting new strategies. The postural deviation can either be of a habitually or ontogenetically origin. Postural assessment for athletes has become an emerging trend during the recent years. Coaches and scientists are realising and analysing the effects of posture on athletic performance. A good posture is defined as when an individual has a muscular and skeletal balance which can prevent injury and progressive deformity (Britnell et al., 2005). Any deviation from the normal posture can be categorized as a malalignment. Schamberger (2012) declares that correcting the malalignment allows the athletes to progress in their sporting activity and in some cases even avoid injury (Schamberger, 2012). Having a good posture would allow the body to efficiently produce force as a result of an equilibrium state (Kritz & Cronin, 2008). Malalignment may also predispose athletes whom running or sprinting is an essential part of their sporting activity to injuries by adopting different mechanics in their locomotion (Ferber & Macdonald, 2014).

Soccer players have shown a tendency for having higher anterior pelvic tilt angle when compared to the non-athletes (Wodecki, Guigui, Hanotel, Cardinne, & Deburge, 2002). One can regard excessive anterior pelvic tilt as a malalignment since it would deviate from the normal postural alignment. The anterior tilt of the pelvic may stem from various factors including but not limited to muscle imbalances present in the pelvic region (Clark & Lucett, 2010). The inflexibility of the hip flexors and weakness of hip extensors can cause an anterior rotation in the pelvis. Muscles such as the Iliacus, rectus femoris and sartorius, due to their origin on the pelvis and their line of action, can incite anterior pelvic tilt if they are shortened or inflexible (Standring, 2015). In some cases it is not the muscle inflexibility that causes the anterior tilt, but rather the weakness of the antagonist muscles which are unable to control the rotation of pelvis. Muscles such as: the hamstring and gluteus complex, which originate from the pelvis are responsible for the posterior rotation specifically control of anterior rotation of the pelvis (Standring, 2015). Muscle imbalances can arise from adaptive mechanisms for example high repetitive activities (Page, Frank, & Lardner, 2010). Soccer players tend to incorporate their hip flexors more frequently compared to the extensors in certain activities: kicking, passing, etc. which would be followed by adaptive changes in the pelvis (Rasch, Grabiner, Gregor, & Garhammer, 1989).

It has also been suggested by the national academy of sport medicine of America (NASM) that the imbalance present in the pelvic region can predispose the hamstring to injury (Clark et al., 2010). Surprisingly, hamstring strain is a common injury among soccer players (Ekstrand, Hägglund, & Waldén, 2011; Ekstrand, Waldén, & Hägglund, 2016; Waldén, Hägglund, & Ekstrand, 2005) with the biceps femoris having the highest prevalence in the hamstring muscle complex (Ekstrand, Healy, et al., 2011). One could expect that as the amount of anterior pelvic tilt angle increases the chances of sustaining a hamstring injury rises. Anterior pelvic tilt has been disputed as a risk factor for hamstring injury (Woods et al., 2004a). It is assumed that the anterior rotation of the pelvic would cause the hamstring muscle to elongate, putting the muscle at higher strain levels. According to the kinetic chain and length-force principle, the anterior pelvic presumably can induce changes to certain properties of the muscular function such as strength and flexibility as a result of the pelvic malalignment.

Kinematic chain principle emerged from an engineering concept which describes a series of linked rigid bodies. It was later adopted to biomechanics which different body segments were referred as rigid bodies that are connected via joints (Steindler, 1977) . In this theory it is believed that movement in a segment or joint will affect other adjacent segments' or joints' kinematics due to connective tissues crossing them. With this in mind the human movements, based on the kinetic chain principle, are in forms of open chain and close chain movements. The open kinetic chain movement is identified as a movement where the distal segment is not restrained (Knudson, 2013). Movements such as the swing phase of running where the leg moves freely without restrain is an example of open kinetic chain movement.

Although the concept has been adopted for a while, but the use of this concept for movement analysis is scares with only limitations to training interventions. We can expect that since the body is interlinked through our joints with muscles and tendons overcrossing them, a movement in a segment can influence the adjacent segments. One research showed that anterior pelvic tilt influences the hip range of motion (Ross et al., 2014b). Ross et al. (2014) reported that as the pelvic anterior tilt angle increases the amount of hip flexion decreases up to 10 degrees in the static position. This is a clear demonstration of how the kinetic chain functions in our body and how some alterations in a movement influence other segments in the link. Although the consequences of altered pelvis malalignment on joint and segment kinematics in locomotion may sound logical, but the practical implications of such malalignments on components like kinematics, strength and flexibility remain unclear.

Sprinting is a requisite for soccer athlete and it has been found that elite soccer players cover an eight to twelve kilometre distance during a game (Bangsbo, Nørregaard, & Thorsoe, 1991; Reilly, 2003). Each player is said to complete 20 to 35 sprints per game which emphasizes the importance of the sprinting technique (Andrzejewski, Chmura, Pluta, Strzelczyk, & Kasprzak, 2013; Di Salvo, Gregson, Atkinson, Tordoff, & Drust, 2009). Sprinting technique is important so that it has been considered as a determinant which can affect the outcome of a game (Faude, Koch, & Meyer, 2012). The sprint enables the players to gain advantage for positioning themselves in a goal situation which is why optimization of the technique is essential in order to gain high levels of performance. Several different kinematic factors have been associated with the performance of sprinting, some of which are directly while others indirectly determine the performance outcome (Mann & Herman, 1985). Hence analysing the kinematics of a sprint in soccer players helps us better optimize and understand the sprinting mechanism and its role in performance enhancement and injury prevention.

Sprinting cycle is divided into two distinguishable phases: stance and swing. Each phase serves a purpose for forward propulsion and smooth transition between phases. The swing phase can be further divided into early swing and late swing phases (terminal phase). The late swing phase is where the knee starts its extension until foot contact. The muscles especially the hamstrings are highly active to control lower leg momentum to prepare for foot contact and also avoid injury (Chumanov, Heiderscheit, & Thelen, 2011; Novacheck, 1998). The hamstring at this stage is responsible for controlling both hip flexion (Jonkers, Stewart, & Spaepen, 2003) and knee extension (Chumanov, Schache, Heiderscheit, & Thelen, 2012) as it eccentrically contracts prior to foot contact (Schache, Dorn, Blanch, Brown, & Pandy, 2012). Coincidently, the non-contact hamstring strain in soccer players is reported to occur at the late swing phase while performing a sprint (Malone et al., 2018). During this phase the hamstring undergoes elongation beyond its neutral position, with the biceps femoris experiencing the highest amount of stretch (Wan, Qu, Garrett, Liu, & Yu, 2017a). The extensive elongation is believed to be the trigger of the hamstring injury. The muscles which control the pelvic motion is said to influence the onset of a hamstring injury (Chumanov, Heiderscheit, & Thelen, 2007; Heiderscheit, Sherry, Silder, Chumanov, & Thelen, 2010). As mentioned previously due to the kinetic chain, changes in the kinematics are expected to occur as a result of anterior pelvic tilt.

Intrinsically, the anterior pelvic tilt angle increases as the speed of locomotion rises (Novacheck, 1998). The excessive anterior tilt of the pelvic while being static may affect hip and knee kinematics during the late swing phase during the sprint which can produce high level of stretch on the hamstring causing micro traumas which after repetitive cycles can accumulate and ultimately lead to strain (Stauber, 2004). Some injuries may seem acute, but in fact they are the result of repetitive microtraumas happening in high repetitions over extensive period of time (Putz-Anderson, 2017). Although theoretically sound, but the influence of pelvic tilt on late swing kinematics is yet to be studied.

Another important aspect influenced by the anterior pelvic tilt would be the flexibility of the muscles surrounding the pelvic region. Preseason hamstring inflexibility in soccer players is considered to be an important factor for developing hamstring strain (García-Pinillos, Ruiz-Ariza, Moreno del Castillo, & Latorre-Román, 2015; Witvrouw, Danneels, Asselman, D'Have, & Cambier, 2003c). It can be proposed that due to the inability of the hamstring to stretch, the athlete has to overstretch the muscle to gain better performance which can put the muscle at risk of injury. However some findings report differently, stating that the hamstring flexibility is not a good indicator of future hamstring strain (Arnason, Andersen, Holme, Engebretsen, & Bahr, 2008; van Doormaal, van der Horst, Backx, Smits, & Huisstede, 2017). The non-persistent findings lead to obscurity of result interpretation. The influence of pelvic tilt while measuring the hamstring flexibility has been previously established (Sullivan, Dejulia, & Worrell, 1992). Research has yet to be done on soccer players to understand the effects of anterior pelvic tilt on muscle flexibility of the pelvis and hip region.

Strength for soccer players serves as a crucial component in terms of enhancing performance and preventing injury. Muscle strength deficiency is considered to be a risk factor proposed for hamstring injury (Dauty, Menu, Fouasson-Chailloux, Ferreol, & Dubois, 2016; Lee, Mok, Chan, Yung, & Chan, 2017; Orchard, Marsden, Lord, & Garlick, 1997). Apart from independent muscle strength, the balance between the agonist and antagonist muscle has also been argued to have predictive properties for determining an injury (Croisier, Ganteaume, Binet, Genty, & Ferret, 2008; Lee et al., 2017). Both conventional and functional ratios (Aagaard, Simonsen, Magnusson, Larsson, & Dyhre-Poulsen, 1998) of strength have been utilized as predictors for hamstring injury. The anterior pelvic tilt which disrupts the muscle balance in terms of length may also affect the force production via alteration in the length-force generation. According to the length-force curve when the muscle changes its length the amount of force production decreases due to changes in the cross-bridge connection in the actin and myosin (Plowman & Smith, 2013).

Considering previous studies related to soccer players, none have investigated the association between the pelvic tilt and related factors to hamstring injury such as muscle flexibility, kinematics, and muscle strength. Earlier studies suggest a supposed relationship between pelvic tilt and the mentioned factors, however the lack of empirical studies are evident. The aim of this study was to analyze the association of anterior pelvic tilt with hip and hamstring muscle flexibility, late swing phase kinematics and EMG while sprinting, and maximum concentric and eccentric isokinetic strength of the knee and hip muscles as well as their conventional and functional ratios.

2 Theoretical background

Repetitive movement with impaired form can elicit postural deviations which, over time, can change the normal movement pattern and influence our daily activities. Clinicians and sporting communities constantly strive to rectify the postural impairments, which they believe could lead to injuries and performance limitations. Athletes are also prone to postural deviations, some even been mentioned that certain malalignments may be advantageous in regards to performance enhancement (Yaniv et al., 2006). The medical definition for malalignment is an incorrect or imperfect alignment of the bones at the joint. It can be argued that postural changes can hamper the mechanics of the motion by modifying the muscular balance which ultimately predisposes an athlete to injury (Ribeiro, Akashi, Sacco, & Pedrinelli, 2003). Pelvic malalignments are among the postural deviations which an individual may suffer either in a singular or multiple forms. Since the pelvis is located near the centre of mass, any malalignment in this structure can significantly influence the movement pattern and translate it to the upper and lower extremities (Sasaki et al., 2015).

Anterior pelvic tilt is among the many malalignments which a person can suffer in the pelvis region. Presumably, excessive amount of anterior pelvic tilt disrupts movement patterns by altering the neuromuscular function. The changes in the neuromuscular function would lead to changes in the neural signal generation which ultimately impairs muscle related functions such as force generation and movement control. Regardless of how the changes small are an adaptation is expected to appear in both osteokinematic and arthrokinematic movements (Page et al., 2010). The changes in the osteokinematic and arthrokinematic movements can possibly invoke altered reciprocal inhibition. In general, when an individual suffers from a pelvis malalignment, they enter a faulty cycle (Figure 1) which can be broken by correcting the main cause i.e. anterior pelvic tilt.

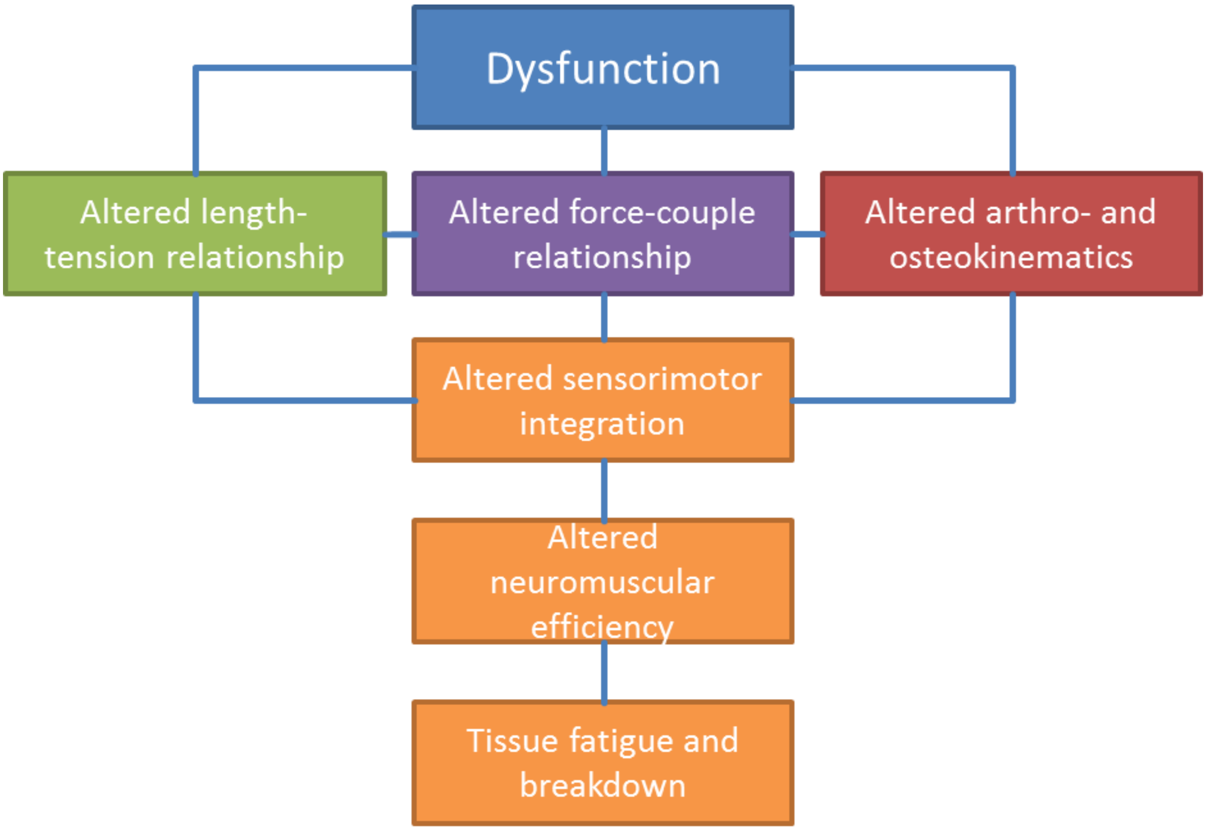


Figure 1 Human Movement Impairment (Clark et al., 2010)

Altered reciprocal inhibition, which is expected to be induced by anterior pelvic tilt, is a phenomenon that explains the source of muscle inhibition through the activation of the agonist muscle. The agonist muscle's neural activity would allow the antagonist to relax by decreasing the neural drive. This phenomenon happens every time when a movement is occurring, but when the agonist muscle is constantly under activation then prolonged inhibition is theorized to happen in the antagonist muscle. In the case of an anterior pelvic tilt, the constant activation of the hip flexors would ultimately inhibit the hip extensors (gluteus and hamstring) due to this phenomenon (Page et al., 2010). An inhibition in the muscle would cause weakening of the muscle reducing the capability to perform at its optimal level.

As the inhibited muscle reduces its tension it would become more pliable allowing the muscle to deform more easily extending its lengths, causing an elongation in the hamstring as the pelvis rotates anteriorly. The change in muscle length, which is a mechanical property of the muscle, is also related to other muscular properties, namely force production and the overall muscle length.

Pelvic malalignments are presumably prevalent in soccer athletes. Ganesh et al. (2014) investigated into this fact by assessing the pelvic for its various malalignments: anterior and posterior pelvic tilt, up and down slip of the innominate, out and inflare of the innominate and etc. in soccer players (Elumalai, Thangamani, Palayathan, Kumar, & Singh, 2014). Based on their findings the pelvic malalignments can present itself either unilaterally or bilaterally. In their follow up paper, after assessing 40 players from the national football team, over 92% of the players exhibited some form of pelvic malalignment (Elumalai, Declaro, Sanyal, Bareng, & Mohammad, 2015) with the anterior pelvic tilt being included. In their observation they witnessed that the frequency of the anterior pelvic tilt increased as the players' training commenced at the beginning of the season. Anterior pelvic tilt is regarded as an adaptive mechanism responding to high frequency repetitive movements, causing muscle imbalances.

Another study compared the pelvic alignment of 37 soccer players with 47 normal healthy subjects with no sporting activity. Radiography of the entire spine from the lateral/sagittal plane was obtained and certain parameters were calculated such as the kyphosis, lumbar lordosis and pelvic tilt for further evaluation (Wodecki et al., 2002). The groups were matched for sex and age. It was reported that soccer players tend to have higher pronounced anterior pelvic tilt and lumbar lordosis angle (Wodecki et al., 2002). Unfortunately no further data was available on the amount of pelvic tilt difference between the two groups. In comparison with the non-athletic population the literature suggests that soccer players due to the specific form of their training can develop an excessive amount of anterior pelvic tilt.

Ganesh et al. (2014) presented a schematic figure describing the possible muscular imbalances as result of an anterior pelvic tilt (Figure 2). This schematic figure, which has been often used by sport scientists, was also suggested by other communities such as NASM. Many may commonly refer to it as a lower-cross syndrome, since the muscles are diagonally either weakened/stretched or shortened/tightened.

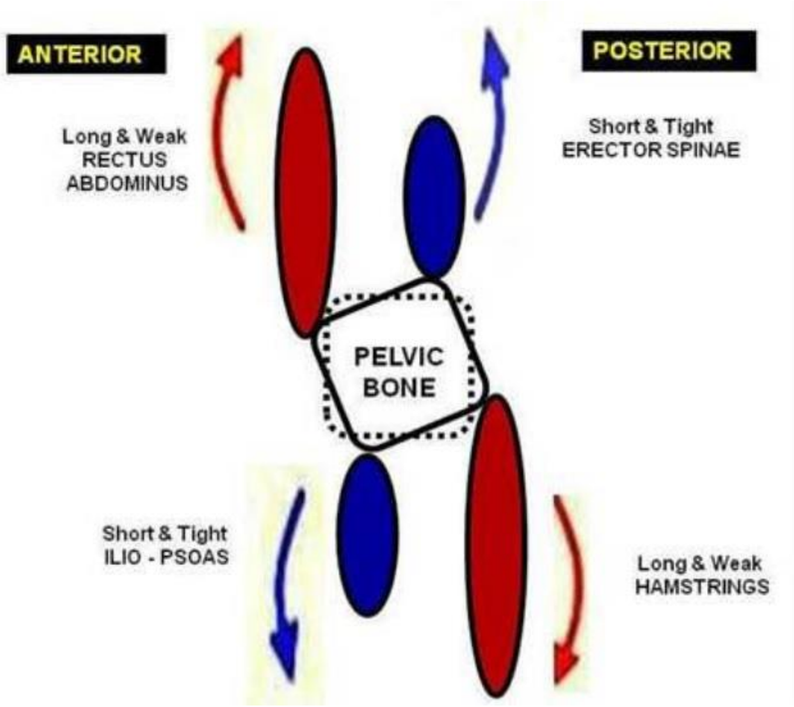


Figure 2 Muscle imbalances in anterior pelvic tilt (Elumalai et al., 2015)

Some studies support Ganesh's depiction of an anterior pelvic tilt muscle imbalance by reporting weakness of the rectus abdominus (Idoate, Calbet, Izquierdo, & Sanchis-Moysi, 2011) and muscle imbalances in the lower extremity in soccer players (Daneshjoo, Rahnama, Mokhtar, & Yusof, 2013). It is believed that the tightness of the iliopsoas, which is often used with specific soccer training, is responsible of the anterior tilt of the pelvis (Müller-Wohlfahrt, Ueblacker, & Hänsel, 2015). Uncertainty exists as to whether the muscle imbalances are the cause or the consequence of the anterior pelvic tilt; however, it seems that the muscular imbalances are likely to occur in soccer players as a result of specific repetitive movements which utilize certain muscles such as hip flexors.

The imbalances in the pelvic region are expected to impair the normal movement and muscular function with respect to mechanical changes in the pelvis. The alteration of the pelvis movement pattern and its adjacent joints during locomotion are the product of anterior pelvic tilt which have been mentioned to increase the risk of the injury of the hamstring (Cabello et al., 2015; Hoskins & Pollard, 2005a; Mendiguchia, Alentorn-Geli, & Brughelli, 2012; Opar, Williams, & Shield, 2012; Woods et al., 2004a). It was further explained that the anterior pelvic tilt will change the biomechanics and function of the hamstring and may lead to injury (Hoskins et al., 2005a). In their case report they mentioned that certain manipulations to the pelvic joint, which they believed that changes the biomechanics of the pelvis, resulted in an improvement in strength and flexibility of the hamstring without any reinjures (Hoskins & Pollard, 2005b). They discussed that a dysfunction in the pelvis' biomechanics, produces hamstring muscle insufficiency via thoracolumbar fascia system.

The thoracolumbar fascia system is proposed to have central role in sustaining postural stability of the body. The mechanical stability of the pelvis is crucial as it is located close to the centre of mass and any variations in this area would impinge on other segmental mechanics. Since thoracolumbar fascia system shares similar connection with the hamstring at the pelvis (Willard, Vleeming, Schuenke, Danneels, & Schleip, 2012) it is suggested that insufficiencies of this tissue would translate into the pelvis deficiencies and possibility the hamstring muscle. According to the report from Hoskin et al. (2005) the manipulation was performed on the pelvis and not the thoracolumbar fascia system, which advises the central role of the pelvic mechanics on hamstring muscle. Another significant improvement after receiving manipulation was the flexibility which was assessed pre and post treatment. The flexibility of the hamstring improved from 20 to 25 degrees as well as the flexibility of the hip flexors after receiving the manipulation. However it is questionable as to whether the treatment itself caused such an improvement or was it related to other factors.

Due to the origin of the hamstring muscle it is speculated that the changes in the pelvis' orientation would influence the function of the muscles surrounding it. It was proposed that the anterior pelvic tilt can be considered as a risk factor for hamstring injury. It was explained that the anterior rotation of the pelvis would increase the length of the hamstring thus increasing the tensile tension in the muscle which he considered it to be a possible risk factor associated with hamstring strain (Woods et al., 2004a). Another research further clarifies the mechanism by stating that the excessive elongation increases the muscle tension resulting in an increment of the tensile load experienced by the hamstring during the late swing phase (Opar et al., 2012). In another interpretation it was mentioned that the pelvic stability may prevent injuries of the hamstring. The stability mentioned by Mendiguchia is presumably the range of motion of the pelvis which it undergoes while performing activities such as sprinting. The range of motion of the pelvis is normally limited by the muscles, ligaments surrounding it (Mendiguchia et al., 2012). The suggestion that the anterior pelvic tilt can be considered as a plausible risk factor for hamstring injury is mentioned only for the non-contact incidents which commonly occur during a sprint. In order to understand how the orientation of the pelvis would contribute to the outcome of a hamstring strain while performing a sprint, it is necessary to present a clear definition of muscle injury in terms of biomechanics.

Various definitions of injury have been proposed throughout the recent years; one of which states that the damage sustained by the tissue of the body in response to physical trauma (Whiting & Zernicke, 2008). Determining the cause of an injury is not limited to a certain factor. It is clear that the orientation of the pelvis is not solely responsible for a hamstring injury; however it has been suggested by multiple studies that it may play a role in increasing the susceptibility of it. Preventing an injury especially the non-contact form, involves identifying multiple risk factors that may contribute to the occurrence of an injury. A multifactorial model is presented in figure 3 which showcases the multiple factors associated with injury (Meeuwisse, 1994).

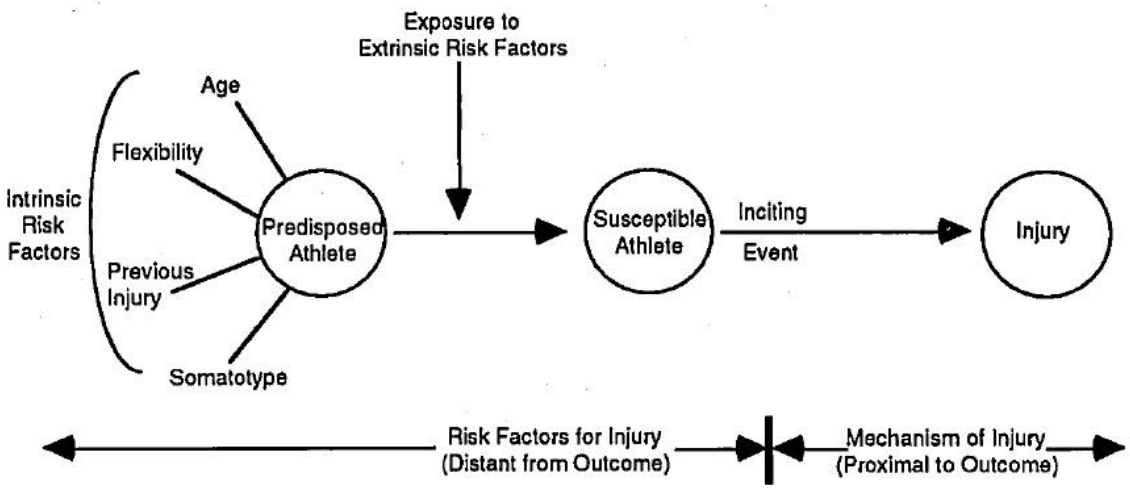


Figure 3 Multifactorial model of athletic injury aetiology (Meeuwisse, 1994)

2.1 Anterior pelvic tilt kinematics during swing phase of a sprint

In order to understand how the pelvic tilt can contribute to the non-contact form of a hamstring injury, it is mandatory to analyze the mechanisms where the hamstring is suggested to be at a higher risk of sustaining a strain during the sprint. Assessing the movement of the pelvis, hip and knee, which are influenced by the hamstring, from the sagittal plane, would provide us with valuable insight of how these joints coordinate in a sprinting motion. A sample swing phase simulation during sprint was illustrated in previous researches (Figure 4); however no kinematic value has been depicted in the past researches.

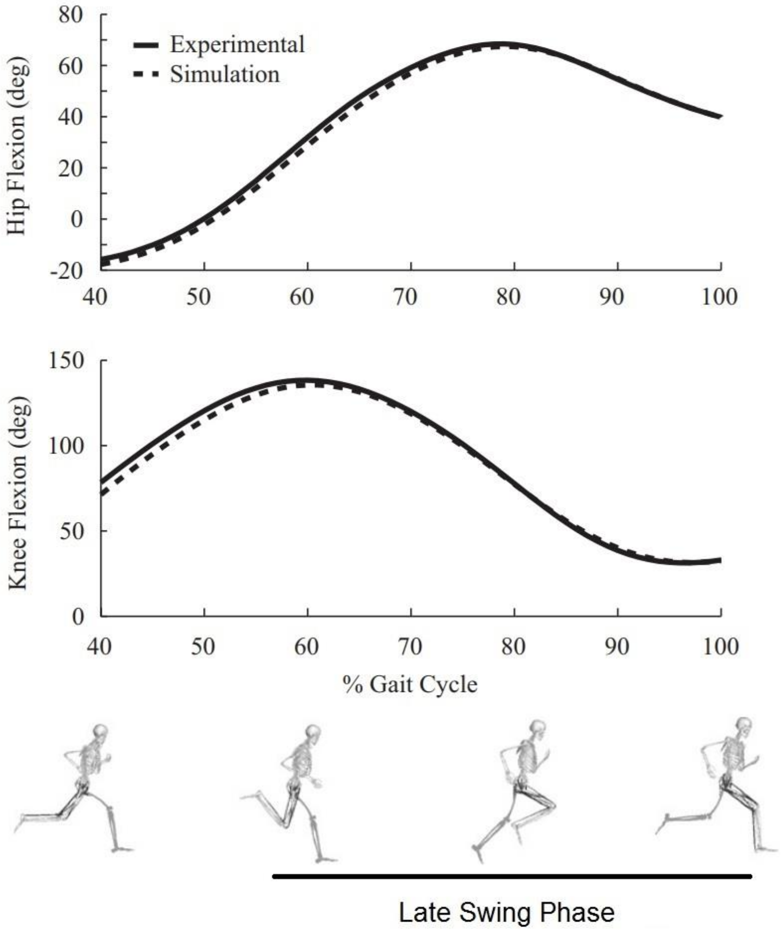


Figure 4 Hip and knee kinematics illustrated using data collected from athletes (experimental data) and inverse dynamics (simulated data) for an entire swing sprint cycle (in relation to the entire cycle) with the late swing phase depicted under the graphs. Late swing phase: the start of knee extension from maximum flexion during swing (Chumanov et al., 2007)

Starting from the pelvis' mechanics it has been exhibited that the movement pattern remains relatively same from walking to sprinting. Although the pattern remains similar for all velocities, the angular magnitude of the tilt increases as the speed of locomotion increases from walking to sprinting (Figure 5) (Novacheck, 1998). As the locomotion speed increases, the magnitude of the angular displacement is expected to rise. It is presumed that higher amplitudes of angular displacement might explain the amount of strain that happens during a sprint and not during normal walking or running speeds. Considering the hamstring's line of action, by looking at its anatomy, it is discerned that the main function of the muscle is knee flexion, hip extension and posterior tilt of the pelvis. Since all of these movements happen at the sagittal plane assessing the biomechanics of the sprint from this plane would provide a better understanding of the muscle contribution.

The mean pelvic tilt during running oscillates from 15 to 20 degrees anteriorly (Schache, Bennell, Blanch, & Wrigley, 1999). As the speed of the locomotion increases the amount of anterior pelvic tilt rises. During running at the beginning of the swing phase the pelvis tilts posteriorly and as it progresses towards the terminal phase the pelvis begins rotates anteriorly (Ounpuu, 1990). However higher angles are to be expected as the speed increases and the motion changes from running to sprinting. The difference between running and sprinting in terms of biomechanical changes are considered to be the stepping kinematics namely the stride rate and stride length.

As the speed of the locomotion increases the stride length and stride frequency work in conjunction to respond to the demands of the high velocity. Up to 7.0 m/s most of the speed gain occurs from changes in stride length and speeds above that are mainly achieved by increasing the stride frequency (Mero, Komi, & Gregor, 1992). it is recognized that stride length is responsible for the angular changes in the human locomotion in comparison to stride frequency (Huang et al., 2010). Presumably one could expect greater anterior pelvic tilt as the stride length reaches its peak. Conversely Novacheck (1998) stated that little difference can be observed for the magnitude of the pelvic tilt angle between the running and sprinting motion which seems to be related to the insignificant difference between the two velocities measured by the author (Run = 3.2 m/s, Sprint = 3.9 m/s). In the same paper another group category classified as elite sprinters which have an average speed of 9.0 m/s, show considerable amount of angular changes from normal sprint i.e. 3.9 m/s to elite sprint i.e. 9.0 m/s in the knee joint flexion-extension motion (Figure 6) (Mann & Hagy, 1980). Although the finding proposed by Noacheck (1998) seems to have significant impact for normal running analysis it lacks the sprinting variable due to insufficient speed presented in this study. Typically it has been recorded that soccer players have a peak sprinting velocity of 8.1 m/s – 9.7 m/s (Haugen, Tønnessen, Hisdal, & Seiler, 2014; Rampinini, Coutts, Castagna, Sassi, & Impellizzeri, 2007). So certain kinematic changes are to be expected to happen as the motion changes from running to walking as the stride length reaches it maximum stated when reaching the 7 m/s mark.

High amount of anterior pelvic tilt can put great strain on the hamstring which can increase the risk of injury during a sprint (Dugan & Bhat, 2005). During a sprint the pelvis would reach its highest anterior pelvic angle twice: toe-off and at the late swing phase (Franz, Paylo, Dicharry, Riley, & Kerrigan, 2009). Peak values can be represented as the indication where it is possible that the hamstring would face a potential injury. Abnormal pelvic mechanics, as mentioned previously, can lead to muscle imbalances in the pelvis region (Nicola & Jewison, 2012) which in itself can modify the kinetic chain of movement. During a static measurement the pelvic rotation is significantly influenced by hip flexion and knee flexion angle (Congdon, Bohannon, & Tiberio, 2005). The question however remains whether the excessive amount of pelvic tilt in the stationary mode (static standing) can also be generalized to the amount of pelvic tilt during a sprint and how it would influence the biomechanics of the adjacent joints such as the hip or the knee.

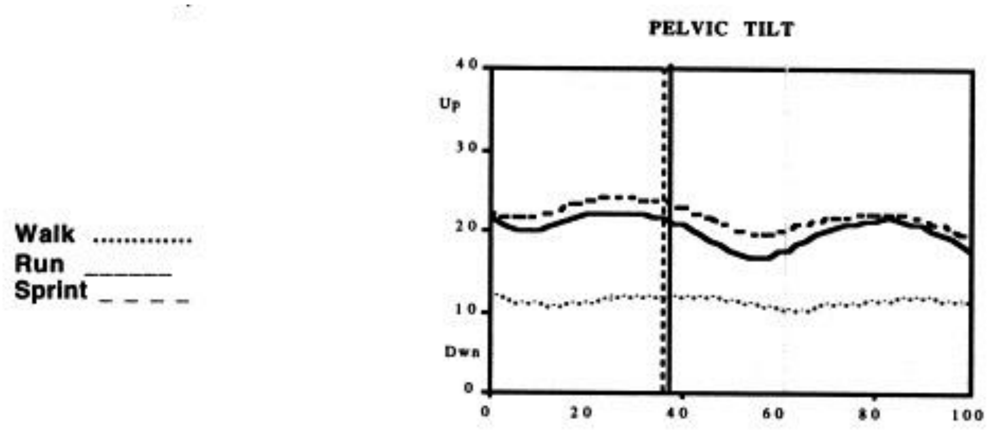


Figure 5 Changes in the position of the pelvic in the sagittal plane during an entire gait cycle. The vertical dashed line represents the toe off. Walking is represented by the lightly-dashed line, running the solid line, and sprinting the heavy-dashed (Novacheck, 1998).

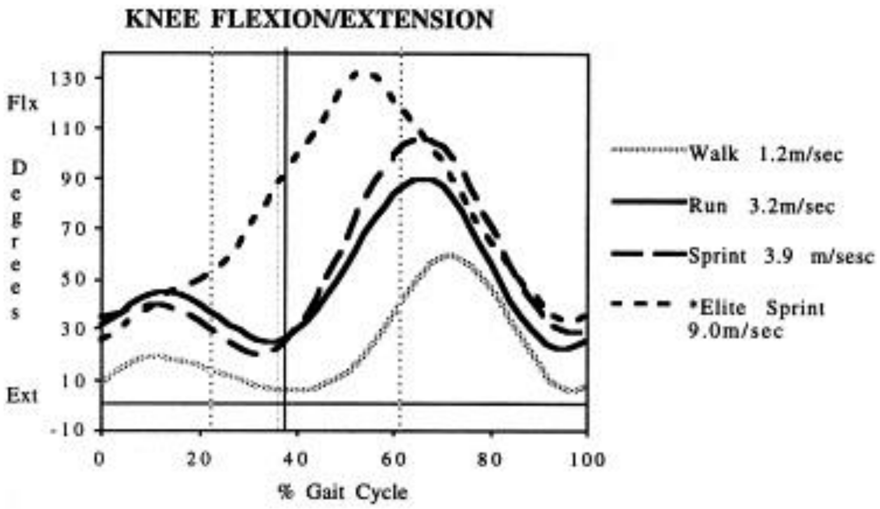


Figure 6 Knee motion during the entire gait cycle: Knee flexion-extension denotes the angle between the femur and the tibia. 0° indicates full extension, vertical lines represent toe off at each speed with respect to their curve (Novacheck, 1998).

2.2 Hip kinematics during swing phase of a sprint

The hip motion plays a significant role during the swing. During the swing while running the hip reaches 80 degree at full flexion (Figure 7). As the speed rises to sprint, hip flexion increases to almost 130 degrees and starts extending at the second half of the swing which would allow the avoidance of excessive deceleration that would occur at the time of initial contact (Novacheck, 1998). During the swing phase, the hip would flex and continue flexing through the first two third until a maximum position is reached. The degree of hip flexion during swing phase shows the most consistent and dramatic increases with faster running. The more the hip is flexed the longer stride length (Deshon & Nelson, 1964).

At the end of swing phase, while running, it is observed that the hip is slightly flexed. It is believed that the hip flexion at ground contact helps absorb the initial contact force (Dillman, 1975; Mann & Hagy, 1980). The increase in the hip flexion aids the athlete to achieve longer stride length given them the advantage in performance (Novacheck, 1998). In the swing phase the hamstring coordinates extension at the hip and prevent extension at the knee (Koulouris & Connell, 2005). Inflexibility of the hamstring muscle complex limits the range of motion of the hip in a way that prevents full hip flexion unless the knee is in the flexed position (Kaeding & Borchers, 2014). Presumably since the pelvis is the origin of the hamstring it is expected that the pelvis would also influence the hip motion during the sprint. One study found that there is a correlation between hip and pelvic movement both in running and walking (Franz et al., 2009). Schache et al. (2000) described that the anterior pelvic tilt has a positive correlation with hip extension during running. They proposed that this limitation in range of motion may arise from the inflexibility of the soft tissue which would determine the path of the least resistant movement (Schache, Blanch, & Murphy, 2000). However it is still debatable whether the anterior pelvic tilt would result in a change of kinematics of the hip during a sprint.

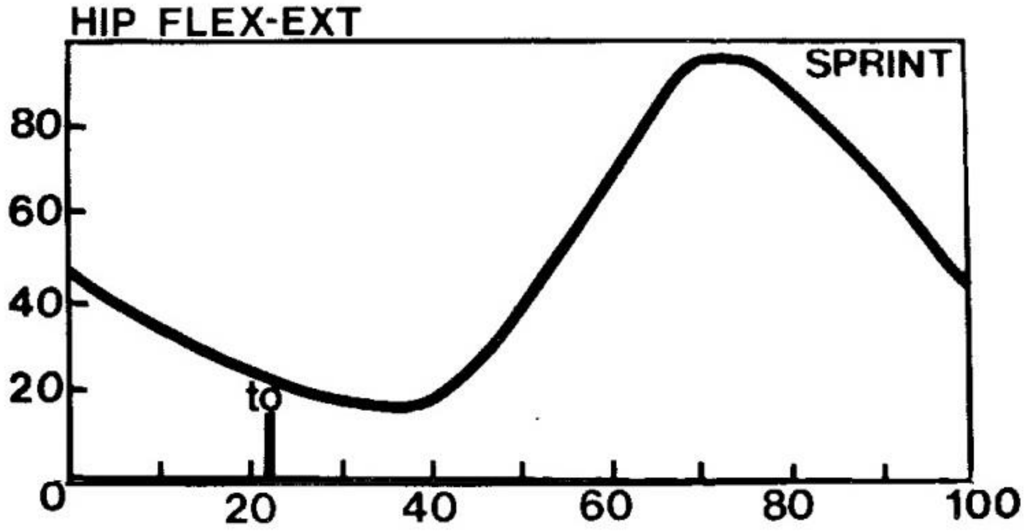


Figure 7 Hip range of motion during sprint. To = toe off, y-axis: units in degrees (Novacheck, 1998)

During the floating phase the athlete experience anterior pelvic tilt and hip flexion that is caused by the psoas and other pelvic muscles (Nicola et al., 2012). The floating phase is when the athlete has no ground contact having both their legs in the swing phase. It is during this phase where the motion of the pelvic also manipulates the kinematics of the hip (Dugan et al., 2005). Nevertheless the changes in the kinematic are proposed to happen at the beginning of the swing phase not during late swing phase. The hip motion during late swing phase remains unclear especially when analysing the entire movement.

2.3 Knee kinematics during swing phase of a sprint

During the swing phase the knee is expected to be maximally flexed between 90° and 130° depending on the speed (Figure 8). At this stage the knee is flexed passively to prevent strain from happening at the hamstring (Thelen, Chumanov, Hoerth, et al., 2005). As the knee reaches its maximum flexion it starts extending during the late swing phase where the quadriceps function to extend the knee (Nicola et al., 2012). The pattern of knee motion has been said to be identical across all speed only the extremes of motion are considered to be different (Novacheck, 1998). The extreme angles would be significantly influenced if the athletes where to deliberately over stride, amounting to the tension and strain the hamstring experiences. The late swing phase is considered as the stage where hamstring muscle is at its most venerable state for injury. At this stage the hamstring is at its maximal length and maximal muscle unit eccentric contraction, increasing the risk of an acute strain (Thelen, Chumanov, Best, Swanson, & Heiderscheit, 2005; Thelen, Chumanov, Hoerth, et al., 2005). Coordination in the pelvis, hip and knee is essential to maintain while sprinting as the hamstring contributes to each of their movements. It can be anticipated that extreme cases of movement variations can enforce high tensile load on the hamstring increasing the risk of developing a hamstring strain.

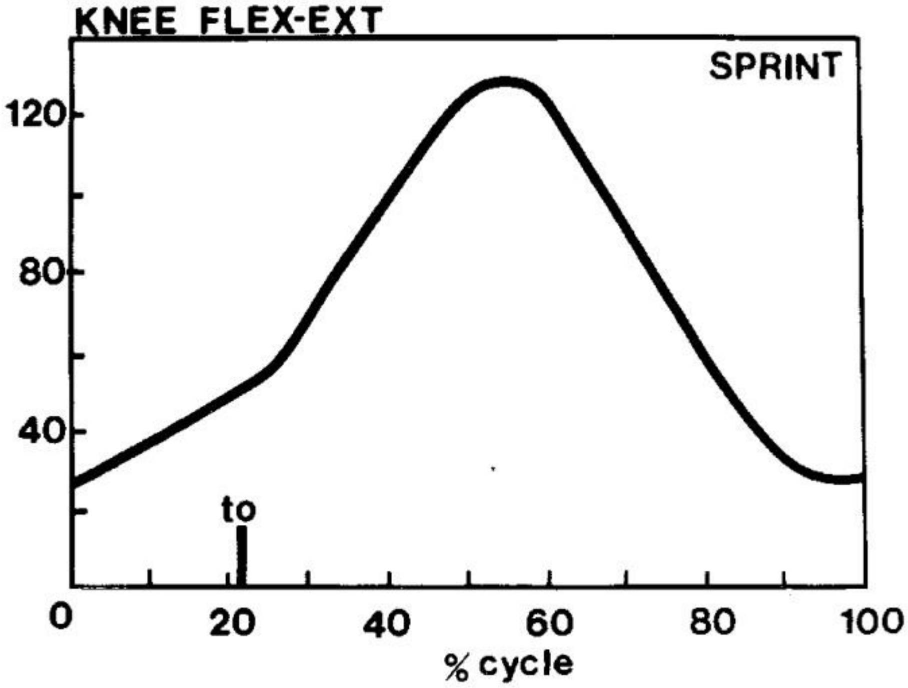


Figure 8 Hip range of motion during sprint. To = toe off, y-axis: units in degrees (Novacheck, 1998)

2.4 Kinematics of muscle strain during sprint

Understanding the mechanism of muscle strain from a biomechanical perspective is important to further our understanding of the influence of joint mechanics on muscle function. A simplistic definition is mandatory from a mechanical point of view to comprehend the biomechanics of muscle strain. Strain is a result of fiber tears when the internal force exceeds the mechanical limits of the tissue (Garret, 1990). Both forms of micro and macro tears, when distinguishable by either MRI or ultrasound, can be identified as strain (Volpi, 2015). Several factors can be involved which may impede the muscles’ mechanical limit i.e. smaller internal force production (Whiting et al., 2008). One way of altering the amount of internal force is by changing the muscle length through variation of its spatial orientation of insertion or origin. Navarro et al. (2015) explains the biomechanics of the hamstring strain in soccer players and how the pelvic alignment possibly increases the susceptibility of a hamstring strain. Their biomechanical model for understanding the injury mechanism in the hamstring is based on Newton’s Second Law ($F = ma$) with the biceps femoris been chosen as the reference. He specifically focuses on the late swing phase, where the deceleration of the shank occurs, which is reported to be the onset of the hamstring strain (Chumanov et al., 2007; Chumanov et al., 2012; Higashihara, Nagano, Ono, & Fukubayashi, 2016). Evidence suggests that deviation in the running kinematics and rate of injury are correlated (Nigg & Bobbert, 1990; Schuermans, Van Tiggelen, Palmans, Danneels, & Witvrouw, 2017). Figure 9 depicts the forces acting upon the muscles during the late swing phase where the positive forces are implicating the forces attempting to shorten the muscle and the negative forces are implicating the forces attempting to lengthen the muscle.

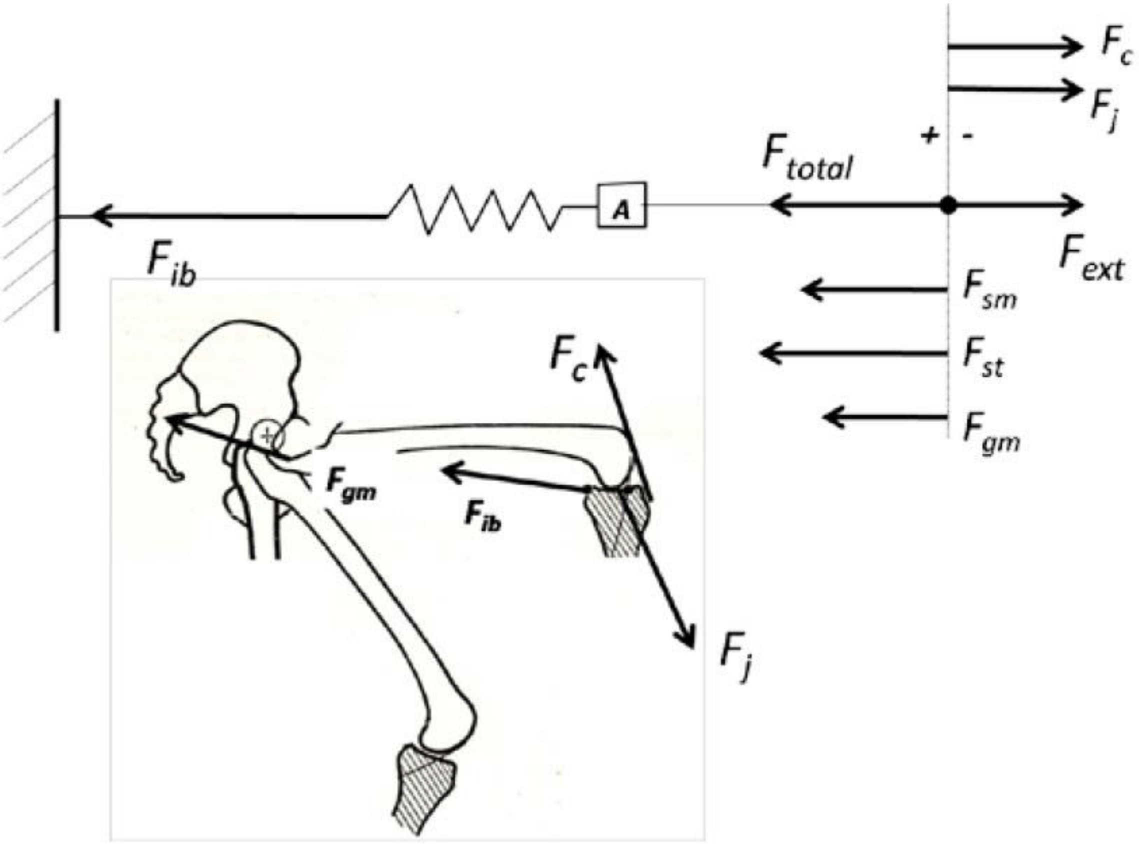


Figure 9 Force applied in the shank during knee extension (Cabello et al., 2015)

Where F_{ib} is the biceps femoris force, F_{st} is semitendinosus force, F_{sm} is the semimembranosus force, F_{gm} is the gluteus maximum force, F_c is the quadriceps force, F_j is the tibia knee joint force, F_{ext} is the external force, F_{total} is the total force and A is the shank's mass. The hamstring, during the late swing phase, contracts eccentrically to control the extension angular momentum in the knee for contact preparation and injury avoidance. In order to reduce the angular velocity of the shank the F_{total} has to be positive. Which means the amount of force shortening the muscle should be greater than the amount lengthening it. One reason which an injury can occur is the shortening forces are smaller than the lengthening forces which results in forcefully elongating the muscles in the process. In other words the inability of the hamstring to produce adequate force would result in its injury. If the elongation reaches the mechanical limit, tissue failure is possible (Whiting et al., 2008). Hamstring and gluteus muscles work synchronously having the same objective to decrease the knee extension momentum (Cabello et al., 2015). The function of the gluteus muscle is dependent on the positioning of the pelvis. Proper pelvic stability avoids excessive anterior pelvic tilt, preventing extreme elongation of the hamstring (Franz et al., 2009; Mendiguchia et al., 2012) which can also cause premature fatigue (Geraci Jr, 1996; Klein & Roberts, 1976). From a biomechanical perspective, it conceivable that the changes in the pelvic position i.e. anterior pelvic tilt can increase the susceptibility of a hamstring injury incident.

A form of decreased stability of the pelvis movement can present itself after induced fatigue which ebbs muscle control from maintaining a stable pelvic position. In a study by Small et al. (2009) they found that after the soccer-specific aerobic field test (SAFT^{90}) impairment in sprinting biomechanics were observed. The muscle fatigue can be exacerbated as the amount of actin-myosin cross-bridge interactions decreases (Fitch & McComas, 1985), which happens when the muscle is elongated. Maximum hip flexion and knee extension were significantly reduced as well maximum anterior pelvic tilt was increased as a result of fatigue (Figure 10). In their schematic representation they showcased and generalised the alteration of the pelvis's kinematics for all three critical stages of a running gait namely: take-off, recovery, and late swing phase. They argued that the increased pelvic tilt in combination with lower extremity velocity increases the potential risk of sustaining a hamstring injury while sprinting (Small, McNaughton, Greig, Lohkamp, & Lovell, 2009). As the fatigue rises the ability to control segmental motion deteriorates allowing the pelvic to oscillate to higher amplitudes. The impairment in stabilizing the pelvic would also put their surrounding muscles and tissues in high risk of sustaining an injury.

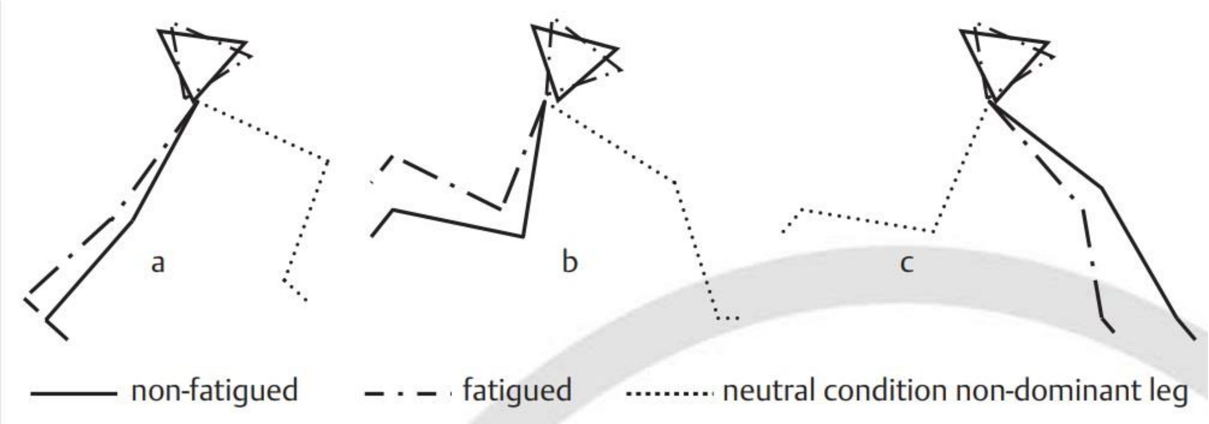


Figure 10 Schematic representation of sprinting stride comparison between non-fatigued and fatigued condition. a = take-off, b = recovery part of swing phases, c = end of swing phase / initial contact (Small et al., 2009).

Allegedly fatigue is not the only factor which can distort the position the pelvis, by placing it in extreme angles. Muscular dysfunctions such as tightness, hypertonicity of the pelvic muscles can place the pelvic at extreme angles. It was proposed that the increase of the anterior pelvic tilt, imposed by the iliopsoases muscle, induces greater hamstring stretch at the late swing phase; increasing the risk of sustaining an injury (Heiderscheit et al., 2010). The tightness of the iliopsoas can cause the pelvis to tilt to a higher anterior angle resulting in lengthening of the hamstring. They point out that the flexibility and stretching of the iliopsoases muscle should be taken into consideration to avoid hamstring strain. The lengthening of the hamstring is considered at its peak during the late swing phase.

Generally it is believed that the late swing phase of a sprint to be the onset of a non-contact hamstring injury. The eccentric contraction and the energy absorption of the hamstring during this phase increases the susceptibly of the hamstring to sustain an injury (Chumanov et al., 2012). The nature of the eccentric contraction is forcibly stretching the muscle while contracting. One factor which can augment the amount of lengthening is to tilt the pelvic anteriorly. This way the hamstring would go under a great amount of tensile strain as it tries to control the shank motion which eventually increases the risk of sustaining a hamstring injury.

This notion is forwarded in a study by Schache et al. (2010) in which they clarify the role of hamstring during the late swing phase. During this phase the hamstring is responsible for hip extension torque and knee extension torque. Simultaneously during their measurements one subject suffered a hamstring strain while performing a sprint. The average sprinting speed was recorded at 7.44 m/s and at the injury trial it was registered at 6.93 m/s. By using inverse dynamics they discovered that prior to the injury the subject demonstrated an increase in hamstring length and force production. Figure 11 depicts the force production of the right leg prior to injury while sprinting. Immediately hamstring showed a reduction in peak length and force at this phase indicating intolerance to perform an eccentric contraction (Schache, Kim, Morgan, & Pandy, 2010). The length of the hamstring prior to injury rose significantly prior to injury, from 0.15% stretch relative to the resting muscle-tendon unit length to 6.83% indicating a 0.62% increase in length. The amount of muscle force prior to the injury increased by 6.2% and occurred 21.7 ms earlier during the swing phase. However Schache et al. (2010) did not argue as to why and how the earlier occurrence of force production can lead to a hamstring strain incident. Overall he concluded that the late swing phase to be the phase where the hamstring is susceptible to strain.

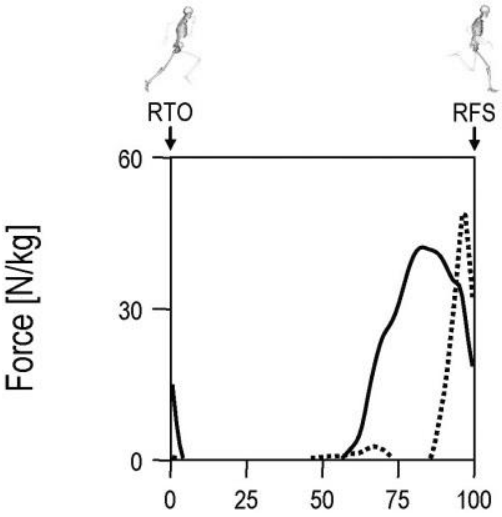


Figure 11 Hamstring force. Data are for the right leg for a single representative pre-injury trial (solid line) compared to the injury trial (dotted line). RTO, right toe-off; RFS, right foot-strike (Heiderscheit et al., 2005).

In a case study Heiderscheit et al. (2005) also recognised the late swing phase as the period of sustaining a hamstring injury. The subject was running at 5.36 m/s with a 15% incline on the treadmill as he suffered a strain. According to their findings, the biceps femoris musculotendon length reached peak length which was 12% beyond the length of the normal upright posture (Heiderscheit et al., 2005). They mentioned that due to the smaller moment arm of the biceps femoris (Arnold, Salinas, Hakawa, & Delp, 2000) muscle it is more likely to suffer a strain in this muscle compared to the semimembranosus and semitendinosus. With regards to the moment arm the shorter the moment arm the more force it is exerted on the muscle to control the motion of the lower leg. Only maximum angles which are not a suitable representative for foot strike angles, Kim et al. (2014) found that as the incline of the treadmill increases so does the inclination of the pelvic towards an anterior tilt (Kim & Yoo, 2014). In addition the knee extension angle also increases as the inclination is raised. Although Heiderscheit et al. (2005) describe the musculotendon junction as the site of injury during the late swing phase. Later the muscle belly was identified as the site of injury (Yu et al., 2008). They described the difference in findings as to the method for calculating the change of length in the muscle unit. Yu et al. (2008) mentioned that he utilized the absolute length changes rather than relative change while standing. In a study it was shown that using the standing position as a baseline for calculating relative changes was not a valid approach towards musculotendon length when using computer simulation modelling techniques (Wan, Qu, Garrett, Liu, & Yu, 2017b). The role of speed in the locomotion on the hamstring mechanics should be considered as well as the changes in the pelvic motion. In both previous case studies it is made clear that the speed was considered relatively high close to 7.0 m/s where it is expected to observe changes in the stride length to gain speed.

As the speed of the locomotion increases the contribution of the muscles surrounding the pelvic influences the hamstring susceptibility. As the speed rises from running to near maximum speed the amount of hamstring contribution during the late swing phase increases (Figure 12) (Higashihara, Ono, Kubota, Okuwaki, & Fukubayashi, 2010).

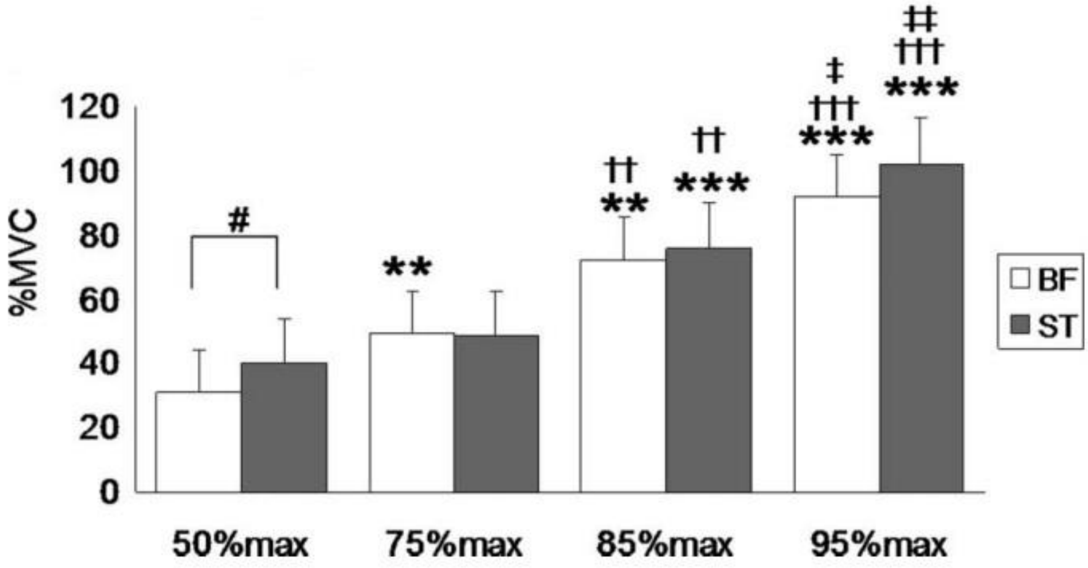


Figure 12 Mean (± s_x) %MVC values for the biceps femoris (BF) and semitendinosus (ST) muscles at each phase during different running speeds. *P<0.05; **P<0.01; ***P<0.001 (vs. 50%max); † P<0.05; ††P<0.01; †††P<0.001 (vs. 75%max); ‡P<0.05; ‡‡ P<0.01 (vs. 85%max); #P<0.05; ##P<0.01; ###P<0.001 (BF vs. ST) (Higashihara et al., 2010).

Chumanov et al. (2007) explain the mechanics of hamstring at the late swing phase of a sprint where the contribution of the muscles is accounted for. They describe that as the speed of the locomotion increases the influence of muscle activity which contributes to the pelvic motion and eventually on the hamstring length is notable (Figure 13). Using a forward dynamic simulation they argued that the iliopsoas influences the amount of stretch on hamstring muscle especially on the biceps femoris. They reason that the hamstring is more susceptible to injury during the late swing phase based on the amount of negative work (Thelen, Chumanov, Best, et al., 2005) performed and fluctuations of neuromuscular control at high speed (Chumanov et al., 2007). These fluctuations would ultimately effect the stretch-shortening cycle by altering the compliance of the contractile element and changing the threshold of injury (Butterfield & Herzog, 2005b). The implication of high tensile loads while contracting eccentrically can be observed in the electromyography data where it was found that the EMG of the biceps femoris rises during the late swing phase (Higashihara, Nagano, Ono, & Fukubayashi, 2015). EMG data from the hamstring muscles could be associated with the angles of the hip and knee joint while going under eccentric contraction as they rose prior to foot contact. The EMG data is also in accordance with force production and length changes while using the inverse dynamics system (Thelen, Chumanov, Sherry, &

Heiderscheit, 2006). The iliopsoas is a muscle where it has the ability to tilt the pelvic anteriorly which can justify the amount of influence on the hamstring stretch during the late swing phase.

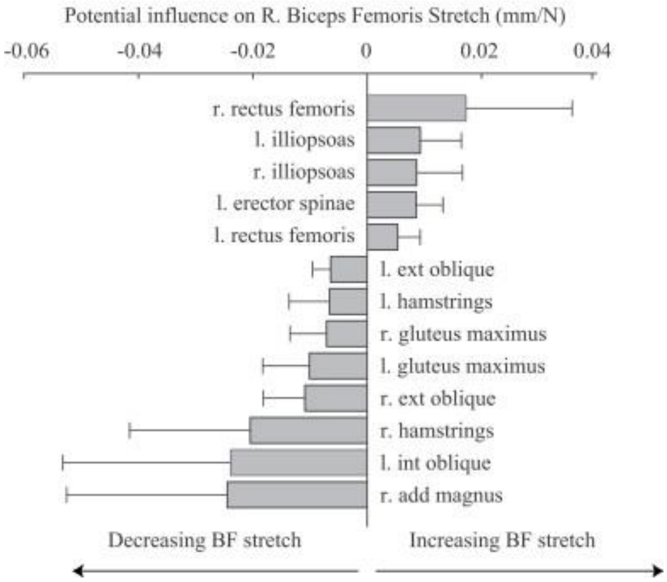


Figure 13 Muscle Contribution to the amount of hamstring stretch (Chumanov et al., 2007)

The importance of the muscle function at the pelvic region was emphasized (Thelen et al., 2006). They describe that perturbation of the muscles in the trunk and pelvic region induces a greater hamstring stretch. One can speculate that the existing anterior pelvic tilt, which itself is a result of muscular imbalances would disrupt the muscular function of the hamstring even putting it at high risk of injury (Clark et al., 2010). The increase in the anterior pelvic tilt it is believed to effect the kinematics of the adjacent segments causing a susceptibility to injury (Higashihara, Nagano, Takahashi, & Fukubayashi, 2015). Higashihara et al. (2015) observed when athletes attempt to run with a flexed trunk position it would greatly influence the hamstring muscle length. The forward lean caused the pelvic to rotate anteriorly increasing from 2.6 degrees to 12.8 degrees at foot contact. The entire musculotendon unit of the hamstring at foot strike also showed increase in their length. They explain the reason behind this phenomenon as the direct effect of trunk flexion on pelvic position. As the trunk flexes anteriorly so does the pelvis and as a result it influencing the hamstring length (Higashihara, Nagano, Takahashi, et al., 2015). It has also been mentioned that it could be possible when the athlete is attempting to decelerate from a high velocity sprint; they are inclined to lean forward to reduce the speed. This forward flexion motion of the is suggested to place additional eccentric load similar to what would happen when the pelvic is rotated forward (Volpi, 2015).

Mechanics of the lower extremities are influenced as a result of anterior pelvic tilt. It was mentioned that the anterior pelvic tilt had a correlation with hip peak range of motion during running (Schache et al., 2000). They pointed out that the flexibility of the muscles in the hip region may be a result of the alteration in the dynamics of the hip. Similar results were reported which showed that an increase in the pelvic tilt resulted in an increase of the knee flexion and hip flexion angles (Higashihara, Nagano, Takahashi, et al., 2015). Muscle length changes in hamstring can be the result of pelvic orientation, hip and knee flexion. Previous studies observed that the majority of length changes in the hamstring was attributable to hip flexion and not knee flexion (Thelen, Chumanov, Best, et al., 2005; Visser, Hoogkamer, Bobbert, & Huijing, 1990). According to the reports the hamstring length and function would be correlated with not just the knee angular position but the pelvis' orientation as well as hip flexion-extension motion.

Anterior pelvic tilt was found to reduce the peak hip extension while running (Franz et al., 2009). They mentioned that these changes in hip motion may be traceable to flexibility changes of the muscles surrounding that region. Other possibilities may include bone to bone contact of the hip and pelvis and/or soft tissue contact or restriction such as muscle bulk or ligament, tendon and capsule restrictions (McGinnis, 2013). One article suggests that the pelvic imbalances i.e. anterior pelvic tilt increases the functional load on the hamstring in terms of tensile stress on the hamstring. The author also suggests that increasing the hamstring flexibility should be targeted to reduce the amount of tensile load (Panayi, 2010). The pelvic orientation appears to modify certain aspects of the hamstring muscle such as their flexibility.

Generally it appears that the pelvic orientation during the late swing phase of a sprint significantly influences both the mechanics of the adjacent segments such as the hip and the knee and also impacts the muscular function as well. These changes supposedly increase the risk of a hamstring injury during the late swing phase while sprinting; however it is still debatable whether the anterior pelvic tilt present in the static posture would translate its alteration to sprint kinematics.

2.5 Pelvic tilt and flexibility

Flexibility is considered as an important risk factor for predicting hamstring injury in soccer players. Insufficient hamstring flexibility has shown to be correlated with hamstring strain (Witvrouw, Danneels, Asselman, D'Have, & Cambier, 2003a). The flexibility of the hamstring is particularly important for the non-contact injury incidences which happen at the late swing phase. Hamstring length has a negative correlation with peak hamstring strain at the late swing phase of a sprint (Wan et al., 2017a), meaning that as the flexibility increases the amount strain endured decreases. Anatomical features such as posture and attachment sites are considered an example of many determinants which can influence the overall flexibility of the muscle. It is believed that the pelvis's orientation can change the amount of hamstring's extensibility in addition to other muscles attached to the pelvis. When a joint angles changes i.e. anterior pelvic tilt; the distance from the muscle origin to the insertion (length of the muscle-tendon complex) also changes. Information regarding as to how the pelvic tilt would contribute to the extensibility of the muscle, could provide valuable knowledge for soccer players.

Although it is widely believed that limited flexibility increases the risk of hamstring injury, but recent studies have found little to no relationship between the hamstring flexibility and injury (van Doormaal, van der Horst, Backx, Smits, & Huisstede, 2016; van Dyk, Farooq, Bahr, & Witvrouw, 2018). The inconsistencies between the findings lie in methods used to assess the hamstring's flexibility. Using the sit-and-reach a flexibility test is considered a questionable method (van Doormaal et al., 2017). Low reliability compared to the active knee extension test, which is considered as the golden standard for assessing hamstring flexibility, (Ayala, Sainz de Baranda, De Ste Croix, & Santonja, 2012; Davis, Quinn, Whiteman, Williams, & Young, 2008) indicates that it is not considered to be an accurate method for assessment.

Although a decrease in hamstring flexibility for the injured group was reported by a recent study, but nonetheless they considered it to be a weak risk factor due to the small effect size ($d < 0.2$) (van Dyk et al., 2018). Aside from accurate test the values of which the population should be classified modifies the test results. Van Dyk did not however grouped their participants according to the suggested recommendation of physiotherapists (Magee, 2013) for hamstring flexibility. Magee (2013) stated that an individual who cannot reach the 20 degree range of full knee extension is considered to have tight hamstring. By examining the data from van Dyk et al. (2018) it could be seen that the mean values for injured and non-inured group are within the 20 degree range of full extension. Methodological inaccuracies and differences can lead to inconsistency of the findings resulting into false interpretation. It was mentioned that pelvic tilt significantly influences the hamstring's extensibility, so it would seem reasonable to control the pelvic region while attempting to measure the flexibility of the hamstring.

The mechanism of how the flexibility will predict a hamstring injury can be described through the neural reflex system and its role in a sprint. During the sprint the hamstring particularly goes under a stretch-shortening cycle which has been found to induce micro strains per cycle (Butterfield & Herzog, 2005a). Stretch immediately followed by shortening is called the stretch-shortening cycle (SSC). SSC is influenced by two reflex mechanisms: 1. the stretch reflex 2. The Golgi tendon organ (GTO) reflex (Zatsiorsky & Prilutsky, 2012). The stretch reflex, also called myotatic reflex, operates on a length feedback control system. When a muscle is stretched, the muscle spindles, the sensory receptors within the muscle belly, are also stretched and their activity increases. The increased activity of the spindles provides direct excitatory feedback to the alpha motor neurons innervating the muscle. As a result, the muscle contracts and its length decrease. The GTO functions as a tension-feedback control. The receptors are located in the muscle-tendon junction which detect the muscle tension and behaves as an inhibitory reflex system. This reflex is to prevent muscle and tendon injuries. These reflexes are regulated by the muscles initial length. As the muscle lengths the amount of response after the stretch would decrease (Polus, Patak, Gregory, & Proske, 1991) and the timing of force production of the concentric phase delays (Finni, 2001). Furthermore initial longer muscle length has shown to have altered eccentric enhancement forces at real-time. A previous study reported the inability of the longer muscle lengths, which can be accomplished through larger angles, to produce eccentric force which can expose the muscle to injury (Cutlip et al., 2004). The combination of these findings shows that longer length may not serve beneficial in terms of injury prevention.

The flexibility of a muscle is not just important to avoid injury, it is also essential for optimal performance. The effect of acute stretching bouts on 40m sprint performance was investigated. Although no significant changes were found between two groups there was a significant correlation between the sit-and-reach baseline score and mean changes of velocity (Favero, Midgley, & Bentley, 2009). The change in velocity can be justified through the alteration of the stride length or changes in the kinematics of the lower extremity. In a study the simulated effect of short hamstring in running kinematics was conducted (Whitehead, Hillman, Richardson, Hazlewood, & Robb, 2007). In order to simulate short hamstring an adjustable brace was attached around the pelvis and the other end to inferior to the tibia condyles. Angular parameters were obtained from the subjects while running at a comfortable speed. During the swing maximum hip flexion was reduced as a result of restricted hamstring flexibility. Maximum anterior pelvic tilt was also reduced in the total running cycle as well as stride length. The stride length has been linked with performance in athletes. In a research by Lockie et al. (2013) they studied step kinematic predictors in short sprint performance. They found that both step length and step frequency were correlated with the sprinting velocities (Lockie, Murphy, Jeffriess, & Callaghan, 2013). In a review article it was proclaimed that reduced stride length reduces the magnitude of several biomechanical factors (Schubert, Kempf, & Heiderscheit, 2014a; Whitehead et al., 2007). Interestingly longer stride length is also believed to have influence on energy output. In terms of performance it is said that the best and ideal method for energy preservation is freely choosing the stride length and not over stepping (Högberg, 1952). The increase in the hamstring flexibility can also be addressed not only by conventional stretching methods, but also controlling the movement of the pelvic region. So far no direct research has been carried out to assess the effect of pelvic tilt on performance of the sprint, but we can postulate that since the rotation of the pelvic is expected to influence the surrounding muscle flexibilities, it is also likely that the flexibility would modify some kinematic parameters.

The influence of hamstring muscle extensibility on pelvic tilt in cyclists has been studied. The cyclists were classified into three different groups based on their hamstrings flexibility. Their hamstring flexibility was measure using the passive straight leg raise test. Their results indicate that the pelvic in the flexible group tends to tilt anteriorly when performing a sit-and-reach test, but did not find any differences in standing or sitting posture (Muyor, Alacid, & López-Miñarro, 2011). Similar findings were observed by Gojdosik et al. (1994). They grouped their subjects based on the toe-touch position test and identified individuals with short, normal and long hamstring. No difference was found for the pelvic tilt angle between the three groups in a standing posture (Gajdosik, Albert, & Mitman, 1994). These findings were also supported by another study done by Lopez-Minarro et al. (2010). Measuring the hamstring extensibility using passive straight leg raise test they grouped their athletes into reduced, normal and improved hamstring flexibility. They showed that the pelvic tilt did not differ in the standing position (López-Miñarro & Alacid, 2010). Rockey (2008) reported same findings for female athletes. Hamstring flexibility was obtained using the active knee flexibility test and pelvic tilt angles were measured using a pelvic inclinometer. She didn’t find any correlation regarding the degree of anterior pelvic tilt and hamstring flexibility (Rockey, 2008). These reports suggest there is no correlation between the anterior pelvic tilt in standing position and hamstring muscle length.

Lopez-Minarro et al. (2012) studied the influence of hamstring extensibility on pelvic tilt and other spinal curvatures in young kayakers. Similar to previous studies, they grouped their athletes using the passive straight leg raise test into two groups. Kayakers with less hamstring flexibility demonstrated a posterior tilt in comparison to their counterpart (López-Miñarro, Muyor, & Alacid, 2012). This notion is further supported by the findings of Braman (2016) whom analyzed the effect of hamstring lengthening on pelvic tilt angle. He found that flexibility exercises which targeted the hamstring increase the anterior pelvic tilt in walking (2.2 ± 1.2°) and standing (2.1 ± 3.1°) (Braman, 2016). So far mixed findings have been associated with the effect hamstring flexibility and anterior pelvic tilt and no study has assessed both factors in soccer players.

Small amount of research investigated the effect of hip flexor tightness on anterior pelvic tilt angles in the asymptomatic population. The anterior pelvic tilt seems to have no relationship with hip flexors. Youdas et al. (1996) recruited 90 asymptomatic adults to assess the relationship between their hip flexors flexibility and pelvic tilt. No correlation was found between the pelvis's angle of inclination with the hip flexors flexibility (Youdas, Garrett, Harmsen, Suman, & Carey, 1996). The findings of Rockey (2008) were also in agreement with the finding of Youdas et al (1996). She measured the hip flexors tightness using the Thomas test. No relationship was found for the hip flexor tightness and anterior pelvic tilt angle (Rockey, 2008). It seems that further research is needed to assess the hip flexors flexibility in the anterior pelvic tilt population.

2.6 Pelvic tilt and strength

Since it is the subject matter of pelvic tilt and it may influence the flexibility of the muscles surrounding the pelvis area, it would be necessary to consider the effect of anterior pelvic tilt in term of muscle flexibility (length) on the force production. Figure 14 depicts the relationship of force production and the sarcomere length.

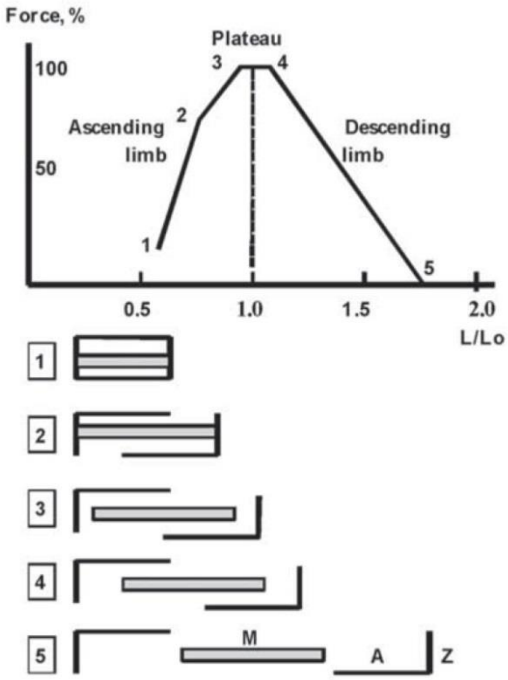


Figure 14 Dependence of the force produced by a sarcomere on its length (top) and sarcomeres at the crucial points 1-5 (bottom), schematic. M, myosin filaments; A, actin filaments; Z, membranes separating the sarcomeres (Z-membranes); L_o, optimal length of the sarcomere at which maximal force is exerted. Force is presented as percentage of the maximal force at the optimal length L_o. At length 5, the filaments do not overlap and hence do not produce any force. At lengths 3 and 4, the overlap of the actin and myosin filaments, and hence the force, are maximal. There is no difference between the forces at lengths 3 and 4 because the central zone of the myosin filament does not have crossbridges (Zatsiorsky & Prilutsky, 2018).

It can be observed that both decrease and increase in length results in decreased force production of the muscle. This concept is supported by the crossbridge theory of muscle contraction. In the longer lengths the filaments do not overlap hence cannot generate any force (Gordon, Huxley, & Julian, 1966). The figure represents the effect on concentric contraction whereas during the late swing phase it is believed that the hamstring muscle is going under eccentric contraction. For two joint muscles such as the hamstring, the tension-length can be estimated by changing the joint angle at one joint. When the joint position varies the length of the two-joint muscle also changes.

The postural changes in our alignment would have two consequences: 1.stretch weakness and 2.tightness weakness, as a result of adaptive changes. The stretch weakness explains a situation where the muscle remains elongated beyond the physiological neutral but does not exceeds the normal range of motion (Kendall Peterson, McCreary Kendall, Provance Geise, & McIntyre Rodgers, 2005; Page et al., 2010; Sahrmann, 2002). Due to the changes in the cross bride binding it is assumed that the length tension curves are affected causing muscle weakness (Page et al., 2010). Considering the filament crossbridge theory that it could be explained of how the force-length can be changed increase in muscle length. The increase in length decreases the overlapping between the actin and myosin thus resulting in a decrease of potential force production (Herzog, 2017).

In tightness weakness concept the muscle is tightened or shortened after a prolonged overuse of the muscle (Page et al., 2010). We can see the overuse of certain muscle groups such as hip flexors in soccer players as result of repetitive action such as kicking or passing the ball (Kellis & Katis, 2007; Śliwowski, Grygorowicz, Hojszyk, & Jadczak, 2017).

Strength also shares the same value of importance when considering performance and injury susceptibility of soccer players. There is a significant relationship between strength and movement velocity (Bührle & Schmidtbleicher, 1977) which states that as the strength diminished so does the performance in term of velocity. The speed is also directly related to the physical fitness and the performance of the soccer player. The maximum strength of soccer players has shown to have a correlation with sprinting performance (Wisløff, Castagna, Helgerud, Jones, & Hoff, 2004). Other than running muscular strength shows relationship with kicking performance which is an essential technique for football players (Masuda, Kikuhara, Demura, Katsuta, & Yamanaka, 2005).

Other than performance aspects deficits in strength have been linked to injuries such as hamstring injuries. Strength imbalances has been proposed as a predictive risk factor and athletes should aim to reduce the imbalances to avoid injury (Croisier et al., 2008). In contrast studies are reporting in significant findings for the relationship between the strength imbalances and their predictive ability for hamstring strain (Dauty, Menu, & Fouasson-

Chailloux, 2018; Green, Bourne, & Pizzari, 2018; Grygorowicz et al., 2017; van Dyk et al., 2016).

A recent study showed that the hamstring's flexibility is not correlated with its strength (Wan et al., 2017b). The authors explain that the fact that the hamstring flexibility is not correlated with strength might be a result of length-tension relationship. They further continue that the group with better flexibility witnessed a shift of the length-tension relationship and this is due to the shift of change in muscle optimal length.

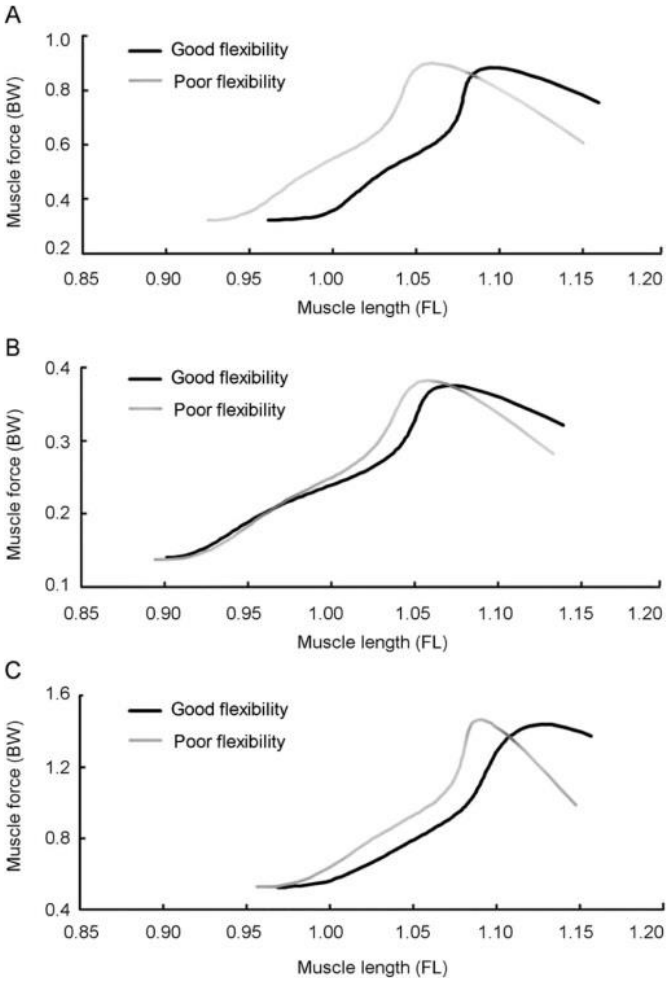


Figure 15 Hamstring muscle force-length relationships of 2 participants with different flexibility: (A) biceps long head; (B) semimembranosus; (C) semitendinosus. Muscle length was normalized as a fraction of femur length (FL). Muscle force was normalized as a fraction of body weight (BW)(Wan et al., 2017b).

In another study the effect of pelvic tilt on hamstring muscle strength was investigated. Upon investigation no relationship was found between concentric or eccentric peak hamstring torque for both right and left sides. Although it is mentioned that weakness was present but it was not significantly different (Rockey, 2008).

2.7 Summary

Hamstring strain is among the highest injuries sustained by soccer players. The literature suggests that the pelvic tilt is factor that associated with a non-contact hamstring injury. In relation to the muscular attachment of the hamstring with the pelvis the flexibility of the hamstring and the hip flexors are assumed to have contribution to the alignment of the pelvis. Furthermore since the muscle strength is related to its length, changes in the maximum strength of the muscles surrounding the pelvis are expected, as it changes its orientation i.e. anterior pelvic tilt. Additionally due to the mutual muscles crossing over the pelvis, hip, and knee it is probable that during the late swing phase of a sprint, where it is suspected to be the onset of a hamstring strain, the kinematics would be affected. The neuromuscular activation of certain muscles which promote the progression of angles during the late swing phase would presumably differ as the tilt angle increases in the pelvis. All of the mentioned factors have been previously assumed to be associated with hamstring strain in soccer players, thus the study of how the pelvis alignment would change the values displayed by the parameters would further our understanding of the pelvis' contribution.

3 Questions and Hypotheses

1. Does hamstring flexibility differ between soccer players with and without anterior pelvic tilt?

H_1: Hamstring flexibility differs between soccer players with and without anterior pelvic tilt.

H_0: Hamstring flexibility does **not** differ between soccer players with and without anterior pelvic tilt.

2. Does hip flexors' flexibility differ between the soccer players with and without anterior pelvic tilt?

H_1: Hip flexors' flexibility differs between soccer players with and without anterior pelvic tilt.

H_0: Hip flexors flexibility does **not** differ between soccer players with and without anterior pelvic tilt.

3. Do sagittal kinematic parameters, i.e. knee, hip, and pelvis angle differ at the late swing phase during a sprint between soccer players with and without anterior pelvic tilt?

H_1: Sagittal kinematic parameters i.e. knee, hip and pelvis angle differ at the late swing phase in a sprint between soccer players with and without anterior pelvic tilt.

H_0: Sagittal kinematic parameters i.e. knee, hip and pelvis angle do **not** differ at the late swing phase in a sprint between soccer players with and without anterior pelvic tilt.

4. Do neuromuscular activities of the gluteus maximus, rectus femoris, vastus medialis, and hamstring biceps femoris differ at the late swing phase during a sprint between soccer players with and without anterior pelvic tilt?

H_1: Neuromuscular activities of the gluteus maximus, rectus femoris, vastus medialis, and hamstring biceps femoris at the late swing phase during a sprint differ between soccer players with and without anterior pelvic tilt.

H_0: Neuromuscular activities of the gluteus maximus, rectus femoris, vastus medialis, and hamstring biceps femoris at the late swing phase during a sprint do **not** differ between soccer players with and without anterior pelvic tilt.

5. Do maximum concentric and eccentric isokinetic strength for knee flexors, knee extensors, hip flexors and hip extensors and their ratio differ between soccer players with and without anterior pelvic tilt?

H_1: Maximum concentric and eccentric isokinetic strength for knee flexors, knee extensors, hip flexors and hip extensors and their ratio differ between soccer players with and without anterior pelvic tilt.

H_0: Maximum concentric and eccentric isokinetic strength for knee flexors, knee extensors, hip flexors and hip extensors and their ratio do **not** differ between soccer players with and without anterior pelvic tilt.

4 Methods

4.1 Study design

A cross sectional, single measurement under lab conditions was used to compare the kinematics of the pelvis, hip and knee in the sagittal plane. Players were also tested for their quadriceps, hamstring, hip flexors and hip extensors strength. The flexibility of the hamstring as well as the flexibility of the hip flexors was determined using flexibility clinical tests.

4.2 Participants

A total number of 38 male amateur soccer players participated in this study. All players were recruited from the first division Hamburg’s soccer club, Vfl 93. A minimum of 5 year experience with an average of 3 training and/or match sessions per week were considered as the inclusion criteria. Players with a history of muscle strains, and ligament sprains in the past 6 months as well as spinal pain or neurological disorders were excluded from the study. Players were briefed on the measurement procedure and signed an informed consent. After measurement of the spinal alignment the players were divided into control and experimental groups where they proceeded to their next measurements. The study was approved by the University of Hamburg’s local scientific committee (ID: 2017_85).

4.3 Procedure

Prior to the measurement session, the players were informed about the whole procedure and what type of data would we be collecting. After the familiarization session the players wore their normal sporting clothes and shoes. The players warmed up for 5 minutes on a self-selected pace on the motorized treadmill followed by 3 minutes of their normal stretching routine. Next the players proceeded to the spinal evaluation where they have their posture scanned. Afterwards the players completed the flexibility test for hamstring and hip flexors using clinical tests. Then they proceeded to the biomechanics laboratory where their kinematics and neuromuscular activity was recorded while sprinting. Finally maximum isokinetic muscle strength of the knee flexors, knee extensors, hip flexors and hip extensors were obtained using an isokinetic dynamometer.

4.3.1 Posture assessment

At this stage the players were asked to take off their shoes and clothes for their scan. It was emphasized that they should try to maintain their normal posture and try not to correct themselves. They were instructed that during the measurement to face forward and maintain normal breathing while remaining still. Prior to the starting of the scan we asked the subjects to stand on the platform provided from the manufactures company. On this platform a grid was embedded which allowed to take coordinates of the feet. The height of the first horizontal line was adjusted in a way that was position below the hair line. As the scanning started the players were asked to set their pants bellow their buttocks in order to get a full scan including the sacrum region (Figure 16). Each player performed 3 scans with a 1-minute rest between each measurement. It was ensured that the player's feet were placed at the similar position to the initial scan for reproducibility. No audio or visual feedback was given to the players during and between the scans to avoid compensation.

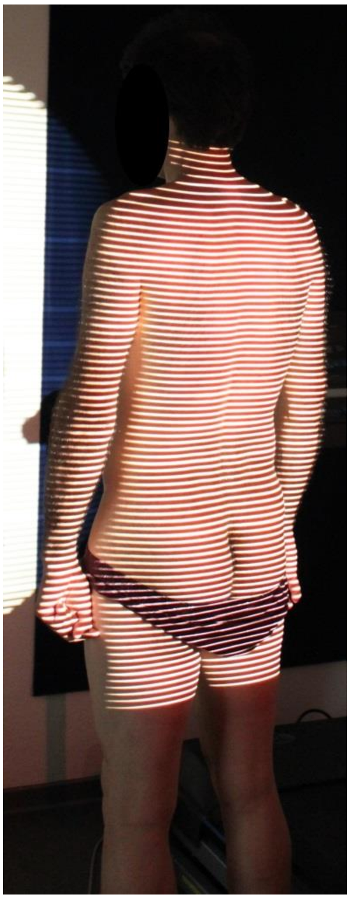


Figure 16 Spinal scan from the DIERS Formetric 4D

4.3.2 Flexibility tests

The players were then guided to the next station to have their flexibilities taken. At first the modified Thomas test for the assessment of hip flexor flexibility was used. Reflective markers were placed on the lateral malleolus, lateral epicondyle and the great trochanter. The players sat on the edge of the physiotherapy portable table. With holding their legs to their chest, the players gently laid back on the table with the assistance of the instructor. The tested leg was gently lowered to the point where it couldn't go further. It was crucial for the players to maintain their lower back in contact with the table, since the movement of the pelvis would change the outcome (Vigotsky et al., 2016). It was also important for the players not to lift their buttocks from the table as well (Figure 17). The modified Thomas test has been shown to be a reliable test for assessing the true hip extension range of motion when the pelvic tilt is controlled (r = 0.98) (Vigotsky et al., 2016). When actively stabilizing the pelvis the modified Thomas test has demonstrated high reliability (ICC =0.99, SEM =0.85 °) (Kim & Ha, 2015).

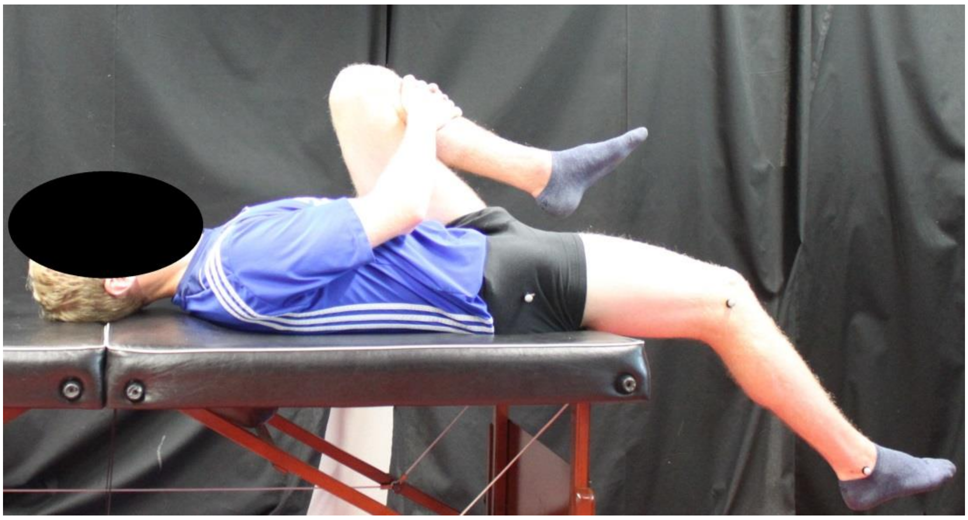


Figure 17 Modified Thomas test (hip flexor flexibility)

Next the players did the 90:90 active knee extension hamstring flexibility test. It was demonstrated to the players that as they lay supine they grab their leg from the posterior of the thigh to avoid movement. Then they should actively extend their test leg to the point where they can no longer further extend it. The players were informed to maintain contact of their lower back on the table since it will affect the knee joint angles (Herrington, 2013) (Figure 18). The 90:90 active knee extension test has been reported to be reliable test for assessing the hamstring length (ICC = 0.96-0.99, SEM =1.75-1.82 °) (Worrell, Sullivan, & DeJulia, 1992). For each flexibility test, three attempts were completed and there was a one minute rest between each test. It was made sure that the tripod was level on the horizontal plane.

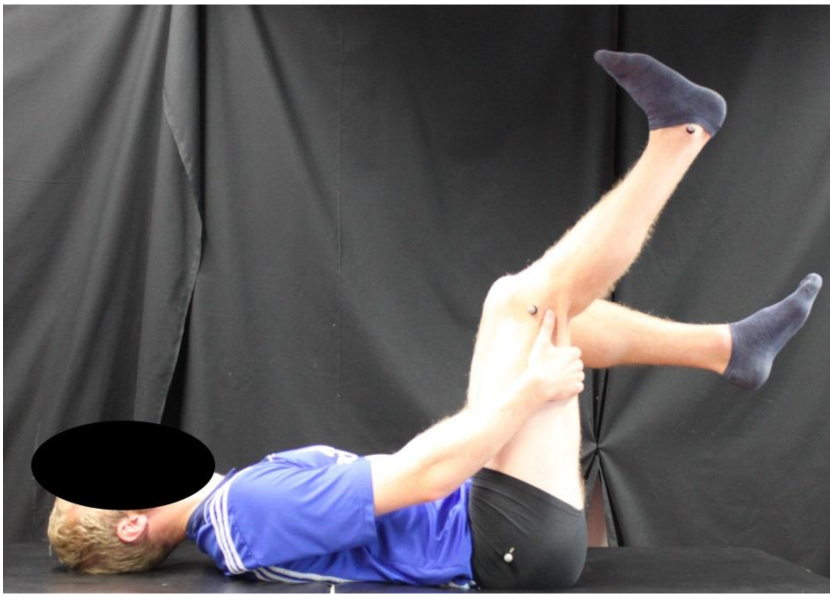


Figure 18 90:90 active knee extension test (hamstring flexibility)

4.3.3 Sprint test

At the next station the athletes completed 3 trails of sprinting with a 3-minute rest between each trial. The participants warmed up at 2.2 ± 0.1 m/s for five minutes. Next, the participants completed a familiarization test on the treadmill for the speed at 6.9 ± 0.1 m/s. EMG electrodes were attached to the gluteus maximus, rectus femoris, vastus medialis, and hamstring biceps femoris while sprinting on the treadmill. The players had their kinematics data and muscle activation recorded during a sprint. Forty reflective markers were attached to various anatomical and segmental sites using a double-sided circular adhesive (13 × 15 mm, TerniMed, Meisenstr. 96, Bielefeld, Deutschland): posterior superior iliac spine, anterior superior iliac spine, four thigh cluster markers, lateral and medial epicondyle, four lower leg cluster markers, lateral and medial malleolus, three calcaneus markers, first metatarsal head, fifth metatarsal head and hallux (Figure 19) (Della Croce, Leardini, Chiari, & Cappozzo, 2005). The participants were strapped with a harness safety belt to avoid injury due to risk of falling. The kinematic acquisition was done using Vicon 3D motion analysis system. All the angles were defined based on their relative change from their static position (knee angel = the alignment between the shank and thigh, hip angle = alignment between thigh and pelvis centre of rotation, pelvis angle = angular changes of the pelvic tilt from its centre of rotation with regards to its reference position). Although stride length and stride frequency are a determinant factors for angular kinematics, but previous studies have only found relationship of these variables with sprinting phases from initial contact to toe-off, and not during the swing phase (Schubert, Kempf, & Heiderscheit, 2014b).

Figure 19 Marker placement on one leg

The markers were secured using a non-woven retention tape (Omnifix ®, Laboratorios Hartmann S.A., Mataro, Spain).

The muscles were located as follows:

- Gluteus maximus: at the 50% line between the sacral vertebrae and the greater trochanter. This position corresponds with the greatest prominence of the middle of the buttocks well above the visible bulge of the greater trochanter.
- Hamstring biceps femoris long head: at the 50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia.
- Rectus femoris: at the 50% line from the anterior spina iliaca superior to the superior part of the patella.
- Vastus medialis oblique: at the 80% line between the anterior spina iliaca superior and the joint space in front of the anterior border of the medial ligament.

Electrode placement for the muscles was also confirmed by having the players isometrically contract each muscle separately. The skin for the electrode placement was shaved and abraded using a fine sand paper. Afterwards the skin was cleaned using disinfection liquid (Desinfektionsschaum, ISG Intermed Service GmbH & Co, KG) to remove debris. The electrodes were attached on to the muscle site; and the electrodes were secured in place with a double-sided adhesive tape and non-woven retention tape. The muscle location was confirmed with the subject performing an isometric contraction and evaluating the EMG signals on the software.

Static measurement was acquired as a reference values for further kinematic analysis, by informing the subject to take the T-pose for 3 seconds. For safety, the players were fastened to a harness to prevent fall. Each player completed three attempts of sprint at 6.9 m/s for five seconds, with a 3-minute rest between each trail.

4.3.4 Strength tests

The players proceeded to the final station for strength test. For the quadriceps, hamstring, hip flexors and hip extensors strength test flexion and extension speed were set to 120 °/s; involving both concentric and eccentric contractions. The test included 2 sets of 3 maximum repetitions with the first set being considered as the familiarisation test. Prior to the measurement the players warmed up on the device with moderate intensity. For the quadriceps and hamstring strength test, the players were seated and strapped to the seat with their back resting at an 80-90˚ angle horizontally. The seating position was adjusted so that the back of the knee maintained contact with the seat pad. The range of motion for knee flexion – extension motion was set to 90˚, with 0˚ being the knee at its full extension (Figure 20). For the players who couldn’t fully extended their knees, the starting angle was slightly altered but maintaining the null position at 0˚. The adapter was positioned directly above the lateral malleolus and the centre of rotation was identified with an embedded laser pointer at the lateral epicondyle. The starting position for knee flexion – extension was at 0˚ where the knee was fully extended. Between each set subjects has a 3-minute rest. Visual and verbal feedbacks were given to gain maximum effort and maximum peak torque values were extracted for further analysis. The angular velocity was chosen according to previous studies measuring the peak torque value of soccer players (Croisier, Forthomme, Namurois, Vanderthommen, & Crielaard, 2002). This angular velocity also allows for muscle imbalance comparison which was also cited by previous studies in soccer players (Aagaard, Simonsen, Trolle, Bangsbo, & Klausen, 1995).

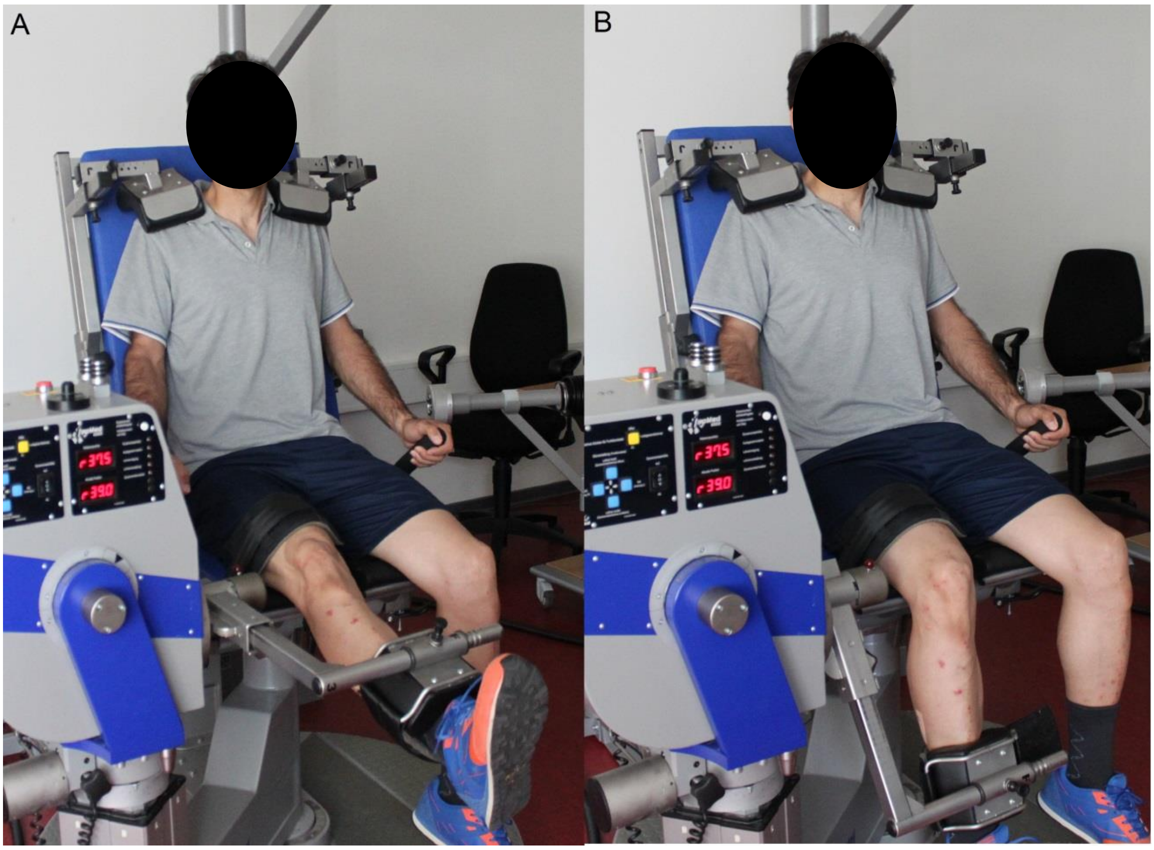


Figure 20 Knee flexion – extension strength test. A: starting position 0 degrees, B: Ending position 90 degrees flexed

For the hip flexion – extension strength test, the players laid down supine on the table with the knees hanging from the edge of the table (Figure 21). The adapter was position on the thigh above the patella when the knee was fully extended. The centre of rotation was determined at the great trochanter with the range of motion of 120 degrees. The starting position was where the hip was fully extended (0 degrees) (Zapparoli & Riberto, 2017). Previous studies have shown and approved the reproducibility of using isokinetic for hip flexors and extensor peak torque measurement both concentrically and eccentrically (Julia et al., 2010; Zapparoli et al., 2017). The players performed a moderate intensity warmup then proceeded to the main measurement. Verbal and visual feedbacks were given to achieve maximum efforts. In total the players completed 2 sets of 3 repetitions for each test. The first set was considered as the familiarisation set followed up by a 3 minute rest. Peak torque values were extracted for further analysis.

Figure 21 Hip flexion – extension strength test. A: Starting position 0 degree hip flexion, B: End position 120 degree hip flexion

4.4 Instruments

The pelvic tilt was assessed using a video raster stereography, DIERS Formetric 4D (Formetric®-System, Diers International, Schlangenbad, Germany). This is a non-invasive instrument for measuring different components of the spinal alignment using indirect high-resolution back shape reconstruction (reconstruction error 0.2–0.5 mm; resolution 10 pts/cm^2). The device projects a series of horizontal line on the back then reconstructs the shape of the back using algorithms for determining spinal alignment using landmarks. The validity of the DIERS for pelvic measurements was assessed using X-ray radiography. The results showed high validity for all pelvic measurements including pelvic tilt (ICC = 0.989, r = 0.930). The intra- and inter-examiner reliability of the device for pelvic measurements were also revealed to be high (Abdel Raoof, Battecha, Elsayed, & Soliman, 2016). The pelvis tilt was defined as the angle produced between the plumb line and the tangent of the lumbar lordosis dimples (Schroeder, Reer, & Braumann, 2015). Normal values for pelvis tilt were obtained from previous studies using a sample size of 103 subjects. For male subjects the average value was 17.3° (Schröder, Braumann, & Reer, 2014).

Vicon motion analysis system (Vicon Motion Systems, Oxford, England) was used for obtaining kinematic data. Eight cameras with the sampling frequency of 200 Hz were set for motion capture system. Forty spherical reflective markers (15 mm) were used to attach to different anatomical and segments for the lower extremity. The motion analysis system was synchronized with a wireless electromyography system.

Muscle activation was recorded using a 16-channel wireless Myon surface electromyography (EMG) device (Myon AG, Schwarzenberg, Switzerland) at 2 kHz sampling rate. Electrodes

(Ambu® BlueSensor N) were placed in accordance with SENIAM recommendations (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000) for the following muscles: gluteus maximus, hamstring biceps long head, rectus femoris and vastus medialis oblique (VMO). A motorised instrumental treadmill (h/p/cosmos; quasar–FDM-THQ-M der Firma Zebris Medical GmbH) was used for warmup and measurement purposes.

Strength tests were carried out using the Isomed 2000 isokinetic dynamometer (D&R Ferstl GmbH, Hemau, Germany). Prior to each test the device was calibrated according to the manufacture's manual. Knee adaptor (Nr. 3) in addition to the single pad adaptor (Nr. F) was used for strength measurements. High reliability for concentric and eccentric peak torque for quadriceps and hamstring strength (ICC = 0.907 – 0.984, SEM = 4.5 – 19.1) was reported (Dirnberger, Kösters, & Müller, 2012). No reports are available on the hip peak torque reproducibility.

Hip flexors' and hamstring's flexibility was assessed using a stationary photographic camera (Canon Inc. Model: 500D) with a shutter speed of 1/4000 to sec and a resolution of 4752 × 3168. Photographic tools have been shown to be both reliable and valid methods for assessing joint angles range of motion (Mourcou, Fleury, Diot, Franco, & Vuillerme, 2015). A tripod was used to mount the camera and to avoid differences in perspective angle the location of the tripod where it was adjusted was marked. The camera lens was adjusted to the height of the table and was placed 10 meters away perpendicular to the plane of the measurement (Bradley & Portas, 2007). Three reflective markers were used to calculate the joint angles.

4.5 Data processing

The angle of the pelvis's tilt was calculated as a mean value between the right and left dimple inclination with the plumb line (Figure 22).

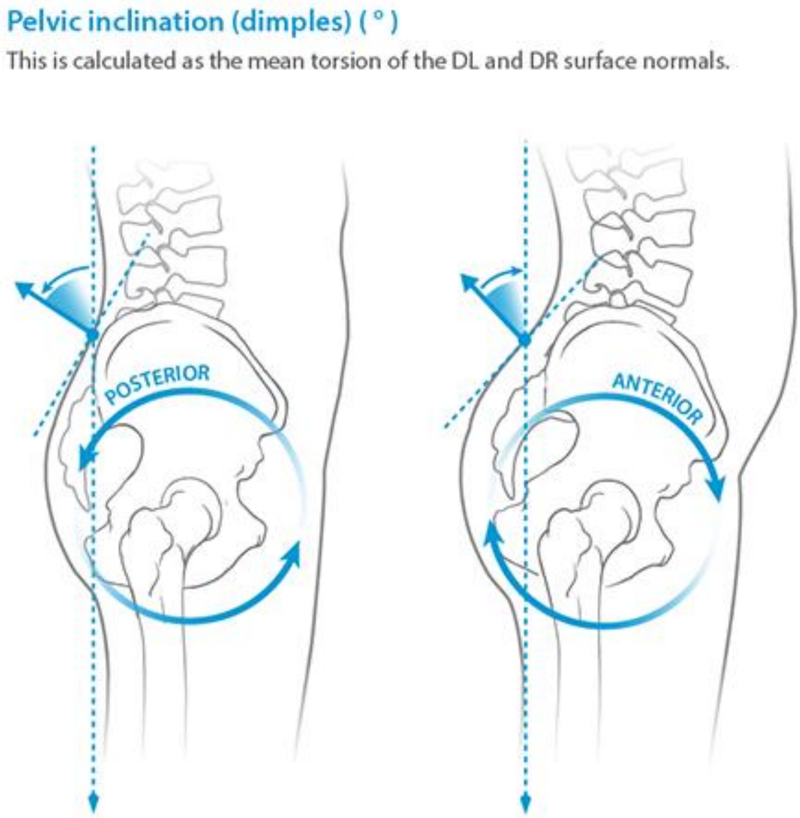
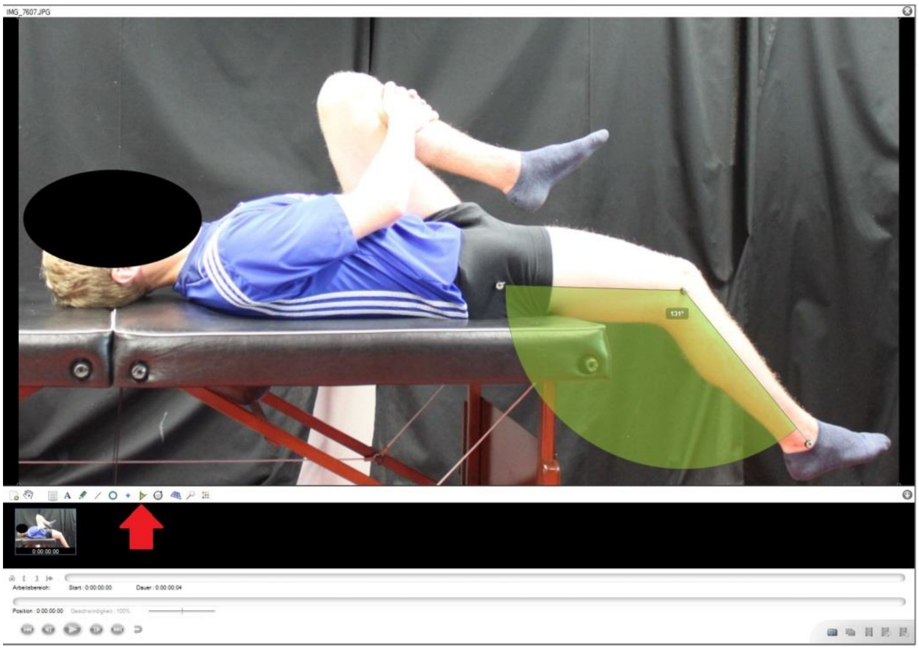


Figure 22 Calculation method of the pelvic tilt

Data for flexibility was obtained using the Kinovea software version 0.8.15 (www.kinovea.org). Kinovea is an open source project licenced under the GPL version 2. Studies have revealed good reliability for using the software for orthopaedic measurements such as range of motion (Guzmán-Valdivia, Blanco-Ortega, Oliver-Salazar, & Carrera-Escobedo, 2013). Angles were obtained using the angle function (red arrow in Figure) for all three measurements for both modified Thomas test and 90:90 active knee extension tests. For the modified Thomas test the knee angle (Figure 23) was calculated in addition to observing the raise of the thigh from the table. Thigh raise indicated as a positive test for hip flexor flexibility. Although the extension of the knee is also considered as a positive indicator but normative values were taken to compare between the two groups. Similarly knee angle was also calculated for hamstring flexibility test. The mean value from three measurements were calculated and used for further analysis.



[redacted]

Figure 23 Kinovea software interface for angle calculation (red arrow: angle function).

Marker gaps were filled using the Vicon Nexus software 2.6.1. Kinematic data were filtered and extracted using the Motrack version 1.8 MATLAB function. All trials were filtered using a zero-lag low pass 4th order Butterworth filter. The cut-off frequency was set to 13 Hz by calculating the optimum cut-off frequency (Formula 1) (Yu, Gabriel, Noble, & An, 1999). It has been found that the optimum cut-off frequency for kinematic and EMG studies can be calculated directly from the sampling frequency. Where f_c is the cut-off frequency and f_s is the sampling frequency.

Formula 1: $$f_c = 0.071f_s - 0.00003f_s^2$$

Late swing phased was defined as the time point where the maximum knee flexion during the swing started extending until the foot contact time point (Figure 24). The foot contact was determined using an algorithm on the knee marker trajectory (Fellin, Rose, Royer, & Davis, 2010). The algorithm was compared using the golden standard for foot contact which is the ground reaction force. This algorithm uses the first time of peak knee extension in a sprinting cycle to identify the foot contact. This algorithm detects foot contact in comparison to the ground reaction force with delays less than 6 ms. All markers were optimized to reduce the amount of skin movement artefact (Leardini, Chiari, Della Croce, & Cappozzo, 2005). During a task, the position of the markers can change relative to the true segment based on their attachment on the skin, thus depicting a motion which is not representative of the true motion. The amount of these movements can be reduced with global optimisation technique which minimises the weighted sum of squared distances marker positions. Joint and segment angles were calculated with regards to their static reference pose. An average of five late swing phases was calculated from each player for further analysis.

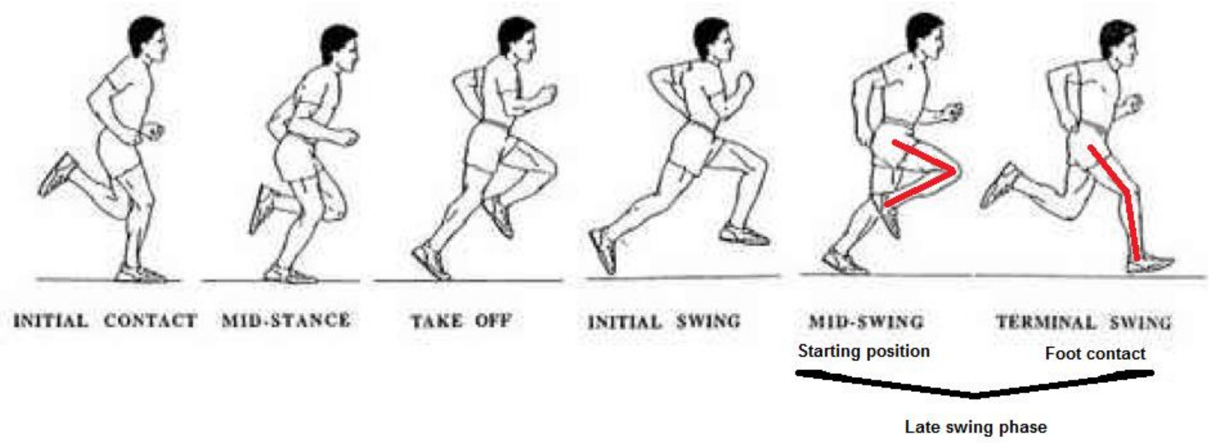


Figure 24 Relative position of the right leg during a sprint. Starting position = maximum knee flexion

EMG data were also filtered using the zero-lag low pass 2th order Butterworth filter with a cut-off frequency of 20 Hz in the ProEMG software (Motion Lab Systems, Inc. LA. USA). ProEMG is designed to make the acquisition and processing of EMG signals easy. EMG signals were filtered using a full wave ratification which inverts negative values from the EMG signals to positive values. All EMG signals were normalized based on the average of 5 peak values of each muscle during the trails (Konrad, 2005). Average of five late swing phases of muscular activity were extracted for further analysis. Many methods have been introduced to be able to compare the findings of the EMG. The most common method is known as the maximum voluntary contraction (MVC). However for test which involve high-speed tasks the amount of reliability would reduce if normalized by the MVC, thus the amount of peak activity during the dynamic test has been proposed to have a high reliability in comparison to the MVC method (Ball & Scurr, 2013; Halaki & Ginn, 2012). The peak value activities was extracted from the entire linear envelop after signal filtration. A window frame of 20 ms was considered for the peak values and averaged by the amount of total amount of cycles which was five (Figure 25).

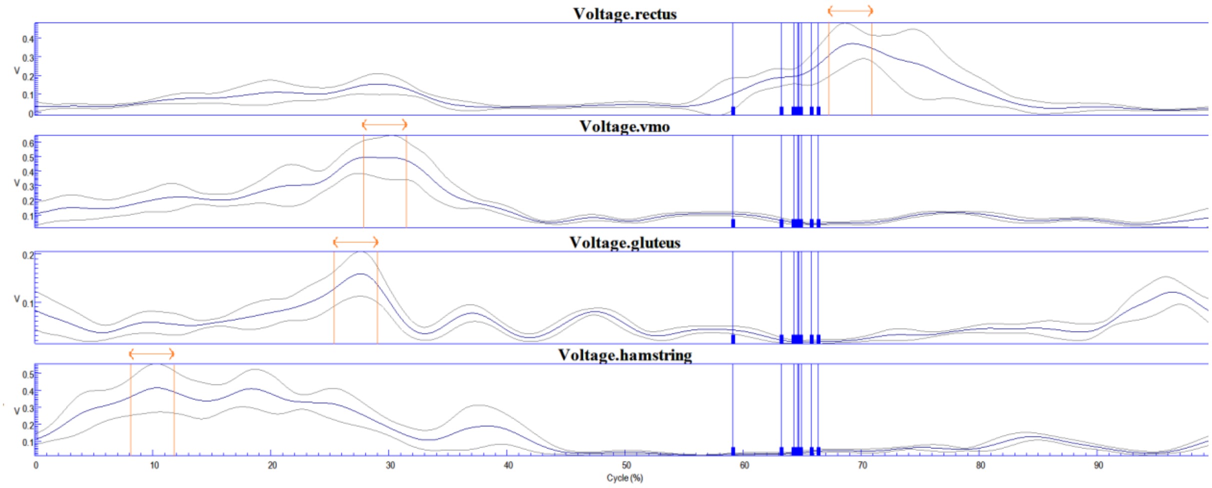


Figure 25 Filtered EMG activity normalized by mean of an entire stride cycle (foot strike – foot strike). The blue curves represent the mean voltage of the EMG for each muscle. The grey curves are ± one standard deviation. The vertical blue lines represent the time of maximum knee flexion in each cycle, which signifies the start of the late swing phase for each cycle. The average value between the two orange lines was (20 ms) to normalize the EMG values. The peak value was extracted based on the average peak values of 5 strides cycles.

After normalization the pattern of the neuromuscular electrical activity was used to compare the muscle activity at the late swing phase.

Peak torque values were extracted using the manufacture's custom built software (IsoMed analyse V.1.05). Ratio values such as conventional and functional hamstring to quadriceps and hip flexors to extensors were calculated for further analysis. The conventional hamstring to quadriceps ratio (H:Q$_C$) was calculated using:

Formula 2:
$$H\colon Q_{Conventional} = \frac{Hamstring_{Concentric}}{Quadriceps_{Concentric}}$$

The functional hamstring to quadriceps ratio (H:Q$_F$) was also calculated using:

Formula 3:
$$H\colon Q_{Functional} = \frac{Hamstring_{Eccentric}}{Quadriceps_{Concentric}}$$

For the hip flexors to hip extensors conventional (HF:HE$_C$) ratio to following formula was used:

Formula 4:
$$HF\colon HE_{Conventional} = \frac{Hip\ Flexors_{Concentric}}{Hip\ Extensors_{Concentric}}$$

The calculation for functional hip flexors to hip extensors (HF:HE$_F$) was done using:

Formula 5:
$$HF\colon HE_{Functional} = \frac{Hip\ Flexors_{Eccentric}}{Hip\ Extensors_{Concentric}}$$

4.6 Statistical analysis

Kinematic and EMG signals were statistically analysed using statistical parametric and non-parametric mapping (SPM & SnPM). Originally SPM was developed for analysis of functional brain imaging (Friston et al., 1994) and was later adapted to biomechanical studies. Pataky generalized the biomechanical signal analysis using SPM (Pataky, 2010). SPM uses random field theory (Adler, 1981) to assess the statistical inference level by mathematical foundation. Random field theory is a recent body of mathematics defining theoretical results for smooth statistical maps. The way that random field theory solves this problem is by using results that give the expected Euler characteristic (EC) for a smooth statistical map that has been thresholded. The expected EC leads directly to the expected number of clusters above a given threshold, and that this in turn gives the height threshold that we need. Using the random field theory requires two assumptions. The first is that the error fields are a reasonable lattice approximation to an underlying random field with a multivariate Gaussian distribution. The second is that these fields are continuous, with a twice-differentiable autocorrelation function (Brett, Penny, & Kiebel, 2004).

These assumptions can be tested using a built-in function in the spm1d program developed by Pataky which can be downloaded at www.spm1d.org. The current version for our analysis is 0.4 using the MATLAB R2016a software as the platform to run the calculations. If the assumption of the Gaussian distribution is not met then the data would be analyzed using the equivalent non-parametric test. For our purposes the independent t-test was used as our basis of statistical tests. The non-parametric equivalent for the t-test is the permutation t-test which can identify the statistical differences between the two means (Nichols & Holmes, 2002). The threshold value in the non-parametric t-test is reliant on the amount of permutations assigned to the calculation. Basically the more permutations the better, but as the number of permutations increases the fluctuation of p-values decreases and variations converge (Cardot, Prchal, & Sarda, 2007). For our statistical purposes a number of 4×10^5 was calculated which would suffice to avoid drastic fluctuation of the threshold value.

To evaluate the normality of the curves all of the kinematic and EMG curves were time normalized to 201 points for the late swing phase. Afterwards the mean value curve was calculated from 5 strides from the dominant leg. The data were then uploaded as two separate matrices for each of the kinematic and EMG parameters. The following code was run as a prerequisite for the normality test prior to the t-test.

```
alpha      = 0.05;

spm        = spm1d.stats.normality.ttest2(A, B);
```

```
spmi       = spm.inference(0.05);
```

Where A and B are the matrices for the selected kinematic or EMG parameters. After confirming the normality the independent sample t-test was carried out on the same parameters. The following code was run for the t-test.

```
spm        = spm1d.stats.ttest2(A, B);

spmi       = spm.inference(0.05, 'two_tailed',true, 'interp',true);
```

In the case of a non-parametric test the non-parametric equivalent of the two independent sample t-test was carried out using the following code.

```
rng(0)

alpha      = 0.05;

two_tailed = true;

iterations = 400000;

snpm       = spm1d.stats.nonparam.ttest2(A, B);

snpmi           =  snpm.inference(alpha,  'two_tailed',  two_tailed,
'iterations', iterations);
```

The codes for the normality, independent sample t-test, and non-parametric test can be found in the MATLAB package function available on the website.

SPSS version 23 was also used to compare the mean differences between flexibility and strength data. Since the flexibility and strength data have multiple variables to be analyzed a p-value adjustment was calculated for each test separately based on the numbers of test for each hypothesis using the Bonferroni adjustment. The standard error of measurement (SEM) was calculated using:

Formula 6: $$SEM = SD\sqrt{1 - ICC}$$

Where SD is the standard deviation and ICC is the intraclass correlation coefficient of the test.

The effect size of the difference was calculated using Cohen's d equation:

Formula 6: $$Cohen's\ d = \frac{M_2 - M_1}{SD_{pooled}}$$

Where the M_1 and M_2 are the mean values for each group and SD_{pooled} is the pooled standard deviation. The magnitudes of 0 – 0.20, 0.20 - 0.50 and 0.80 – 1 are considered to be small, medium and large effect size respectively (Cohen, 1988).

5 Results

Table 1 shows the demographic information of the soccer players. The total number of participant were 38 but due to incapability of some players to continue with the testing the number of participants reduced to 34.

Table 1 demographic information of the soccer players (mean ± SD)

Group	Mass (kg)	Height (cm)	Age (years)	Experience (years)	Pelvis Tilt (°)
Normal Pelvic Tilt (15)	77.6 ± 6.1	181.2 ± 8.2	27.4 ± 4.7	17.1 ± 4.6	15.6 ± 2.6
Anterior Pelvic Tilt (19)	78.6 ± 7.2	181.6 ± 7.6	26.7 ± 5.2	17.3 ± 3.1	21.8 ± 2.3

Shapiro-Wilk normality tests reveal that the players were normally distributed based on their mass, height, years of experience and age *p* > 0.05 (Table 2). All subjects were matched by mass, height, age and years of experience. The amount of pelvic tilt was found to be different between the two groups (Table 3). The interclass correlation showed high reliability for the measurement of pelvic tilt angle measurement (ICC (1, 1) = 0.976, CI = 0.960 – 0.987, F (33, 66) = 42.064, *p* < 0.001, SEM (1, 1) = 0.78°).

Table 2 Mass, height, experience and age normality test, N = 34

Variable	Group	Shapiro-Wilk		
		Statistic	df	Sig.
Mass	Normal Pelvic Tilt	.984	15	.991
	Anterior Pelvic Tilt	.985	19	.983
Height	Normal Pelvic Tilt	.959	15	.681
	Anterior Pelvic Tilt	.970	19	.779
Experience	Normal Pelvic Tilt	.942	15	.409
	Anterior Pelvic	.940	19	.259

	Tilt			
Age	Normal Pelvic Tilt	.970	15	.862
	Anterior Pelvic Tilt	.942	19	.286

Table 3 Mean ± SD and t-test results for pelvic tilt angle between soccer players with and without pelvic tilt, N = 34

Variable	Pelvis Tilt (°) (Mean ± SD)		Levene's Test for Equality of Variances		t-test for Equality of Means				
			F	Sig.	t	df	Sig.	95% Confidence Interval	
								Lower	Upper
Pelvic Tilt	Normal Pelvic Tilt	15.6 ± 2.6							
	Anterior Pelvic Tilt	21.8 ± 2.3	2.40	.131	-7.22	32	.000	-8.93	-4.97

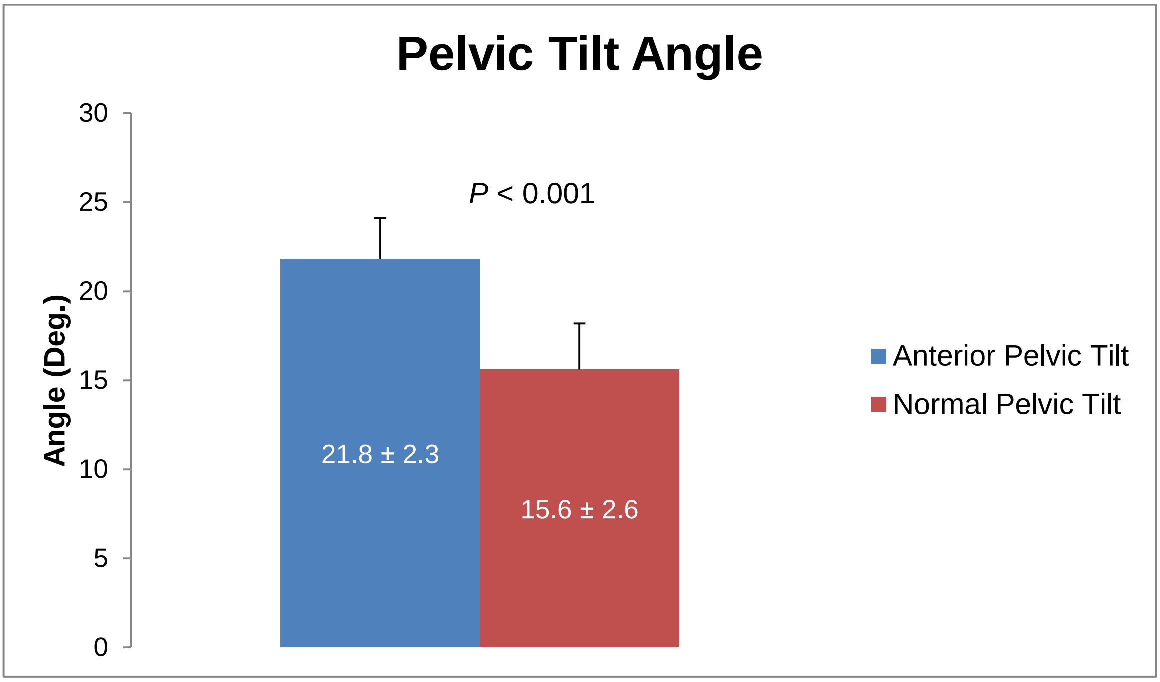


Figure 26 Pelvic tilt angle for soccer players with and without pelvic tilt

5.1 Flexibility

To measure the hamstring's and hip flexors' flexibility the 90:90 active knee extension test and modified Thomas test was used respectively. The results of the normality test for hamstring and hip flexibility tests show that players were normally distributed between the two groups. For the 90:90 active knee extension test and modified Thomas test Shapiro-Wilk revealed that the distribution was normal $p > 0.05$ (Table 4).

Table 4 Mean ± SD and normality test for Hamstring flexibility and hip flexor flexibility, N = 34

Test	Group	Angle (°)	Shapiro-Wilk	
			Statistic	Sig.
Modified Thomas test	Normal Pelvic Tilt	123.8 ± 10.4	.975	.914
	Anterior Pelvic Tilt	123.1 ± 9.9	.961	.598
90:90 Active Knee Extension	Normal Pelvic Tilt	152.5 ± 9.8	.918	.155
	Anterior Pelvic Tilt	160.5 ± 10.2	.974	.845

The interclass correlation showed high reliability for the measurement of 90:90 active knee extension (ICC (1, 1) = 0.981, CI = 0.966 – 0.990, F (33, 66) = 51.296, $p < 0.001$, SEM (1, 1) = 1.358°) and modified Thomas test (ICC (1, 1) = 0.937, CI = 0.890 – 0.966, F (33, 66) = 15.950, $p < 0.001$, SEM (1, 1) = 2.648°).

Levene's test for equality of variance showed no significant difference between the control and experimental group for both modified Thomas test and 90:90 active knee extension test. Independent t-test revealed no significant difference between the hip flexibility for the two groups ($p > 0.05$). The analysis showed a significant difference ($p < 0.05$) for the 90:90 active knee extension test between the two groups with players having an anterior pelvic tilt demonstrating higher knee angles (increased flexibility) (Table 5).

Table 5 Equality of variance test for hip flexor flexibility and hamstring flexibility, N = 34

Test	Group	Angle (°)	Levene's test for equality of Variances	
			F	Sig.
Modified Thomas	Normal Pelvic Tilt	123.8 ± 10.4	.161	.691
	Anterior Pelvic	123.1 ± 9.9		

	Tilt			
90:90 active knee extension	Normal Pelvic Tilt	152.5 ± 9.8	.101	.753
	Anterior Pelvic Tilt	160.5 ± 10.2		

Table 6 Independent samples t-test for hip flexor flexibility and hamstring flexibility, N = 34

Test	t	df	Sig.	95% Confidence Interval of the Difference	
				Lower	Upper
Modified Thomas	-.235	32	.851	-6.42	7.69
90:90 Active Knee Extension	.190	32	.025	-14.91	-1.09

After adjusting the p-value of the 90:90 active knee extension test, the result is still significant (*p* = 0.05) (Figure 27). It was revealed that the effect size was 0.80 which is considered as a large effect size. Since the difference in the mean is greater than the SEM, that constitutes as a practical difference for the hamstring flexibility.

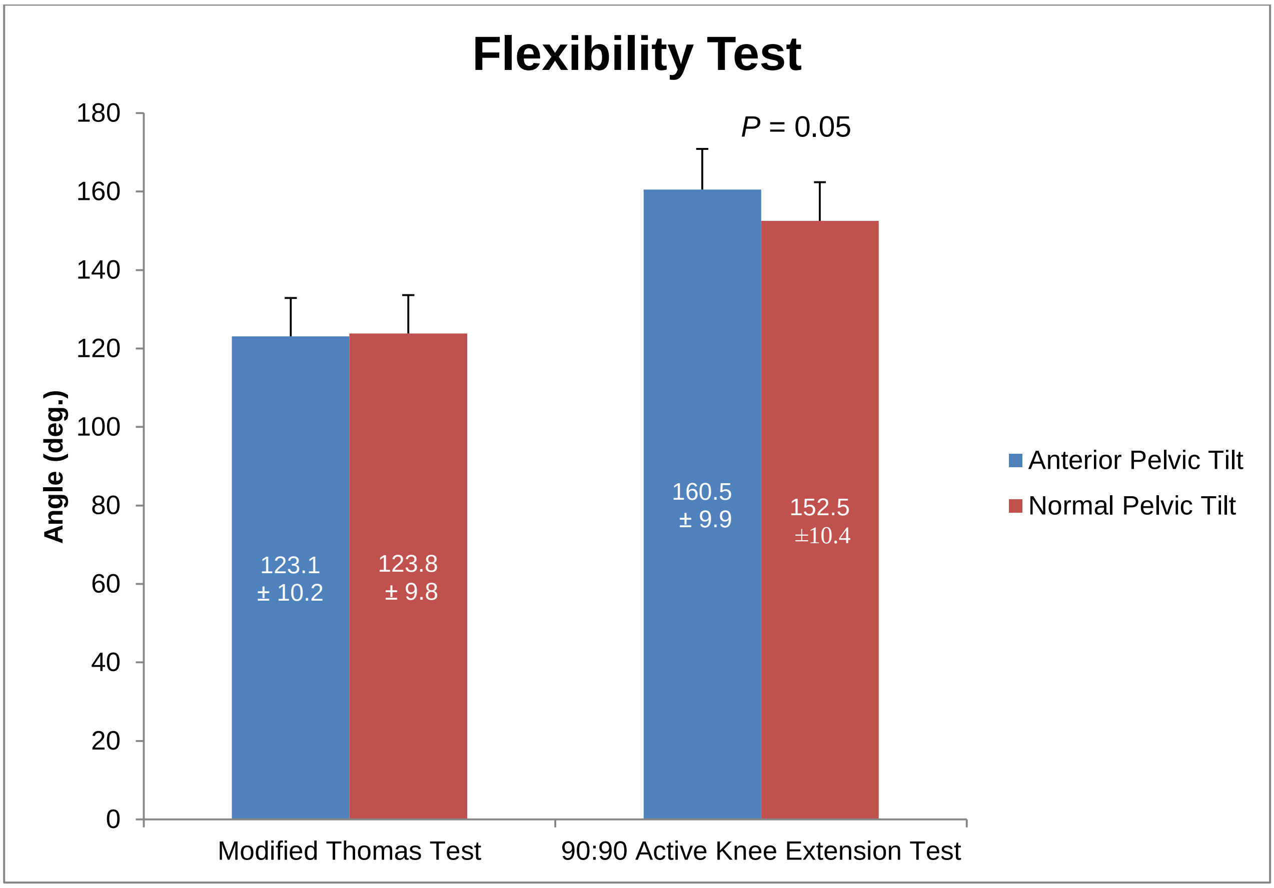


Figure 27 Flexibility tests for the soccer players with and without anterior pelvic tilt

Thigh raise and the combination thigh raise and knee extension showed no significant difference using the Mann-Whitney test (Table 7).

Table 7 Thigh raise and positive Thomas test results, N = 34

Test	Group	Mean Rank	Sum of Ranks	Mann-Whitney U	Z	Asymp. Sig. (2-tailed)	Exact Sig. (1-tailed)
Hip Flexors Flexibility	Normal Pelvic Tilt	18.84	301.5	138.5	-.516	.606	.659
	Anterior Pelvic Tilt	17.29	328.5				
Thomas Test (Thigh Raise and Knee Extension)	Normal Pelvic Tilt	17.81	285	149	-.180	.857	.935
	Anterior Pelvic Tilt	18.16	345				

5.2 Sprint Test

5.2.1 Kinematics of the late swing phase

The duration of the late swing phase for soccer players was calculated and compared between the two groups. Shapiro-Wilk normality test showed that the late swing phase duration was normally distributed between the two groups ($p > 0.05$) (Table 8.). No significant difference was observed for the duration of the late swing phase between the two groups (Table 9).

Table 8 Mean ± SD and normality test for late swing phase duration (ms), N = 34

Variable	Group	Time (ms)	Shapiro-Wilk	
			Statistics	Sig.
Duration of Late Swing Phase	Normal Pelvic Tilt	174 ± 12	.902	.103
	Anterior Pelvic Tilt	176 ± 13	.913	.083

Table 9 Late swing phase duration (ms) mean ± SD and t-test results, N = 34

Variable	Group	Time (ms)	t	df	Sig.	95% Confidence Interval of the Difference	
						Lower	Upper
Duration of Late Swing Phase	Normal Pelvic Tilt	174 ± 12	-.275	32	.785	-10	7
	Anterior Pelvic Tilt	176 ± 13					

Figure 29 depicts the angular displacement for pelvis, hip and knee joint at the late swing phase from the sagittal angle.

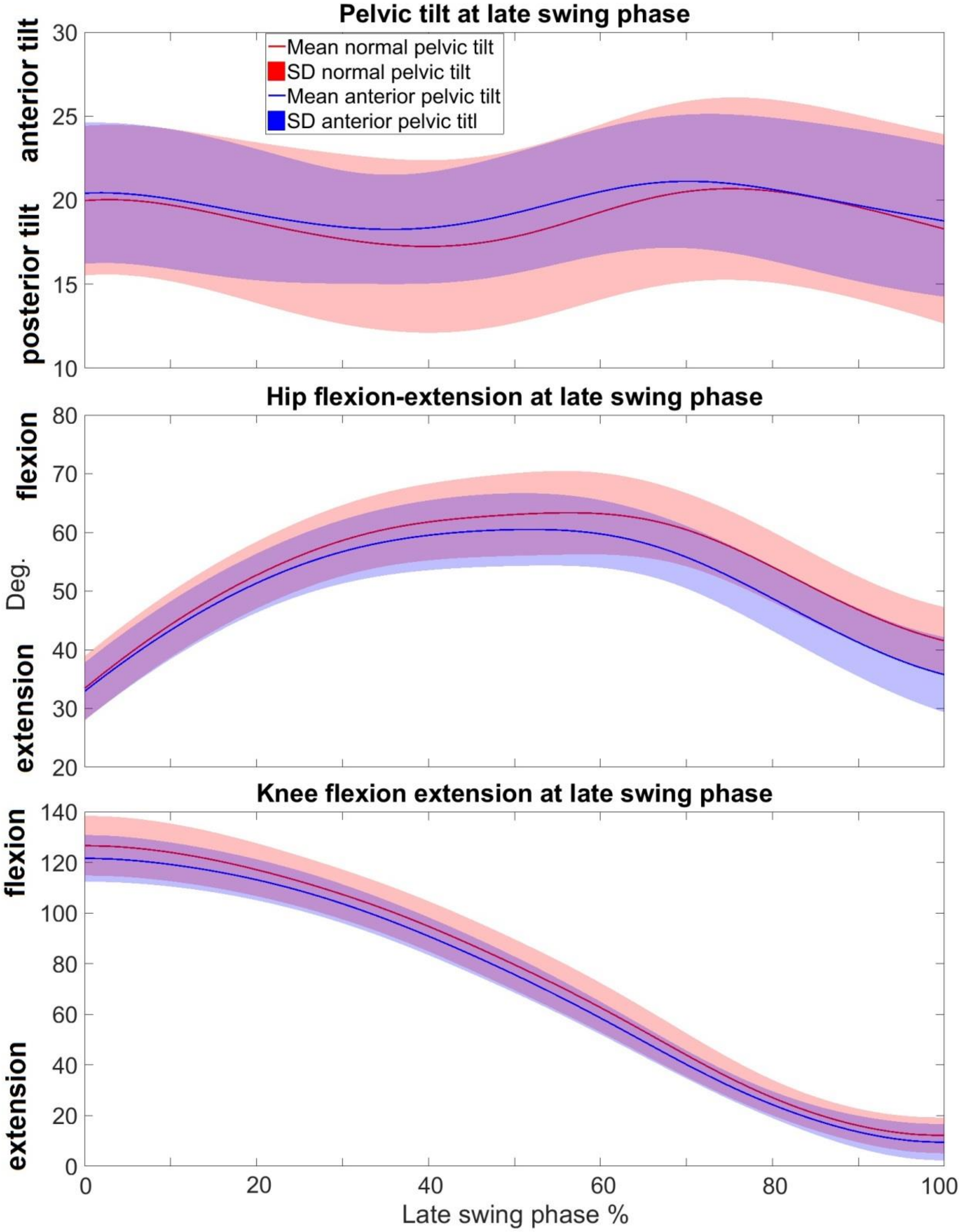


Figure 28 Angular changes for pelvis, hip and knee at the late swing phase from the sagittal plane

Pelvis, hip and knee kinematic data throughout the late swing phase were normally distributed and did not exceed the threshold (Figure 30).

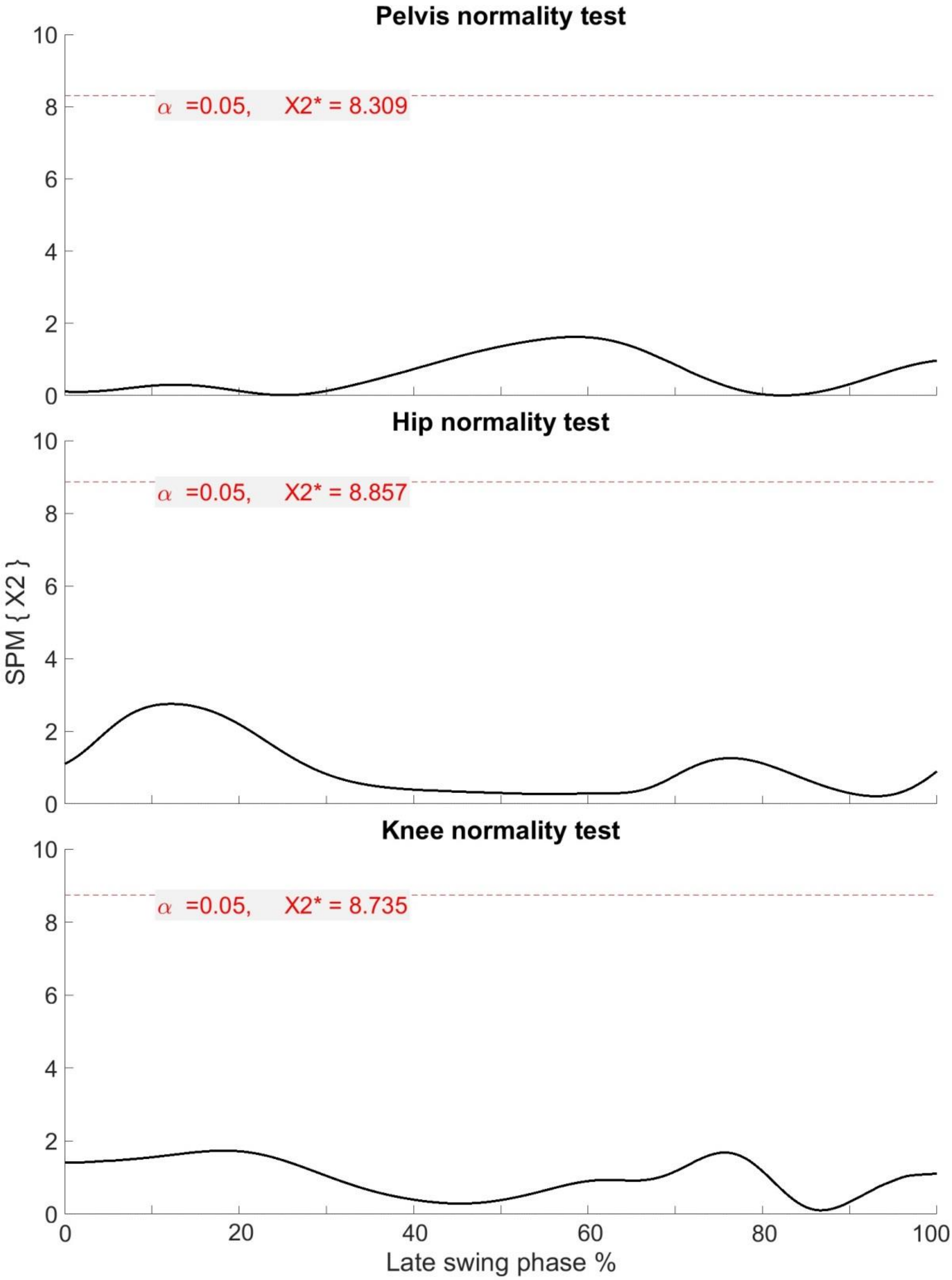


Figure 29 Pelvis, hip and knee normality distribution not exceeding the threshold (dashed red line); α: the alpha level, $x^2$is the chi-square distribution using the D'Agostino-Pearson Omnibus test for assessing the normality of the data

The SPM test showed no significant difference for the pelvis and knee angular displacement at the late swing phase between the player with and without anterior pelvic tilt $p > 0.05$. Hip flexion ($p = 0.04$) revealed to be significantly different between the two groups at the late swing phase. Players without anterior pelvic tilt demonstrated a higher hip flexion compared to the players with anterior pelvic tilt between 85.2% - 100% of the late swing phase (Figure 31).

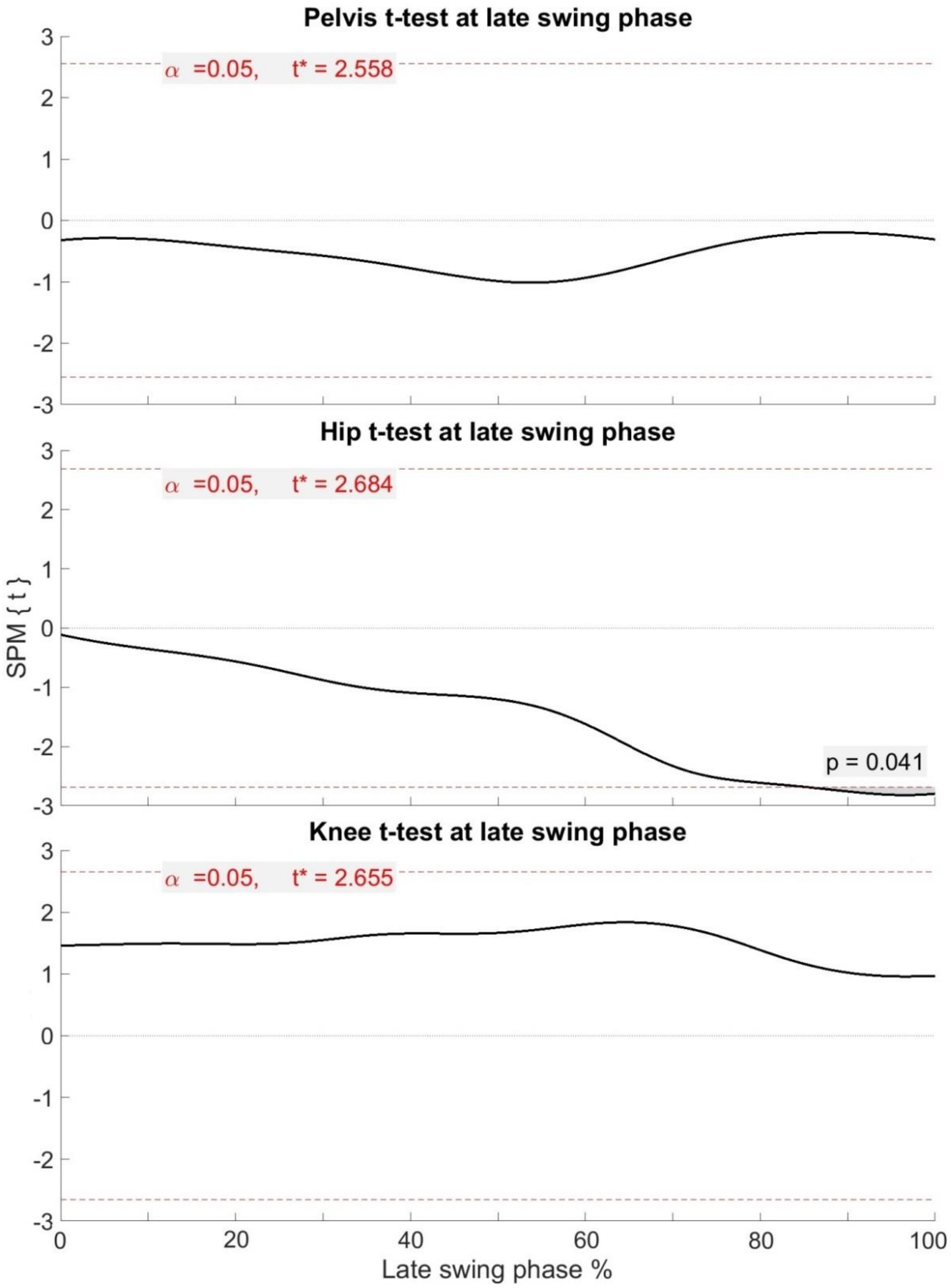


Figure 30 T-test results for pelvis, hip and knee angular displacement at the late swing phase); α: the alpha level, t: t score value for t-test

Since three separate t-tests were carried out for the calculation of the p-value a built-in Bonferroni correction was adjusted for the alpha level using the code:

```
alpha = 0.05;

n = 3;

p = spm1d.util.p_critical_bonf(alpha, n)

p = 0.0170

p_corrected = spm1d.util.p_corrected_bonf(p, n)

p_corrected = 0.0500
```

The results indicate that after the adjustment of the alpha level, the critical value remains unchanged and thus the results for the kinematic data remains the same and only the hip flexion at the end of the late swing phase shows significant difference between the players with and without the anterior pelvic tilt.

After calculating the Cohen’s d for the hip flexion angular displacement, the amount of effect size for the range between 85.2% - 100%, which was found significantly different, varied from 0.901-0.985. This value indicates a large effect size for the difference in the angular displacement.

5.2.2 EMG of the late swing phase

Muscle activity for gluteus maximus, hamstring bicep femoris, rectus femoris and vastus medialis oblique are depicted in figure 32. The overall hamstring activity was reduced at the late swing phase during a sprint.

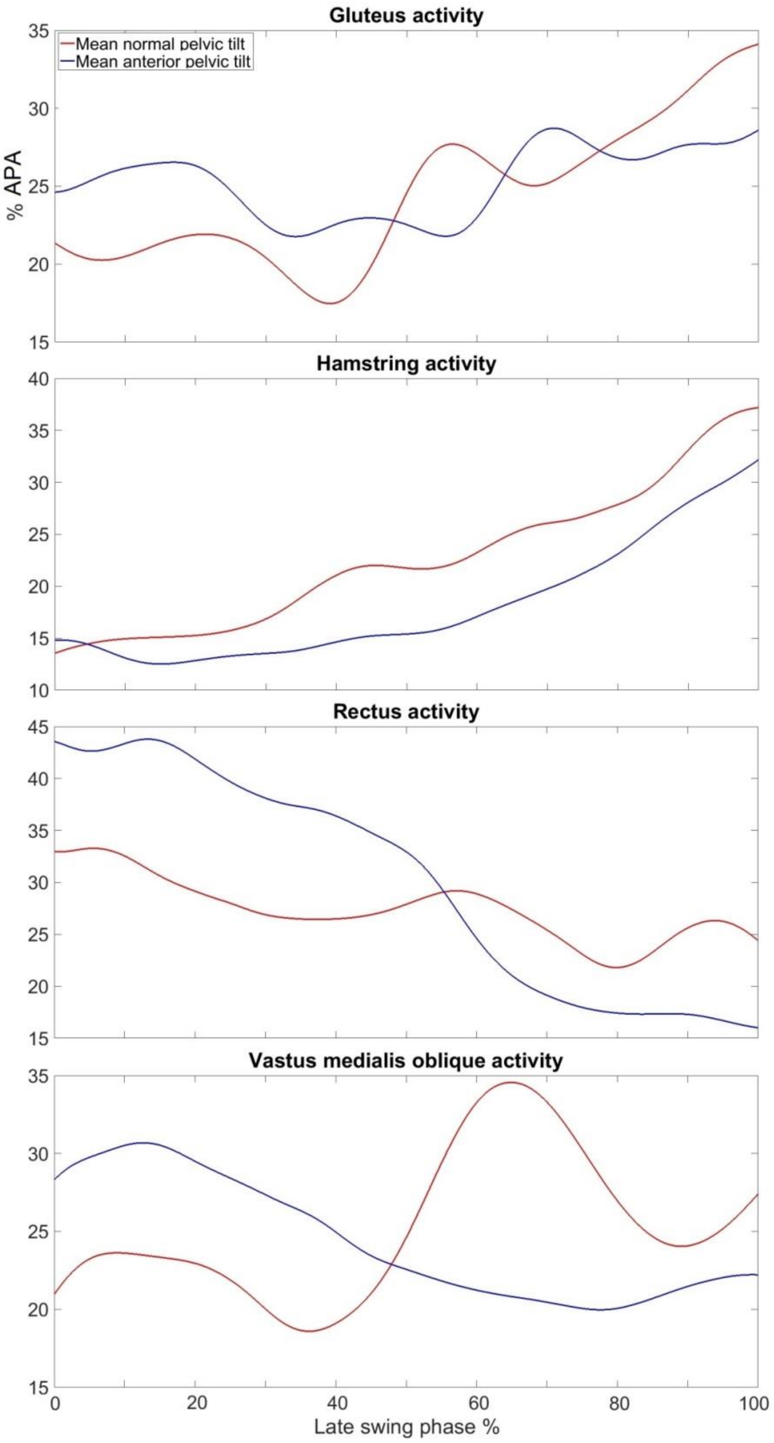


Figure 31 mean muscle activity for gluteus maximus, hamstring biceps femoris, rectus femoris and vastus medialis oblique during the late swing phase (red: players with normal pelvic tilt, blue: players with anterior pelvic tilt). APA: average peak activity of 5 cycles with duration of 20 ms

Normality results showed that none of the muscular activities during the late swing phase were normally distributed (Figure 33). Thus a non-parametric permutation t-test was used to compare the muscle activity between the two groups.

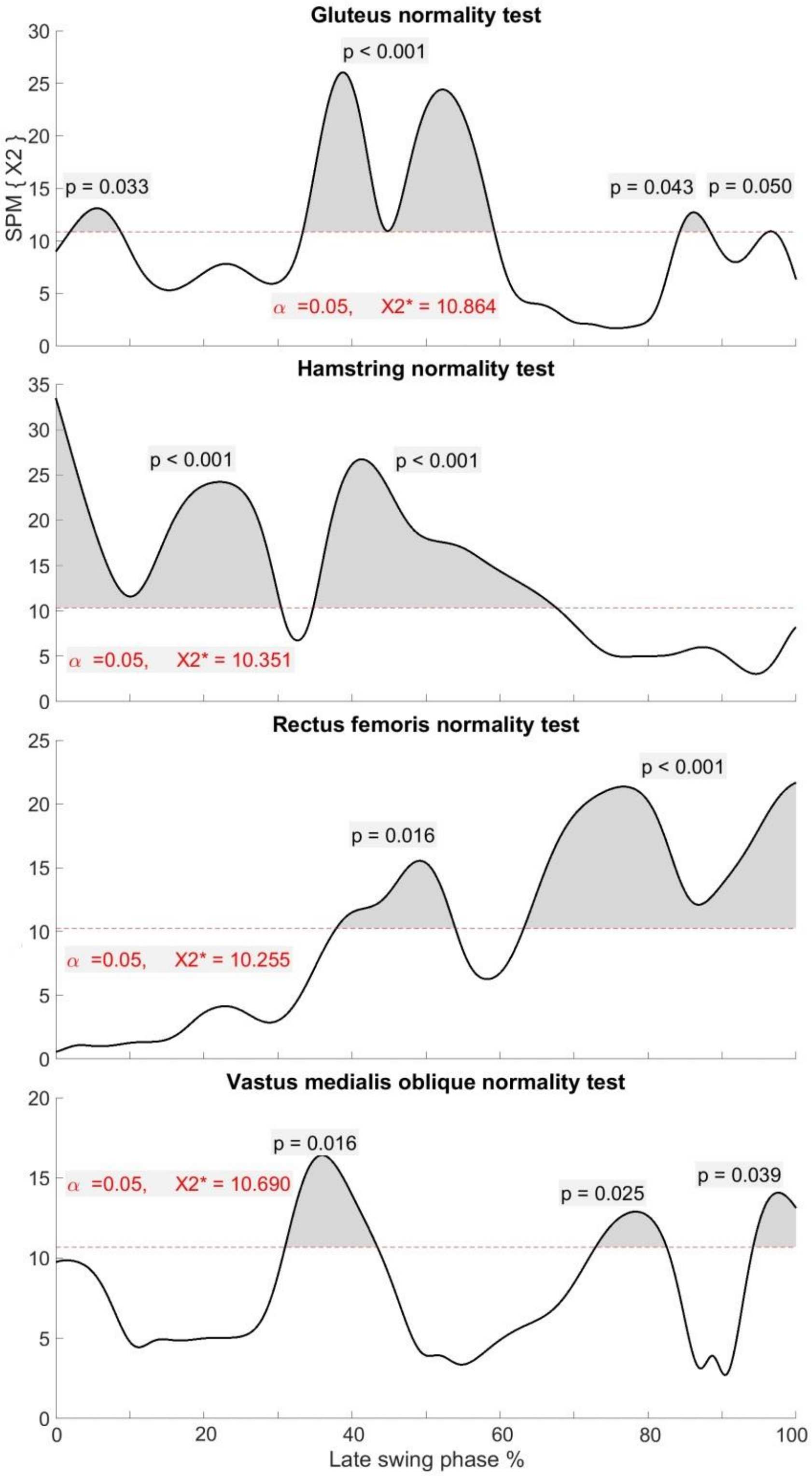


Figure 32 gluteus maximus, hamstring biceps femoris, rectus femoris and vastus medialis oblique normality distribution test. The grey shaded areas indicate clusters exceeding the threshold showing that in those regions the data is not normally distributed ($p < 0.05$)

The permutation test for muscle activity revealed no significant difference for all the muscles between the players with normal and anterior pelvic tilt (Figure 34).

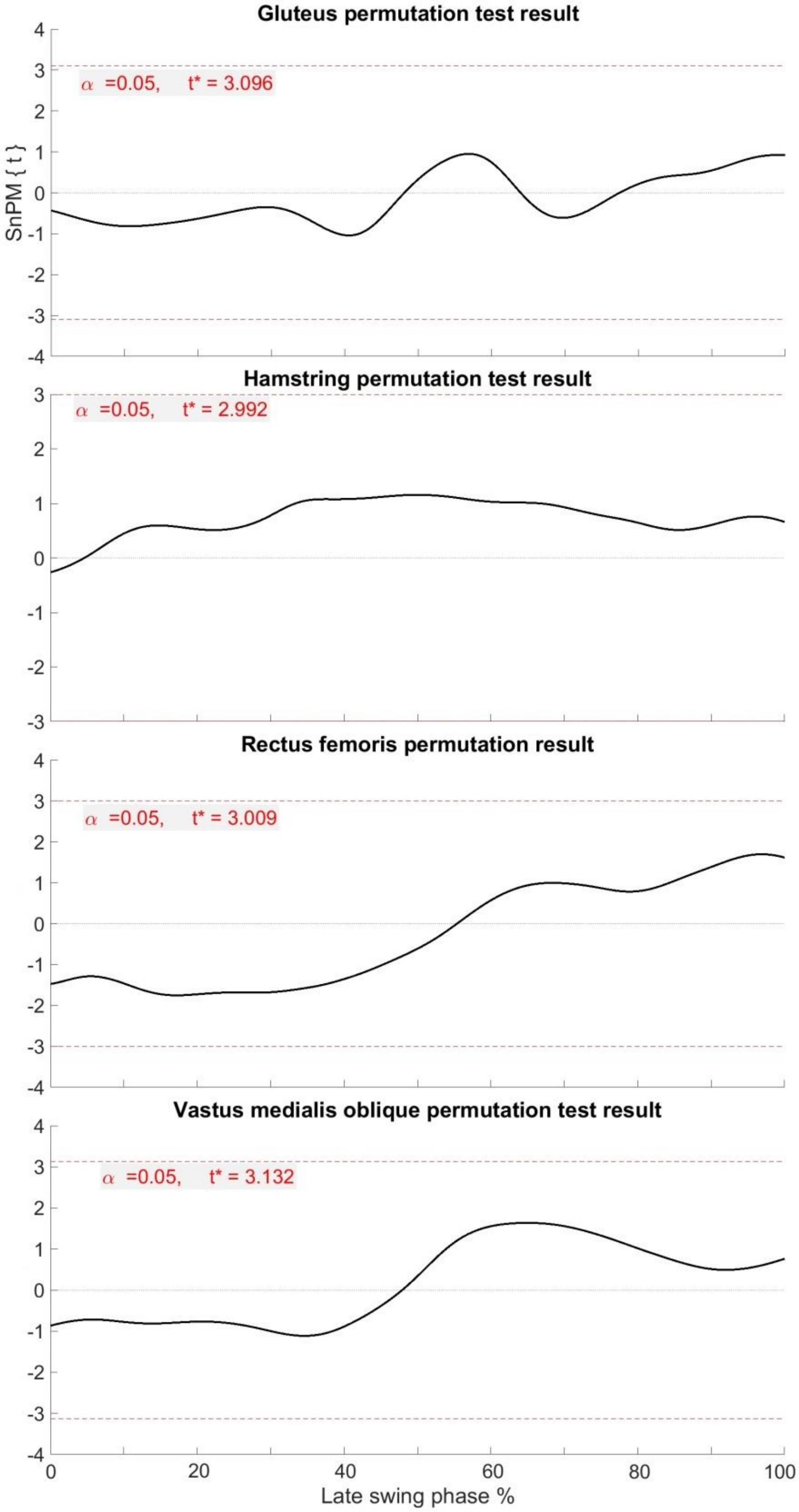


Figure 33 gluteus maximus, hamstring bicep femoris, rectus femoris and vastus medialis oblique permutation test results. The black solid line indicates the t-value throughout the late swing phase. The red dashed line indicates the threshold level

5.4 Strength

Peak torque strength for knee flexion, knee extension, hip flexion and hip extension are displayed in table for both concentric and eccentric contractions at 120 °/s. Normality test revealed that all strength data were normally distributed between the two groups (Table 10).

Table 10 Peak torque strength (mean ± SD) and normality test for concentric and eccentric knee flexion, knee extension, hip flexion and hip extension; in addition to conventional and functional strength ratios for knee and hip flexion-extension, N = 34

Test	**Group**	**Peak Torque (Nm)**	**Shapiro-Wilk**	
			Statistic	Sig.
Knee Extensors Concentric	Anterior Pelvic Tilt	203.6 ± 28.6	.919	.163
	Normal Pelvic Tilt	206 ± 30.7	.990	.999
Knee Flexors Concentric	Anterior Pelvic Tilt	161.9 ± 24.7	.945	.415
	Normal Pelvic Tilt	157.1 ± 20.3	.958	.628
Knee Extensors Eccentric	Anterior Pelvic Tilt	297.7 ± 67.4	.911	.121
	Normal Pelvic Tilt	287.6 ± 88.3	.954	.555
Knee Flexors Eccentric	Anterior Pelvic Tilt	182.2 ± 32.1	.960	.665
	Normal Pelvic Tilt	179 ± 37.5	.950	.490
Hip Flexors Concentric	Anterior Pelvic Tilt	131.2 ±17.8	.917	.153
	Normal Pelvic Tilt	136.1 ±20.6	903	.090
Hip Extensors Concentric	Anterior Pelvic Tilt	248 ± 39.6	.899	.079
	Normal Pelvic Tilt	253.3 ± 63	.989	.999
Hip Flexors Eccentric	Anterior Pelvic Tilt	153.4 ±29.1	.978	.950
	Normal Pelvic Tilt	173.6 ±26	.979	.955
Hip Extensors Eccentric	Anterior Pelvic Tilt	325.2 ±64.5	.973	.884
	Normal Pelvic Tilt	362.2 ±68.7	.983	.958
Conventional H:Q Ratio	Anterior Pelvic Tilt	0.8 ±0.1	.943	.353
	Normal Pelvic Tilt	0.7 ±0.1	.940	.381
Functional H:Q Ratio	Anterior Pelvic Tilt	0.9 ±0.1	.953	.544
	Normal Pelvic Tilt	0.9 ±0.1	.964	.739
Conventional HF:HE Ratio	Anterior Pelvic Tilt	0.5 ±0.1	.923	.189
	Normal Pelvic Tilt	0.5 ±0.1	.917	.152
Functional HF:HE Ratio	Anterior Pelvic Tilt	0.4 ±0.1	.920	.169
	Normal Pelvic Tilt	0.4 ±0.1	.938	.330

The variances were equality distributed between the two groups for all the peak torque variables (Table 11). Independent 2-tailed t-test results show a significant difference for hip flexors eccentric peak torque strength between players with anterior and normal pelvic tilt angle (*p* = 0.047). Other peak torque variables plus the conventional and functional strength ratios did not show any significant difference between the two groups (*p* > 0.05) (Table 11).

Table 11 Peak torque (Nm) mean ± SD; Levene's test equality of variances and independent 2-tailed t-test for concentric and eccentric knee flexion, knee extension, hip flexion and hip extension; and conventional and functional strength ratios for knee and hip flexion-extension peak torque strength, N = 34

Test	Group	Peak Torque (Nm)	Levene's test for equality of variances		T-test for equality of means			
			F	Sig.	t	Sig. (2-tailed)	95% confidence interval of the difference	
							Lower	Upper
Knee Extensors Concentric	Anterior Pelvic Tilt	203.6 ± 28.6	.038	.846	.226	.823	-19.09	23.83
	Normal Pelvic Tilt	206 ± 30.7						
Knee Flexors Concentric	Anterior Pelvic Tilt	161.9 ± 24.7	.627	.435	-.609	.547	-21.24	11.49
	Normal Pelvic Tilt	157.1 ± 20.3						
Knee Extensors Eccentric	Anterior Pelvic Tilt	297.7 ± 67.4	.864	.360	-.364	.718	-67.04	46.79
	Normal Pelvic Tilt	287.6 ± 88.3						
Knee Flexors Eccentric	Anterior Pelvic Tilt	182.2 ± 32.1	.217	.645	-.263	.794	-28.48	21.98
	Normal Pelvic Tilt	179 ± 37.5						
Hip Flexors Concentric	Anterior Pelvic Tilt	131.2 ±17.8	.000	.997	.726	.474	-8.96	18.84
	Normal Pelvic Tilt	136.1 ±20.6						
Hip Extensors Concentric	Anterior Pelvic Tilt	248 ± 39.6	2.896	.099	.285	.778	-32.99	43.62
	Normal Pelvic Tilt	253.3 ± 63						
Hip Flexors Eccentric	Anterior Pelvic Tilt	153.4 ±29.1	.163	.690	2.071	.047	.273	40.1
	Normal Pelvic	173.6 ±26						

	Tilt							
Hip Extensors Eccentric	Anterior Pelvic Tilt	325.2 ±64.5	.195	.662	1.572	.126	-11.08	85.2
	Normal Pelvic Tilt	362.2 ±68.7						
Conventional H:Q Ratio	Anterior Pelvic Tilt	0.8 ±0.1	3.570	.069	-1.004	.325	-.11	.04
	Normal Pelvic Tilt	0.7 ±0.1						
Functional H:Q Ratio	Anterior Pelvic Tilt	0.9 ±0.1	.021	.884	-.579	.567	-.14	.08
	Normal Pelvic Tilt	0.9 ±0.1						
Conventional HF:HE Ratio	Anterior Pelvic Tilt	0.5 ±0.1	.024	.879	.690	.496	-.04	.08
	Normal Pelvic Tilt	0.5 ±0.1						
Conventional HF:HE Ratio	Anterior Pelvic Tilt	0.4 ±0.1	4.146	0.51	-1.300	.207	-.06	.01
	Normal Pelvic Tilt	0.4 ±0.1						

Although the hip eccentric peak torque was found significantly different, but after adjusting the p-value the level of *p* raised to 0.564 which is deemed insignificant.

The maximum concentric and eccentric isokinetic peak torque strength for knee flexors and knee extensors at 120 °/s were not found to be significantly different between soccer players with and without anterior pelvic tilt (Figure 35).

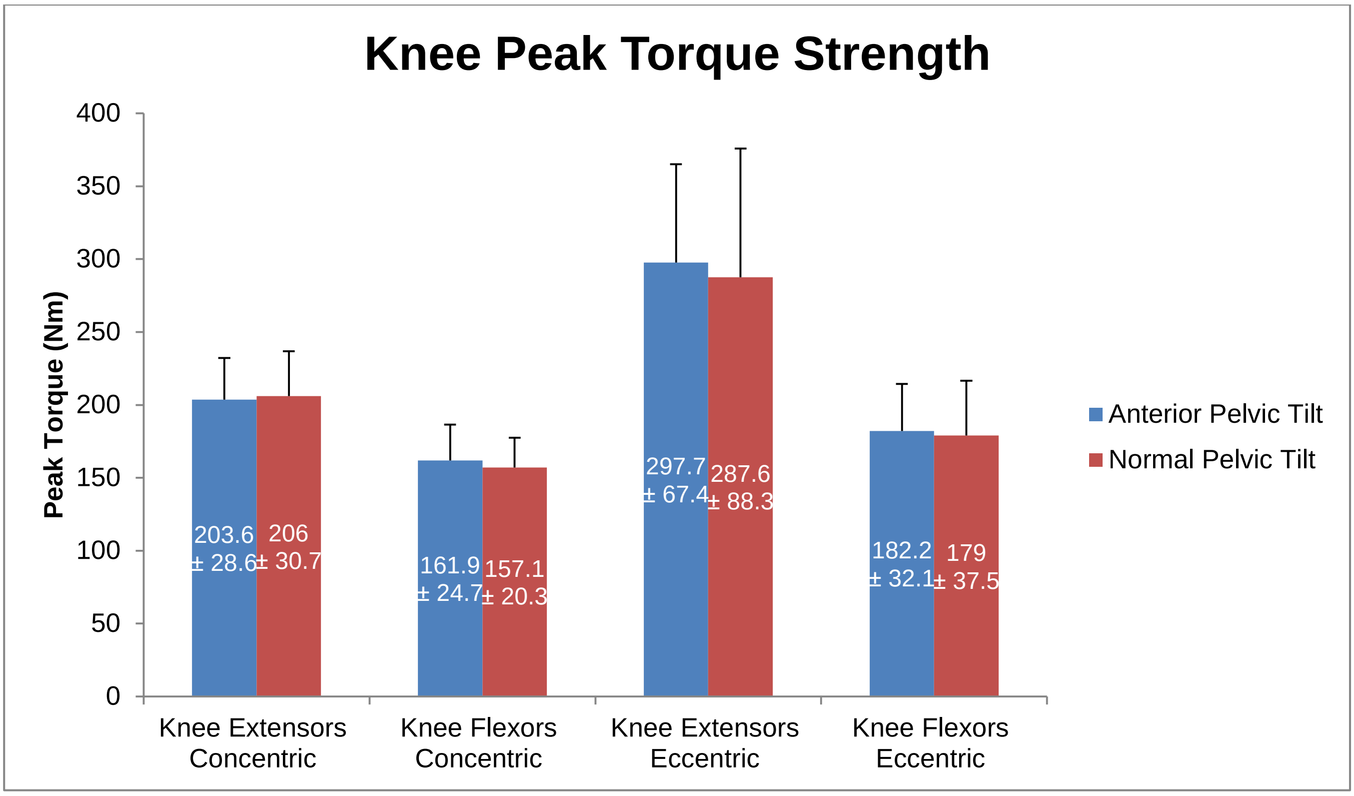


Figure 34 Concentric and eccentric peak torque strength for knee flexors and extensors at an angular speed of 120 °/s between soccer players with and without anterior pelvic tilt

The maximum concentric and eccentric isokinetic peak torque strength for hip flexors and knee extensors at 120 °/s were not found to be significantly different between soccer players with and without anterior pelvic tilt (Figure 36).

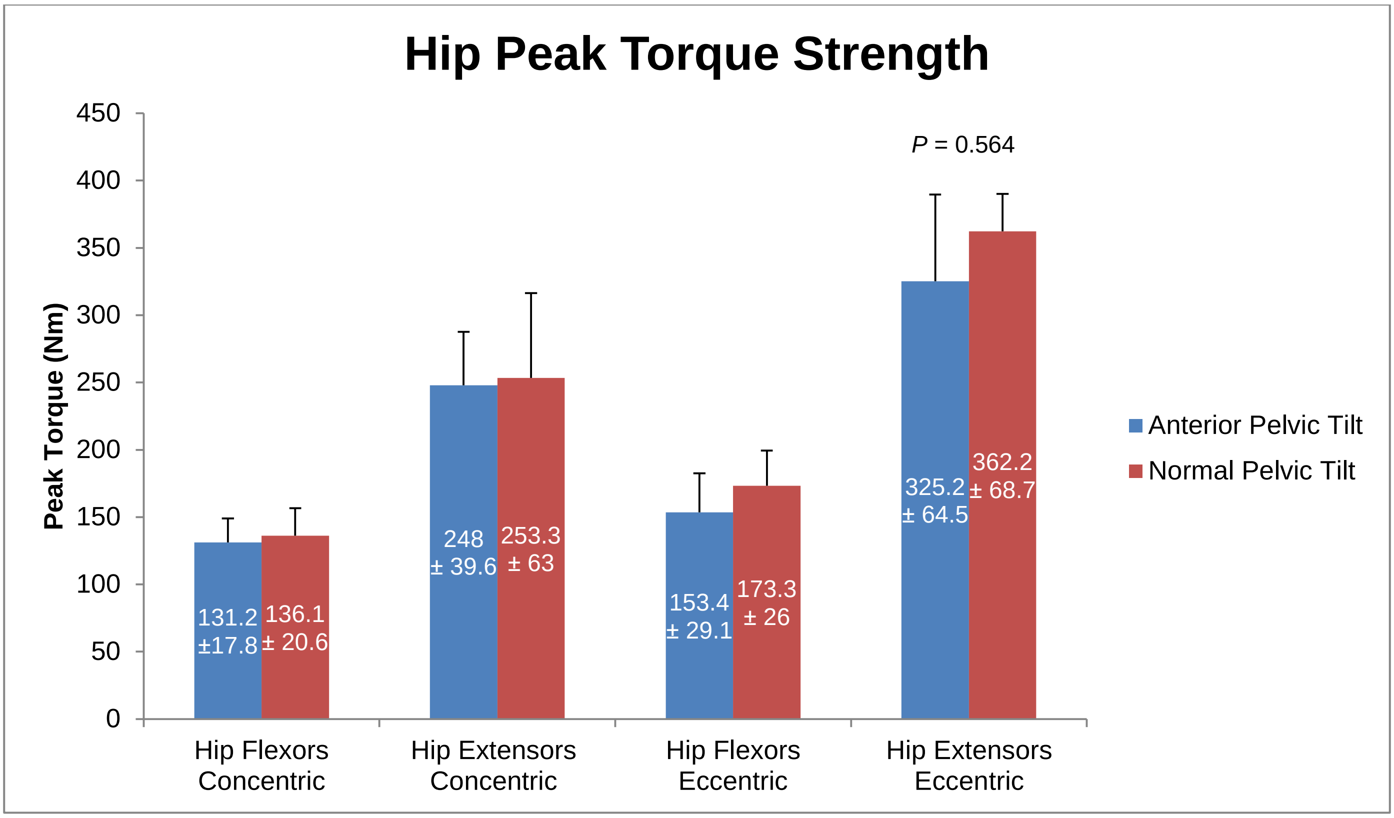


Figure 35 Concentric and eccentric peak torque strength for hip flexors and extensors at an angular speed of 120 °/s between soccer players with and without anterior pelvic tilt

No significant difference was found for the conventional (Hcon:Qcon) and functional strength (Hecc:Qcon) ratio between soccer players with and without anterior pelvic tilt (Figure 37).

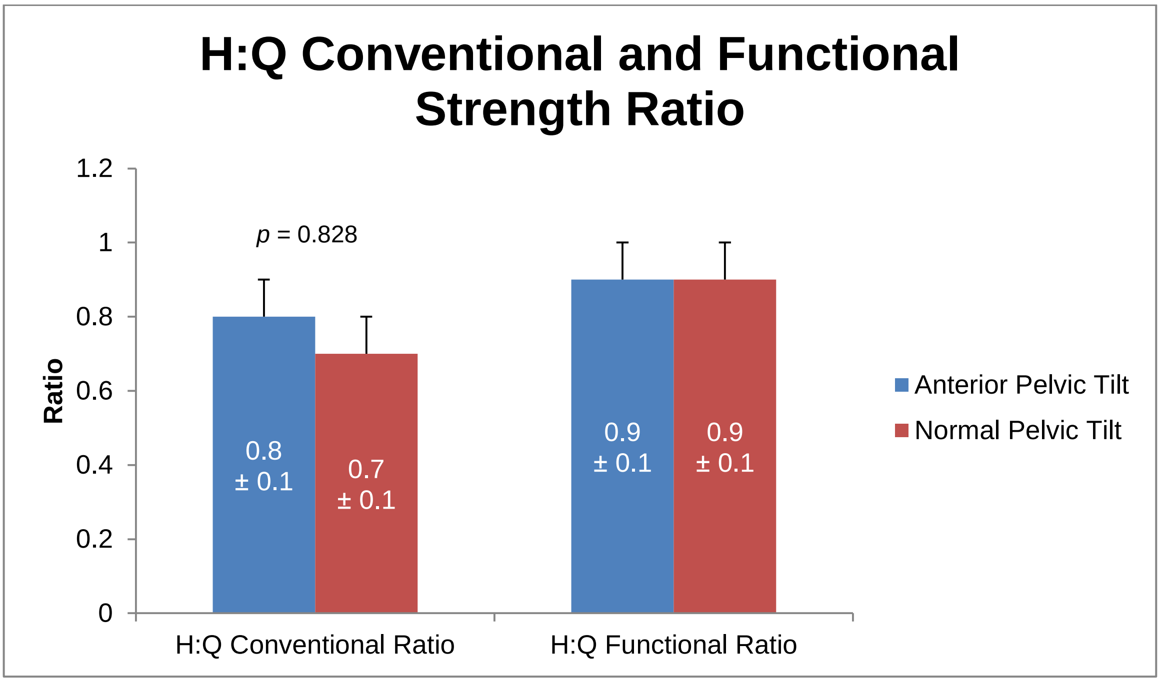


Figure 36 Hamstring to quadriceps conventional (H_{con}:Q_{con}) and functional (H_{ecc}:Q_{con}) strength ratio between soccer players with and without anterior pelvic tilt

No significant difference was found for the conventional (HFcon:HEcon) and functional strength (HFecc:HEcon) ratio between soccer players with and without anterior pelvic tilt (Figure 38).

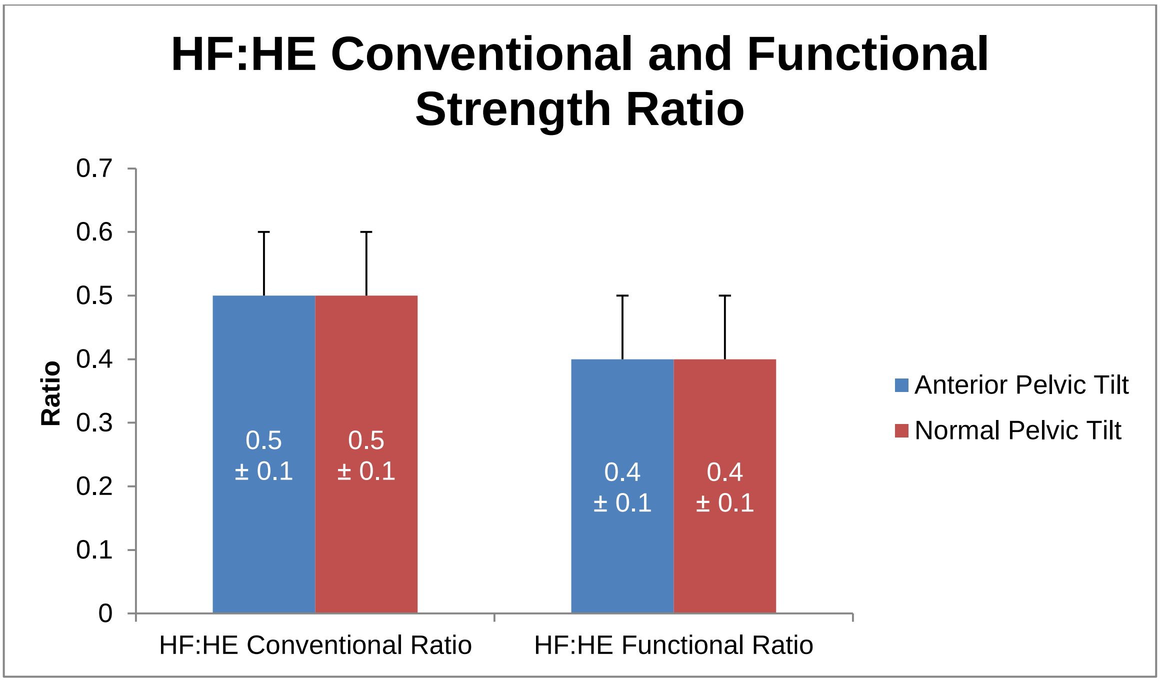


Figure 37 Hip flexors to hip extensors conventional (HF_{con}:HE_{con}) and functional (HF_{ecc}:HE_{con}) strength ratio between soccer players with and without anterior pelvic tilt

To summarize no difference was found for the anthropometric data between the two groups except for the amount of anterior pelvic tilt. The hamstring showed a significant higher flexibility in soccer players with anterior pelvic tilt. No significant difference was observed for hip flexors' flexibility between the two groups.

Hip flexion angle reduced significantly from 85.2% - 100% late swing phase of a sprint for soccer players with anterior pelvic tilt. No significant difference was found for pelvis and knee angle at the late swing phase during a sprint for soccer players with and without anterior pelvic tilt. Muscle activity of gluteus maximus, rectus femoris, vastus medialis, and hamstring biceps femoris did not differ significantly at the late swing phase during a sprint between the two groups.

Maximum concentric and eccentric isokinetic strength of the knee flexors and extensors, and hip flexors and extensors were not found to be significantly different between the two groups. Conventional and functional hamstring to quadriceps as well as hip flexors to hip extensors wasn't found to be significantly different for soccer players with and without anterior pelvic tilt.

6 Discussion

The aim of this study was to investigate the association of pelvic tilt while standing with flexibility (hip flexors and hamstring), sagittal kinematic parameters (pelvis, hip, and knee angle), neuromuscular activity (gluteus maximus, rectus femoris, vastus medialis, and hamstring bicep femoris) and, maximum isokinetic strength (knee flexors, knee extensors, hip flexors, and hip extensors). The reason for choosing these variables were that in previous studies they were assumed to have a correlation with hamstring injury, but due to contradiction in the reports the association of the pelvic angle with these variables were investigated. As for the kinematic and EMG, the recordings were analyzed only for the late swing phase which has been proposed as the time which the hamstring has been said to have a high risk of injury during a sprint.

Choosing valid and reliable tests and instruments for this research was of an imperative priority. Thus tests such as: modified Thomas test (hip flexor flexibility) and 90:90 active knee extension test (hamstring flexibility) have shown high reliability and validity in comparison to other forms of tests. Instruments such as the Diers formetric (pelvic tilt), photographic camera (flexibility), Vicon (kinematics), Myon EMG (neuromuscular activity) and Isomed 2000 dynamometer (maximum isokinetic strength) were reported by previous studies as highly reliable and valid tools for measurement.

Player recruitment was done from the first division teams of Hamburg league. The anthropometric data (age, mass, height, experience) was comparable between soccer players with and without anterior pelvic tilt. With that said the groups were considered to be homogenous. Moreover, the anthropometric data from this study were consistent with previous studies with male amateur soccer players (Hägglund, Walden, & Ekstrand, 2007), other than the pelvic tilt. The findings indicate that the amount of anterior pelvic tilt was significantly higher for the players which were included in the anterior pelvic group. The mentioned variables would be discussed in the following paragraphs.

6.1 Comparison of hamstring and hip flexors’ flexibility

The amount of hamstring flexibility was significantly different between the players with and without anterior pelvic tilt. Soccer players with anterior pelvic tilt exhibited an increase of hamstring flexibility, by a factor of eight degrees. A large amount of effect size (0.8) was also found for the hamstring flexibility which signifies an important difference observed between players with and without anterior pelvic tilt. Since the differences between means for the hamstring flexibility test were greater than the standard error of measurement, it could be stated that the flexibility are practically different between the two groups. Thus hypothesis (1) which stated a difference in hamstring flexibility between soccer players with and without anterior pelvic tilt was confirmed. Consistent with the findings of this study a significant correlation between the pelvic tilt and hamstring flexibility in kayakers (López-Miñarro et al., 2012), was observed. Muyor et al. (2011) and Gajdosik et al. (1994) found no relationship between the pelvic tilt in the standing position and hamstring flexibility (Gajdosik et al., 1994; Muyor et al., 2011). Norris and Matthews (2006) assessed whether if there was a correlation between the anterior pelvic tilt and the length of the hamstring. Although the assessment of the hamstring's flexibility was in par with the measurement in this study the pelvic tilt was tested as the subjects were bending forward (Norris & Matthews, 2006).

Lopez-Minarro et al. (2010), Rockey (2008) and Li et al. (1996) reported that the pelvic tilt does not have a correlation with hamstring flexibility (Li, McClure, & Pratt, 1996; López-Miñarro et al., 2010; Rockey, 2008) in a normal active population, which contradicts with the results of this study in soccer players. When considering the muscular attachment of the hamstring, which originates from the pelvis, it would be expected that an increase in the amount of pelvic tilt would result in the lengthening of the muscle. However, when measuring the amount of flexibility it is crucial that a valid and reliable test should be chosen with the pelvic tilt accounted for.

The discrepancies found between the findings can be largely explained as methodological differences. While sit-and-reach test has been widely accepted to be a good assessment of the overall body's flexibility, however studies have shown low reliability and validity for assessing the hamstring flexibility (Mayorga-Vega, Merino-Marban, & Viciana, 2014; Mier, 2011). Upper extremity length and the flexibility of the trunk would influence the outcome of the sit-and-reach test in addition to the movement of the pelvis. Furthermore, another source of discrepancy can be explained through the use of mixed sex participants in previous studies. If conclusions ought to be inferred it is necessary to use reliable methods for hamstring flexibility assessment. While using valid and reliable tests such as the active knee extension test it is suggested to control the pelvis movement as it highly affects the hamstring flexibility outcome (Bohannon, Gajdosik, & LeVeau, 1985; Gajdosik & Lusin, 1983; Herrington, 2013; Sullivan et al., 1992).

Hamstring flexibility has been suggested as an indicator of a non-contact hamstring strain in soccer players (Witvrouw, Danneels, Asselman, D'Have, & Cambier, 2003b; Witvrouw et al., 2003c). Less hamstring flexibility has been correlated with higher rates of hamstring injuries. The flexibility of the muscle can be altered due to the difference of the anatomical attachments of the muscle. Thus an increase in the hamstring length is to be expected as the pelvis tilts anteriorly. Although anterior pelvic tilt has been proposed as a potential risk factor for hamstring injury (Woods et al., 2004a), the mechanism is not in an agreement with the concept of hamstring flexibility.

As the pelvis increases its tilt angle the hamstring stretches and overtime it will adopt to a new length. This claim has been noted in a review paper by Gajdosik (2001) whom has also suggested that the changes in the muscle length over long periods may be the result of the optimal length position readjustment (Gajdosik, 2001). The higher flexibility can be justified as a result of sarcomere genesis. Sarcomere genesis occurs when the muscle is passively stretched over long period of time (Caiozzo et al., 2002b). Controversy remains as to whether hamstring flexibility truly predicts an injury outcome (van Doormaal et al., 2017). The findings of this study depict that players with an anterior pelvic tilt demonstrated greater hamstring flexibility and should accounted for while measuring the muscle flexibility due to its association with pelvic tilt.

The results of this study showed that hip flexors' flexibility did not differ between soccer players with and without anterior pelvic tilt. Interestingly the amount of knee flexion which depicts the flexibility of the rectus femoris was relatively similar between the two groups. The measurement for the hip flexors flexibility from the sagittal perspective generally depicts the flexibility of the iliopsoas for hip raise and knee extension for knee extension. Hypothesis (2) which assumed a difference for the hip flexors' flexibility between soccer players with and without anterior pelvic tilt was not verified. The findings from Bridger et al. (1992) support the results of this study. By investigating the hip flexor muscle they concluded that the hip flexor flexibility wouldn't predict the changes in the pelvic tilt while standing (Bridger, Orkin, & Henneberg, 1992). Similar findings were reported by Toppenberg et al. (1986) in female subjects (Toppenberg & Bullock, 1986). Youdas et al. (1996) reported similar findings when assessing the hip flexibility muscle and its correlation with pelvic tilt in asymptomatic adults (Youdas et al., 1996). They found that the flexibility of the hip flexors did not correlate with the amount of pelvic tilt. Even during dynamic movements such as running no correlation was found between pelvic tilt in running and the hip flexibility using Thomas test (Schache et al., 2000).

However, Müller-Wohlfahrt suggested that the anterior pelvic tilt is associated with the flexibility of the hip flexors the results of this study contradicts this premise (Müller-Wohlfahrt et al., 2015). This claim has been suggested by other scientists as well, but more often than not failed to introduce a practical observation (Heiderscheit et al., 2010; Woods et al., 2004a). Hip flexor flexibility is considerably important for soccer players since it has been suggested to have a relationship with muscle strain during the competitive season (Bradley et al., 2007). However hip flexors' flexibility assessments were either not mentioned (Ekstrand & Gillquist, 1982) or were different from the valid clinical test (Bradley et al., 2007). Hip flexors' flexibility wasn't found to be significantly different between the players with and without anterior pelvic tilt. This contradicts the notion of an anterior pelvic tilt being caused by hip flexor flexibility (Clark et al., 2010; Page et al., 2010). Although evidence shows that soccer players have a relative less flexible muscles in comparison to the non-athlete population the etiology of the flexibility is obscure (Ekstrand et al., 1982).

One explanation would be that the orientation of the pelvis may not be a result of the flexibility or shortness of a single muscle group, but rather weakness of its antagonist that fails to support the movement of the pelvis by not adequately stabilizing it. In the pelvic crossed syndrome, it has been determined that the cause of the rotation to be a combination of different dysfunctions in the pelvic region (Janda, Frank, & Liebenson, 1996). They proposed four muscle groups as a result of a possible cause of the pelvis disorientation; however, this does not indicate that all four or just a single muscle dysfunction should be present to justify the misalignment in the pelvis (Idoate et al., 2011).

It cannot be directly inferred that hip flexor flexibility doesn’t contribute to anterior pelvic tilt in soccer players. Furthermore, the anterior tilt of the pelvis may be a result of boney morphological differences and thus should be taken into account (Preece et al., 2008). One other main factor is that in order to acquire valid findings from the modified Thomas test it is necessary to control the pelvic rotation while conducting the test (Kim et al., 2015; Vigotsky et al., 2016). Failing to control the movement of the pelvis would result in non-valid and non-reliable findings (Peeler & Anderson, 2007; Peeler & Anderson, 2008). In order to fully understand the cause and effects of hip flexors on the rotation of the pelvis it would be suggested that a test battery from both sagittal and frontal plane to be performed so that other muscle groups would also be accounted for.

6.3 Comparison of the sagittal kinematics of the pelvis, hip, and knee at the late swing phase during a sprint

During the sprint test, the amount of hip flexion was less in the players with anterior pelvic tilt during the last stages of the late swing phase. At the end of the late swing phase a supercluster exceeded the threshold signifying significant difference between the hip flexion between the two groups. The results of the effect size also showed a considerably large value for the range identified significantly different which signifies an important difference of the hip flexion angle between the two groups. In contrast, the angular progression of pelvis and knee in the sagittal plane at the late swing phase showed no significant difference during the late swing phase between the two groups while sprinting. In general the amount of anterior pelvic tilt was increased during the late swing phase of the sprint but was not found to be significantly different compared to players with normal pelvic tilt. Knee flexion also decreased throughout the late swing phase for players with anterior pelvic tilt but was not found to be significantly different between the two groups.

The findings of this study found that hip angles from 85.2% - 100% of the late swing phase between the two groups were significantly different while sprinting. Therefor the hypothesis for the difference of hip flexion was confirmed and simultaneously wasn't verified for pelvis and knee angles. Kinematic angles in this study are in agreement with maximum angles reported from previous studies (Higashihara, Nagano, Ono, et al., 2015; Nicola et al., 2012; Novacheck, 1998). This is the first study to use the SPM method for statistical comparison at the late swing phase with regards to pelvic changes. No other study has investigated the effect of a pelvic tilt on dynamic task such as sprinting.

Our findings show that soccer players with anterior pelvic tilt in standing have decreased hip flexion at the late swing phase during a sprint prior to foot contact. Upon closer investigation it is revealed that as the sprinting cycle approaches the end of the late swing phase (foot contact) soccer players, with anterior pelvic tilt in the standing posture, display a relative higher anterior pelvic tilt and knee extension angle (not statistically significant) prior to foot contact. These small changes in the adjacent joint angles can possibly impose limitation to the hip flexion due to muscle elongation which happens at the late swing phase to avoid injury.

The relationship between anterior pelvic tilt and hip range movement has been previously studied (Franz et al., 2009; Ross et al., 2014a). It was mentioned that the as the pelvic tilt had a negative correlation with hip motion but only during terminal stance (Schache et al., 1999; Schache et al., 2000). This assumption was justified by mentioning that the restriction in the range of motion can cause the inverse relationship between the pelvis and hip. One can assume that the pelvis and hip joint position affect each other's kinematics due to the mutual muscles and tendons overcrossing the two segments. It seems that as the anterior pelvic tilt increases the hamstring, which is responsible for controlling hip flexion and knee extension motion during the late swing phase, would exert a pulling force limiting the hip flexion motion. The decrease in hip flexion may result in lower stride lengths which would lead to decreased performance (Krzysztof & Mero, 2013). The alteration in angular value is presumably due to the kinetic chain link. This relationship is also supported by a study which showed that an increase in pelvis tilt resulted in a loss of 10 degrees of hip flexion (Ross et al., 2014a). The result of this decreased hip flexion is compensated by adjacent segments to maintain optimum stride length. As a compensation mechanism, the knee would extend to a higher angle lengthening the hamstring. The lengthening is what studies consider to be a risk factor for hamstring strain during the late swing phase (Schache, Dorn, Wrigley, Brown, & Pandy, 2013; Woods et al., 2004b). The decreased hip flexion has also been associated with lower hamstring activity (Guex, Gojanovic, & Millet, 2012). More studies have to be conducted using a time series analysis to have a better understanding of the overall changes that may happen if changes in the postural alignment occurs.

Although higher amount of tilt was observed in the players with anterior pelvic tilt, the amount of difference was not considered to be significantly different. It seems that the standing posture pelvic tilt did not translate to the dynamic motion. The justification could possibly be due to the measurement a setting which was carried out on the motorized treadmill rather than a natural environment. Pelvic tilt at foot contact was shown to be different between treadmill and overground running, with the overground running exhibiting a higher degree of anterior pelvic tilt at foot contact (Schache et al., 2001).

Another explanation would be that the antagonist muscles responsible for controlling the anterior rotation of the pelvis are not inhibited as the literature suggests (Page et al., 2010; Panayi, 2010). Although extreme anterior pelvic tilt has been proposed as a risk factor for hamstring injury, especially during late swing phase, the findings from this study did not reveal any significant difference in the pelvic tilt for soccer players with and without pelvic tilt angel while sprinting. It appears that soccer players with anterior pelvic tilt are able to control the pelvic motion during a high-speed locomotion and the pelvic tilt in a standing in not an indicator for the pelvic tilt in sprint.

It can also be noted that, despite the popular beliefs; the early stages of the stance phase can also be considered as the time where the kinematics may be different (Liu, 2007). The logic behind this is the fact that during the early stages of the stance phase the loads associated with the ground contact transfers to the upper segments causing a knee flexion momentum and hip extension momentum which may be related to cause of hamstring injury (Mann & Sprague, 1980; Mann, 1981). Both kinematic and kinetic models support this theory as well, so it could be that changes in the pelvis' orientation may be transferred to the early stages of the stance phase. More research is needed to assess the relationship of an anterior pelvic tilt and its kinematics on hamstring injury susceptibility.

6.4 Comparison of the neuromuscular activity at the late swing phase in a sprint

Muscle activity of gluteus maximus, rectus femoris, vastus medialis, and hamstring biceps femoris did not show any difference between players with and without anterior pelvic tilt. Thus hypothesis (4) which assumed a difference in the neuromuscular activity of the mentioned muscles was not verified. These muscles were specifically chosen on the basis of their relationship to the pelvis, through muscle attachment, or their functional contribution during the late swing phase. This was the first study to incorporate SPM analysis to EMG data, which makes the comparison difficult with other studies. Furthermore no other studies have compared the effect of an anterior pelvic tilt on the muscles during a dynamic task. The amount of neuromuscular activity of the hamstring, during the late swing phase, was consistent with the findings in previous studies (Hansen, Einarson, Thomson, & Whiteley, 2017; Yu et al., 2008). The notable difference can be seen in the hamstring biceps femoris activity. Although difference can be observed during the late swing phase but statistically it isn't significant. One explanation could be that the muscles responsible for pelvic tilt are different than the muscles selected in this study. Reports show that the neuromuscular activity of the hamstring, rectus femoris, and gluteus maximus while tilting the pelvis has no change (Takaki et al., 2016). Other muscles such as the multifidus and transversus abdominis show an increase in activity while tilting the pelvis (Drysdale, Earl, & Hertel, 2004).

In another study, neuromuscular activity of the upper and lower rectus abdominis, external obliques, lower abdominal stabilizers, rectus femoris, and biceps femoris were measured while performing the Janda sit-up and double straight leg lift under three different pelvic positions (posterior, neutral, and anterior tilt). In this dynamic task the muscular activity of the rectus femoris and the biceps femoris did not differ in comparison to the other muscles (Workman, Docherty, Parfrey, & Behm, 2008). Although the functional task was different from this study, but considering the muscular selection, it can be seen that the amount of pelvic tilt would not affect the amount of muscular activation of the muscles selected in this study.

The difference in the measurement setting is a contributing factor which can change the amount of muscle activation. Overground walking in healthy adults has shown to produce different muscular activation between treadmill and overground walking (Lim & Lee, 2018). In the same study it was also shown that the amount of pelvic range of motion decreased in treadmill comparison with overground which can also explain the difference in the muscular activity observed between treadmill and overground. The reduction of pelvic angle has also been mentioned by previous study during a treadmill sprint in comparison to overground sprint (Schache et al., 2001).

Classification methods for grouping the soccer players can also be regarded as a justification for not observing any difference in the neuromuscular activity of the selected muscles. Choosing a higher cut-off point for the pelvic tilt to group the players might have had shown significant differences in the muscle activity. Hamstring activity showed an overall decrease in its activity for soccer players with higher anterior pelvic tilt during the late swing phase. This decrease can be the result of stretch weakness mechanism (Sahrmann, 2002). A study has shown that prolonged passive stretching of a muscle can decrease the sensitivity of the muscle reflex (Avela, Kyröläinen, & Komi, 1999). The reduction in sensitivity leads to decrease neural drive to activate the muscle as it is eccentrically contracting. The decrease in the hamstring activity has been associated with lower horizontal ground reaction force production which serves as propelling force to gain higher speed during a sprint (Kyröläinen, Komi, & Belli, 1999; Morin et al., 2015; Orchard, 2012). Low motor recruitment, as a result of anterior pelvic tilt, may obstruct the soccer player from achieving their optimum sprinting abilities thus reducing their performance.

Another important finding from Higashihara et al. (2018) points out that the muscle activity of different hamstring muscles and their contribution based on the phase of the sprint. They reported that when sprinting at maximum speed compared to the acceleration phase the semitendinosus displays a higher activity compared to the biceps femoris long head (Higashihara, Nagano, Ono, & Fukubayashi, 2018). We could infer that the anterior pelvic tilt might have a greater effect on other hamstring muscles such as semitendinosus compared to the biceps femoris long head which was measured in this study.

6.5 Comparison of maximum isokinetic strength of knee flexors, knee extensors, hip flexors and hip extensors

None of the maximum isokinetic strengths and ratios was significantly different between the players with and without pelvic tilt. Thus hypothesis (5), which expected a difference for the maximum concentric and eccentric isokinetic strength; as well as conventional and functional strength ratio, between soccer players with and without anterior pelvic tilt was not verified. This has also been confirmed by Rockey (2008) which found no relationship between anterior pelvic tilt and hamstring muscle strength (Rockey, 2008). Although the studied accounted for hip flexors flexibility and genu recurvatum no relationship was found between the peak hamstring torque (concentric and eccentric) and pelvic angle.

Isokinetic hip strength was measured for cross-country runners and it’s correlation with pelvic motion was assessed. It was shown that frontal pelvic obliquity was inversely correlated with hip extension strength. There was no correlation was determined between pelvic tilt and maximum isokinetic hip extensors (Ford, Taylor-haas, Genthe, & Hugentobler, 2013).

Other studies have shown that higher pelvic tilt was associated with other muscles such as the internal and external hip rotators and hip abductor and adductors (Rodriguez, 2009). According to the findings from the Rodriguez (2009) and Ford et al. (2013), it appears that the abnormality in the pelvic alignment from the sagittal plane is not correlated with isokinetic strength and pelvic postural abnormality from frontal plane can be related to isokinetic strength.

The logic for this hypothesis was based on the length-force relationship which states that muscles in lengthened position produce less amount of force. It can be justified that since the lengthening in this condition happens over a period of time players might be experiencing sarcomere chain genesis (Caiozzo et al., 2002a; Peviani et al., 2018). In this process the lengthened muscles would start generating sarcomere chain leading to adaptation to new length and to some extend increase in force production as a result of increased sarcomere chain (Ryan et al., 2011). A study also acquired subjects that performed two forms of stretching (static and proprioceptive neuromuscular facilitation) which resulted in an increase of peak torque generation of the hamstring (Worrell, Smith, & Winegardner, 1994). The static stretching was performed while the subjects maintained an anterior pelvic tilt position. Although the reports of this study didn't indicate any significant increase in the amount flexibility of the hamstring, the amount of peak production increased. In a paper presented at the Biomechanics and Neural Control of Movement Conference (2016), a report was given as to how the long duration length change may not affect the peak torque of the muscles surrounding the joints (Lieber, Roberts, Blemker, Lee, & Herzog, 2017). It seems that the first week of the length change, the muscle reorganise its length by increasing the length of the sarcomere chain, but after the first initial weeks it was shown that the sarcomere length returned to its previous state (Lieber et al., 2017). It was witnessed that after the initial week the tendon adapted itself, reshaping to new length. This could explain why there was no difference witnessed in the peak torque, due to the reorientation of the optimal length of the muscle.

6.6 Limitations

One limitation was that the during the hip flexors flexibility test the flexibility of the tensor fascia lata/ iliotibial band (TFL/ITB) was not accounted for (Harvey, 1998). The flexibility of TFL/ITB would also produce a positive result when using the modified Thomas test, thus it is recommended that the flexibility of these two muscles be accounted for in future studies. Another limitation was the fact that the kinematic data was only analysed from the sagittal plane and thus limited to only one plane. It would be advised that the kinematic angles from the frontal plane be considered in future studies. Do to the time limitation and limited sample size the athletes were recruited from the amateur league and it is expected that the results differ from the professional soccer players.

The measurement setting is also a factor that needs to be taken into consideration. As mentioned previously some kinematic angles would be different if the measurements were to be conducted in the overground sprinting environment. Furthermore all the athletes were subject to run at similar speeds which is different compared to their maximum sprinting speed, thus it is encouraged that this notion should also be considered as a limiting issue of this study. This was a cross sectional study under lab conditions, and the changes the measured parameters cannot be directly associated with predisposition to injury. Likewise a prospective study we need to determine the relationship between anterior pelvic tilt angle and hamstring injury rate.

Accounting for the pelvic posture from frontal and horizontal plane is also a factor that was not considered in this study. Previous studies have shown that frontal plane pelvic obliquity has moderate correlation with isokinetic strength of the hip muscle. Furthermore muscular activity of trunk muscles such as the multifidus and rectus abdominis may be related to pelvic tilt which was not accounted for in this study.

7 Conclusion

Our findings show that soccer players with anterior pelvic tilt demonstrate a higher amount of flexibility of the hamstring. When assessing the flexibility of the hamstring the amount of pelvic tilt is a factor that should be taken into account. When reporting the hamstring flexibility it is suggested that a pelvic evaluation should be conducted as a complementary test. In contrast hip flexors did not differ and was not associated with the pelvic tilt. The amount of hip flexion during the late swing phase of a sprint was also associated with pelvic tilt angle. The pelvic alignment should be considered as a factor which would influence the sprinting pattern which may lead to performance hindrance and susceptibility to injury during the late swing phase. In terms of pelvis and knee kinematics, and muscular activity during the late swing phase the anterior pelvic tilt remains questionable as to whether it would alter these parameters. The amount of anterior pelvic tilt did not influence the peak torque values for knee extensors, knee flexors, hip flexors and hip extensors both concentrically and eccentrically. Furthermore, the anterior pelvic tilt did not indicate a change in the muscular ratio strength. The argument which that the hamstring would be susceptible at the late swing phase for players with an anterior pelvic tilt still remains controversial and further research is needed to clarify this assumption. Future studies should investigate how a malalignment in the pelvic would affect the kinematics during a sprint with and flexibility of the muscular structure and its relationship with hamstring injury.

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Curriculum vitae

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Education	**Bachelor of Sciences** • Sport Science and Physical Education, University of Tehran, Tehran, Iran. 2010-2013, GPA : 18.49/20 **Master of Sciences** • Sports Injuries and Corrective Exercises, University of Tehran, Tehran, Iran. 2013-2015, Thesis Title: Muscular activity of selected knee and core muscles of collegiate male athletes with limited ankle dorsiflexion range of motion during single leg jump landing. GPA: 18.80/20 **Ph.D.** • Movement and Training Science (Biomechanics), University of Hamburg, Hamburg, Germany. *(Present)*
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