UNIVERSIDAD POLITÉCNICA DE MADRID

FACULTAD DE CIENCIAS DE LA ACTIVIDAD FÍSICA Y DEL
DEPORTE

EFFECT OF HAMSTRING INJURIES ON KICKING IN FOOTBALL

EFFECTO DE LAS LESIONES DE LOS ISQUIOTIBIALES EN EL
GOLPEO DEL FÚTBOL

TESIS DOCTORAL

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LICENCIADO EN INGENIERÍA MECÁNICA

2016

DEPARTAMENTO DE SALUD Y RENDIMIENTO HUMANO

FACULTAD DE CIENCIAS DE LA ACTIVIDAD FÍSICA Y DEL DEPORTE

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2016

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Agradecimientos

En primer lugar, quiero agradecer el tiempo y dedicación de mi tutor, Dr. Enrique Navarro no sólo en este trabajo, sino desde mayo de 2009, ya que me ha apoyado y confiado en mí en varios proyectos en todo el mundo. Desde que me motivó a trabajar en esa línea sobre lesiones de isquiotibiales para mi trabajo fin de máster, me ha aconsejado y respaldado constantemente, algo sin lo cual este trabajo no hubiera sido posible.

Quiero agradecer a los clubes de Rayo Vallecano S.A.D. y Club Atlético de Madrid por facilitar jugadores para el estudio. También quiero dar las gracias a mis compañeros del laboratorio de biomecánica deportiva quienes me han ayudado en la toma de datos.

Tengo que gratificar especialmente a Vanesa Alonso Aldavero y Leticia Buesa, quienes han confiado plenamente en mi trabajo a pesar de no conocerme y no haber tenido experiencia previa como docente. Con su ayuda, tanto en cosas profesionales como personales, he podido llegar aquí con más facilidad.

También quiero dar las gracias a mis amigos cercanos, que me han acogido como uno más y me han respaldado en todo momento. A Raquel, Miguel, y María, quienes siempre me han empujado a terminar mi tesis, y se han asegurado de que siguiera el camino correcto para llegar a mi meta y me han ayudado. A Fátima y Santi, y Laura e Inma porque compañeros de piso como ellos hay muy pocos, y me han tratado como un miembro más de la familia siempre, apoyándome en los momentos fáciles y difíciles y dándome muy buenos consejos en todo momento. A Sergio Fernández, Fran y José Melli, no podría hacer un trabajo de fútbol sin que participaran ellos. Y también a mis amigos de dentro y fuera de INEF, especialmente a Rodri, David, Rafa, Violeta, Esti, Ernesto, Cuco, Dani, Juan, Carlos, Javi, Alessandra, Ángela, Juan

Carlos, Elsa, Mónica y José por estar incondicionalmente allí pase lo que pase, y ayudarme a desahogarme.

Por último, pero no por ello menos importante, estoy extremadamente agradecido a mis padres y abuelos, que han sido siempre un modelo a seguir en términos de trabajo duro y dedicación. Siempre han sido una fuente de inspiración, y ha sido su fervor el que me ha hecho perseguir y poder vivir mi sueño.

Muchísimas gracias a todos!

Abbreviations

- FIFA : Fédération Internationale de Football Association
- TO : Toe Off
- MHE : Maximal Hip Extension
- MKF : Maximal Knee Flexion
- BI : Ball Impact
- EFT : End of Follow Through
- UI : Uninjured limb
- I : Injured limb
- F : Female
- M : Male
- ND : Non-dominant limb kick
- D : Dominant limb kick

Contents

Agradecimientos	VII
Abbreviations	IX
List of Figures	XIII
List of tables.....	XIV
Abstract.....	XVII
Resumen	XIX
Introduction	1
Injuries in soccer	3
Hamstring strain injuries	5
The hamstring muscle group.....	5
Epidemiology	7
Risk factors	8
How did the hamstring injuries occur?.....	9
How are hamstring muscle injuries in soccer evaluated?	10
Kicking in soccer	12
The kicking technique	12
Limb Asymmetry	16
Sex differences	17
Objectives	19
Methods	21

Participants	23
Data capture	25
Calculation of kinematic and kinetic parameters	30
Statistical analysis	34
Results & Discussion	37
I. Comparing across previous injury.....	39
Results	41
Discussion and implications	51
II. Comparing across sex	55
Results	57
Discussion and implications	71
III. Comparing across limb dominance.....	79
Results	81
Discussion and implications	95
Conclusions	105
Limitations.....	109
Future lines of investigation	110
References	113
Annex	125
Annex I: Informed Consent	127
Annex II: Questionnaire	129

Annex III: Vicon® Workstation Marker set.....	135
Annex IV: Vicon® BodyLanguage Models	141
A: Static Model	141
B: Dynamic Model	146

List of Figures

Figure 1 : The hamstring muscle complex	5
Figure 2: Elongation stress on hamstrings during the running cycle (Guex & Millet, 2013) ...	9
Figure 3: Toe off	13
Figure 4: Maximum hip extension	14
Figure 5: Maximum knee flexion	15
Figure 6: Ball impact.....	16
Figure 7: End of follow through	16
Figure 8: The calibration of the motion capture system.....	25
Figure 9: Marker positions based according to the lower body model.....	26
Figure 10: Attachment of markers on the foot.....	27
Figure 11: Placement of markers on the ball.....	27
Figure 12: The dynamic capture	29
Figure 13: Example of reconstructed 3D model of a trial and the reconstruction parameters	30
Figure 14: The different phases of the goal kick	31
Figure 15: The different segments and its local coordinate system.....	32
Figure 16: Peak hip velocities (m/s) compared across previous injury	51
Figure 17: Sequential increase of angular velocities seen in uninjured, non-dominant limbs	71
Figure 18: Pattern of ground reaction forces seen in females (green) and males (red)	76
Figure 19: Knee flexion angle at ball impact between a non-dominant limb (left) and dominant limb (right) in females in kicks with the uninjured limb	99
Figure 20: Sprint analysis on artificial turf.....	110
Figure 21: Electromyography tests	111

List of tables

Table 1: Participating clubs	23
Table 2: Characteristics of the participants	24
Table 3: The warm-up protocol	28
Table 4: Linear velocities while comparing across injury (mean $\pm$ standard deviation).	43
Table 5: Time intervals while comparing across injury (mean $\pm$ standard deviation)	44
Table 6: Hip flexion/extension angles while comparing across injury (mean $\pm$ standard deviation)	45
Table 7: Knee flexion/extension angles while comparing across injury (mean $\pm$ standard deviation)	46
Table 8: Hip flexion/extension angular velocities while comparing across injury (mean $\pm$ standard deviation)	47
Table 9: Knee flexion/extension angular velocities while comparing across injury (mean $\pm$ standard deviation)	48
Table 10: Peak moments of the kicking leg while comparing across injury (mean $\pm$ standard deviation)	49
Table 11: Support leg variables while comparing across injury (mean $\pm$ standard deviation).	50
Table 12: Linear velocities while comparing across sex (mean $\pm$ standard deviation).	63
Table 13: Time intervals while comparing across sex (mean $\pm$ standard deviation)	64
Table 14: Hip flexion/extension angles while comparing across sex (mean $\pm$ standard deviation)	65
Table 15: Knee flexion/extension angles while comparing across sex (mean $\pm$ standard deviation)	66

Table 16: Hip flexion/extension angular velocities while comparing across sex (mean $\pm$ standard deviation).	67
Table 17: Knee flexion/extension angular velocities while comparing across sex (mean $\pm$ standard deviation).	68
Table 18: Peak moments of the kicking leg while comparing across injury (mean $\pm$ standard deviation).	69
Table 19: Support leg variables while comparing across sex (mean $\pm$ standard deviation). ..	70
Table 20: Linear velocities while comparing across limb dominance (mean $\pm$ standard deviation).	87
Table 21: Time intervals while comparing across limb dominance (mean $\pm$ standard deviation).	88
Table 22: Hip flexion/extension angles while comparing across limb dominance (mean $\pm$ standard deviation).	89
Table 23: Knee flexion/extension angles while comparing across limb dominance (mean $\pm$ standard deviation).	90
Table 24: Hip flexion/extension angular velocities while comparing across limb dominance (mean $\pm$ standard deviation).	91
Table 25: Knee flexion/extension angular velocities while comparing across limb dominance (mean $\pm$ standard deviation).	92
Table 26: Peak moments of the kicking leg while comparing across limb dominance (mean $\pm$ standard deviation).	93
Table 27: Support leg variables while comparing across limb dominance (mean $\pm$ standard deviation).	94

Abstract

The hamstring strain injury is one of the most common injuries in professional soccer and it has a high rate of recurrence as well. Although the hamstring muscle group gets loaded during the kicking motion, the effect of a previous hamstring injury on the kicking skill has not been studied in detail. Kicking technique is known to differ based on sex and limb dominance, but these effects on professional soccer players has not been studied. The objective of this thesis dissertation was to quantify if the biomechanical factors of kicking in a group of professional soccer players were affected by a previous hamstring injury, sex and limb dominance, and the interaction of these factors. Forty-five professional soccer players (females = 26, males = 19) were captured kicking the ball with their dominant and non-dominant limbs using a three dimensional motion capture system and force platform on artificial turf. A previous hamstring injury caused changes in the kinematics especially in the phases where the hamstring muscles are known to be actively working, namely the backswing, the leg cocking and follow through phases. Although male soccer players had superior kinematics accounting for the better technique, the difference in kinetics between the sexes did not exist. A previous injury in males favored a faster knee flexion while simultaneously inhibiting hip flexion. Elite female soccer players have different kicking techniques with the dominant and non-dominant limbs which accounts for the differences in linear velocities, with the differences being reduced with the presence of an injury. As far as male soccer players go, differences on limb dominance is not seen unless one considers the effect of previous injury. The results clearly show that the hamstring strain injury affects the kicking technique. Its effect also depends on whether the injury was suffered by a male or a female, and whether the kick was taken by a dominant limb or a non-dominant limb. Thus the consequences of this injury cannot be studied in isolation, rather it has to be considered a multi-factorial problem.

Keywords: *motion capture, limb dominance, sex differences, inverse dynamics, biomechanics.*

Resumen

La lesión de los isquiotibiales es una de las más comunes en el fútbol profesional con una alta probabilidad de recaída. Aunque los isquiotibiales participan activamente durante el golpeo, no se sabe con certeza la relación entre técnica de golpeo y lesión. No existe datos concluyentes sobre las diferencias en la técnica de golpeo entre hombres y mujeres o entre piernas dominantes y no dominantes. El objetivo de esta tesis doctoral es estudiar el efecto de la lesión previa de isquiotibiales, el sexo y la pierna dominante en el golpeo de un grupo de jugadores de fútbol profesionales y la interacción de estos factores. El golpeo de cuarenta y cinco jugadores de fútbol profesionales (mujeres = 26, hombres = 19) ha sido registrado con sus piernas dominantes y no dominantes utilizando un sistema de captura de movimiento tridimensional y una plataforma de fuerza sobre césped artificial. Los resultados mostraron que la lesión previa de los isquiotibiales causa cambios en la cinemática, especialmente en las fases donde se sabe que los músculos isquiotibiales trabajan de forma activa, es decir, la subida de la pierna (*backswing*), el armado de la pierna (*leg cocking*) y el *follow through*. Aunque los futbolistas hombres tenían una técnica de golpeo más eficaz con respecto a las mujeres en términos de variables cinemáticas, no se encontraron diferencias la cinética del movimiento entre los sexos. La lesión previa lesión en los hombres parece favorecer una rápida flexión de la rodilla mientras que inhibe simultáneamente la flexión de la cadera. Por otro lado, las futbolistas mujeres de élite tienen diferentes técnicas del golpeo con las piernas dominantes y no dominantes lo que explica las diferencias en las velocidades lineales, aunque las diferencias se reducen con la presencia de una previa lesión. En cuanto a los futbolistas hombres, las diferencias en el golpeo entre la pierna dominante y no dominante no existen excepto en el caso que el jugador tenga una previa lesión de los isquiotibiales. En definitiva, los resultados muestran claramente que la lesión de isquiotibiales afecta a la técnica del golpeo, pero de forma

diferente según el sexo y la pierna dominante. lo que demuestra que las consecuencias de esta lesión no pueden ser estudiadas en forma aislada, sino que de una forma multifactorial.

Palabras clave: *captura de movimiento, pierna dominante, diferencias de género, dinámica inversa, biomecánica.*

The ball is round, the game lasts ninety minutes,

and everything else is pure theory.

Josef “Sepp” Herberger

Introduction

Soccer, also known as "football" is a team sport played between two teams of 11 players each. It is widely considered the most popular sport in the world, with about 270 million people involved, of which 265 million are players (Giulianotti, 2015; Kunz, 2007). In Spain, there are 52,421 clubs in Spain with 810,141 federal licenses for players (RFEF, 2014).

Injuries in soccer

An injury, defined by the medical committee of UEFA and adapted from Ekstrand (1982), is *“something that happens during a training session or match which causes the absence of the player affected from the next training session or match.”* Soccer injuries have been ranked first among other sports with a rate ranging from 3.7 to 29.1 injuries per 1000 h of practice and games (Katis, Kellis, & Gissis, 2004). In Spanish professional soccer, 8.92 lesions per 1000 h. of exposure were found (Noya, 2015), with a greater number of injuries occurred during competitions (55.8 lesions per 1000 h.) with respect to those in training (22.6 lesions per 1000 h.)(Mallo, González, Veiga, & Navarro, 2011).

Noya (2015) also reported that an average of 81 lesions were registered per team and season, causing an average of 11.3 days of absence per lesion. Apart from loss of playing time, these injuries add up to being a financial burden on the clubs. It was estimated that the average loss of output of first and second division clubs in England during the 1999–2000 soccer season due to injury alone may be as much as £74.7 million (Woods, Hawkins, Hulse, & Hodson, 2002). Furthermore, the cost of medical fees increased insurance premiums and reduced match attendance due to absence of first choice players may further raise the overall financial impact of injury. (Foreman et al., 2006).

A ten year epidemiologic study on European football found that one third of all injuries in European football in professional football were muscle injuries (Ekstrand, Häggglund, &

Waldén, 2011). In the Spanish football, muscle injuries accounted for 49.1% of all the injuries in professional clubs (Noya, 2015). The thigh was the most prevalent site for injury, with 81% of thigh injuries in English soccer players classified as muscular strains.(Greig & Siegler, 2009). In Spanish soccer, 84.4% of the lesions registered in the 2008-09 season were located in the inferior extremities, the thigh being the anatomical region, with 30.5% of all the lesions, the most affected body region (Mallo et al., 2011). In turn, 53% of the lesions to the thigh occurred in the posterior area, and within these injuries 73% of the cases affected the biceps femoris (Noya, 2015).

Hamstring strain injuries

The hamstring muscle group

Figure 1 : The hamstring muscle complex

The hamstring muscle complex is composed of three muscles (Figure 1), which include the biceps femoris, semitendinosus, and semimembranosus, crossing the hip and knee joints. The biceps femoris muscle is in the posterior compartment of the thigh. It has two heads, which include the long head arising from the medial facet of the ischial tuberosity and the short head arising from the middle third of the linea aspera and the lateral supracondylar ridge of the femur, and having its insertion on the head of the fibula (Drake, Vogl, & Mitchell, 2009). The semitendinosus muscle (so called from the great length of its tendon) and the

semimembranosus muscle (so called from its membranous tendon of origin) arise from the ischial tuberosity and have their insertions on the medial surface of the tibia and medial tibial condyle respectively (Drake et al., 2009). Therefore, while the long head of the biceps femoris, the semitendinosus and the semimembranosus cross two joints, including the hip joint proximally and the knee joint distally, while the short head of the biceps femoris muscle only crosses the knee joint (Beltran, Ghazikhanian, Padron, & Beltran, 2012).

The hamstring muscles are extensors of the hip and flexors of the knee in the gait cycle (Drake et al., 2009). In the swing phase, the hamstring muscles become active in the last 25% just as hip extension begins and continue for 50% of the swing phase, when they actively produce extension at the hip and actively resist extension of the knee (Koulouris & Connell, 2005). Complete flexion of the hip cannot be affected unless the knee joint is also flexed, which is a consequence of the shortness of the hamstring muscles (Beltran et al., 2012).

During the heel strike, the hamstring muscles also contribute to deceleration of the forward translation of the tibia, when the knee is extended and the weight of the body is shifted forward as the foot strike occurs (Koulouris & Connell, 2005). The hamstring muscles in conjunction with the anterior cruciate ligament (ACL), are therefore important dynamic and static stabilizers of anterior tibial translation, respectively (Drake et al., 2009). When foot strike occurs, the hamstring muscles are elongated to their optimal length over both hip and knee joints to provide extension of the hip and serve as stabilizers of the knee. With takeoff, the weight-bearing leg is supported by the combined contraction of the hamstring muscles in conjunction with the quadriceps muscle. The stabilization of the leg during takeoff is the consequence of the contraction of antagonists, the hamstring muscles and the disproportionately larger quadriceps muscle (Drake et al., 2009).

The biarticular nature of these muscles is thought to predispose the hamstring muscles to injury (Beltran et al., 2012). Since these muscles, with the exception of the short head for the biceps femoris, span two joints, their contraction cannot be localized to only one joint. Therefore, one joint has to be stabilized to act on the other, which means that the hamstring muscles must create sufficient force to absorb or counteract these forces (Koulouris & Connell, 2005). Strain injury eventually results from failure to counteract these forces (Beltran et al., 2012; Koulouris & Connell, 2005).

Epidemiology

One of the most common injuries in nearly all forms of team and individual sports involving the lower body is the hamstring strain. (Chumanov, Heiderscheit, & Thelen, 2011; Ebben, 2009; Ekstrand et al., 2012; Freckleton & Pizzari, 2013; Greig & Siegler, 2009; Mendiguchia, Alentorn-Geli, & Brughelli, 2012; Navarro et al., 2015; Schache, Dorn, Blanch, Brown, & Pandy, 2012; Schache, Wrigley, Bake, & Pandy, 2009; Woods et al., 2002; Woods et al., 2004). Studies on European soccer accounted injuries to the hamstrings contributed to 37% of all non-contact injuries (Ekstrand et al., 2011). Woods et al. (2004) showed that the hamstring strain injuries account for 12–16% of all injuries in English professional soccer. In sub-elite Spanish soccer, 37% of all injuries were hamstring strain injuries (Mallo et al., 2011). On an average, 18 days and 3–3.5 matches are missed per hamstring strain. (Petersen & Holmich, 2005). A recent longitudinal study on European soccer showed that 22% of players sustained at least one hamstring injury during a season (Ekstrand, Waldén, & Hägglund, 2016). The overall hamstring injury rate over the 13-year period was 1.20 injuries per 1000 h; the match injury rate (4.77 injuries per 1000 h) being 9 times higher than the training injury rate (0.51 injuries per 1000 h), with the number of hamstring strain injuries increased annually by 4% in men's teams (Ekstrand et al., 2016).

Risk factors

In their reviews, Freckleton and Pizzari (2013) and Navarro et al. (2015) mentioned that the risk factors most consistently associated with hamstring muscle strain-type injuries were age, previous hamstring injury and hamstring to quadriceps strength ratio. The recurrence rate varying between 13% (Ekstrand et al., 2016) to 17% (Petersen, Thorborg, Nielsen, & Holmich, 2010). Studies on professional soccer have also found that 17–22 year old age groups sustained fewer hamstring strains than the older soccer players (Woods et al., 2004). The dominant leg accounts for a greater frequency of lesions – 54.4% vs 36.5% in the non-dominant leg (Noya, 2015), but no significant differences were observed in the number of hamstring injuries between the dominant and the non-dominant leg (Freckleton & Pizzari, 2013). Men were 64% more likely to sustain a hamstring strain injury than women (Cross, Gurka, Saliba, Conaway, & Hertel, 2013) and they had a higher rate of re-injury as well (22% vs 12%) (Cross et al., 2013). The hamstring muscle strain-type injury is considered to be a multifactorial problem, and the factors of age and previous hamstring injury must be considered alongside any other risk factors being examined (Freckleton & Pizzari, 2013).

How did the hamstring injuries occur?

Figure 2: Elongation stress on hamstrings during the running cycle (Guex & Millet, 2013)

Woods et al. (2004) found over two seasons of professional soccer in England, sprinting and shooting were the first and the third most common causes of a non-contact hamstring injury. Studies done on athletes indicate that hamstring muscle strain injuries most commonly occur during maximal or sub-maximal sprinting (Schache et al., 2012) during the latter part of the swing phase when the hamstrings work to decelerate knee extension in preparation for heel strike (Guex & Millet, 2013; Lee, Reid, Elliott, & Lloyd, 2009; Petersen & Holmich, 2005). The muscle fibers are rapidly lengthened when they change from functioning eccentrically, to decelerate knee extension in the late swing, to concentrically, in becoming an active extensor of the hip joint (Chumanov et al., 2011). It has been suggested that it is during this rapid change from eccentric to concentric increases the susceptibility of the hamstrings to injury as a result of the biomechanical loads placed on the muscle (Chumanov et al., 2011; Petersen & Holmich, 2005) which makes the hamstring muscle complex subject to peak elongation stress (Guex & Millet, 2013) (Figure 2). From scientific literature previously published, it is believed that an association may exist between hip and knee biomechanical anomalies in running and an increased risk of injury/re-injury (Lee et al., 2009).

How are hamstring muscle injuries in soccer evaluated?

In soccer players, the effects of the hamstring injury have previously been studied using various analysis techniques prospectively (Arnason, Andersen, Holme, Engebretsen, & Bahr, 2008; Askling, Tengvar, Saartok, & Thorstensson, 2007; Engebretsen, Myklebust, Holme, Engebretsen, & Bahr, 2010; Foreman et al., 2006; Hägglund, Waldén, & Ekstrand, 2006, 2013; Orchard, 2001) and retrospectively (Fousekis, Tsepis, & Vagenas, 2010; Greig & Siegler, 2009; Guex & Millet, 2013; Lee et al., 2009; Navandar et al., 2015; Navandar, Gulino, Antonio, & Navarro, 2013; Navarro et al., 2015; Schache et al., 2012; Schache et al., 2009; Silder, Thelen, & Heiderscheit, 2010; Sole, Milosavljevic, Nicholson, & Sullivan, 2011; Tourny-Chollet, Leroy, Leger, & Beuret-Blanquart, 2000). A majority of the studies based on evaluating their strength with players being seated and using the isokinetic machine (Clark, Bryant, Culgan, & Hartley, 2005; Croisier, Ganteaume, & Ferret, 2005; Fousekis et al., 2010; Greig & Siegler, 2009; Opar et al., 2015; Wright, Ball, & Wood, 2009), or performing certain exercises (Arnason et al., 2008; Askling, Tengvar, & Thorstensson, 2013; Ebben, 2009; Mjolsnes, Arnason, Osthagen, Raastad, & Bahr, 2004). However these techniques do not accurately represent the normal sporting actions carried out by the players on the field (Navandar et al., 2013) and study the risk factors such as hamstring strength and in isolation. The tendency to assess the variables in isolation may further confound the picture, since important interactions between variables may be missed and the influence of some risk factors may be overstated (Freckleton & Pizzari, 2013).

There have been studies which have evaluated the effect of hamstring injuries in sprinting in elite athletes (not in soccer specifically) using motion capture and ground reaction forces (Chumanov et al., 2011; Lee et al., 2009; Schache et al., 2012; Schache et al., 2009), whose results have been used to explain when and where these injuries might occur. Although the

hamstring muscle complex can also potentially get loaded during kicking (Schache et al., 2012), the number of studies on this front are limited (Navandar et al., 2015; Navandar et al., 2013). These investigations have revealed that a previous injury affects female soccer players differently as compared to male football players (Navandar et al., 2015). An inverse dynamics (Winter, 2009) approach to analyzing kicking could help understand the effect of previous injuries on the kicking technique, which in turn could potentially explain why the hamstring strain injury has a high rate of re-injury (Navarro et al., 2015).

Kicking in soccer

Kicking is one of the most important skills in soccer. A good soccer kicking technique is important to score more goals. While shooting at goal, a higher ball velocity gives the goalkeeper and the defence lesser time to react thus improving one's chances of scoring (Dorge, Bull-Andersen, Sorensen, & Simonsen, 2002). This good kicking technique is based on a good inter-limb coordination (Nunome, Ikegami, Kozakai, Apriantono, & Sano, 2006) and inter-segmental transfer of energy (Dorge et al., 2002). These actions increase thus the chances of scoring a goal (Kellis & Katis, 2007). For this reason, improvement of soccer instep kick technique is one of the most important aims of training programs in young players. (Kellis & Katis, 2007).

The kicking technique

Several three-dimensional biomechanical studies have investigated the instep kicking of a stationary ball as hard as possible in male soccer players (Kellis & Katis, 2007; Lees, Asai, Bull-Andersen, Nunome, & Sterzing, 2010; Navandar et al., 2013; Nunome, Asai, Ikegami, & Sakurai, 2002; Nunome, Ikegami, et al., 2006; Nunome, Lake, Georgakis, & Stergioulas, 2006) although, in a minor quantity, there have also been studies analysing the instep kicking pattern in female soccer players (Alcock, Gilleard, Hunter, Baker, & Brown, 2012; Barfield, Kirkendall, & Yu, 2002; Katis, Kellis, & Lees, 2015; Orloff et al., 2008; Shan, Daniels, Wang, Wutzke, & Lemire, 2005).

Kicking has been explained as an open kinetic chain model (Lees et al., 2010). The motion pattern of kicking is generally accepted as a proximal-to-distal sequence of segmental motions in which the proximal segment (the thigh) initiates the movement, causing the more distal

segment (shank and foot) to lag behind, followed by a deceleration of the proximal segment and an acceleration of the more distal segment just before impact. (Kellis & Katis, 2007).

Figure 3: Toe off

After the toe of the kicking limb takes off from the ground (Figure 3), the hip extends up to 29° (0° is defined as the neutral orientation with respect to hip flexion / extension (Levanon & Dapena, 1998)) while the knee simultaneously flexes (Figure 4). This is known as the backswing phase (Kawamoto, Miyagi, Ohashi, & Fukushima, 2007; Lees, 2013). During the backswing phase, the hip extends with a velocity of 3-5 rad/s (Levanon & Dapena, 1998; Nunome et al., 2002). The hip is also slowly adducted and externally rotated (Levanon & Dapena, 1998). The knee flexes (at an angular velocity of 13-15 rad/s) and internally rotates (Kellis & Katis, 2007; Nunome et al., 2002). Given that the neutral position of the ankle is 0° , the ankle is plantarflexed (10°), abducted (20°) and slightly pronated (Kellis & Katis, 2007; Levanon & Dapena, 1998) reaching maximum plantarflexion velocities of 15 rad/s (Nunome et al., 2002). The back swing motion of the kicking leg is completed just after the hip extension reaches a maximum (Lees, 2013), and then the forward motion of the hip initiates with the rotation of the pelvis (Lees & Nolan, 1998). Previous studies have spoken about the “Soccer paradox” (Lees et al., 2010) where the hip experienced an extension moment although it was undergoing flexion, and the knee experienced a flexion moment although it was extending.

Thus, the hip flexion moment increased as the hip extended, reaching a peak right at the end of the backswing phase (Lees et al., 2010).

Figure 4: Maximum hip extension

The knee continues to flex and reaches a peak flexion (Kawamoto et al., 2007) (Figure 5). This is known as the leg cocking phase (Kawamoto et al., 2007; Lees, 2013). The term refers to the flexion of the knee as the thigh is brought forwards during the pre-contact phase (Nunome et al., 2002). In this phase the thigh rotates forwards while the shank rotates backwards (Lees, 2013). The hip flexion reaches speeds up to 13 rad/s (Levanon & Dapena, 1998; Nunome et al., 2002) and abducts while it remains externally rotated (Kellis & Katis, 2007). In the same period, the ankle is adducted and plantarflexed (Kellis & Katis, 2007). As the knee flexed, it reached a maximum extension moment which occurred before the knee reached maximum flexion (Lees et al., 2010). The cocking of the leg reduces the moment of inertia of the leg and allows the work done by muscles around the hip to enhance kicking leg angular velocity (Lees, Steward, Rahnama, & Barton, 2009). This is a well-known mechanical principle but, in addition, cocking of the kicking leg produces a stretch-shorten cycle, responsible for maximizing the extension moment and work done at the knee joint (Dorge et al., 2002). Just before the knee reaches maximal flexion, the support limb is planted near the ball and it reaches

a peak force which is about 2.5 to 3.8 times the body weight of the player (Juarez, López de Subijana, Mallo, & Navarro, 2011; Orloff et al., 2008).

Figure 5: Maximum knee flexion

The knee then begins to extend as the hip continues to flex, this is known as the leg acceleration phase (Lees, 2013). Here both the shank and the thigh increase in angular velocity (Lees, 2013). The knee reaches a peak extension velocity before impact of 15-30 rad/s (Kellis & Katis, 2007). The hip flexion moment converted to a hip extension moment in the leg acceleration phase (Nunome et al., 2002). while the knee experienced a flexion moment as it extended in the leg acceleration phase and reached a maximum just before ball impact (Nunome et al., 2002). The hip experienced an adduction moment throughout the backswing, leg cocking and leg acceleration phases until ball impact (Kellis & Katis, 2007; Nunome et al., 2002). Finally, ankle moments were generally very low during the first half of the kick duration and then increase before ball impact (Kellis & Katis, 2007). Rotation moments around the hip and knee, and ankle inversion moments were rather minimal (Kellis & Katis, 2007).

At ball impact (Figure 6), the hip is flexed, abducted and externally rotated (Kellis & Katis, 2007), the knee is flexed to 57° (Lees et al., 2009) and the ankle plantarflexed and adducted (Levanon & Dapena, 1998). The impact lasts approximately 9 ms (Nunome, Lake, et al., 2006).

Figure 6: Ball impact

The phase following ball impact is known as the follow through (Lees, 2013). The hip continues to flex and reaches a maximum at the end of the follow through (Shan, 2009) (Figure 7), defined as when the toe reaches the highest position (Navandar et al., 2013), while the knee simultaneously began to flex after reaching a peak extension just after ball impact (Lees, 2013).

Figure 7: End of follow through

Limb Asymmetry

Although professional soccer players are required to be skilful with either limb (Starosta, 1988), kicking is an asymmetric task (Barbieri, Bucken Gobbi, Pereira Santiago, & Augusto

Cunha, 2015) and the players are predominantly one-footed (Carey et al., 2001). Therefore, the preparation of soccer players should develop a left-right symmetry in shooting (Starosta, 1988). Differences on the kicking technique between the dominant and non-dominant limb produce a greater ball speed when kicking with the dominant limb (Barfield et al., 2002; Dorge et al., 2002; Kellis & Katis, 2007; Nunome, Ikegami, et al., 2006; Sinclair et al., 2014; van den Tillaar & Ulvik, 2014). The differences were explained based on better inter-segmental coordination (Barbieri et al., 2015; Dorge et al., 2002; Nunome, Ikegami, et al., 2006; Sinclair et al., 2014) and greater moments (Nunome, Ikegami, et al., 2006) produced while kicking with the dominant limb.

However, these findings have been reported in small sample sizes of non-professional and semi-professional male soccer players kicking on the laboratory floor, and only Sinclair et al. (2014) reported results in an elite soccer team, although the participants were youth players and not fully professional. Previous studies have indicated that higher the skill level (Nunome, Ikegami, et al., 2006) and maturity (Katis et al., 2015), the better the co-ordination for both limbs. To our knowledge, only one study has examined the dominant and non-dominant limb kicking in non-professional female soccer players (Barfield et al., 2002). There is a need of research to see if these differences exist in elite professional soccer players of either sex.

Sex differences

Several differences in kick biomechanics between male and female players have been reported in the literature (Barfield et al., 2002; Katis et al., 2015; Orloff et al., 2008; Sakamoto & Asai, 2013; Shan, 2009). Previous studies have found lower ball velocity (Barfield et al., 2002; Katis et al., 2015; Shan, 2009) and lower joint velocities (Barfield et al., 2002) in females compared to males. These differences are accompanied by altered kinetic characteristics (Lyle, Sigward, Tsai, Pollard, & Powers, 2011) of both limbs as well as differences in placement of the support

foot placement (Orloff et al., 2008) between sexes. There is a lack of published literature about the difference in kinetics of the kicking technique across sex. All these afore-mentioned studies were carried out in small samples of amateur and recreational soccer players, and there is a paucity of studies involving professional soccer players.

Objectives

Keeping the afore-mentioned points in mind, the main objective of this dissertation was to determine the effect of previous hamstring injuries on the biomechanical pattern of kicking in elite men's and women's soccer. This comparison was done across:

- I. Previous injury: To see if there was a difference between the kicking technique between players kicking with a previously injured limb and those without.
- II. Sex: To study the consequence of a previous hamstring injury on the difference in kicking technique between elite male and female soccer players.
- III. Limb dominance: To ascertain if the influence of limb dominance on kicking is affected by a previous hamstring injury to either limb.

Methods

Participants

In order to find participants for the study, players were approached through the different clubs rather than individually, in order to get homogeneity when it comes to number of training hours and matches on a week by week basis. These conditions were finally accepted by three clubs: Rayo Vallecano de Madrid S.A.D. ‘B’, Rayo Vallecano de Madrid Femenino and Club Atlético de Madrid “Feminas”. The number of participants from each club can be seen from the table given below:

Table 1: Participating clubs

Club	Sex	División (2013/14)	Number of Players
Rayo Vallecano de Madrid S.A.D. ‘B’	Male	2 ^a B	19
Rayo Vallecano de Madrid S.A.D. Femeninas	Female	1 ^a división Femenina	15
Club Atletico de Madrid ‘Feminas’	Female	1 ^a división Femenina	11

All players provided written informed consent (Annex I) in accordance with the departmental and university ethical procedures and following the principles outlined in the Declaration of Helsinki. Before the data capture session, they had to fill up a questionnaire (Annex II, adapted from Garcia-Gonzalez, Albaladejo, Villanueva, and Navarro (2014)) which included questions about their previous injury history in the hamstring muscle group and preferred kicking limb (considered as the dominant limb). They were also asked to wear boots appropriate for the artificial turf. Table 2 summarizes the participants ‘characteristics and their injury history. For a player to be categorized as “previously injured”, the player must have sustained a grade I, II or III hamstring injury which caused the player to miss at least one official match in season or

a friendly match in preseason. The injured players had suffered a unilateral hamstring injury in the last two years.

Table 2: Characteristics of the participants

Characteristic	Number
Age	21.73 $\pm$ 3.63 years
Age (Male players)	21.16 $\pm$ 2.00 years
Age (Female players)	22.15 $\pm$ 4.50 years
Weight	65.25 $\pm$ 9.72 kg
Weight (Male players)	71.46 $\pm$ 6.22 kg
Weight (Female players)	60.71 $\pm$ 9.48 kg
Height	170.94 $\pm$ 7.18 cm
Height (Male players)	177.33 $\pm$ 5.22 cm
Height (Female players)	166.26 $\pm$ 4.28 cm
Injured players	14
Uninjured players	31
Injured male players	4
Injured female players	10
Injured in the dominant limb	9
Injured in the non-dominant limb	5

Data capture

A six-camera VICON® motion capture system (Oxford Metrics Ltd, United Kingdom) recording at 250Hz synchronized with a Kistler® Force Platform (Kistler Group, Switzerland) at a sampling frequency of 1000 Hz was used to capture the kicking motion. This frequency of motion capture was chosen as previous studies varied between 200Hz (Nunome, Ikegami, et al., 2006) and 500 Hz (Sakamoto & Asai, 2013). A 15 m x 3 m strip of FIFA approved artificial turf was placed over the platform, and the position of the platform was marked on it. The system was calibrated (Figure 8) in accordance with VICON® guidelines, and yielded calibration residuals such that positional data accurate within 2 mm was obtained.

Figure 8: The calibration of the motion capture system.

All participants were asked to wear soccer shoes specific for artificial turf for the trial. A lower body model was used to capture and analyze the data (Annex III). The data capture session was divided into static and dynamic capture. For the static capture, twenty-two retro-reflective markers with a diameter of 14mm were attached to the anatomical landmarks of each participant's body (Figure 9): the right and left anterior superior iliac spines, the right and left posterior iliac spines, the right and left medial and lateral epicondyles, the right and left lateral and medial malleoli, the right and left calcaneus, and the right and left heads of the second and fifth metatarsals.

Figure 9: Marker positions based according to the lower body model

To identify the marker positions on the metatarsal heads (Figure 10), the participants were asked to repeatedly lift and lower their hallux, and the point about which the movement of the toes were hinged along the second and fifth metatarsals was where the markers were placed. Markers were also placed laterally on the right and left thigh and shank to determine the alignment of the thigh and shank flexion axes (Tebutt, Wood, & King, 2002).

Figure 10: Attachment of markers on the foot.

Figure 11: Placement of markers on the ball

A soccer ball officially approved by the International Football Federation (FIFA) was used (diameter = 225 cm, pressure = 12 psi). Four hemispherical retro-reflective markers (diameter 14mm) were placed on the ball to determine the timing of impact and the resultant ball velocity after the impact from the motion capture data. Two markers were placed at diametrically opposite ends (B1 and B2), while the other two markers were placed at the midpoints of the circumferential arc formed between B1 and B2. These two markers were placed so that angle formed between the imaginary lines to the center of the ball (the radial line) was 90° (Figure 11).

Each participant performed a 15-minute warm-up in the gym (determined by the strength and conditioning coaches of all participating teams, Table 3) consisting of static cycling on an

exercise bike (7 minutes), aerobic and stretching exercises (6 minutes) and soccer-specific strength exercises (2 minutes). Static cycling was chosen as the players were wearing soccer boots and running on the treadmill in such conditions would not have been possible.

The participants then proceeded to perform warm-up kicks until they were familiarized and comfortable with the dynamic data capture. For the dynamic data capture, each participant performed instep kicks at a target net 7m away, kicking as hard possible with a four-step run-up such that the support leg was placed on the platform (Figure 12). The distance of 7m was chosen because of space restrictions in the laboratory. Kicks were repeated until 5 kicks were obtained with either limb which met the criteria mentioned before.

Table 3: The warm-up protocol

Exercise	Time/No. Of reps.
Static Bike	6' 65%
	1' 75%
Planks	30'' on each side
Stretching	2'
Single Leg Squat	8 with either leg, hands on the waist
Skipping with instep kicking motion, alternating the foot.	10m, 2 reps

Figure 12: The dynamic capture

Calculation of kinematic and kinetic parameters

The recordings of chosen static and dynamic trials were reconstructed to generate a 3D model of the kick (Figure 13). The reconstruction parameters were chosen based on the Vicon® guidelines (Tebutt et al., 2002), taking into account the calibration residuals for each day of data capture, and the max noise factor, intersection limit and residual factor being varied as a consequence (Figure 13). The reconstruction gave many trajectories which were labelled according to the different markers they corresponded to. Trajectories belonging to the same marker were defragmented. Stray trajectories considered as ghost markers were eliminated finally giving 28 trajectories for the static trials and 20 trajectories for the dynamic trials.

Figure 13: Example of reconstructed 3D model of a trial and the reconstruction parameters

To facilitate analysis, each dynamic trial was divided into different intervals using characteristic time instances to determine the different phases of the kick previously defined by Lees (2013). The characteristic time instances were: toe-off of kicking leg (TO), maximum extension of the hip (MHE), maximum flexion of the knee (MKF), ball impact (BI); and the end of the follow through (EFT), when the 5th metatarsal marker reached the highest position (Figure 14). To determine the frame of ball impact, first, a virtual marker, “CentreBall” which

was the mid-point between the diametrically opposite ball markers, B1 and B2, was calculated. The frame in which this marker was displaced by a value greater than 3mm from its initial position was determined, and the first frame before this instance was defined as that of ball impact. The intervals defined for analysis were: backswing (MHE-TO), leg-cocking (MKF-MHE), leg acceleration (BI-MKF) and follow-through (EFT-BI) (Figure 14).

Figure 14: The different phases of the goal kick

The impact of the foot with the ball is known to cause a serious distortion of the kinetic data (Nunome, Ikegami, et al., 2006) near impact when the data are filtered. In a procedure similar to Reid, Elliott, and Alderson (2007) one frame before and five after ball impact were deleted, and interpolated using Vicon®'s cubic spline “fill gaps” algorithm (Reid et al., 2007). The raw data was then filtered using Woltring’s method (Woltring, 1985) with a mean square error of 4. The trial was then cropped between TO and EFT. The velocity of “CentreBall” was computed, and this was established as the ball velocity for the trial. In order to best represent a kick in match situations, the kick with the median ball velocity in the five trials was selected for further analysis.

To calculate the variables, in the static trial the lower body was modelled (Annex IV-A) as a link-segment model composed of the foot, the shank, the thigh and the pelvis. Each segment was connected to the other through joint centres at the ankle, knee and hip. The hip joint centre

was calculated based on the method suggested by Davis III, Ounpuu, Tyburski, and Gage (1991). The knee joint centre was defined as the mid-point of the imaginary line connecting the markers on the lateral and medial epicondyle of the femur. Similarly, the ankle joint centre was defined as the mid-point of the imaginary line connecting the lateral and medial malleoli. A local co-ordinate system was defined at each segment. These co-ordinate systems were defined such that the origin was at the distal marker attached to the segment, the longitudinal axis was the Z (the positive direction being from the distal to proximal segment), the medio-lateral axis being Y (the positive direction being from lateral to medial), and X being mutually perpendicular to both (Figure 15). The positions of joint centres and the body weight calculated in the static trial were saved in the model parameters file for each participant, and data from this file was used for calculations in the dynamic trial (Annex IV-B).

Figure 15: The different segments and its local coordinate system

A standard inverse-dynamics approach (Winter, 2009) was used to calculate the reaction forces and moments developed by the lower limb joints. The adduction, flexion and internal rotation moments were determined as positive moments, while abduction, extension and external moments were represented as negative moments. To determine the kinetic parameters,

segmental inertial parameters were taken from de Leva's modification to the Zatsiorsky model(De Leva, 1996). The force and moment data was normalized in function with the body mass of the participant. All the calculations were carried out using the VICON® BodyBuilder software (VICON; Oxford Metrics Ltd., United Kingdom).

Statistical analysis

Peak linear velocities of the ball and the joint centers and 2nd metatarsal head virtual marker (henceforth referred to as the toe marker) and normalized time intervals were determined and compared. Only sagittal plane kinematic and kinetic variables of the kicking and support leg affected by the hamstring muscle were compared in the statistical analysis 3-way ANOVA. This is because hip and knee flexion/extension joint postures have the greatest influence on hamstring length (Lee et al., 2009). In the kicking limb, the variables analyzed were angles and angular velocities at MHE, MKF, BI and EFT; peak angular velocities of the hip and knee; and peak flexion and extension moments of the hip and knee. In the support limb, normalized peak ground reaction forces and normalized peak reaction forces in the hip and knee were determined along with time to reach these peak forces (henceforth referred to as time to peak). All the variables were extracted from the data exported from the trials using macros developed on Microsoft Excel 2013 and Visual Basic (Microsoft Corp., Redmond, USA).

For analysis, each limb was considered independent of the other as previously done in three-dimensional studies analyzing hamstring injuries (Schache et al., 2012) and limb dominance (Nunome, Ikegami, et al., 2006). A 3-way ANOVA was carried out to compare the variables, with the independent factors being previous injury, sex and limb dominance. When a significant effect was observed between ANOVA levels, multiple comparisons were performed with the Bonferroni correction, and the results were interpreted with 95% confidence intervals (CIs) and effect sizes (as partial η^2 values). The threshold values for small, medium and large effect sizes were set as 0.01, 0.06 and 0.14 respectively (Cohen, 1992; Richardson, 2011). The statistical analysis was carried out using SPSS® 20.0 (SPSS® Inc., Chicago, IL, USA).

To facilitate easier interpretation of the document the following sections on the results and discussion will be divided into three sections, with the analysis focused on each independent factor (previous injury, sex and limb dominance) and its interaction with the other two factors.

Results & Discussion

I. Comparing across previous injury

Results

The uninjured females showed a higher maximal hip velocity (Table 4) while kicking with the dominant limb (partial $\eta^2 = 0.05$, $p = 0.037$). This difference between the injured and uninjured hip velocities disappeared when grouping based on sex (irrespective of kicks with the dominant or non-dominant limb) or limb dominance only (irrespective of sex). For the ball, toe, ankle and knee similar kicking velocities were observed while comparing the effect of previous injury across sex and limb dominance. No differences were noted in the time intervals or the total time when comparing the injured and uninjured limbs across sex and limb dominance (Table 5). However, when grouping the variables irrespective of sex, for the non-dominant limb kicks the uninjured limbs had a greater backswing than the injured limb (partial $\eta^2 = 0.08$, $p = 0.012$). This was not observed in the dominant limb. This difference disappeared when comparing the time interval variables solely across previous injury.

While comparing the angular variables across injury (Tables 6 and 7), the females demonstrated greater knee flexion angles at the moment of maximal hip extension for uninjured non-dominant limb when compared to the injured limb (partial $\eta^2 = 0.05$, $p = 0.048$). This difference was not seen in the dominant limb kicks of the females, or in the dominant or non-dominant limb kicks for males. This difference in knee flexion at MHE is not seen when the variables were grouped irrespective of sex or of limb dominance. The hip extension angle at this instance showed no difference across the groups. The hip and knee flexion-extension angles at the instances of maximal knee flexion, ball impact and the end of follow through were similar across previous injury for the different groups.

Comparing the hip and knee angular velocities in kicks with and without a previous injury to the hamstring muscles (Tables 8 and 9), at maximal knee flexion the hip flexion velocity is greater in the uninjured limb than in the injured limb for females kicking with the non-dominant

limbs only (partial $\eta^2 = 0.06$, $p = 0.030$). The difference in the dominant limb kicks, or in males at the same instant were not observed. The hip flexion and extension velocities were similar in the instances of maximal hip extension, ball impact, the end of follow through and at peak values. Grouping the variables irrespective of limb dominance, this difference in hip flexion velocity at maximal knee flexion between the uninjured and injured limb stays in the case of females only (partial $\eta^2 = 0.07$, $p = 0.019$). Grouping the variables ignoring sex, this difference disappears. On globally comparing across previous hamstring injury, no differences between the two groups was found.

Previous injury did not seem to directly affect the peak flexion-extension moments in the hip and knee (Table 10). Similarly, on grouping the variables ignoring sex or limb dominance, no difference across previous injury history was obtained. Analyzing the effect of previous injury between the different groups in the support leg forces or time intervals (Table 11). No differences were observed on grouping the variables ignoring limb dominance or sex.

Table 4: Linear velocities while comparing across injury (mean $\pm$ standard deviation).

			Ball (m/s)			Toe (m/s)			Ankle (m/s)			Knee (m/s)			Hip (m/s)		
ND	F	UI	22.19	±	2.86	17.71	±	2.31	14.76	±	1.37	8.33	±	1.06	3.81	±	0.60
		I	23.25	±	1.26	18.00	±	1.41	15.50	±	1.00	8.50	±	0.58	4.00	±	0.00
	M	UI	26.06	±	2.78	20.83	±	1.38	17.11	±	1.28	9.22	±	0.81	4.22	±	0.65
		I	27.00	±	0.00	23.00	±	0.00	18.00	±	0.00	10.00	±	0.00	4.00	±	0.00
D	F	UI	25.25	±	2.47	19.70	±	2.03	16.25	±	1.48	9.05	±	0.83	4.10	±	0.45*
		I	24.17	±	2.48	19.17	±	1.17	15.67	±	0.82	8.67	±	0.82	3.50	±	0.84*
	M	UI	28.63	±	1.75	22.81	±	1.11	18.38	±	1.02	10.13	±	0.62	4.38	±	0.62
		I	28.00	±	0.00	22.00	±	1.00	18.00	±	0.00	9.67	±	0.58	4.33	±	1.15
Total ND		UI	23.97	±	3.40	19.15	±	2.48	15.85	±	1.77	8.74	±	1.04	4.00	±	0.65
		I	24.00	±	2.00	19.00	±	2.55	16.00	±	1.41	8.80	±	0.84	4.00	±	0.00
Total D		UI	26.75	±	2.74	21.08	±	2.29	17.19	±	1.67	9.53	±	0.91	4.22	±	0.54
		I	25.44	±	2.74	20.11	±	1.76	16.44	±	1.33	9.00	±	0.87	3.78	±	0.97
Total F		UI	23.68	±	3.06	18.68	±	2.37	15.49	±	1.60	8.68	±	1.01	3.95	±	0.55
		I	23.80	±	2.04	18.70	±	1.34	15.60	±	0.84	8.60	±	0.70	3.70	±	0.67
Total M		UI	27.26	±	2.65	21.76	±	1.60	17.71	±	1.31	9.65	±	0.85	4.29	±	0.63
		I	27.75	±	0.50	22.25	±	0.96	18.00	±	0.00	9.75	±	0.50	4.25	±	0.96
Total		UI	25.31	±	3.38	20.08	±	2.56	16.49	±	1.84	9.12	±	1.05	4.11	±	0.61
		I	24.93	±	2.53	19.71	±	2.05	16.29	±	1.33	8.93	±	0.83	3.86	±	0.77
Total			25.25	±	3.25	20.02	±	2.48	16.46	±	1.76	9.09	±	1.02	4.07	±	0.64

*UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick. * Significantly different with $p < 0.05$*

Table 5: Time intervals while comparing across injury (mean $\pm$ standard deviation)

			Total Time (s)			Backswing %			Leg Cocking %			Leg Acceleration %			Follow Through %		
ND	F	UI	0.40	±	0.07	26.24	±	5.64	17.76	±	5.14	14.24	±	2.00	41.71	±	6.66
		I	0.39	±	0.06	21.25	±	2.99	20.50	±	2.65	15.50	±	1.29	42.75	±	5.91
	M	UI	0.39	±	0.04	24.94	±	2.88	17.22	±	2.46	15.44	±	2.25	42.11	±	3.69
		I	0.34	±	0.00	16.00	±	0.00	18.00	±	0.00	14.00	±	0.00	52.00	±	0.00
D	F	UI	0.39	±	0.04	26.85	±	4.96	18.15	±	4.98	15.00	±	1.86	40.10	±	5.78
		I	0.40	±	0.04	28.50	±	4.14	16.33	±	1.75	15.17	±	2.04	39.83	±	5.42
	M	UI	0.39	±	0.05	29.44	±	4.47	17.06	±	1.98	14.75	±	1.81	38.81	±	5.39
		I	0.36	±	0.02	29.67	±	7.64	16.00	±	0.00	16.33	±	0.58	37.67	±	7.09
Total ND		UI	0.40	±	0.06	25.64	±	4.57*	17.51	±	4.08	14.79	±	2.18	41.90	±	5.43
		I	0.38	±	0.06	20.20	±	3.49*	20.00	±	2.55	15.20	±	1.30	44.60	±	6.58
Total D		UI	0.39	±	0.04	28.00	±	4.86	17.67	±	3.93	14.89	±	1.82	39.53	±	5.57
		I	0.39	±	0.04	28.89	±	5.06	16.22	±	1.39	15.56	±	1.74	39.11	±	5.67
Total F		UI	0.40	±	0.06	26.54	±	5.26	17.95	±	5.00	14.61	±	1.95	40.93	±	6.23
		I	0.40	±	0.05	25.60	±	5.15	18.00	±	2.94	15.30	±	1.70	41.00	±	5.50
Total M		UI	0.39	±	0.04	27.06	±	4.31	17.15	±	2.22	15.12	±	2.06	40.56	±	4.80
		I	0.35	±	0.02	26.25	±	9.25	16.50	±	1.00	15.75	±	1.26	41.25	±	9.22
Total		UI	0.39	±	0.05	26.77	±	4.83	17.59	±	3.98	14.84	±	2.00	40.76	±	5.59
		I	0.39	±	0.05	25.79	±	6.18	17.57	±	2.59	15.43	±	1.55	41.07	±	6.37
Total			0.39	±	0.05	26.62	±	5.04	17.58	±	3.79	14.93	±	1.94	40.81	±	5.68

UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick. * Significantly different with $p < 0.05$

Table 6: Hip flexion/extension angles while comparing across injury (mean $\pm$ standard deviation)

Maximal Hip Extension (°)						Maximal Knee Flexion (°)			Ball Impact(°)			End of Follow Through (°)		
ND	F	UI	-13	±	10	14	±	9	30	±	9	83	±	18
		I	-8	±	7	13	±	5	30	±	10	83	±	15
	M	UI	-10	±	9	16	±	9	30	±	10	93	±	15
		I	-1	±	0	21	±	0	37	±	0	110	±	0
D	F	UI	-15	±	9	12	±	10	27	±	11	86	±	17
		I	-14	±	11	14	±	10	30	±	8	89	±	12
	M	UI	-13	±	8	15	±	6	28	±	9	97	±	16
		I	-12	±	4	11	±	4	23	±	4	90	±	13
Total ND		UI	-11	±	9	15	±	9	30	±	9	88	±	17
		I	-7	±	7	14	±	6	32	±	9	88	±	18
Total D		UI	-14	±	9	13	±	8	27	±	10	91	±	17
		I	-13	±	9	13	±	8	28	±	7	90	±	11
Total F		UI	-14	±	9	13	±	9	28	±	10	84	±	17
		I	-11	±	10	14	±	8	30	±	8	87	±	12
Total M		UI	-11	±	9	15	±	8	29	±	9	95	±	15
		I	-9	±	6	14	±	6	27	±	8	95	±	15
Total		UI	-13	±	9	14	±	8	29	±	10	89	±	17
		I	-11	±	9	14	±	7	29	±	8	89	±	13
Total			-12	±	9	14	±	8	29	±	9	89	±	16

A positive value indicates flexion and negative value extension. UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick.

Table 7: Knee flexion/extension angles while comparing across injury (mean $\pm$ standard deviation).

			Maximal Hip Extension (°)			Maximal Knee Flexion (°)			Ball Impact(°)			End of Follow Through (°)		
ND	F	UI	72	±	14*	114	±	12	58	±	12	26	±	14
		I	58	±	10*	110	±	8	51	±	15	27	±	14
	M	UI	72	±	8	116	±	9	46	±	14	28	±	16
		I	75	±	0	122	±	0	66	±	0	29	±	0
D	F	UI	67	±	19	112	±	11	45	±	9	26	±	12
		I	73	±	6	113	±	13	45	±	9	31	±	14
	M	UI	74	±	10	118	±	8	43	±	11	27	±	20
		I	79	±	10	118	±	9	44	±	5	36	±	19
Total ND		UI	72	±	12	115	±	10	53	±	14	27	±	15
		I	61	±	11	113	±	8	54	±	15	27	±	13
Total D		UI	71	±	16	115	±	11	44	±	10	27	±	16
		I	75	±	8	115	±	12	44	±	7	32	±	14
Total F		UI	70	±	17	113	±	12	52	±	12	26	±	13
		I	67	±	11	112	±	11	47	±	12	29	±	13
Total M		UI	73	±	9	117	±	9	45	±	13	28	±	17
		I	78	±	8	119	±	8	50	±	12	34	±	16
Total		UI	71	±	14	115	±	10	49	±	13	27	±	15
		I	70	±	11	114	±	10	48	±	11	31	±	14
Total			71	±	13	115	±	10	48	±	13	27	±	15

A positive value indicates flexion and negative value extension. UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick.

Table 8: Hip flexion/extension angular velocities while comparing across injury (mean $\pm$ standard deviation).

			Maximal Hip Extension (rad/s)			Maximal Knee Flexion (rad/s)			Ball Impact (rad/s)			End of Follow Through (rad/s)			Peak (rad/s)		
ND	F	UI	0	±	0	10	±	2*	-2	±	2	2	±	3	13	±	2
		I	0	±	0	8	±	0*	-1	±	1	1	±	3	13	±	3
	M	UI	0	±	0	10	±	2	0	±	3	2	±	3	12	±	2
		I	0	±	0	10	±	0	0	±	0	-1	±	0	14	±	0
D	F	UI	0	±	0	12	±	2	-3	±	3	1	±	2	15	±	2
		I	0	±	0	11	±	2	-1	±	2	-1	±	2	14	±	2
	M	UI	0	±	0	11	±	1	-1	±	3	3	±	2	14	±	2
		I	0	±	0	11	±	1	-1	±	2	4	±	1	14	±	3
		Total ND	UI	0	±	0	10	±	2	-1	±	3	2	±	3	13	±
	I	0	±	0	9	±	1	0	±	1	0	±	3	13	±	2	
Total D	UI	0	±	0	11	±	2	-2	±	3	2	±	3	14	±	2	
	I	0	±	0	11	±	1	-1	±	2	1	±	3	14	±	2	
Total F	UI	0	±	0	11	±	2*	-2	±	3	1	±	3	14	±	2	
	I	0	±	0	10	±	2*	-1	±	2	0	±	2	13	±	2	
Total M	UI	0	±	0	10	±	2	0	±	3	3	±	3	13	±	2	
	I	0	±	0	11	±	1	-1	±	2	3	±	3	14	±	2	
Total	UI	0	±	0	11	±	2	-1	±	3	2	±	3	13	±	2	
	I	0	±	0	10	±	2	-1	±	2	1	±	3	14	±	2	
Total			0	±	0	10	±	2	-1	±	3	2	±	3	13	±	2

A positive value indicates flexion and negative value extension. UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick. * Significantly different with $p < 0.05$

Table 9: Knee flexion/extension angular velocities while comparing across injury (mean $\pm$ standard deviation).

Maximal Hip Extension (rad/s)						Maximal Knee Flexion (rad/s)			Ball Impact (rad/s)			End of Follow Through (rad/s)			Peak (rad/s)		
ND	F	UI	14	±	3	0	±	1	-26	±	4	4	±	4	15	±	2
		I	17	±	1	0	±	1	-25	±	3	2	±	4	17	±	1
	M	UI	16	±	2	0	±	1	-28	±	5	4	±	5	17	±	3
		I	20	±	0	0	±	0	-31	±	0	0	±	0	21	±	0
D	F	UI	15	±	3	0	±	1	-28	±	5	4	±	5	16	±	3
		I	14	±	3	0	±	1	-26	±	4	1	±	4	15	±	2
	M	UI	17	±	5	0	±	1	-32	±	4	5	±	3	18	±	4
		I	16	±	2	0	±	1	-32	±	3	9	±	1	17	±	3
Total ND	UI	15	±	3	0	±	1	-27	±	5	4	±	5	16	±	3	
	I	17	±	2	0	±	1	-26	±	4	2	±	4	18	±	2	
Total D	UI	16	±	4	0	±	1	-30	±	5	4	±	5	17	±	4	
	I	14	±	3	0	±	1	-28	±	5	4	±	5	15	±	3	
Total F	UI	14	±	3	0	±	1	-27	±	4	4	±	5	16	±	2	
	I	15	±	3	0	±	1	-26	±	3	2	±	4	16	±	2	
Total M	UI	17	±	4	0	±	1	-30	±	5	4	±	5	18	±	4	
	I	17	±	3	0	±	1	-32	±	3	7	±	4	18	±	3	
Total	UI	15	±	3	0	±	1	-28	±	5	4	±	5	17	±	3	
	I	15	±	3	0	±	1	-27	±	4	3	±	4	16	±	3	
Total			15	±	3	0	±	1	-28	±	5	4	±	5	17	±	3

A positive value indicates flexion and negative value extension. UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick.

Table 10: Peak moments of the kicking leg while comparing across injury (mean $\pm$ standard deviation).

			Peak Hip Flexion Moment (Nm/kg)			Peak Hip Extension Moment (Nm/kg)			Peak Knee Flexion Moment (Nm/kg)			Peak Knee Extension Moment (Nm/kg)		
ND	F	UI	3.76	±	1.14	-2.67	±	1.24	1.57	±	0.60	-1.00	±	0.32
		I	3.75	±	0.50	-2.50	±	0.58	1.25	±	0.50	-1.00	±	0.00
	M	UI	3.44	±	0.86	-3.28	±	0.89	1.67	±	0.49	-1.17	±	0.38
		I	4.00	±	0.00	-4.00	±	0.00	2.00	±	0.00	-1.00	±	0.00
D	F	UI	3.95	±	0.76	-3.55	±	1.05	1.70	±	0.57	-1.10	±	0.31
		I	4.67	±	1.37	-4.00	±	1.41	1.83	±	0.75	-1.33	±	0.52
	M	UI	4.13	±	0.72	-3.88	±	0.72	1.94	±	0.25	-1.19	±	0.40
		I	4.00	±	0.00	-3.33	±	0.58	2.00	±	0.00	-1.33	±	0.58
Total ND	UI	3.62	±	1.02	-2.95	±	1.12	1.62	±	0.54	-1.08	±	0.35	
	I	3.80	±	0.45	-2.80	±	0.84	1.40	±	0.55	-1.00	±	0.00	
Total D	UI	4.03	±	0.74	-3.69	±	0.92	1.81	±	0.47	-1.14	±	0.35	
	I	4.44	±	1.13	-3.78	±	1.20	1.89	±	0.60	-1.33	±	0.50	
Total F	UI	3.85	±	0.96	-3.10	±	1.22	1.63	±	0.58	-1.05	±	0.31	
	I	4.30	±	1.16	-3.40	±	1.35	1.60	±	0.70	-1.20	±	0.42	
Total M	UI	3.76	±	0.85	-3.56	±	0.86	1.79	±	0.41	-1.18	±	0.39	
	I	4.00	±	0.00	-3.50	±	0.58	2.00	±	0.00	-1.25	±	0.50	
Total	UI	3.81	±	0.91	-3.31	±	1.09	1.71	±	0.51	-1.11	±	0.35	
	I	4.21	±	0.97	-3.43	±	1.16	1.71	±	0.61	-1.21	±	0.43	
Total			3.88	±	0.93	-3.33	±	1.10	1.71	±	0.53	-1.12	±	0.36

A positive value indicates flexion and negative value extension. UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick.

Table 11: Support leg variables while comparing across injury (mean $\pm$ standard deviation).

			SLS%		Peak GRF (N/kg)		Time to GRF%		MSHF (N/kg)		Time to MSHF%		MSKF (N/kg)		Time to MSKF%	
ND	F	UI	28.16	$\pm$ 4.91	29.04	$\pm$ 4.98	33.47	$\pm$ 3.96	23.11	$\pm$ 3.74	40.05	$\pm$ 10.16	28.32	$\pm$ 4.82	36.74	$\pm$ 7.09
		I	28.67	$\pm$ 4.46	33.74	$\pm$ 9.20	33.33	$\pm$ 5.28	24.50	$\pm$ 5.61	41.50	$\pm$ 8.87	30.33	$\pm$ 6.12	37.83	$\pm$ 8.16
	M	UI	27.19	$\pm$ 3.90	29.31	$\pm$ 6.71	41.38	$\pm$ 10.71	25.19	$\pm$ 4.81	43.56	$\pm$ 9.91	28.06	$\pm$ 6.87	36.00	$\pm$ 5.38
		I	28.67	$\pm$ 4.93	29.67	$\pm$ 4.93	32.67	$\pm$ 3.21	21.33	$\pm$ 3.79	51.33	$\pm$ 13.65	25.67	$\pm$ 3.06	34.33	$\pm$ 4.04
D	F	UI	29.14	$\pm$ 5.13	27.99	$\pm$ 4.15	39.82	$\pm$ 11.96	24.36	$\pm$ 3.96	47.95	$\pm$ 12.84	27.77	$\pm$ 4.39	40.23	$\pm$ 8.34
		I	31.50	$\pm$ 5.80	30.09	$\pm$ 5.47	46.00	$\pm$ 13.04	27.75	$\pm$ 5.50	53.00	$\pm$ 14.70	31.75	$\pm$ 6.29	40.00	$\pm$ 5.10
	M	UI	33.44	$\pm$ 5.41	33.50	$\pm$ 7.99	44.44	$\pm$ 8.77	27.33	$\pm$ 6.67	51.67	$\pm$ 12.20	29.00	$\pm$ 7.84	47.78	$\pm$ 11.78
		I	31.00	$\pm$ 0.00	28.00	$\pm$ 0.00	47.00	$\pm$ 0.00	26.00	$\pm$ 0.00	56.00	$\pm$ 0.00	27.00	$\pm$ 0.00	41.00	$\pm$ 0.00
Total ND		UI	27.71	$\pm$ 4.44	29.17	$\pm$ 5.75	37.09	$\pm$ 8.65	24.06	$\pm$ 4.32	41.66	$\pm$ 10.06	28.20	$\pm$ 5.75	36.40	$\pm$ 6.29
		I	28.67	$\pm$ 4.30	32.38	$\pm$ 7.95	33.11	$\pm$ 4.48	23.44	$\pm$ 5.08	44.78	$\pm$ 10.95	28.78	$\pm$ 5.59	36.67	$\pm$ 6.98
Total D		UI	31.08	$\pm$ 5.63	30.47	$\pm$ 6.69	41.90	$\pm$ 10.77	25.70	$\pm$ 5.48	49.63	$\pm$ 12.54	28.33	$\pm$ 6.13	43.63	$\pm$ 10.60
		I	31.40	$\pm$ 5.03	29.67	$\pm$ 4.83	46.20	$\pm$ 11.30	27.40	$\pm$ 4.83	53.60	$\pm$ 12.80	30.80	$\pm$ 5.85	40.20	$\pm$ 4.44
Total F		UI	28.68	$\pm$ 4.99	28.48	$\pm$ 4.53	36.88	$\pm$ 9.62	23.78	$\pm$ 3.86	44.29	$\pm$ 12.20	28.02	$\pm$ 4.54	38.61	$\pm$ 7.89
		I	29.80	$\pm$ 4.94	32.28	$\pm$ 7.78	38.40	$\pm$ 10.72	25.80	$\pm$ 5.51	46.10	$\pm$ 12.29	30.90	$\pm$ 5.88	38.70	$\pm$ 6.85
Total M		UI	30.50	$\pm$ 5.66	31.53	$\pm$ 7.60	43.00	$\pm$ 9.70	26.32	$\pm$ 5.88	47.85	$\pm$ 11.76	28.56	$\pm$ 7.30	42.24	$\pm$ 10.97
		I	29.25	$\pm$ 4.19	29.25	$\pm$ 4.11	36.25	$\pm$ 7.63	22.50	$\pm$ 3.87	52.50	$\pm$ 11.39	26.00	$\pm$ 2.58	36.00	$\pm$ 4.69
Total		UI	29.51	$\pm$ 5.35	29.86	$\pm$ 6.26	39.65	$\pm$ 10.07	24.93	$\pm$ 5.01	45.91	$\pm$ 12.06	28.27	$\pm$ 5.92	40.25	$\pm$ 9.52
		I	29.64	$\pm$ 4.58	31.41	$\pm$ 6.92	37.79	$\pm$ 9.70	24.86	$\pm$ 5.19	47.93	$\pm$ 11.98	29.50	$\pm$ 5.54	37.93	$\pm$ 6.26
Total			29.53	$\pm$ 5.21	30.11	$\pm$ 6.35	39.36	$\pm$ 9.98	24.92	$\pm$ 5.01	46.22	$\pm$ 12.00	28.46	$\pm$ 5.85	39.89	$\pm$ 9.09

UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick. SLS%: support leg strike moment, GRF: ground reaction force, MSHF: maximum support hip reaction force, MSKF: maximum support knee reaction force

Discussion and implications

In the first part of the statistical analysis, a comparison between kicks with previously injured hamstring muscles and kicks with the uninjured limbs were made. The analysis gave some differences in the backswing and leg cocking phases, when the hamstring muscles were the most active extending the hip and flexing the knee, and these varied on whether the injury was sustained in the dominant or non-dominant limb, or in males or females.

Figure 16: Peak hip velocities (m/s) compared across previous injury

A previous injury to the dominant limb in female soccer players inhibited them from reaching a maximal velocity in the hip on par with the uninjured dominant limbs (Table 4, Figure 16). Kicking is a proximal-to-distal movement (Juarez et al., 2011; Lees & Nolan, 1998), with peak velocities also being reached in the same sequential order (Lees & Nolan, 1998). In the initial part of the movement, the hamstring muscles are the most active, working actively in the extension of the hip and flexion of the knee. The peak hip velocity is reached in the backswing and leg cocking phases, and a previous hamstring injury impedes the hip from reaching peak velocities when the hamstring muscles are the most active in females but not in males. It is

clear that an injury to dominant limb affected females differently than it did to males, and this difference was not seen in the non-dominant limb.

In accordance to studies previously reported in literature (Navandar et al., 2015; Navandar et al., 2013) no differences between the injured group and uninjured group was found in the ball velocities. No differences were found in the peak velocities of the toe, ankle and knee either, indicating that a previous hamstring injury did not influence the peak velocities in these joints. One must note that the peak linear velocity in the knee is reached when the knee is extending while the hip is flexing, and this is possibly why no difference is seen in this velocity while one observes a difference in the peak hip velocity since the hamstring muscle activation is minimal in this phase.

Uninjured non-dominant limbs had a greater backswing than the dominant uninjured limbs (Table 5). When an injury occurred in the non-dominant limb, the players intended to restrict the backswing. In the backswing phase, the hamstring muscles are the most active, and possibly as a preventive measure the players tended to cut short their backswing. One must notice that the total time of the kick was similar across the different groups. This difference was not seen in the dominant limbs, further evidencing that an injury to the dominant and non-dominant limbs must be treated differently for both male and female players. No other differences were seen in the time intervals between the different groups.

Navandar et al. (2013), who had studied the dominant limb kick in professional male players, had mentioned observed insignificant differences in the backswing phase, although the values were greater in the uninjured limb as reported in this study. They also noted large differences in the follow through phase, a result contrary to what was seen in the same group of players in this study. This could be due to the surface on which the kicks were performed (laboratory floor in Navandar et al. (2013) vs artificial turf here), type of kick selected (peak velocity kick

in in Navandar et al. (2013) and median velocity kick here) and the different statistical analyses performed in the two studies (non-parametric Mann-Whitney U test in Navandar et al. (2013) and 3-way ANOVA here).

At maximal hip extension, the hamstrings are the most active work to extend the hip and flex the knee. A previous injury appears to hamper this knee flexion in females in the non-dominant limb, causing a lesser flexion compared to an uninjured non-dominant limb (Table 7). This could be due to a comparatively poor activation of the hamstring muscles in the non-dominant limb. This difference was not seen in the dominant limb or in males, and disappeared when one of the independent factors was taken out of the equation, indicating that the interaction of sex and limb dominance plays an important role while comparing across previous injury. The other angles for the hip and knee at the other instances were similar between the groups (Tables 6 and 7).

Comparing angular velocities between the different groups, the uninjured limbs in females had a greater hip flexion velocity at maximal knee flexion compared to injured limbs. These differences were small in the dominant limb and medium in the non-dominant limb (Table 8), and disappeared when sex difference was not taken into consideration. At this instance, the hamstring muscles are active as antagonist muscles preventing to flex the hip at a faster rate. This could be seen in the differences in the peak hip velocity (Table 8).

No differences were observed in the peak moments in the sagittal plane between the injured and uninjured limbs (Table 10). For male soccer players, this is a finding in contrary to Navandar et al. (2013). They had found a difference in the flexion moment of the hip at MHE, being greater in the injured limb. It is important to note that the values reported in this study were much higher than those reported by them. The discrepancies can be explained on the methodological differences previously explained.

In accordance to previous studies (Navandar et al., 2015; Navandar et al., 2013), a previous injury did not affect the peak reaction forces or time to peak reaction forces (Table 11). The values reported were also greater than the values reported by Orloff et al. (2008) in amateur players and similar to values reported by Juarez et al. (2011) in elite youth players. The ground reaction forces are almost three times the body weight, and this greater force perhaps contributes to a greater ball velocity in professional soccer players.

Practical applications

A previous hamstring injury affects the mechanics of the female kick more than the male kick, being different in the non-dominant and dominant limbs. The non-dominant limb appeared to be more affected than the dominant limb in the females. Coaches and biomechanists must work on exercises that try to improve the backswing and leg cocking phase mechanics, specifically knee flexion and simultaneous hip flexion especially in previously injured limbs. Working on bilateral symmetry would also help as the dominant limb appeared to be less affected than the non-dominant limb. While working on rehabilitation programs, one must treat hamstring injuries differently based on limb dominance and sex.

II. Comparing across sex

Results

Observing the linear velocities (Table 12), males showed a substantially higher kicking ball velocity compared to females when kicking with the uninjured limb (partial $\eta^2 = 0.23$, $p < 0.001$ for the non-dominant limb and partial $\eta^2 = 0.17$, $p < 0.001$ for dominant limb). Medium differences between the two groups was observed while kicking with the injured dominant limb (partial $\eta^2 = 0.06$, $p = 0.031$) but this difference did not appear with the injured non-dominant limb. Males also had higher toe velocities across all groups (partial $\eta^2 = 0.27$, $p < 0.001$ for the uninjured non-dominant limb, partial $\eta^2 = 0.26$, $p < 0.001$ for the uninjured dominant limb, partial $\eta^2 = 0.07$, $p = 0.013$ for the injured non-dominant limb and partial $\eta^2 = 0.06$, $p = 0.025$ for the injured dominant limb). The maximum velocities for the ankle showed a pattern similar to that of the ball velocities: males showing greater velocities than females in all types of kick except in the injured non-dominant limb kick (partial $\eta^2 = 0.29$, $p < 0.001$ for the uninjured non-dominant limb kick, partial $\eta^2 = 0.24$, $p < 0.001$ for the uninjured dominant limb, partial $\eta^2 = 0.08$, $p = 0.025$ for the injured dominant limb). The maximum knee velocities were greater in the males than in the females only for the uninjured limb (partial $\eta^2 = 0.12$, $p = 0.002$ for the uninjured non-dominant limb kick, partial $\eta^2 = 0.15$, $p < 0.001$ for the uninjured dominant limb). This difference was not observed for the kicks with the injured limb, irrespective of limb dominance. A medium difference between males and females was observed in the hip velocity while kicking with the uninjured non-dominant limb (partial $\eta^2 = 0.05$, $p = 0.038$), while no differences between the groups were observed across a previously injured limb or a previously uninjured dominant limb.

On grouping the variables irrespective of limb dominance and comparing sex across previous injury, males exhibited a higher velocities in the ball (partial $\eta^2 = 0.33$, $p < 0.001$ for the uninjured limb, partial $\eta^2 = 0.06$, $p = 0.022$ for the injured limb), toe (partial $\eta^2 = 0.42$, $p <$

0.001 for the uninjured limb, partial $\eta^2 = 0.12$, $p = 0.001$ for the injured limb), ankle (partial $\eta^2 = 0.42$, $p < 0.001$ for the uninjured limb, partial $\eta^2 = 0.09$, $p = 0.005$ for the injured limb) and knee (partial $\eta^2 = 0.24$, $p < 0.001$ for the uninjured limb, partial $\eta^2 = 0.06$, $p = 0.028$ for the injured limb). This difference between sexes was not seen in the hip velocity of previously injured limbs, but was seen in the uninjured hip velocity (partial $\eta^2 = 0.07$, $p = 0.017$).

On grouping the variables irrespective of previous injury, and comparing the effect of sex across limb dominance, males had substantially greater velocities for the ball (partial $\eta^2 = 0.08$, $p = 0.009$ for the non-dominant limb, and partial $\eta^2 = 0.15$, $p < 0.001$ for the dominant limb), toe (partial $\eta^2 = 0.16$, $p < 0.001$ for the non-dominant limb, and partial $\eta^2 = 0.19$, $p < 0.001$ for the dominant limb), ankle (partial $\eta^2 = 0.12$, $p = 0.001$ for the non-dominant limb, and partial $\eta^2 = 0.20$, $p < 0.001$ for the dominant limb), knee (partial $\eta^2 = 0.07$, $p = 0.017$ for the non-dominant limb, and partial $\eta^2 = 0.11$, $p = 0.002$ for the dominant limb) and the dominant limb hip (partial $\eta^2 = 0.06$, $p = 0.023$). The sex difference was not observed in the maximal hip velocity for the non-dominant limb. On comparing across sexes globally, males exhibited substantially higher maximal ball (partial $\eta^2 = 0.19$, $p < 0.001$), toe (partial $\eta^2 = 0.29$, $p < 0.001$), ankle (partial $\eta^2 = 0.25$, $p < 0.001$), and knee (partial $\eta^2 = 0.15$, $p < 0.001$) velocities than females. This sex difference was not observed in maximal hip velocities.

No differences were observed between the sexes when comparing the time intervals and total time across the different groups across previous injury and limb dominance (Table 13).

On contrasting the values of hip and knee flexion-extension angles (Tables 14 and 15) in the instances of maximal hip extension and maximal knee flexion, no differences were found across sex between the different groups. However, at ball impact the females displayed greater knee flexion angles than males for the uninjured, non-dominant limb kick (partial $\eta^2 = 0.10$, $p = 0.003$). This difference was not found in the injured non-dominant limb kicks or the uninjured

and injured dominant limb kicks. At the end of follow through, the males showed a higher hip flexion angle in the uninjured, dominant limb kicks (partial $\eta^2 = 0.05$, $p = 0.041$). This difference was not seen in the uninjured non-dominant limb kicks nor in the injured dominant or non-dominant limb kicks. The values for the hip flexion angle at ball impact, and knee extension at the end of the follow through were similar across the different groups.

Grouping the variables ignoring the limb dominance, the uninjured males had a lesser knee flexion angle at ball impact (partial $\eta^2 = 0.08$, $p = 0.011$) and a higher hip flexion angle at the end of follow through (partial $\eta^2 = 0.09$, $p = 0.005$) when compared to uninjured females. This difference was not seen in injured limb kicks. On grouping the variables irrespective of previous injury, only a greater hip flexion angle at the end of follow through in males than in females for the non-dominant limb was observed (partial $\eta^2 = 0.05$, $p = 0.048$). In the dominant limb kicks, the values were similar between sexes. Comparing globally across sexes alone, males had a higher hip flexion angle at the end of follow through (partial $\eta^2 = 0.06$, $p = 0.030$). The difference in knee flexion angle at ball impact was not observed (partial $\eta^2 = 0.003$, $p = 0.956$).

The hip flexion velocity (Table 16) was greater in males than in females at ball impact for the uninjured non-dominant limbs (partial $\eta^2 = 0.09$, $p = 0.006$). On the contrary, similar velocities were obtained across sexes for the uninjured dominant limbs, and the injured non-dominant and dominant limbs. At the end of follow through, kicks by previously injured factor, dominant limbs of males had a greater hip flexion velocity than females for the uninjured, dominant limb kicks (partial $\eta^2 = 0.08$, $p = 0.012$). This difference was not seen in kicks by the uninjured non-dominant limbs, or previously injured, dominant or non-dominant limbs. At the other instances and at peak values, the hip flexion-extension velocities were similar between the two groups.

Kicks from the uninjured non-dominant male limbs had a higher knee flexion velocity (Table 17) at maximal hip extension than females (partial $\eta^2 = 0.06$, $p = 0.024$), a pattern not seen in uninjured dominant limb kicks or in previously injured, dominant or non-dominant limb kicks. At maximal knee flexion, no differences between the sexes across the different groups were seen for the knee flexion-extension velocity. At ball impact, the females had a lower knee extension velocity than males for the uninjured, dominant limb kicks (partial $\eta^2 = 0.08$, $p = 0.013$). This difference was not observed for the uninjured, non-dominant limb kicks or for injured, dominant or non-dominant limb kicks. At the end of follow through, the males showed a greater knee flexion velocity than females in the previously injured, dominant limb kicks (partial $\eta^2 = 0.07$, $p = 0.021$). At the same instance, the knee flexion velocities for the previously injured, non-dominant limb kicks, previously uninjured, non-dominant or dominant limb kicks were similar between the sexes. The peak knee flexion-extension velocity was also similar between the different groups.

Grouping the variables without considering limb dominance, the afore-mentioned differences in the hip flexion velocities between sexes at ball impact (partial $\eta^2 = 0.12$, $p = 0.002$) and end of follow through (partial $\eta^2 = 0.07$, $p = 0.014$) are seen; these differences were not seen in the injured limb. The sex difference in the knee flexion velocity was seen at maximal hip extension in the case of uninjured limbs only (partial $\eta^2 = 0.10$, $p = 0.004$). At ball impact, the greater knee extension velocity in males was observed in the uninjured (partial $\eta^2 = 0.09$, $p = 0.007$) and previously injured limbs (partial $\eta^2 = 0.05$, $p = 0.040$). The difference in knee flexion velocity at the end of follow through was not observed. A difference in the peak knee flexion angular velocity in the uninjured limb only was also noted, being greater in males than in females (partial $\eta^2 = 0.07$, $p = 0.017$).

Grouping the variables irrespective of previous injury history, the difference in hip flexion velocity at the end of follow through is observed for the dominant limb alone (partial $\eta^2 = 0.14$, $p < 0.001$). The difference in hip flexion velocity at ball impact is not seen. The aforementioned differences in knee flexion-extension velocities was seen only in the dominant limb at maximal hip extension (partial $\eta^2 = 0.05$, $p = 0.048$), ball impact (partial $\eta^2 = 0.09$, $p = 0.005$) and the end of follow through (partial $\eta^2 = 0.08$, $p = 0.011$).

Globally contrasting sexes, differences only in the knee flexion velocity at maximal hip extension (partial $\eta^2 = 0.07$, $p = 0.016$) and the knee extension velocity at ball impact (partial $\eta^2 = 0.10$, $p = 0.005$) were noted. The peak knee flexion velocity was also greater in males than in females (partial $\eta^2 = 0.06$, $p = 0.022$).

Comparing the peak hip and knee flexion and extension moments between males and females, the values obtained are similar across the different groups (Table 18). Similarly, no difference was obtained in the peak moments on grouping the variables irrespective of limb dominance or whilst ignoring previous injury.

Looking at the support leg variables (Table 19), in the uninjured, dominant limb kicks males had a greater normalized peak reaction force as compared to females (partial $\eta^2 = 0.09$, $p = 0.007$). For the same group, the support leg strike occurred later in males than in females (partial $\eta^2 = 0.09$, $p = 0.007$) and so did the peak knee reaction force (partial $\eta^2 = 0.09$, $p = 0.005$). The peak ground reaction force occurred later in males for the previously uninjured, non-dominant limb kicks (partial $\eta^2 = 0.07$, $p = 0.014$). The peak hip and knee reaction forces, as well time to peak hip reaction force were similar in males and females for the different groups. Analyzing the variables across sex notwithstanding limb dominance, differences in the uninjured limb only for normalized ground reaction force (partial $\eta^2 = 0.05$, $p = 0.049$), peak hip reaction force, being greater in males than in females (partial $\eta^2 = 0.06$, $p = 0.030$), and

time to peak ground reaction force (partial $\eta^2 = 0.09$, $p = 0.005$) were observed. These differences were not seen in the previously injured limbs. The differences in peak knee reaction force and times to peak hip and knee reaction forces were very small. On clustering the variables while ignoring previous injury history, no differences based on sex were noted in the support leg variables. Similarly, on considering sex differences as a whole, no differences in the support leg variables were seen.

Table 12: Linear velocities while comparing across sex (mean $\pm$ standard deviation).

			Ball (m/s)		Toe (m/s)		Ankle (m/s)		Knee (m/s)		Hip (m/s)	
UI	ND	F	22.19	± 2.86**	17.71	± 2.31**	14.76	± 1.37**	8.33	± 1.06*	3.81	± 0.60*
		M	26.06	± 2.78**	20.83	± 1.38**	17.11	± 1.28**	9.22	± 0.81*	4.22	± 0.65*
	D	F	25.25	± 2.47**	19.70	± 2.03**	16.25	± 1.48**	9.05	± 0.83**	4.10	± 0.45
		M	28.63	± 1.75**	22.81	± 1.11**	18.38	± 1.02**	10.13	± 0.62**	4.38	± 0.62
I	ND	F	23.25	± 1.26	18.00	± 1.41*	15.50	± 1.00	8.50	± 0.58	4.00	± 0.00
		M	27.00	± 0.00	23.00	± 0.00*	18.00	± 0.00	10.00	± 0.00	4.00	± 0.00
	D	F	24.17	± 2.48*	19.17	± 1.17*	15.67	± 0.82*	8.67	± 0.82	3.50	± 0.84
		M	28.00	± 0.00*	22.00	± 1.00*	18.00	± 0.00*	9.67	± 0.58	4.33	± 1.15
Total UI		F	23.68	± 3.06**	18.68	± 2.37**	15.49	± 1.60**	8.68	± 1.01**	3.95	± 0.55*
		M	27.26	± 2.65**	21.76	± 1.60**	17.71	± 1.31**	9.65	± 0.85**	4.29	± 0.63*
Total I		F	23.80	± 2.04*	18.70	± 1.34*	15.60	± 0.84*	8.60	± 0.70*	3.70	± 0.67
		M	27.75	± 0.50*	22.25	± 0.96*	18.00	± 0.00*	9.75	± 0.50*	4.25	± 0.96
Total ND		F	22.36	± 2.68*	17.76	± 2.17**	14.88	± 1.33*	8.36	± 0.99*	3.84	± 0.55
		M	26.11	± 2.71*	20.95	± 1.43**	17.16	± 1.26*	9.26	± 0.81*	4.21	± 0.63
Total D		F	25.00	± 2.47**	19.58	± 1.86**	16.12	± 1.37**	8.96	± 0.82*	3.96	± 0.60*
		M	28.53	± 1.61**	22.68	± 1.11**	18.32	± 0.95**	10.05	± 0.62*	4.37	± 0.68*
Total		F	23.71	± 2.87**	18.69	± 2.20**	15.51	± 1.47**	8.67	± 0.95**	3.90	± 0.57
		M	27.32	± 2.52**	21.82	± 1.54**	17.74	± 1.25**	9.66	± 0.81**	4.29	± 0.65
Total			25.25	± 3.25	20.02	± 2.48	16.46	± 1.76	9.09	± 1.02	4.07	± 0.64

UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick. * Significantly different with $p < 0.05$. ** Significantly different with $p < 0.001$

Table 13: Time intervals while comparing across sex (mean $\pm$ standard deviation).

			Total Time (s)			Backswing %			Leg Cocking %			Leg Acceleration %			Follow Through %		
UI	ND	F	0.40	±	0.07	26.24	±	5.64	17.76	±	5.14	14.24	±	2.00	41.71	±	6.66
		M	0.39	±	0.04	24.94	±	2.88	17.22	±	2.46	15.44	±	2.25	42.11	±	3.69
	D	F	0.39	±	0.04	26.85	±	4.96	18.15	±	4.98	15.00	±	1.86	40.10	±	5.78
		M	0.39	±	0.05	29.44	±	4.47	17.06	±	1.98	14.75	±	1.81	38.81	±	5.39
I	ND	F	0.39	±	0.06	21.25	±	2.99	20.50	±	2.65	15.50	±	1.29	42.75	±	5.91
		M	0.34	±	0.00	16.00	±	0.00	18.00	±	0.00	14.00	±	0.00	52.00	±	0.00
	D	F	0.40	±	0.04	28.50	±	4.14	16.33	±	1.75	15.17	±	2.04	39.83	±	5.42
		M	0.36	±	0.02	29.67	±	7.64	16.00	±	0.00	16.33	±	0.58	37.67	±	7.09
Total UI		F	0.40	±	0.06	26.54	±	5.26	17.95	±	5.00	14.61	±	1.95	40.93	±	6.23
		M	0.39	±	0.04	27.06	±	4.31	17.15	±	2.22	15.12	±	2.06	40.56	±	4.80
Total I		F	0.40	±	0.05	25.60	±	5.15	18.00	±	2.94	15.30	±	1.70	41.00	±	5.50
		M	0.35	±	0.02	26.25	±	9.25	16.50	±	1.00	15.75	±	1.26	41.25	±	9.22
Total ND		F	0.40	±	0.07	25.44	±	5.58	18.20	±	4.89	14.44	±	1.94	41.88	±	6.44
		M	0.39	±	0.04	24.47	±	3.47	17.26	±	2.40	15.37	±	2.22	42.63	±	4.25
Total D		F	0.39	±	0.04	27.23	±	4.75	17.73	±	4.48	15.04	±	1.87	40.04	±	5.60
		M	0.39	±	0.05	29.47	±	4.81	16.89	±	1.85	15.00	±	1.76	38.63	±	5.48
Total		F	0.40	±	0.05	26.35	±	5.20	17.96	±	4.64	14.75	±	1.91	40.94	±	6.04
		M	0.39	±	0.04	26.97	±	4.85	17.08	±	2.12	15.18	±	1.98	40.63	±	5.24
Total			0.39	±	0.05	26.62	±	5.04	17.58	±	3.79	14.93	±	1.94	40.81	±	5.68

UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick.

Table 14: Hip flexion/extension angles while comparing across sex (mean $\pm$ standard deviation).

Maximal Hip Extension (°)					Maximal Knee Flexion (°)				Ball Impact(°)			End of Follow Through (°)		
UI	ND	F	-13	±	10	14	±	9	30	±	9	83	±	18
		M	-10	±	9	16	±	9	30	±	10	93	±	15
	D	F	-15	±	9	12	±	10	27	±	11	86	±	16*
		M	-13	±	8	15	±	6	28	±	9	97	±	16*
I	ND	F	-8	±	7	13	±	5	30	±	10	83	±	15
		M	-1	±	0	21	±	0	37	±	0	110	±	0
	D	F	-14	±	11	14	±	10	30	±	8	89	±	12
		M	-12	±	4	11	±	4	23	±	4	90	±	13
Total UI	F	-14	±	9	13	±	9	28	±	10	84	±	17*	
	M	-11	±	9	15	±	8	29	±	9	95	±	16*	
Total I	F	-11	±	10	14	±	8	30	±	8	87	±	12	
	M	-9	±	6	14	±	6	27	±	8	95	±	15	
Total ND	F	-12	±	9	13	±	8	30	±	9	83	±	17*	
	M	-9	±	9	16	±	9	31	±	10	94	±	15*	
Total D	F	-15	±	9	13	±	10	27	±	10	87	±	15	
	M	-12	±	8	14	±	6	27	±	9	96	±	15	
Total	F	-13	±	9	13	±	9	28	±	10	85	±	16*	
	M	-11	±	8	15	±	7	29	±	9	95	±	15*	
Total			-12	±	9	14	±	8	29	±	9	89	±	16

*A positive value indicates flexion and negative value extension. UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick. * Significantly different with $p < 0.05$.*

Table 15: Knee flexion/extension angles while comparing across sex (mean $\pm$ standard deviation).

Maximal Hip Extension (°)						Maximal Knee Flexion (°)			Ball Impact(°)			End of Follow Through (°)		
UI	ND	F	72	±	14	114	±	12	58	±	12*	26	±	14
		M	72	±	8	116	±	9	46	±	14*	28	±	16
	D	F	67	±	19	112	±	11	45	±	9	26	±	12
		M	74	±	10	118	±	8	43	±	11	27	±	20
I	ND	F	58	±	10	110	±	8	51	±	15	27	±	14
		M	75	±	0	122	±	0	66	±	0	29	±	0
	D	F	73	±	6	113	±	13	45	±	9	31	±	14
		M	79	±	10	118	±	9	44	±	5	36	±	19
Total UI		F	70	±	17	113	±	12	52	±	12*	26	±	13
		M	73	±	9	117	±	9	45	±	13*	28	±	17
Total I		F	67	±	11	112	±	11	47	±	12	29	±	13
		M	78	±	8	119	±	8	50	±	12	34	±	16
Total ND		F	70	±	15	114	±	11	57	±	13	26	±	14
		M	72	±	8	116	±	9	47	±	14	28	±	15
Total D		F	69	±	17	112	±	12	45	±	9	27	±	13
		M	75	±	10	118	±	8	43	±	10	29	±	19
Total		F	69	±	16	113	±	11	51	±	12	27	±	13
		M	74	±	9	117	±	8	45	±	12	28	±	17
Total			71	±	13	115	±	10	48	±	13	27	±	15

*A positive value indicates flexion and negative value extension. UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick. * Significantly different with $p < 0.05$.*

Table 16: Hip flexion/extension angular velocities while comparing across sex (mean $\pm$ standard deviation).

			Maximal Hip Extension (rad/s)			Maximal Knee Flexion (rad/s)			Ball Impact (rad/s)			End of Follow Through (rad/s)			Peak (rad/s)		
UI	ND	F	0	±	0	10	±	1	-2	±	2*	2	±	3	13	±	2
		M	0	±	0	10	±	2	0	±	3*	2	±	3	12	±	2
	D	F	0	±	0	12	±	2	-3	±	3	1	±	2*	15	±	2
		M	0	±	0	11	±	1	-1	±	3	3	±	2*	14	±	2
I	ND	F	0	±	0	8	±	1	-1	±	1	1	±	3	13	±	3
		M	0	±	0	10	±	0	0	±	0	-1	±	0	14	±	0
	D	F	0	±	0	11	±	2	-1	±	2	-1	±	2	14	±	2
		M	0	±	0	11	±	1	-1	±	2	4	±	1	14	±	3
Total UI	F	0	±	0	11	±	2	-2	±	3*	1	±	3*	14	±	2	
	M	0	±	0	10	±	2	0	±	3*	3	±	2*	13	±	2	
Total I	F	0	±	0	10	±	2	-1	±	2	0	±	2	13	±	2	
	M	0	±	0	11	±	1	-1	±	2	3	±	3	14	±	2	
Total ND	F	0	±	0	10	±	2	-2	±	2	2	±	3	13	±	2	
	M	0	±	0	10	±	2	0	±	3	2	±	3	13	±	2	
Total D	F	0	±	0	11	±	2	-2	±	3	0	±	2*	14	±	2	
	M	0	±	0	11	±	1	-1	±	3	3	±	2*	14	±	2	
Total	F	0	±	0	11	±	2	-2	±	3	1	±	3	14	±	2	
	M	0	±	0	10	±	2	0	±	3	3	±	3	13	±	2	
Total			0	±	0	10	±	2	-1	±	3	2	±	3	13	±	2

*A positive value indicates flexion and negative value extension. UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick. * Significantly different with $p < 0.05$.*

Table 17: Knee flexion/extension angular velocities while comparing across sex (mean $\pm$ standard deviation).

			Maximal Hip Extension (rad/s)			Maximal Knee Flexion (rad/s)			Ball Impact (rad/s)			End of Follow Through (rad/s)			Peak (rad/s)		
UI	ND	F	14	±	3*	0	±	1	-26	±	4	4	±	4	15	±	2
		M	16	±	2*	0	±	1	-28	±	5	4	±	5	17	±	3
	D	F	15	±	3	0	±	1	-28	±	5*	4	±	5	16	±	3
		M	17	±	5	0	±	1	-32	±	4*	5	±	3	18	±	4
I	ND	F	17	±	1	0	±	1	-25	±	3	2	±	4	17	±	1
		M	20	±	0	0	±	0	-31	±	0	0	±	0	21	±	0
	D	F	14	±	3	0	±	1	-26	±	4	1	±	4*	15	±	2
		M	16	±	2	0	±	1	-32	±	3	9	±	1*	17	±	3
Total UI	F	14	±	3*	0	±	1	-27	±	4*	4	±	5	16	±	2*	
	M	17	±	4*	0	±	1	-30	±	5*	4	±	5	18	±	4*	
Total I	F	15	±	3	0	±	1	-26	±	3*	2	±	4	16	±	2	
	M	17	±	3	0	±	1	-32	±	3*	7	±	4	18	±	3	
Total ND	F	14	±	3	0	±	1	-26	±	4	4	±	4	16	±	2	
	M	16	±	3	0	±	1	-28	±	5	3	±	5	17	±	3	
Total D	F	15	±	3*	0	±	1	-28	±	4*	3	±	5*	16	±	3	
	M	17	±	4*	0	±	1	-32	±	4*	6	±	3*	18	±	4	
Total	F	14	±	3*	0	±	1	-27	±	4*	3	±	4	16	±	2*	
	M	17	±	4*	0	±	1	-30	±	5*	5	±	5	18	±	4*	
Total			15	±	3	0	±	1	-28	±	5	4	±	5	17	±	3

*A positive value indicates flexion and negative value extension. UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick. * Significantly different with $p < 0.05$.*

Table 18: Peak moments of the kicking leg while comparing across injury (mean $\pm$ standard deviation).

			Peak Hip Flexion Moment (Nm/kg)			Peak Hip Extension Moment (Nm/kg)			Peak Knee Flexion Moment (Nm/kg)			Peak Knee Extension Moment (Nm/kg)		
UI	ND	F	3.76	±	1.14	-2.67	±	1.24	1.57	±	0.60	-1.00	±	0.32
		M	3.44	±	0.86	-3.28	±	0.89	1.67	±	0.49	-1.17	±	0.38
	D	F	3.95	±	0.76	-3.55	±	1.05	1.70	±	0.57	-1.10	±	0.31
		M	4.13	±	0.72	-3.88	±	0.72	1.94	±	0.25	-1.19	±	0.40
I	ND	F	3.75	±	0.50	-2.50	±	0.58	1.25	±	0.50	-1.00	±	0.00
		M	4.00	±	0.00	-4.00	±	0.00	2.00	±	0.00	-1.00	±	0.00
	D	F	4.67	±	1.37	-4.00	±	1.41	1.83	±	0.75	-1.33	±	0.52
		M	4.00	±	0.00	-3.33	±	0.58	2.00	±	0.00	-1.33	±	0.58
Total UI		F	3.85	±	0.96	-3.10	±	1.22	1.63	±	0.58	-1.05	±	0.31
		M	3.76	±	0.85	-3.56	±	0.86	1.79	±	0.41	-1.18	±	0.39
Total I		F	4.30	±	1.16	-3.40	±	1.35	1.60	±	0.70	-1.20	±	0.42
		M	4.00	±	0.00	-3.50	±	0.58	2.00	±	0.00	-1.25	±	0.50
Total ND		F	3.76	±	1.05	-2.64	±	1.15	1.52	±	0.59	-1.00	±	0.29
		M	3.47	±	0.84	-3.32	±	0.89	1.68	±	0.48	-1.16	±	0.37
Total D		F	4.12	±	0.95	-3.65	±	1.13	1.73	±	0.60	-1.15	±	0.37
		M	4.11	±	0.66	-3.79	±	0.71	1.95	±	0.23	-1.21	±	0.42
Total		F	3.94	±	1.01	-3.16	±	1.24	1.63	±	0.60	-1.08	±	0.34
		M	3.79	±	0.81	-3.55	±	0.83	1.82	±	0.39	-1.18	±	0.39
Total			3.88	±	0.93	-3.33	±	1.10	1.71	±	0.53	-1.12	±	0.36

A positive value indicates flexion and negative value extension. UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick.

Table 19: Support leg variables while comparing across sex (mean $\pm$ standard deviation).

			SLS%			Peak GRF (N/kg)			Time to GRF%			MSHF (N/kg)			Time to MSHF%			MSKF (N/kg)			Time to MSKF%		
UI	ND	F	28.16	±	4.91	29.04	±	4.98	33.47	±	3.96*	23.11	±	3.74	40.05	±	10.16	28.32	±	4.82	36.74	±	7.09
		M	27.19	±	3.90	29.31	±	6.71	41.38	±	10.7*	25.19	±	4.81	43.56	±	9.91	28.06	±	6.87	36.00	±	5.38
	D	F	29.14	±	5.13*	27.99	±	4.15*	39.82	±	11.96	24.36	±	3.96	47.95	±	12.84	27.77	±	4.39	40.23	±	8.34*
		M	33.44	±	5.41*	33.50	±	7.99*	44.44	±	8.77	27.33	±	6.67	51.67	±	12.20	29.00	±	7.84	47.78	±	11.8*
I	ND	F	28.67	±	4.46	33.74	±	9.20	33.33	±	5.28	24.50	±	5.61	41.50	±	8.87	30.33	±	6.12	37.83	±	8.16
		M	28.67	±	4.93	29.67	±	4.93	32.67	±	3.21	21.33	±	3.79	51.33	±	13.65	25.67	±	3.06	34.33	±	4.04
	D	F	31.50	±	5.80	30.09	±	5.47	46.00	±	13.04	27.75	±	5.50	53.00	±	14.70	31.75	±	6.29	40.00	±	5.10
		M	31.00	±	0.00	28.00	±	0.00	47.00	±	0.00	26.00	±	0.00	56.00	±	0.00	27.00	±	0.00	41.00	±	0.00
Total UI		F	28.68	±	4.99	28.48	±	4.53*	36.88	±	9.62*	23.78	±	3.9*	44.29	±	12.20	28.02	±	4.54	38.61	±	7.89
		M	30.50	±	5.66	31.53	±	7.60*	43.00	±	9.70*	26.32	±	5.9*	47.85	±	11.76	28.56	±	7.30	42.24	±	10.97
Total I		F	29.80	±	4.94	32.28	±	7.78	38.40	±	10.72	25.80	±	5.51	46.10	±	12.29	30.90	±	5.88	38.70	±	6.85
		M	29.25	±	4.19	29.25	±	4.11	36.25	±	7.63	22.50	±	3.87	52.50	±	11.39	26.00	±	2.58	36.00	±	4.69
Total ND		F	28.28	±	4.72	30.17	±	6.36	33.44	±	4.19	23.44	±	4.17	40.40	±	9.70	28.80	±	5.10	37.00	±	7.20
		M	27.42	±	3.96	29.37	±	6.34	40.00	±	10.36	24.58	±	4.79	44.79	±	10.54	27.68	±	6.41	35.74	±	5.13
Total D		F	29.50	±	5.19	28.31	±	4.32	40.77	±	12.07	24.88	±	4.28	48.73	±	12.96	28.38	±	4.80	40.19	±	7.85
		M	33.32	±	5.29	33.21	±	7.86	44.58	±	8.55	27.26	±	6.49	51.89	±	11.90	28.89	±	7.64	47.42	±	11.55
Total		F	28.90	±	4.95	29.22	±	5.44	37.18	±	9.75	24.18	±	4.25	44.65	±	12.12	28.59	±	4.90	38.63	±	7.63
		M	30.37	±	5.49	31.29	±	7.31	42.29	±	9.65	25.92	±	5.79	48.34	±	11.66	28.29	±	6.98	41.58	±	10.62
Total			29.53	±	5.21	30.11	±	6.35	39.36	±	9.98	24.92	±	5.01	46.22	±	12.00	28.46	±	5.85	39.89	±	9.09

*UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick. SLS%: support leg strike moment, GRF: ground reaction force, MSHF: maximum support hip reaction force, MSKF: maximum support knee reaction force. * Significantly different with $p < 0.05$.*

Discussion and implications

Elite male soccer players had a different kicking technique as compared to elite female soccer players, a finding consistent with previous research (Barfield et al., 2002; Katis et al., 2015; Orloff et al., 2008; Sakamoto & Asai, 2013; Shan, 2009). However, a previous injury to the hamstring muscle group appeared to hinder the normal tendency and affected males and females differently, an important finding of this study. These differences were also affected by whether the kick was with a dominant limb or not.

Figure 17: Sequential increase of angular velocities seen in uninjured, non-dominant limbs

Kicking follows a proximal to distal sequential motion (Juarez et al., 2011; Lees & Nolan, 1998), with the linear velocities occurring in and increasing in magnitude in succession from the hip, to the knee, followed by the ankle, toe and ball (Figure 17). Across all uninjured limbs, whether they were dominant or non-dominant, males had higher ball, toe, ankle and knee velocities than females, concurrent with previous research (Barfield et al., 2002; Katis et al., 2015; Sakamoto & Asai, 2013). However, for the previously injured limbs small or no

differences in peak knee velocities were observed for kicks with the dominant and non-dominant limbs (Table 12). This translated to no differences in the peak ankle and final ball velocities in the previously injured non-dominant limbs. It is interesting to note that the sex differences showed up across all limbs when previous injury history or limb dominance or both were not considered. Thus it is clear that a previous injury to the hamstring muscles affects the non-dominant limb in males, inhibiting it from reaching higher velocities, although its effect on the non-dominant female limbs is not as pronounced. An interesting finding is that the hip velocity is greater in males with the uninjured non-dominant limbs, which could play a role in the substantial differences seen between the sexes, while simultaneously explaining why the difference in limb dominance does not show up in males (Table 20).

Although the statistical results were similar to those published, the values of ball velocities were generally greater than those reported for female and male soccer players (Alcock et al., 2012; Barfield et al., 2002; Katis et al., 2015; Orloff et al., 2008; Sakamoto & Asai, 2013; Shan, 2009). This was despite the fact that the median and not the maximum ball velocity trial was selected for further analysis. A greater number of participants (45), a higher skill level of soccer players (Katis et al., 2015; Kellis & Katis, 2007; Nunome, Ikegami, et al., 2006) and the familiarity of the environment (artificial turf which best mimics the settings in which they train and play) could explain greater linear ball velocities in the present research. On the other hand, ball velocities were lower than those of male soccer players both for the non-dominant and dominant limbs (27.1 m/s and 32.1 m/s respectively in Nunome, Ikegami, et al. (2006)). The reason could be that the male players in our research kicked the ball under instructions of accuracy (van den Tillaar & Ulvik, 2014). The toe and ankle velocities were higher than those reported in literature (Barfield et al., 2002; Lyle et al., 2011; Sakamoto & Asai, 2013). The peak knee and hip velocities, to the best of the author's knowledge, were not reported previously in three-dimensional studies.

Differences on linear velocities were not explained by differences on the normalized time intervals (Table 13) indicating that elite female soccer players have a well-developed general kicking technique with either limb as did the professional male players, and that there were other adjustments which could contribute to the higher ball velocities.

An interesting finding in this study was that the angles of the hip and knee between the males and females across maximal hip extension and maximal knee flexion were similar between the two phases. However, at ball impact for the uninjured, non-dominant limb, the females had greater knee flexion angle (Table 15). This difference persisted when limb dominance was disregarded and disappeared when previous injury was ignored. A previous injury appeared to reduce knee flexion but this did not translate to a better foot to ball contact, which could possibly indicate a difference in angular adjustments made in the ankle, which was not considered in this study. Possibly, men transmit forces from foot to ball during impact in a different way than women. The values for knee flexion at ball contact were much lower than those previously reported in literature for males and females (Lees, 2013; Lees et al., 2009) which could account for the higher ball velocities owing to a better foot-ball contact. In professional male soccer players, the values for the angles at ball impact were similar to those reported by Sinclair et al. (2014) in a similar group of players.

At the end of follow through, male soccer players had a higher hip flexion angle in the uninjured dominant limb (Table 14). This difference was not seen in previously injured limbs. In the follow through phase, the hamstring muscles work to flex the knee and possibly owing to a pre-emptive action prevented the males from reaching a higher flexion angle. The values obtained by the male soccer players were similar to professional soccer players in Navandar et al. (2013). Shan (2009) had mentioned differences in the follow through between males and females, but had not quantified them, stating that the females counteracted the momentum

generated after kicking the ball with upper-body flexions. The latter could not be corroborated in this study, but the difference in follow through angular mechanics support the first part of the hypothesis.

Differences in angular velocities between males and females went a long way in accounting for the different velocities obtained by the sexes. The leg cocking and leg acceleration phases have been described as the most important from a performance point of view (Lees, 2013) and it is in these phases that the majority of the differences are observed. Previously injured hamstring muscles in males seemed to favour rapid knee flexion and prevent rapid hip flexion.

At maximal hip extension, at the onset of the leg cocking phase, a greater value of knee flexion velocity was seen in males. The peak knee flexion velocity was reached soon after, and this was greater in males than in females. However, these differences in knee flexion velocities were seen only in uninjured limbs. The difference in peak velocity was not seen when limb dominance was factored in (Table 17). At the end of the leg acceleration phase, which is at ball impact, males had a greater hip flexion velocity for the uninjured non-dominant limb. Injured male players had similar hip flexion velocities in the dominant and non-dominant limb, indicating that a previous injury restricted the players from obtaining greater hip flexion velocities. At this instance, the greater knee extension velocity in males was seen in the uninjured dominant limb. A greater knee extension velocity at ball impact resulted in a greater momentum which resulted in an increased ball speed (Table 12). This also led to a lesser knee flexion angle seen in the males for the same group (Table 15). This difference was not seen in non-dominant limbs, which could account for the lower ball velocities recorded (Table 12).

At the end of the follow through, a greater hip flexion velocity (Table 16) was seen in males but only for the uninjured, dominant limbs. This translated to a greater hip flexion angle for the same group (Table 14). Also at this time, previously injured dominant limbs had greater knee

flexion velocities, a difference which disappeared when injury history was not factored in. A previous injury in males appeared to pre-emptively favor rapid knee flexion in dominant limbs while simultaneously preventing rapid hip flexion. Hamstring muscles being flexors of the knee and extensors of the hip are clearly very active in this phase and play an important part in the differences in the angular adjustments seen between the groups. The non-dominant limb kicks did not show a great difference in the follow through phase, which could indicate the importance of kicking through the ball and continuing it in the follow through to obtain better ball velocities.

Professional soccer players, irrespective of sex, generated similar peak moments in the hip and knee. Although males weighed more than their female counterparts, the dynamics were similar when normalized. A greater weight in males (Table 2) could account for a greater transfer of momentum. This is an interesting finding which suggests that the differences in kicking mainly depended on the body weight and kinematics, and an improvement in the kinematics could assist the female soccer players kick with either limb, irrespective of having sustained a previous injury.

Joint moments on the instep kick in the present research were similar to values previously reported in literature in amateur, highly skilled and professional male soccer players (Kellis & Katis, 2007; Navandar et al., 2013), but higher than those reported for experienced male soccer players in the side-foot kick (Kawamoto et al., 2007) and in post-pubertal female soccer players (Lyle et al., 2011) The difference could be explained to the difference in maturity and skill level of the players (Katis et al., 2015) and the type of kick (Nunome et al., 2002).

Although the dynamics of the kicking limb were similar between the sexes, males had a greater normalized peak reaction force than females for the dominant limbs, which translated to small differences in the hip and knee reaction forces (Table 19). During the kick, the hip and knee of

the support limb are flexed, and a previous injury to the knee flexors prevented the males from reaching higher forces.

Figure 18: Pattern of ground reaction forces seen in females (green) and males (red)

Males tended to delay the support leg strike in the dominant limb which translated to peak reaction forces in the knee occurring later (Figure 18). Although support leg strike occurred in similar instances for the uninjured non-dominant limb kicks in females and males, males tended to delay the peak ground reaction force which eventually led to greater ball velocities (Table 12). The ground reaction forces had two peaks (Orloff et al., 2008) one at impact and one when the entire foot landed (Orloff et al., 2008). This possibly indicated that a sudden impact in the support limb does not favor kicking velocities, and players must look at softening the initial impact.

These differences were not seen in the previously injured limbs, dominant or non-dominant, and disappeared when previous injury was not factored in. This clearly indicates that a previous injury affects the support leg as much as the kicking leg, and a detailed investigation into the mechanics could help in the planning in rehabilitation players.

For the ground reaction forces, the values for males and females reported in the present research were higher than those reported by Orloff et al. (2008), who had twelve female amateur players that performed the kicks on the laboratory floor compared to professional players (Nunome, Ikegami, et al., 2006) here who kicked the ball on artificial turf.

Practical implications

Males and females have different kicking techniques, with males usually kicking the ball faster than females. This difference is not down to size alone but also due to different kinematics. A previous hamstring injury clearly affected male players and their “superiority” over female soccer players all but disappeared. A previous injury in males favored a faster knee flexion while simultaneously inhibiting hip flexion. Thus coaches and biomechanists could work on exercises that worked to increase hip flexion and its velocity while the knee is flexed. An injury in the support limb also affects the mechanics, and after having sustained a previous injury, players must work on their strength of that limb.

Females would need to improve the foot to ball contact, especially in the non-dominant limb, and working to reduce knee extension would go a long way in helping that. Female soccer players also need to work on the follow through, looking to kick through the ball and try to increase hip flexion post impact. In the support limb, players must look at softening the initial impact in order to ensure a better transfer of energy to the kicking limb.

III. Comparing across limb dominance

Results

While comparing across limb dominance in the uninjured limb for males and females (Table 20), substantially higher maximum ball (partial $\eta^2 = 0.16$, $p < 0.001$ for females and partial $\eta^2 = 0.10$, $p = 0.003$ for males), toe (partial $\eta^2 = 0.14$, $p = 0.001$ for females and partial $\eta^2 = 0.12$, $p = 0.002$ for males), ankle (partial $\eta^2 = 0.15$, $p < 0.001$ for females and partial $\eta^2 = 0.10$, $p = 0.005$ for males) and knee (partial $\eta^2 = 0.08$, $p = 0.008$ for females and partial $\eta^2 = 0.11$, $p = 0.003$ for males) velocities in the dominant limb as compared to the non-dominant limb were found. However this difference was not seen in the previously injured limbs. No differences were observed in the maximum hip velocity between the dominant and non-dominant limb across sex or previous injury.

On grouping the variables irrespective of sex and comparing across previous injury factor, the same pattern as previously reported was observed: that the uninjured dominant limb had substantially greater velocities in the ball (partial $\eta^2 = 0.23$, $p < 0.001$), toe (partial $\eta^2 = 0.23$, $p < 0.001$), ankle (partial $\eta^2 = 0.21$, $p < 0.001$) and knee (partial $\eta^2 = 0.18$, $p < 0.001$). On grouping the variables irrespective of previous injury and comparing the effect of limb dominance across sex, greater velocities in the dominant limb than in the non-dominant limb only in females for the ball (partial $\eta^2 = 0.06$, $p = 0.027$) and toe (partial $\eta^2 = 0.07$, $p = 0.014$) were seen. In the ankle, knee and hip velocities, no differences were observed between the dominant and non-dominant limbs for females. In males, the dominant and non-dominant limb kicks had similar maximal velocities for the ball, toe, ankle, knee and hip.

While observing the effect of limb dominance alone, differences were only seen in the maximal ball velocity, being greater in the dominant limb than in the non-dominant limb (partial $\eta^2 = 0.06$, $p = 0.032$). No differences were observed between the toe, ankle, knee and hip velocities.

Differences were seen in the kicking pattern while kicking with the dominant or non-dominant limb based on sex and previous injury (Table 21). In the injured limb, the dominant limb had a greater backswing for both males (partial $\eta^2 = 0.07$, $p = 0.013$) and females (partial $\eta^2 = 0.07$, $p = 0.019$) as compared to the non-dominant limb. In the uninjured limb, this pattern was seen only in male soccer players (partial $\eta^2 = 0.09$, $p = 0.006$). The leg cocking and leg acceleration phases were similar across the different groups, and so was the follow through except for the previously injured male limbs, where medium differences were observed (partial $\eta^2 = 0.06$, $p = 0.030$).

On clustering the variables irrespective of sex, the backswing was greater for the dominant limb kicks (partial $\eta^2 = 0.06$, $p = 0.021$ for the uninjured limb; partial $\eta^2 = 0.12$, $p = 0.001$ for the injured limb). An injury to the non-dominant limb caused the resulting kick to have a greater follow through than that of an injured dominant limb (partial $\eta^2 = 0.06$, $p = 0.022$), although no differences were observed across limb dominance for the uninjured limbs. The total time, and the time taken for the leg cocking and leg acceleration phases were similar across the groups. On grouping the variables irrespective of previous injury, the backswing was greater for the dominant limb kicks (partial $\eta^2 = 0.06$, $p = 0.022$ for females; partial $\eta^2 = 0.11$, $p = 0.002$ for males). The follow through was greater in the non-dominant kick only in males (partial $\eta^2 = 0.08$, $p = 0.011$), and females did not show this difference in this phase. Again, the total time, time for leg cocking and leg acceleration were similar between the two groups.

On globally comparing across limb dominance, the backswing was greater for the dominant limb kicks (partial $\eta^2 = 0.16$, $p < 0.001$) while the follow through was greater for the non-dominant limb kicks (partial $\eta^2 = 0.09$, $p = 0.006$). The total time, and the times for leg acceleration and leg cocking phases were similar between the two groups.

Comparing the flexion and extension angles at the hip in the four characteristic time instances (Table 22), no differences between the different groups across limb dominance were found. Similarly, on comparing the knee flexion and extension angles (Table 23) for the knee at maximal hip extension, maximal knee flexion and the end of follow through, similar values across the different groups were observed. However, at ball impact the uninjured non-dominant limb kick had a greater knee flexion angle than the uninjured dominant limb kick in females (partial $\eta^2 = 0.13$, $p = 0.001$). This difference was not seen in the injured limb for females, nor in the males for the injured or uninjured limb kicks. Grouping the variables ignoring the sex, the same large differences in knee flexion angle in the uninjured limb persisted (partial $\eta^2 = 0.10$, $p = 0.003$). On grouping the variables irrespective of previous injury, this difference in the same variable shows up in the case of females only (partial $\eta^2 = 0.06$, $p = 0.024$). Solely comparing across limb dominance, the greater flexion angle in the non-dominant limb continues to show up (partial $\eta^2 = 0.08$, $p = 0.007$).

At maximal knee flexion, the hip flexion velocity (Table 24) was greater in the dominant limb than in the non-dominant limb for females while kicking with the uninjured (partial $\eta^2 = 0.07$, $p = 0.019$) and injured limbs (partial $\eta^2 = 0.06$, $p = 0.026$). This was not seen in males for the injured or uninjured limbs. However, the angular velocities in the flexion-extension axis for the hip were similar between the dominant and non-dominant limb at the instances of maximal hip extension, ball impact and end of follow through across all groups. Comparing across limb dominance for the knee flexion-extension angular velocity (Table 25), at ball impact the dominant limb had a greater extension velocity than the non-dominant limb in the case of uninjured male players (partial $\eta^2 = 0.08$, $p = 0.012$). For the other instances, similar angular velocities were obtained for the different groups in the sagittal plane. The peak hip flexion angular velocity was greater in the dominant limb than in the non-dominant limb in both males (partial $\eta^2 = 0.06$, $p = 0.022$) and females (partial $\eta^2 = 0.07$, $p = 0.019$) for the uninjured limb.

This difference was not seen in previously injured limb kicks. The peak knee flexion velocity was similar between the dominant and non-dominant limbs across the different groups.

Grouping the variables whilst ignoring sex, the same differences mentioned previously persisted but only in the uninjured limbs. At maximal knee flexion, the hip flexion velocity was greater in the dominant limb than in the non-dominant limb (partial $\eta^2 = 0.09$, $p = 0.005$); and at ball impact the dominant limb had a greater knee extension velocity as compared to the non-dominant limb (partial $\eta^2 = 0.10$, $p = 0.005$). These difference was not seen in the previously injured limbs. The difference in the peak hip flexion velocity was seen in the uninjured limb alone (partial $\eta^2 = 0.12$, $p = 0.001$). Grouping the variables without considering previous injury, the difference in hip flexion velocity at maximal knee flexion was seen in females only (partial $\eta^2 = 0.11$, $p = 0.003$). The difference in knee extension velocity at ball impact disappeared, but at the end of follow through the males exhibited a greater flexion velocity at the hip in the dominant limb than in the non-dominant limb (partial $\eta^2 = 0.05$, $p = 0.047$). This difference was not seen in females. The difference in peak hip flexion velocity was not seen in this comparison. On globally comparing across limb dominance, only the difference in hip flexion velocity at maximal knee flexion was seen (partial $\eta^2 = 0.07$, $p = 0.017$).

The peak flexion moment (Table 26) of the hip was greater in the dominant limb than in the non-dominant limb for kicks by previously uninjured male soccer players (partial $\eta^2 = 0.06$, $p = 0.032$). The values for the peak hip flexion moment were similar for the previously injured male soccer players, and in previously injured and uninjured female soccer players. The peak hip extension moment was greater in the dominant limb than in the non-dominant limb for kicks by female players in the previously uninjured (partial $\eta^2 = 0.09$, $p = 0.007$) and injured limbs (partial $\eta^2 = 0.06$, $p = 0.026$). This difference was not seen in the kicks by male soccer

players. The values for knee flexion and extension moments were similar between the dominant and non-dominant limb between the different groups.

Grouping the variables ignoring sex, the afore-mentioned differences in the peak hip flexion (partial $\eta^2 = 0.05$, $p = 0.043$) and extension moment (partial $\eta^2 = 0.11$, $p = 0.003$) existed only in the uninjured limbs and not in the previously injured limbs. On grouping the variables irrespective of previous injury history, the difference in peak hip extension moment was seen in female soccer players only (partial $\eta^2 = 0.12$, $p = 0.003$). The difference in peak hip flexion moment was not seen. On globally comparing the variables across limb dominance alone, the differences in the variables were not seen.

There were differences between the dominant and non-dominant limb in the time intervals for the support leg (Table 27). The support leg strike occurred later in the dominant limbs than in the non-dominant limbs (partial $\eta^2 = 0.15$, $p < 0.001$) for kicks by uninjured males. The values were similar for the previously injured male limbs, and previously injured and uninjured female limbs. The peak ground reaction force occurred later in females' dominant leg for both the uninjured (partial $\eta^2 = 0.06$, $p = 0.032$) and injured limbs (partial $\eta^2 = 0.05$, $p = 0.038$), although this difference was not seen in males with the uninjured or injured limbs. The peak hip reaction force occurred later in the dominant, uninjured limbs for females (partial $\eta^2 = 0.06$, $p = 0.031$) and males (partial $\eta^2 = 0.05$, $p = 0.044$), with the time for the previously injured limbs being the same. The peak knee reaction force occurred later in uninjured male limbs for the dominant limb as compared to the non-dominant limb (partial $\eta^2 = 0.17$, $p < 0.001$). The normalized forces were similar between the dominant and non-dominant limbs were similar across the different groups.

Clustering the time interval variables ignoring sex, the delays in the dominant limb for the uninjured limbs for the support leg strike (partial $\eta^2 = 0.11$, $p = 0.002$), peak ground reaction

force (partial $\eta^2 = 0.06$, $p = 0.032$), peak hip reaction force (partial $\eta^2 = 0.10$, $p = 0.004$), and peak knee reaction force (partial $\eta^2 = 0.16$, $p < 0.001$) persisted. The delay in the dominant limb is also seen in the injured limb for the case of peak ground reaction forces (partial $\eta^2 = 0.06$, $p = 0.031$). The other time variables for the injured limb were similar between the dominant and non-dominant limb. On grouping the time variables ignoring previous hamstring injury history, the delays persisted only in females for the peak ground reaction force (partial $\eta^2 = 0.09$, $p = 0.005$) and peak hip reaction force (partial $\eta^2 = 0.06$, $p = 0.021$). The values for support leg strike and peak knee reaction force were similar between the dominant and non-dominant limbs for females, whereas for males the time intervals were similar across the dominant and non-dominant limbs. Comparing the time variables solely on limb dominance regardless of previous injury history or sex, the delays in the dominant limb for peak ground reaction force (partial $\eta^2 = 0.09$, $p = 0.04$), peak hip reaction force (partial $\eta^2 = 0.05$, $p = 0.049$) and peak knee reaction force (partial $\eta^2 = 0.05$, $p = 0.042$) were observed.

Table 20: Linear velocities while comparing across limb dominance (mean $\pm$ standard deviation).

			Ball (m/s)			Toe (m/s)			Ankle (m/s)			Knee (m/s)			Hip (m/s)		
UI	F	ND	22.19	±	2.86**	17.71	±	2.31*	14.76	±	1.37**	8.33	±	1.06*	3.81	±	0.60
		D	25.25	±	2.47**	19.70	±	2.03*	16.25	±	1.48**	9.05	±	0.83*	4.10	±	0.45
	M	ND	26.06	±	2.78*	20.83	±	1.38*	17.11	±	1.28*	9.22	±	0.81*	4.22	±	0.65
		D	28.63	±	1.75*	22.81	±	1.11*	18.38	±	1.02*	10.13	±	0.62*	4.38	±	0.62
I	F	ND	23.25	±	1.26	18.00	±	1.41	15.50	±	1.00	8.50	±	0.58	4.00	±	0.00
		D	24.17	±	2.48	19.17	±	1.17	15.67	±	0.82	8.67	±	0.82	3.50	±	0.84
	M	ND	27.00	±	0.00	23.00	±	0.00	18.00	±	0.00	10.00	±	0.00	4.00	±	0.00
		D	28.00	±	0.00	22.00	±	1.00	18.00	±	0.00	9.67	±	0.58	4.33	±	1.15
Total F		ND	22.36	±	2.68*	17.76	±	2.17*	14.88	±	1.33	8.36	±	0.99	3.84	±	0.55
		D	25.00	±	2.47*	19.58	±	1.86*	16.12	±	1.37	8.96	±	0.82	3.96	±	0.60
Total M		ND	26.11	±	2.71	20.95	±	1.43	17.16	±	1.26	9.26	±	0.81	4.21	±	0.63
		D	28.53	±	1.61	22.68	±	1.11	18.32	±	0.95	10.05	±	0.62	4.37	±	0.68
Total UI		ND	23.97	±	3.40**	19.15	±	2.48**	15.85	±	1.77**	8.74	±	1.04**	4.00	±	0.65
		D	26.75	±	2.74**	21.08	±	2.29**	17.19	±	1.67**	9.53	±	0.91**	4.22	±	0.54
Total I		ND	24.00	±	2.00	19.00	±	2.55	16.00	±	1.41	8.80	±	0.84	4.00	±	0.00
		D	25.44	±	2.74	20.11	±	1.76	16.44	±	1.33	9.00	±	0.87	3.78	±	0.97
Total		ND	23.98	±	3.25	19.14	±	2.46	15.86	±	1.72	8.75	±	1.01	4.00	±	0.61
		D	26.49	±	2.76	20.89	±	2.21	17.04	±	1.62	9.42	±	0.92	4.13	±	0.66
Total			25.25	±	3.25	20.02	±	2.48	16.46	±	1.76	9.09	±	1.02	4.07	±	0.64

UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick. * Significantly different with $p < 0.05$. ** Significantly different with $p < 0.001$.

Table 21: Time intervals while comparing across limb dominance (mean $\pm$ standard deviation).

			Total Time (s)			Backswing %			Leg Cocking %			Leg Acceleration %			Follow Through %		
UI	F	ND	0.40	±	0.07	26.24	±	5.64	17.76	±	5.14	14.24	±	2.00	41.71	±	6.66
		D	0.39	±	0.04	26.85	±	4.96	18.15	±	4.98	15.00	±	1.86	40.10	±	5.78
	M	ND	0.39	±	0.04	24.94	±	2.88*	17.22	±	2.46	15.44	±	2.25	42.11	±	3.69
		D	0.39	±	0.05	29.44	±	4.47*	17.06	±	1.98	14.75	±	1.81	38.81	±	5.39
I	F	ND	0.39	±	0.06	21.25	±	2.99*	20.50	±	2.65	15.50	±	1.29	42.75	±	5.91
		D	0.40	±	0.04	28.50	±	4.14*	16.33	±	1.75	15.17	±	2.04	39.83	±	5.42
	M	ND	0.34	±	0.00	16.00	±	0.00*	18.00	±	0.00	14.00	±	0.00	52.00	±	0.00*
		D	0.36	±	0.02	29.67	±	7.64*	16.00	±	0.00	16.33	±	0.58	37.67	±	7.09*
Total F		ND	0.40	±	0.07	25.44	±	5.58*	18.20	±	4.89	14.44	±	1.94	41.88	±	6.44
		D	0.39	±	0.04	27.23	±	4.75*	17.73	±	4.48	15.04	±	1.87	40.04	±	5.60
Total M		ND	0.39	±	0.04	24.47	±	3.47*	17.26	±	2.40	15.37	±	2.22	42.63	±	4.25*
		D	0.39	±	0.05	29.47	±	4.81*	16.89	±	1.85	15.00	±	1.76	38.63	±	5.48*
Total UI		ND	0.40	±	0.06	25.64	±	4.57*	17.51	±	4.08	14.79	±	2.18	41.90	±	5.43
		D	0.39	±	0.04	28.00	±	4.86*	17.67	±	3.93	14.89	±	1.82	39.53	±	5.57
Total I		ND	0.38	±	0.06	20.20	±	3.49*	20.00	±	2.55	15.20	±	1.30	44.60	±	6.58*
		D	0.39	±	0.04	28.89	±	5.06*	16.22	±	1.39	15.56	±	1.74	39.11	±	5.67*
Total		ND	0.40	±	0.06	25.02	±	4.76**	17.80	±	4.00	14.84	±	2.09	42.20	±	5.56*
		D	0.39	±	0.04	28.18	±	4.85**	17.38	±	3.60	15.02	±	1.80	39.44	±	5.53*
Total			0.39	±	0.05	26.62	±	5.04	17.58	±	3.79	14.93	±	1.94	40.81	±	5.68

UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick. * Significantly different with $p < 0.05$. ** Significantly different with $p < 0.001$.

Table 22: Hip flexion/extension angles while comparing across limb dominance (mean $\pm$ standard deviation).

Maximal Hip Extension						Maximal Knee Flexion			Ball Impact(°)			End of Follow Through		
(°)						(°)						(°)		
UI	F	ND	-13	±	10	14	±	9	30	±	9	83	±	18
		D	-15	±	9	12	±	10	27	±	11	86	±	17
	M	ND	-10	±	9	16	±	9	30	±	10	93	±	15
		D	-13	±	8	15	±	6	28	±	9	97	±	16
I	F	ND	-8	±	7	13	±	5	30	±	10	83	±	15
		D	-14	±	11	14	±	10	30	±	8	89	±	12
	M	ND	-1	±	0	21	±	0	37	±	0	110	±	0
		D	-12	±	4	11	±	4	23	±	4	90	±	13
Total F		ND	-12	±	9	13	±	8	30	±	9	83	±	17
		D	-15	±	9	13	±	10	27	±	10	87	±	15
Total M		ND	-9	±	9	16	±	9	31	±	10	94	±	15
		D	-12	±	8	14	±	6	27	±	9	96	±	15
Total UI		ND	-11	±	9	15	±	9	30	±	9	88	±	17
		D	-14	±	9	13	±	8	27	±	10	91	±	17
Total I		ND	-7	±	7	14	±	6	32	±	9	88	±	18
		D	-13	±	9	13	±	8	28	±	7	90	±	11
Total		ND	-11	±	9	15	±	8	30	±	9	88	±	17
		D	-14	±	9	13	±	8	27	±	9	90	±	16
Total			-12	±	9	14	±	8	29	±	9	89	±	16

A positive value indicates flexion and negative value extension. UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick.

Table 23: Knee flexion/extension angles while comparing across limb dominance (mean $\pm$ standard deviation).

			Maximal Hip Extension (°)			Maximal Knee Flexion (°)			Ball Impact(°)			End of Follow Through (°)		
UI	F	ND	72	±	14	114	±	12	58	±	12*	26	±	14
		D	67	±	19	112	±	11	45	±	9*	26	±	12
	M	ND	72	±	8	116	±	9	46	±	14	28	±	16
		D	74	±	10	118	±	8	43	±	11	27	±	20
I	F	ND	58	±	10	110	±	8	51	±	15	27	±	14
		D	73	±	6	113	±	13	45	±	9	31	±	14
	M	ND	75	±	0	122	±	0	66	±	0	29	±	0
		D	79	±	10	118	±	9	44	±	5	36	±	19
Total F		ND	70	±	15	114	±	11	57	±	13*	26	±	14
		D	69	±	17	112	±	12	45	±	9*	27	±	13
Total M		ND	72	±	8	116	±	9	47	±	14	28	±	15
		D	75	±	10	118	±	8	43	±	10	29	±	19
Total UI		ND	72	±	12	115	±	10	53	±	14*	27	±	15
		D	71	±	16	115	±	11	44	±	10*	27	±	16
Total I		ND	61	±	11	113	±	8	54	±	15	27	±	13
		D	75	±	8	115	±	12	44	±	7	32	±	14
Total		ND	71	±	12	115	±	10	53	±	14*	27	±	14
		D	71	±	14	115	±	11	44	±	9*	28	±	15
Total			71	±	13	115	±	10	48	±	13	27	±	15

*A positive value indicates flexion and negative value extension. UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick. * Significantly different with $p < 0.05$.*

Table 24: Hip flexion/extension angular velocities while comparing across limb dominance (mean $\pm$ standard deviation).

			Maximal Hip Extension (rad/s)			Maximal Knee Flexion (rad/s)			Ball Impact (rad/s)			End of Follow Through (rad/s)			Peak (rad/s)		
UI	F	ND	0	±	0	10	±	1*	-2	±	2	2	±	3	13	±	2*
		D	0	±	0	12	±	2*	-3	±	3	1	±	2	15	±	2*
	M	ND	0	±	0	10	±	2	0	±	3	2	±	3	12	±	2*
		D	0	±	0	11	±	1	-1	±	3	3	±	2	14	±	2*
I	F	ND	0	±	0	8	±	1*	-1	±	1	1	±	3	13	±	3
		D	0	±	0	11	±	2*	-1	±	2	-1	±	2	14	±	2
	M	ND	0	±	0	10	±	0	0	±	0	-1	±	0	14	±	0
		D	0	±	0	11	±	1	-1	±	2	4	±	1	14	±	3
Total F		ND	0	±	0	10	±	2*	-2	±	2	2	±	3	13	±	2
		D	0	±	0	11	±	2*	-2	±	3	0	±	2	14	±	2
Total M		ND	0	±	0	10	±	2	0	±	3	2	±	3*	13	±	2
		D	0	±	0	11	±	1	-1	±	3	3	±	2*	14	±	2
Total UI		ND	0	±	0	10	±	2*	-1	±	3	2	±	3	13	±	2*
		D	0	±	0	11	±	2*	-2	±	3	2	±	3	14	±	2*
Total I		ND	0	±	0	9	±	1	0	±	1	0	±	3	13	±	2
		D	0	±	0	11	±	1	-1	±	2	1	±	3	14	±	2
Total		ND	0	±	0	10	±	2*	-1	±	3	2	±	3	13	±	2
		D	0	±	0	11	±	2*	-2	±	3	2	±	3	14	±	2
Total			0	±	0	10	±	2	-1	±	3	2	±	3	13	±	2

A positive value indicates flexion and negative value extension. UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick. * Significantly different with $p < 0.05$.

Table 25: Knee flexion/extension angular velocities while comparing across limb dominance (mean $\pm$ standard deviation).

			Maximal Hip Extension (rad/s)			Maximal Knee Flexion (rad/s)			Ball Impact (rad/s)			End of Follow Through (rad/s)			Peak (rad/s)		
UI	F	ND	14	±	3	0	±	1	-26	±	4	4	±	4	15	±	2
		D	15	±	3	0	±	1	-28	±	5	4	±	5	16	±	3
	M	ND	16	±	2	0	±	1	-28	±	5*	4	±	5	17	±	3
		D	17	±	5	0	±	1	-32	±	4*	5	±	3	18	±	4
I	F	ND	17	±	1	0	±	1	-25	±	3	2	±	4	17	±	1
		D	14	±	3	0	±	1	-26	±	4	1	±	4	15	±	2
	M	ND	20	±	0	0	±	0	-31	±	0	0	±	0	21	±	0
		D	16	±	2	0	±	1	-32	±	3	9	±	1	17	±	3
Total F		ND	14	±	3	0	±	1	-26	±	4	4	±	4	16	±	2
		D	15	±	3	0	±	1	-28	±	4	3	±	5	16	±	3
Total M		ND	16	±	3	0	±	1	-28	±	5	3	±	5	17	±	3
		D	17	±	4	0	±	1	-32	±	4	6	±	3	18	±	4
Total UI		ND	15	±	3	0	±	1	-27	±	5	4	±	4*	16	±	3
		D	16	±	4	0	±	1	-30	±	5	4	±	4*	17	±	4
Total I		ND	17	±	2	0	±	1	-26	±	4	2	±	4	18	±	2
		D	14	±	3	0	±	1	-28	±	5	4	±	5	15	±	3
Total		ND	15	±	3	0	±	1	-27	±	4	4	±	5	16	±	3
		D	16	±	4	0	±	1	-30	±	5	4	±	5	17	±	3
Total			15	±	3	0	±	1	-28	±	5	4	±	5	17	±	3

A positive value indicates flexion and negative value extension. UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick. * Significantly different with $p < 0.05$.

Table 26: Peak moments of the kicking leg while comparing across limb dominance (mean $\pm$ standard deviation).

			Peak Hip Flexion Moment (Nm/kg)			Peak Hip Extension Moment (Nm/kg)			Peak Knee Flexion Moment (Nm/kg)			Peak Knee Extension Moment (Nm/kg)		
UI	F	ND	3.76	±	1.14	-2.67	±	1.24*	1.57	±	0.60	-1.00	±	0.32
		D	3.95	±	0.76	-3.55	±	1.05*	1.70	±	0.57	-1.10	±	0.31
	M	ND	3.44	±	0.86*	-3.28	±	0.89	1.67	±	0.49	-1.17	±	0.38
		D	4.13	±	0.72*	-3.88	±	0.72	1.94	±	0.25	-1.19	±	0.40
I	F	ND	3.75	±	0.50	-2.50	±	0.58*	1.25	±	0.50	-1.00	±	0.00
		D	4.67	±	1.37	-4.00	±	1.41*	1.83	±	0.75	-1.33	±	0.52
	M	ND	4.00	±	0.00	-4.00	±	0.00	2.00	±	0.00	-1.00	±	0.00
		D	4.00	±	0.00	-3.33	±	0.58	2.00	±	0.00	-1.33	±	0.58
Total F		ND	3.76	±	1.05	-2.64	±	1.15*	1.52	±	0.59	-1.00	±	0.29
		D	4.12	±	0.95	-3.65	±	1.13*	1.73	±	0.60	-1.15	±	0.37
Total M		ND	3.47	±	0.84	-3.32	±	0.89	1.68	±	0.48	-1.16	±	0.37
		D	4.11	±	0.66	-3.79	±	0.71	1.95	±	0.23	-1.21	±	0.42
Total UI		ND	3.62	±	1.02*	-2.95	±	1.12*	1.62	±	0.54	-1.08	±	0.35
		D	4.03	±	0.74*	-3.69	±	0.92*	1.81	±	0.47	-1.14	±	0.35
Total I		ND	3.80	±	0.45	-2.80	±	0.84	1.40	±	0.55	-1.00	±	0.00
		D	4.44	±	1.13	-3.78	±	1.20	1.89	±	0.60	-1.33	±	0.50
Total		ND	3.64	±	0.97	-2.93	±	1.09	1.59	±	0.54	-1.07	±	0.33
		D	4.11	±	0.83	-3.71	±	0.97	1.82	±	0.49	-1.18	±	0.39
Total			3.88	±	0.93	-3.33	±	1.10	1.71	±	0.53	-1.12	±	0.36

A positive value indicates flexion and negative value extension. UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick. * Significantly different with $p < 0.05$.

Table 27: Support leg variables while comparing across limb dominance (mean $\pm$ standard deviation).

			SLS%			Peak GRF (N/kg)			Time to GRF%			MSHF (N/kg)			Time to MSHF%			MSKF (N/kg)			Time to MSKF%		
UI	F	ND	28.16	±	4.91	29.04	±	4.98	33.47	±	3.96*	23.11	±	3.74	40.05	±	10.2*	28.32	±	4.82	36.74	±	7.09
		D	29.14	±	5.13	27.99	±	4.15	39.82	±	12.0*	24.36	±	3.96	47.95	±	12.8*	27.77	±	4.39	40.23	±	8.34
	M	ND	27.19	±	3.9**	29.31	±	6.71	41.38	±	10.71	25.19	±	4.81	43.56	±	9.91*	28.06	±	6.87	36.00	±	5.4**
		D	33.44	±	5.4**	33.50	±	7.99	44.44	±	8.77	27.33	±	6.67	51.67	±	12.2*	29.00	±	7.84	47.78	±	12**
I	F	ND	28.67	±	4.46	33.74	±	9.20	33.33	±	5.28*	24.50	±	5.61	41.50	±	8.87	30.33	±	6.12	37.83	±	8.16
		D	31.50	±	5.80	30.09	±	5.47	46.00	±	13.0*	27.75	±	5.50	53.00	±	14.70	31.75	±	6.29	40.00	±	5.10
	M	ND	28.67	±	4.93	29.67	±	4.93	32.67	±	3.21	21.33	±	3.79	51.33	±	13.65	25.67	±	3.06	34.33	±	4.04
		D	31.00	±	0.00	28.00	±	0.00	47.00	±	0.00	26.00	±	0.00	56.00	±	0.00	27.00	±	0.00	41.00	±	0.00
Total F	ND	28.28	±	4.72	30.17	±	6.36	33.44	±	4.19*	23.44	±	4.17	40.40	±	9.70*	28.80	±	5.10	37.00	±	7.20	
	D	29.50	±	5.19	28.31	±	4.32	40.77	±	12.1*	24.88	±	4.28	48.73	±	13.0*	28.38	±	4.80	40.19	±	7.85	
Total M	ND	27.42	±	3.96	29.37	±	6.34	40.00	±	10.36	24.58	±	4.79	44.79	±	10.54	27.68	±	6.41	35.74	±	5.13	
	D	33.32	±	5.29	33.21	±	7.86	44.58	±	8.55	27.26	±	6.49	51.89	±	11.90	28.89	±	7.64	47.42	±	11.55	
Total UI	ND	27.71	±	4.44*	29.17	±	5.75	37.09	±	8.65*	24.06	±	4.32	41.66	±	10.1*	28.20	±	5.75	36.40	±	6.3**	
	D	31.08	±	5.63*	30.47	±	6.69	41.90	±	10.8*	25.70	±	5.48	49.63	±	12.5*	28.33	±	6.13	43.63	±	11**	
Total I	ND	28.67	±	4.30	32.38	±	7.95	33.11	±	4.48*	23.44	±	5.08	44.78	±	10.95	28.78	±	5.59	36.67	±	6.98	
	D	31.40	±	5.03	29.67	±	4.83	46.20	±	11.3*	27.40	±	4.83	53.60	±	12.80	30.80	±	5.85	40.20	±	4.44	
Total	ND	27.91	±	4.38	29.82	±	6.29	36.27	±	8.10*	23.93	±	4.43	42.30	±	10.2*	28.32	±	5.66	36.45	±	6.35*	
	D	31.11	±	5.51	30.38	±	6.47	42.38	±	10.8*	25.89	±	5.39	50.07	±	12.5*	28.60	±	6.08	43.24	±	10.1*	
Total			29.53	±	5.21	30.11	±	6.35	39.36	±	9.98	24.92	±	5.01	46.22	±	12.00	28.46	±	5.85	39.89	±	9.09

UI: uninjured limb, I: injured limb, F: Female, M: Male, ND: Non-dominant limb kick, D: dominant limb kick. SLS%: support leg strike moment, GRF: ground reaction force, MSHF: maximum support hip reaction force, MSKF: maximum support knee reaction force. * Significantly different with $p < 0.05$.

Discussion and implications

In the present section, the effect of limb dominance on the kinematic and kinetic variables of the kicking techniques in elite soccer players was studied. As expected, elite soccer players had substantially greater ball velocities while kicking with the dominant limb. These differences were due to different distribution of the phases of the kick, angular adjustments in the flexion-extension axis of the hip and knee, and differences in the kinetics between the dominant and non-dominant limb.

Maximal kicking linear velocities for the ball, toe, ankle and knee in the present research showed substantial inter-limb differences in the previously uninjured limb for males and females, a finding concurrent to previously reported research (Barbieri et al., 2015; Nunome, Ikegami, et al., 2006; Sinclair et al., 2014; van den Tillaar & Ulvik, 2014). This difference was not found in previously injured limbs for males or females. A previous injury to the hamstring muscle group, an active flexor of the knee, in the dominant limb appears to inhibit the characteristic aspects of the kick, and its effect on the non-dominant limb does not seem to be as pronounced (Table 20). This is further evidenced on grouping the variables without taking into consideration previous injury history, differences between the dominant and non-dominant limb are seen only for females for the ball and toe velocities, being non-existent in male soccer players, or in knee velocities for either sex.

The kicking motion is a sequential motion, beginning at the hip and going down to the foot, with each joint attaining a maximal velocity from proximal to distal segments in the same order (Figure 17) (Juarez et al., 2011; Lees & Nolan, 1998). Keeping this pattern in mind, and looking at Table 20, one can say that a previous hamstring injury affects the dominant limb knee from reaching maximal velocities (previously uninjured dominant knee velocity = 9.53 ± 0.91 m/s and previously injured dominant knee velocity 9.00 ± 0.87 m/s) which consequently led to

differences in the ball velocities. The difference in knee velocities showed up only on segregating the variables based on previous injury, whereas on ignoring the effect of previous injury the values were similar between the groups (Table 20).

Male professional soccer players appear to be adept at kicking the ball with either limb owing to the demands of the environment (Starosta, 1988) as limb dominance did not seem to have a marked effect on the linear velocities (Table 20), and the velocities being substantially higher than females with both the non-dominant and dominant limbs (Table 20). An analysis solely based on limb dominance showed that the difference exists only in terms of final ball velocity, a finding that could be explained with the fact that there were greater number of females ($n = 26$) than males ($n = 19$) participating in this study.

The values in this study were generally greater than those usually reported on limb dominance for female soccer players and the values were similar to studies previously done on male soccer players (Barbieri et al., 2015; Dorge et al., 2002; Nunome, Ikegami, et al., 2006; Sinclair et al., 2014). In terms of females, a greater number of participants (26), a higher skill level of soccer players (Katis et al., 2015; Kellis & Katis, 2007; Nunome, Ikegami, et al., 2006) and the familiarity of the environment (artificial turf which best mimics the settings in which they train and play) could explain greater linear ball velocities in the present research. It is important to note that in this investigation, the players kicked the ball under instructions of accuracy (van den Tillaar & Ulvik, 2014), and a median of 5 kicks had been selected (not the kick with the highest velocity) in order to best represent the regular kick of the participants.

To our knowledge, no previous three-dimensional research had reported this kind of inter-limb kicking difference apart from the foot velocities. These values of foot velocity (Table 1) were higher than those reported for experienced futsal players (15.58 m/s and 17.61 m/s respectively, Barbieri et al. (2015)) and similar to those reported for skilled male soccer players where the

run-up was restricted (17 m/s and 18.6 m/s respectively, Dorge et al. (2002)) for both males and females in this study. As expected the female toe velocities in this research for the dominant and non-dominant limb were lower than those observed in male soccer players by Nunome, Ikegami, et al. (2006) who had no restriction on the run-up and where the maximal velocity kick was selected in the case of males in the dominant and non-dominant limbs.

The differences on linear velocities could partly be explained by differences on the normalized time intervals (Table 21). The backswing and follow through phases in the kick are when the hamstring muscles are most active (Navandar et al., 2013; Navarro et al., 2015), and it is here that differences between the dominant and non-dominant limb are seen. In previously injured limbs, irrespective of sex, a greater backswing is observed for the dominant limb. Hamstring muscles are active extensors of the hip, and a previous injury seems to cause the elongation of this phase. It is interesting to note, that the maximum hip extension angle is similar between the dominant and non-dominant limb for the injured group (Table 22), following which the injured limbs had a greater hip flexion velocity in the dominant limb at maximal knee flexion (Table 24). It is important to observe that the total time for the kicks were similar for all groups (Table 21). A previous injury appears to affect the activation of the hip extensors, a hypothesis which could be corroborated by a future study using electromyography on kicking and comparing limb dominance and previous injury history.

Difference in backswing across limb dominance is only seen in kicks with the uninjured male limb, but not in uninjured females. On the subsequent grouping of variables ignoring sex or previous injury history or both, the difference in backswing persists, indicating that a previous history affects the backswing in female soccer players. Since the backswing is an important phase in terms of performance in kicking (Lees, 2013), this difference appears to account for

the lack of difference in ball velocities seen between the dominant and non-dominant limb in the case of males (Table 20).

In the case of previously injured limbs, the difference in backswing was made up in the follow through phase for males and in the subsequent phases for females and uninjured males (Table 21). Previous research has shown the importance of a previous injury in male soccer players in the follow through phase (Navandar et al., 2013), where the hamstring muscles work to flex the knee. An injury to the non-dominant male limbs seemed to inhibit the hamstrings to work in the knee flexion post ball impact. The difference in kicking technique in males and females is evident in these results (Katis et al., 2015; Shan, 2009).

The key differences between the kicking kinematics of the dominant and non-dominant limb of elite soccer players were in the angular adjustments made by the players in the flexion-extension axis. These adjustments appeared to contribute to a higher velocity in the dominant limb and represented as the most important finding of the present research.

In uninjured female soccer players, the non-dominant limb was more flexed than the dominant limb at ball impact (Figure 19). These modifications on the limb positioning increase the surface area of contact with the ball which assists the higher transfer of velocity from the foot to the ball when kicking with the dominant limb (Barbieri et al., 2015; Barfield et al., 2002; Dorge et al., 2002), which can be seen in the greater ball velocity in the dominant limb (Table 20) for the uninjured female soccer players. The difference in knee flexion angle at ball impact evidences the interaction of previous injury and sex, which clearly seems to influence knee flexion angle at ball impact. In male soccer players the difference in linear velocities does not manifest, as can be seen by similar knee flexion angles with the dominant and non-dominant limb kicks (Table 22). Females tend to have their non-dominant limbs more flexed, but a previous injury to the active flexors of the knee, appears to inhibit this characteristic. The values

for the sagittal plane angles on the hip and knee for the dominant and non-dominant limbs were similar to findings in previous research (Barbieri et al., 2015; Dorge et al., 2002; Nunome, Ikegami, et al., 2006; Sinclair et al., 2014).

Figure 19: Knee flexion angle at ball impact between a non-dominant limb (left) and dominant limb (right) in females in kicks with the uninjured limb

Angular velocities played a key role in accounting for the angular adjustments that contributed to different velocities in the dominant limb kicks. At maximal knee flexion, the hip flexion velocity was higher in the dominant limb than in the non-dominant limb for uninjured female limbs. This was not seen in previously injured limbs as further grouping of variables showed.

Subsequently in the leg acceleration phase, the hip reached a peak hip flexion velocity (Kellis & Katis, 2007), which was greater in the dominant uninjured limbs only, a difference which was not seen on grouping the variables disregarding previous injury history. This shows that the hip angular velocity is affected by sex and previous injury history. Previously injured limbs have shown to have a longer backswing (Table 21), and being active flexors of the knee and extensors of the hip, a previous injury appears to inhibit rapid hip flexion. The greater peak hip

angular velocity in the dominant limb is in accordance with findings in previous research (Barbieri et al., 2015; Dorge et al., 2002; Nunome, Ikegami, et al., 2006; Sinclair et al., 2014). These results are in line with Barbieri et al. (2015) who had stated that hip movements were crucial to a skilled kick. This finding also agrees with Lees (2013) who had stressed on the importance of the leg cocking phase and the leg acceleration phase from a performance point of view. Differences were found in the follow through hip flexion velocity, but only in males when considering sex and limb dominance alone, which disappears on including previous injury history. A different technique in females (Katis et al., 2015; Sakamoto & Asai, 2013; Shan, 2009) could explain why this disparity is not seen in females.

Differences were observed in the knee angular velocities along the flexion-extension axis at ball impact for previously uninjured male limbs, a difference seen only when one clusters the variables on limb dominance and previous injury alone, and not when previous injury history is ignored. A higher extension velocity at ball impact transfers a higher velocity to the ball (Table 20). Possibly as a pre-emptive action, a previous injury to the hamstrings appears to affect the generation of a higher knee extension velocity as at ball impact the knee extension ceases and the knee begins to flex (Lees, 2013; Lees & Nolan, 1998). The higher knee extension velocity in the non-dominant limb is in accordance to previous research, which had reported a higher knee extension velocity in the dominant limb kick (Barbieri et al., 2015; Dorge et al., 2002; Nunome, Ikegami, et al., 2006).

Inter-limb differences were also accounted for by differences in peak moments between the dominant and non-dominant limbs. Male soccer players exhibited a greater peak flexion moment when kicking with the uninjured dominant limb, a difference that is seen when on grouping the variables based on previous injury history and limb dominance alone, but not when ignoring previous injury history. Keeping in mind the soccer paradox (Barfield et al.,

2002; Lees et al., 2010), when the hip extends it experiences a flexion moment. Also, from Table 20, it can be seen that male soccer players have a greater backswing with the dominant limb, which further corroborates this finding. Thus a previous injury in male soccer players seems to inhibit the generation of a higher moment.

In the follow through phase, the peak hip extension moment was greater in the dominant limb kicks of females, a difference not seen in male soccer players. In the follow through phase, the hamstring muscles are active decelerating hip flexion (Navandar et al., 2013), and owing to a different kicking technique across sex (Katis et al., 2015; Sakamoto & Asai, 2013; Shan, 2009), the interaction of sex and previous injury is important in this phase in terms of moments.

These results partly contradict findings from previous dynamic kicking analyses in 5 highly skilled male under-17 players(Nunome, Ikegami, et al., 2006) and in 7 skilled male players(Dorge et al., 2002) and represent lower values of peak moments in the present research occurring at different time kicking instances . The differences between the results could be explained by the different skill (Kellis & Katis, 2007) of the players (5 highly skilled male under-17 players versus 46 elite players) and accuracy instructions during kicking. It has been shown that instructions affect the soccer kick(van den Tillaar & Ulvik, 2014).

From the above findings, it is evident that the hip flexors and extensors play an important role in the backswing, which eventually leads to a greater ball velocity while kicking with the dominant limb. In females, the results indicate that the mechanics of the follow through phase in the goal kick are quite important when differentiating a higher velocity kick (dominant limb) from a lower velocity kick (non-dominant limb)

No inter-limb differences in the ground reaction and support leg forces were observed in the two types of kicks as previously observed in Australian football(Ball, 2011). However, the

delays in the dominant limb kicks across the various groups are an important result of this study. Uninjured male players had delayed the support leg strike in the dominant limb, which led to a subsequent delay in time to peak reaction forces of the hip and knee. In females, the time to peak forces was greater in the dominant limb in kicks with the uninjured limb Table 27. These delays in peak forces appeared to favor a better transfer of energy leading to an increase in the ball velocity while kicking with the dominant limb. A previous injury to the support leg appeared to hinder the delay in peak forces with the dominant limb and cause no differences in kicking limb joint and ball velocities (Table 20).

To the best of the author's knowledge, no previous research had examined the time taken to reach the peak ground reaction kicking forces despite the fact that the time to peak seems to play an important role in determining a higher velocity kick. It could be suggested that the peak ground reaction force should not occur immediately after the ball kick, and players should work on "smoothing" the impact while placing the support leg next to the ball as a hard impact would lead to peak force immediately after foot contact as seen in the non-dominant limb kick. A previous injury to the support leg appears to inhibit the delays in peak forces in the hip and knee in the dominant limb.

Practical implications

Previous research has shown the differences between the dominant and non-dominant limbs across either sex (Barbieri et al., 2015; Nunome, Ikegami, et al., 2006; Sinclair et al., 2014; van den Tillaar & Ulvik, 2014). However, this analysis shows that the difference tends to manifest itself in the uninjured limb. A previous injury seems to restrain normal kicking techniques, although the difference is dissimilar in males and females. This information could be employed by coaches and biomechanists to improve the kicking performance on the non-dominant limb, taking into account that the kicking movements seem to be sex specific.

Elite female soccer players have different kicking techniques with the dominant and non-dominant limbs which accounts for the differences in linear velocities, with the differences being reduced with the presence of an injury. If injured, the players must work on their backswing, trying to reach the maximal extension angle in a lower time. They could continue to work to increase the angular velocity of the hip in the sagittal plane, especially when the knee is still flexing, and try to reduce the knee flexion at ball impact to increase the surface area of contact with the ball. This could possibly have a domino effect, leading to greater ball velocities. The follow through phase also plays an important role in females, with the non-dominant limb having lesser extension moments than the dominant limb, and players must look to kick through the ball and reach greater hip flexion angles, as results from this investigation show that males have higher kicking velocities than females (Table 12), and the hip flexion angle at the end of follow through is greater for females (Table 14).

As far as male soccer players go, differences in linear velocities is not seen unless one considers the effect of previous injury. Males seem to have a shorter backswing in the non-dominant limbs, and must work on delaying this phase and not cutting it short. A previous injury appears to hamper the generation of a high hip flexion velocity and hip flexion moment, possibly as a preventive mechanism, and players must work to get over this.

Strength and conditioning coaches and biomechanists should work on bilateral symmetry for both sexes and improving the coordination and strengthening the non-dominant limb. They should also look to prevent a hard impact with the support limb to improve the transfer of energy leading to a greater ball velocity. The loads in female soccer players appear to be lesser than in male soccer players (Table 19) and the coaches and biomechanists must keep this in mind while designing programs to improve the non-dominant limb kicking velocities.

Conclusions

This dissertation comprehensively looked at the effect of a previous hamstring injury on kicking in soccer. In this study, forty-five professional players belonging to three elite teams of both sexes participated in the study, kicking the ball with either limb. A motion capture study is the exact replication of the on-field action – players kick the ball at a target. In order to best represent the actual conditions, artificial turf was used to capture the data.

Looking at the objectives put forth at the beginning of the study, the following conclusions can be drawn about them:

- 1) A previous injury of the hamstring muscles affects the biomechanical factors of kicking in soccer.
- 2) There are differences in the biomechanical factors of kicking between men and women, owing to the superior kinematics in the kicking technique in males.
- 3) A prior injury did not augment the differences between the sexes, rather it appeared to equalize them.
- 4) Male soccer players, owing to their different technique, are more affected by a hamstring injury than female soccer players and hence have a higher rate of re-injury compared to players of the other sex.
- 5) A kick with the dominant limb is superior to that with the non-dominant limb in elite female soccer players.
- 6) An injury to the dominant limb in females affects the kicking technique and tends to minimize the superiority of the dominant limb kick.
- 7) Professional male soccer players are adept at kicking the ball with either limb and there is no difference across limb dominance.

- 8) The presence of a previous hamstring injury affects the non-dominant limb kicks in male soccer players, causing differences in peak linear velocities of the ball and the distal segments.

The results clearly show that the hamstring strain injury affects the kicking technique. The hamstring injury has a high rate of re-injury, and it is clear that the hamstring muscle group gets loaded in kicking, especially in the phases where the hamstring muscles are known to be actively working, namely the backswing, the leg cocking and follow through phases. Its effect also depends on whether the injury was suffered by a male or a female player, and whether the injury occurred in a dominant limb or a non-dominant limb. Thus the consequences of this injury cannot be studied in isolation, rather it has to be considered a multi-factorial problem. Working on minimizing these differences between the injured limb and uninjured limb might help to reduce the loading of the hamstring muscle group and possibly reduce the risk of a subsequent injury.

The protocol used in this investigation allows one to study the technique of the players without subjecting them to loads to which they are not used to. Not only can body kinematics be easily calculated, but also by applying inverse dynamics, one can measure the reaction load at the different joints of the lower body. This gives a good approximation in the case of the hamstring muscle group, which is biarticular, and whose effect on the knee and hip joints can easily be seen rather than studying it in isolation.

Limitations

Teams that were selected had the exact same number of league matches and training sessions during the season. The players belonged to the elite teams in Spain: the male team being the second team of a first division club in Spain and the women's teams played in the first division in Spain and having finished the league in 3rd and 5th positions in the season when the tests were carried out. The men's team and one of the women's teams trained in the same facilities. Trying to maintain a homogeneity of the sample size, a trade-off was made with respect to number of injured players in the study which could have affected the statistics. Although 14 players were injured compared with 31 uninjured players, each limb was considered independent to the other and all players had suffered a unilateral hamstring injury. Only players, who had missed a game due to a previous injury in the last two years, were considered for the "previously injured" group.

Another limitation was that the study was carried out in laboratory conditions, although the use of artificial turf somewhat reduced this effect. All the kicks were dead-ball situations at a target 7m away owing to space limitations where the study was carried out. The space available also inhibited the use of a higher capture frequency, thus impact phase kinematics and kinetics could not be accurately determined.

Activation of the hamstring muscle group was not measured, and the effect was seen on the joints, and the individual muscle mechanics of the hamstring muscle group were not quantified in this study.

Future lines of investigation

This study paves the way for many posterior studies in professional soccer. The most obvious one would be a longitudinal study of a squad through a season or multiple seasons, and see the evolution of the technique of the player, and in case there's an injury, it would definitely help identify patterns which would speed up return-to-play. Using existing models, one can use the information about the joint loads to study individual muscle mechanics of the hamstring muscle group during the kick. A full body study, and not just on the inferior part, would provide valuable information about the trunk loading as well.

Figure 20: Sprint analysis on artificial turf

Although the number of studies on three-dimensional sprint characteristics are ubiquitous, studying maximal and sub-maximal sprint mechanics (Figure 20) in conjunction with kicking mechanics would provide valuable information on the loading of the hamstring muscle group, and the results obtained would be extremely helpful in identifying patterns that aid the return-to-play and reduce the risk of injury.

Such a method is very useful to see the progress of a player during a season and over the course of various seasons too. If a player gets injured, one can monitor his progress and see the susceptibility of the player to a re-injury. This technique can also be used to correct the technique especially in previously injured and young players, and possibly speed up return-to-play in the case of the former.

Although only hip and knee dynamics were reported in the sagittal plane, the same method can be used to study the variables at the ankle and in the longitudinal and transverse planes. This technique can be used to study other injuries in soccer, such as groin and Achilles tendon injuries, and help in the rehabilitation and return-to-play in each case. Three-dimensional motion capture is an extremely powerful tool, and the possibilities that it offers in professional soccer are endless, which can be used to study any type of movement related to soccer.

New technology now permits the use of three-dimensional motion capture in areas outside the laboratory. Repetition of such a study in practical conditions on the field of play, and including the ball moving, would give interesting results.

Figure 21: Electromyography tests

Another possibility is to add electromyography (Figure 21) to see the activation of the different muscle groups. This would give valuable information about the kick, and especially about the

effects of a previous injury. An EMG study would also give a better idea about the differences in activation of the muscles across sex and limb dominance, which could possibly account for the difference in technique.

The possibilities are many, and the applications of the same would only benefit the players, and reduce the risk of injuries.

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Annex

Annex I: Informed Consent

CONSENTIMIENTO INFORMADO

De acuerdo con las directrices éticas dictadas en la declaración de Helsinki por la Asociación Médica Mundial para la investigación en seres humanos, yo D/D^a
..... o en su representación
D/Dñahe sido informado/a de
las características de las pruebas que se van a realizar sobre mi persona en el Laboratorio de Biomecánica Deportiva de la Universidad Politécnica de Madrid. Así mismo autorizo a que los miembros del Grupo de Investigación de Análisis Biomecánico de la Universidad Politécnica de Madrid puedan utilizar los datos con una finalidad exclusivamente *científica* en tanto se respeten la confidencialidad y el anonimato de los datos efectuándose un procedimiento de disociación, de forma que no puedan ser expuestos en relación con mi persona.

En Madrid a

Firma Interesado:

Firma del responsable del estudio:

Fdo: ENRIQUE NAVARRO CABELLO

Annex II: Questionnaire

DATOS DEL SUJETO

Fecha de realización encuesta ----/----/-----

Nº □□□□

1. La Futbolista

1.1. Sexo: Masculino ☐ Femenino ☐

1.2. Edad: □□

1.3. Talla: □□□ (cm) Peso (kgr): □□□,□

1.5. Club _____

1.6. Posición en que juega _____

1.7. Lado dominante: Diestro ☐ Zurdo ☐

1.8. ¿Eres profesional?

Si ☐ No ☐

1.9. ¿Ha sufrido alguna lesión deportiva en los últimos 24 meses?

No ☐ Sí, una ☐ Sí, dos ☐ Sí, tres o más ☐

1.10. ¿Se repitió la misma lesión en alguno de los casos?

Sí ☐ No ☐

2. Carrera futbolística

2.1. ¿Cuántos años lleva jugando a partir de los niveles juveniles?

2.2. ¿Qué es la máxima división en que llegaste a jugar? _____

2.3. ¿Cuántos años ha jugado en cada división?

Primera División Femenina	
Segunda División Femenina	
Otro	

2.4. ¿Ha jugado en otro equipo? _____

3. Tratamiento y secuelas de la lesión deportiva

Sólo a rellenar si ha sufrido la lesión deportiva

3.1 Localización física de la lesión o lesiones: redondear la opción u opciones adecuadas

3.2. Tipo de Lesión producida:

Lesiones Superficiales ☐ Musculares ☐ Tendones ☐ Esguinces ☐

Otras Lesiones articulares ☐ Lesiones de Hueso ☐

3.3. Lesión sufrida:

Cervicalgia ☐ Dorsalgia ☐ Lumbalgia ☐ Tendinitis supraespinoso ☐ Epitrocleítis ☐

Epicondilítis ☐ Ganglión ☐ Tendinitis manguito rot ☐ Esguince tobillo ☐ Esguince Lig

Lat rodilla ☐ Rotura LCA ☐ Tendinitis rodilla ☐ Tendinitis muñeca ☐ Rotura gemelo

☐ Rotura recto anterior ☐ Rotura triceps ☐ Rotura abdomen ☐ Artrosis cadera ☐

Fractura stress ☐ Fascitis plantar ☐ Hernia discal ☐ Tendinopatía aquilea ☐

Síndrome cintilla iliotibial ☐ Contractura muscular ☐

3.4. Atención sanitaria requerida:

Examinado y dado de alta ☐ Tratado y seguido ☐ Hospitalizado ☐

Necesitó atención quirúrgica ☐ No precisó asistencia ☐ Desconocido ☐

3.5. ¿Cuándo se ha lesionado?

Durante partido ☐ Durante entrenamiento ☐ Otro ☐

3.6

¿Dónde? ¿Qué tipo de lesión era?	¿Cuándo? Fecha del accidente (DD/MM/AAAA)	¿Qué pierna ?	¿Cuántos partidos se ha perdido?

3.7 Sobre qué superficie se encontraba en el momento de la lesión?

☐ Tierra-Arena ☐ Hierba ☐ Asfalto-Hormigón

☐ Tierra batida (arcilla) ☐ Moqueta ☐ Césped sintético

☐ Parquet ☐ Tartán ☐ Superficie natural irregular ☐ Otras

3.8 Lugar en el que se encontraba cuando tuvo la lesión:

Instalación deportiva al aire libre ☐ Instalación deportiva cerrada ☐

Medio natural, al aire libre ☐ Otros ☐ Desconocido ☐

3.9 Motivos que han podido ser la principal causa de la lesión (son posibles varias respuestas):

Imprudencia ☐ Descuido ☐ Deficiencias en la instalación ☐

Contacto con otro deportista ☐ Problemas físicos ☐ Problemas psíquicos ☐ No seguir las instrucciones ☐ Falta de información ☐ Otras causas ☐

3.10. ¿Ha necesitado rehabilitación?: Sí ☐ No ☐

3.11. Tiempo de rehabilitación:

Hasta 15 días ☐ 16 a 30 días ☐

1 mes a 2 meses ☐ Más de 2 meses ☐

3.12. Aparición de secuelas: Sí ☐ No ☐

3.13. Tipo de secuela (Si ha contestado SI en la pregunta anterior):

Cicatrices ☐ Disminución movilidad ☐ Dolor ☐ Minusvalía permanente ☐

Disminución masa muscular ☐ Inflamación/Hinchazón ☐ Otras ☐

3.14. ¿Le ha quedado algún tipo de limitación para la práctica deportiva?

Sí ☐ No ☐

Las siguientes preguntas se responden sólo si habrá sufrido una lesión de los isquiotibiales en los últimos 2 años]

3.15 ¿Ha sufrido antes la lesión de los isquiotibiales?

Sí ☐ No ☐

3.16 Si 3.15 es sí, ¿ha sufrido la lesión en la misma pierna antes?

Sí ☐ No ☐

3.17 Si 3.15 es sí, ¿Cuántas veces antes ha sufrido la lesión en los isquiotibiales? _____

3.16 ¿Ha sufrido una lesión antes en la cadera o en el muslo o en la rodilla antes de la lesión de los isquiotibiales?

Sí ☐ No ☐

3.17 ¿Qué tipo de lesión era?

Sobrecarga (Grado I) ☐ Rotura parcial (Grado II) ☐

Rotura completa (Grado III) ☐

3.18 ¿Se ha perdido algún partido por esa lesión? ¿Cuántos?

Sí ☐ No ☐ _____

3.19 ¿Necesito una intervención quirúrgica?

Sí ☐ No ☐

Annex III: Vicon® Workstation Marker set

!MKR#2

[Autolabel]

LASI Left ASIS

RASI Right ASIS

LPSI Left PSIS

RPSI Right PSIS

LTRO Left Trochanter

LTHI Left thigh wand marker

LKNE Left knee lateral

LKN2 Left Knee medial

LTIB Left tibial wand marker

LANK Left ankle lateral marker

LAN2 Left ankle medial marker

LHEE Left heel

L2MT Left 2nd metatarsel head

L5MT Left 5th metatarsal head

RTRO Right Trochanter

RTHI Right thigh wand marker

RKNE Right knee

RKN2 Right knee lateral marker

RTIB Right tibial wand marker

RANK Right ankle lateral marker

RAN2 Right ankle medial marker

RHEE Right heel

R2MT Right 2nd metatarsel head

R5MT Right 5th metatarsal head

B1 Ball Marker 1

B2 Ball Marker 2

B3 Ball Marker 3

B4 Ball Marker 4

Displayed after the model has run

RHJC Right hip joint centre output

RKJC Right knee joint centre output

RAJC Right ankle joint centre

LHJC Left hip joint centre output

LKJC Left knee joint centre output

LAJC Left ankle joint centre output

BALL Centre of ball marker

#Connections between the points

RHJC, LHJC

RHJC, RKJC

RKJC, RAJC

RAJC, R2MT

LHJC, LKJC

LKJC, LAJC

LAJC, L2MT

B1, B2

B3, B4
B1, B3
B1, B4
B2, B3
B2, B4

LASI, RASI, LPSI, RPSI
LASI, LTHI, LKNE
RASI, RTHI, RKNE
LKNE, LTIB, LANK
RKNE, RTIB, RANK
LANK, LAN2, LHEE, L2MT, L5MT
RANK, RAN2, RHEE, R2MT, R5MT

Pelvis = LASI, RASI, LPSI, RPSI

LeftUpperLeg = LTHI, LKNE
LeftLowerLeg = LKNE, LTIB, LANK
LeftFoot = LANK, LAN2, LHEE, L2MT, L5MT

RightUpperLeg = RTHI, RKNE
RightLowerLeg = RKNE, RTIB, RANK
RightFoot = RANK, RAN2, RHEE, R5MT

Pelvis, LeftUpperLeg
LeftUpperLeg, LeftLowerLeg
LeftLowerLeg, LeftFoot
Pelvis, RightUpperLeg
RightUpperLeg, RightLowerLeg
RightLowerLeg, RightFoot

[Force Vectors]

P_ForcePlate1 Base of Plate1 Vector
F_ForcePlate1 Tip of Plate1 Vector
P_ForcePlate2 Base of Plate2 Vector
F_ForcePlate2 Tip of Plate2 Vector

P_ForcePlate1, F_ForcePlate1
P_ForcePlate2, F_ForcePlate2

[Angles]

LHipAngles Left Hip Rotation
RHipAngles Right Hip Rotation
LKneeAngles Left Knee Rotation
RKneeAngles Right Knee Rotation
LAnkleAngles Left Ankle Rotation
RAnkleAngles Right Ankle Rotation

[Linear Velocities]

BallAbsVel Absolute Ball velocity (centre of ball)
BallAbsVelkph Absolute Ball velocity in kmph (centre of ball)
BallAbsAcc Absolute Ball acceleration (centre of ball)
BallMaxVel Maximum velocity of centre of ball

B1AbsVel Absolute B1 velocity
B2AbsVel Absolute B2 velocity
B3AbsVel Absolute B3 velocity

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B4AbsVel	Absolute B4 velocity
B1MaxVel	Maximum B1 velocity
B2MaxVel	Maximum B2 velocity
B3MaxVel	Maximum B3 velocity
B4MaxVel	Maximum B4 velocity
PELCAbsVel	Absolute hip velocity
PELCkphAbsVel	Absolute hip velocity in kmph
PELCAbsAcc	Absolute hip acceleration
LKJCAbsVel	Absolute left knee velocity
RKJCAbsVel	Absolute right knee velocity
LAJCAbsVel	Absolute left ankle velocity
RAJCAbsVel	Absolute right ankle velocity
L2MTAbsVel	Absolute left toe velocity
R2MTAbsVel	Absolute right toe velocity
LKJCAbsAcc	Absolute left knee acceleration
RKJCAbsAcc	Absolute right knee acceleration
LAJCAbsAcc	Absolute left ankle acceleration
RAJCAbsAcc	Absolute right ankle acceleration
L2MTAbsAcc	Absolute left toe acceleration
R2MTAbsAcc	Absolute right toe acceleration
LKJCAbsVelkph	Absolute left knee velocity in kmph
RKJCAbsVelkph	Absolute right knee velocity in kmph
LAJCAbsVelkph	Absolute left ankle velocity in kmph
RAJCAbsVelkph	Absolute right ankle velocity in kmph
L2MTAbsVelkph	Absolute left toe velocity in kmph
R2MTAbsVelkph	Absolute right toe velocity in kmph
[Angular Velocities and Accelerations]	
AVelLHipAngles	
AAccelLHipAngles	
AVelRHipAngles	
AAccelRHipAngles	
AVelLKneeAngles	
AAccelLKneeAngles	
AVelRKneeAngles	
AAccelRKneeAngles	
AVelLAnkleAngles	
AAccelLAnkleAngles	
AVelRAnkleAngles	
AAccelRAnkleAngles	
[Forces]	
Weight	Body Weight
LHipForce	Left Hip Resultant Force
RHipForce	Right Hip Resultant Force
LKneeForce	Left Knee Resultant Force
RKneeForce	Right Knee Resultant Force
LAnkleForce	Left Ankle Resultant Force

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RAnkleForce Right Ankle Resultant Force

[Moments]

LHipMoment Left Hip Resultant Moment
RHipMoment Right Hip Resultant Moment
LKneeMoment Left Knee Resultant Moment
RKneeMoment Right Knee Resultant Moment
LAnkleMoment Left Ankle Resultant Moment
RAnkleMoment Right Ankle Resultant Moment

[Powers]

LHipPower Left Hip Power
RHipPower Right Hip Power
LKneePower Left Knee Power
RKneePower Right Knee Power
LAnklePower Left Ankle Power
RAnklePower Right Ankle Power

[Bones]

PELO
PELP
PELA
PELL
RFEO
RFEP
RFEA
RFEL
LFEO
LFEP
LFEA
LFEL
RTIO
RTIP
RTIA
RTIL
LTIO
LTIP
LTIA
LTIL
RFOO
RFOP
RFOA
RFOL
LFOO
LFOP
LFOA
LFOL
RTOO
RTOP
RTOA
RTOL
LTOO
LTOP
LTOA
LTOL
HEDO
HEDP
HEDA
HEDL

TRXO
TRXP
TRXA
TRXL
RCLO
RCLP
RCLA
RCLL
LCLO
LCLP
LCLA
LCLL
RHUO
RHUP
RHUA
RHUL
LHUO
LHUP
LHUA
LHUL
RRAO
RRAP
RRAA
RRAL
LRAO
LRAP
LRAA
LRAL
RHNO
RHNP
RHNA
RHNL
LHNO
LHNP
LHNA
LHNL

Pelvis = PELO,PELP,PELA,PELL
RightFemur = RFEO,RFEP,RFEA,RFEL
LeftFemur = LFEO,LFEP,LFEA,LFEL
RightTibia = RTIO,RTIP,RTIA,RTIL
LeftTibia = LTIO,LTIP,LTIA,LTIL
RightFoot = RFOO,RFOP,RFOA,RFOL
LeftFoot = LFOO,LFOP,LFOA,LFOL
RightToe = RTOO,RTOP,RTOA,RTOL
LeftToe = LTOO,LTOP,LTOA,LTOL
Thorax = TRXO,TRXP,TRXA,TRXL
Head = HEDO,HEDP,HEDA,HEDL
RightClavicle = RCLO,RCLP,RCLA,RCLL
LeftClavicle = LCLO,LCLP,LCLA,LCLL
RightHumerus = RHUO,RHUP,RHUA,RHUL
LeftHumerus = LHUO,LHUP,LHUA,LHUL
RightRadius = RRAO,RRAP,RRAA,RRAL
LeftRadius = LRAO,LRAP,LRAA,LRAL
RightHand = RHNO,RHNP,RHNA,RHNL
LeftHand = LHNO,LHNP,LHNA,LHNL

Annex IV: Vicon® BodyLanguage Models

A: Static Model

```
{*VICON BodyLanguage (tm) model*}

{*Inverse dynamics of football. This program determines the variables from angles upwards*}

{*Start of macro section*}
{*=*****=}
    macro REPLACE4(p1,p2,p3,p4)

        {*Replaces any point missing from set of four fixed in a segment*}

        s234 = [p3,p2-p3,p3-p4]
        p1V = Average(p1/s234)*s234
        s341 = [p4,p3-p4,p4-p1]
        p2V = Average(p2/s341)*s341
        s412 = [p1,p4-p1,p1-p2]
        p3V = Average(p3/s412)*s412
        s123 = [p2,p1-p2,p2-p3]
        p4V = Average(p4/s123)*s123

        {* Now only replaces if original is missing 11-99 *}

        p1 = p1 ? p1V
        p2 = p2 ? p2V
        p3 = p3 ? p3V
        p4 = p4 ? p4V

    endmacro

macro FORCEVECTOR(FP)

    If ExistAtAll( FP )

        F_#FP = FP(1)
        M_#FP = FP(2)
        C_#FP = FP(3)
        P_#FP = C_#FP
        OUTPUT ( P_#FP, F_#FP )

    EndIf

endmacro

{*End of macro section*}

{*Initialisations*}

$Deadband=10
$MarkerDiameter=14
$SamplingRate=250
PARAM ($Deadband, $MarkerDiameter, $SamplingRate)

{*Set Deadband, except for static trials*}
```

```
If $Static<>1 Deadband = $Deadband EndIf

Gorigin = {0,0,0}
Global = [Gorigin,{1,0,0},{0,0,1},xyz]

{*KINEMATICS*}

{*Pelvis, Sacrum, and Hips*}

Replace4(LASI,RASI,RPSI,LPSI)

SACR = (LPSI+RPSI)/2

$LLegLength=DIST (LASI, LAN2)
$RLegLength=DIST (RASI, RAN2)

LTRO1={0, LTRO(2), 0}
LASI1={0, LASI(2), 0}
RTRO1={0, RTRO(2), 0}
RASI1={0, RASI(2), 0}

$LASisTrocanterDistance =DIST (LASI1, LTRO1)
$RASisTrocanterDistance =DIST (RASI1, RTRO1)
PARAM ($LLegLength, $RLegLength, $LASisTrocanterDistance, $RASisTrocanterDistance)

If $Static==1 { *Save average leg length as parameter* }

$LegLength = ($LLegLength+$RLegLength)/2
PARAM($LegLength)

EndIf

PELF = (LASI+RASI)/2
PELF = PELF+$MarkerDiameter*(SACR-PELF)/(2*DIST(PELF,SACR))

{*Definition of Pelvis segment*}

Pelvis = [PELF,LASI-RASI,PELF-SACR,yzx]

LATD = $LASisTrocanterDistance
RATD = $RASisTrocanterDistance

{*Calculation of LHJC & RHJC from ASIS Trochanter Distance based on Davis III et al.*}

C = $LegLength*0.115-15.3
InterASISDist=DIST(LASI,RASI)
aa = InterASISDist/2
mm = $MarkerDiameter/2
COSBETA = 0.951
SINBETA = 0.309
COSTHETA = 0.880
SINTHETA = 0.476
COSTHETASINBETA = COSTHETA*SINBETA
COSTHETACOSBETA = COSTHETA*COSBETA

LHJC = {C*COSTHETASINBETA - (LATD + mm) * COSBETA,
```

```
-C*SINTHETA + aa,
-C*COSTHETACOSBETA - (LATD + mm) * SINBETA}*Pelvis

RHJC = {C*COSTHETASINBETA - (RATD + mm) * COSBETA,
C*SINTHETA - aa,
-C*COSTHETACOSBETA - (RATD + mm) * SINBETA}*Pelvis

If $Static==1 Then { *Save pelvis size as parameter* }
    $PelvisSize = DIST(LHJC,RHJC)
EndIf
PARAM($PelvisSize)

{*Femura*}

LFemurD=[LKNE,LHJC-LKNE,LASI-LKNE,zxy]
RFemurD=[RKNE,RHJC-RKNE,RKNE-RASI,zxy]

If $Static==1 Then { *Save knee width as parameters* }

    LKJCPR=(LKNE+LKN2)/2
    RKJCPR=(RKNE+RKN2)/2

    $LKJCPR=LKJCPR/LFemurD
    $RKJCPR=RKJCPR/RFemurD

    PARAM($LKJCPR,$RKJCPR)

EndIf

LKJC=$LKJCPR*LFemurD
RKJC=$RKJCPR*RFemurD

{*Definition of Femur segment*}

LFemur=[LKJC,LHJC-LKJC,LTHI-LKJC,zxy]
RFemur=[RKJC,RHJC-RKJC,RKJC-RTHI,zxy]
{*Tibiae*}

LTibiaD=[LANK,LKJC-LANK,LTIB-LANK,zxy]
RTibiaD=[RANK,RKJC-RANK,RANK-RTIB,zxy]

If $Static==1 Then { *Save ankle width as parameters* }

    LAJCPR=(LANK+LAN2)/2
    RAJCPR=(RANK+RAN2)/2

    $LAJCPR=LAJCPR/LTibiaD
    $RAJCPR=RAJCPR/RTibiaD

    PARAM($LAJCPR,$RAJCPR)

EndIf

LAJC=$LAJCPR*LTibiaD
RAJC=$RAJCPR*RTibiaD

{*Definition of Tibia segment*}
```

LTibia=[LANK,LKJC-LAJC,LTIB-LAJC,zyx]
RTibia=[RANK,RKJC-RAJC,RAJC-RTIB,zyx]

{*Foot (and Toes) Segments*}

LFootD = [L5MT,LAJC-L5MT,LAJC-LKJC,zyx]
RFootD = [R5MT,RAJC-R5MT,RAJC-RKJC,zyx]

If \$Static==1 Then {*Save ankle width as parameters*}

\$L2MTPR=L2MT/LFootD
\$R2MTPR=R2MT/RFootD

PARAM(\$L2MTPR,\$R2MTPR)

EndIf

L2MT=\$L2MTPR*LFootD
R2MT=\$R2MTPR*RFootD

{*Definition of Foot segment*}

LFoot = [L2MT,LAJC-L2MT,LAJC-LKJC,zyx]
RFoot = [R2MT,RAJC-R2MT,RAJC-RKJC,zyx]

If \$Static == 1 Then

\$LFootLength = 1.1*DIST(L2MT,LHEE)-mm
\$RFootLength = 1.1*DIST(R2MT,RHEE)-mm
PARAM(\$LFootLength,\$RFootLength)

Endif

OUTPUT(RHJC,LHJC,RKJC,LKJC,RAJC,LAJC, L2MT, R2MT)

{*Force Vectors*}

{*=====*

OptionalReactions(ForcePlate1, ForcePlate2, ForcePlate3, ForcePlate4)

ForceVector(ForcePlate1)

ForceVector(ForcePlate2)

ForceVector(ForcePlate3)

ForceVector(ForcePlate4)

{*Decompose Reactions, Mormalise, Adjust Polarities, Recompose, Re-decompose!*}

{*=====*

{*CALCULATED IN LCS OF EACH SEGMENT*}

FORCEVECTOR(ForcePlate1)

FORCEVECTOR(ForcePlate2)

ForceThreshold=20

DistanceTheshold=200

VelocityThreshold=5000

Weight=(ForcePlate1(1))

\$BodyMass=AVERAGE (Weight)
OUTPUT (\$BodyMass)
PARAM (\$BodyMass)

B: Dynamic Model

```
{*VICON BodyLanguage (tm) model*}  
{*Inverse dynamics of football. This program determines the variables from angles upwards*}  
  
{*Start of macro section*}  
{*=====*}  
macro REPLACE4(p1,p2,p3,p4)  
    {*Replaces any point missing from set of four fixed in a segment*}  
    s234 = [p3,p2-p3,p3-p4]  
    p1V = Average(p1/s234)*s234  
    s341 = [p4,p3-p4,p4-p1]  
    p2V = Average(p2/s341)*s341  
    s412 = [p1,p4-p1,p1-p2]  
    p3V = Average(p3/s412)*s412  
    s123 = [p2,p1-p2,p2-p3]  
    p4V = Average(p4/s123)*s123  
  
    {* Now only replaces if original is missing 11-99 *}  
    p1 = p1 ? p1V  
    p2 = p2 ? p2V  
    p3 = p3 ? p3V  
    p4 = p4 ? p4V  
endmacro  
  
macro BREPLACE4(p1,p2,p3,p4)  
  
    {*Replaces any point missing from set of four fixed in a segment*}  
  
    s234 = [p3,p2-p3,p3-p4]  
    p1V = Average(p1/s234)*s234  
    s341 = [p4,p3-p4,p4-p1]  
    p2V = Average(p2/s341)*s341  
    s412 = [p1,p4-p1,p1-p2]  
    p3V = Average(p3/s412)*s412  
    s123 = [p2,p1-p2,p2-p3]  
    p4V = Average(p4/s123)*s123  
  
    p1 = (p1+p1v)/2 ? p1 ? p1V  
    p2 = (p2+p2v)/2 ? p2 ? p2V  
    p3 = (p3+p3v)/2 ? p3 ? p3V  
    p4 = (p4+p4v)/2 ? p4 ? p4V  
  
endmacro  
  
macro LINVELACC(Point)  
{*When called, this macro calculates the linear velocity in m/s and the linear acceleration in m/s^2 of a  
point, using numerical differentiation. For numerical differentiation, reference one of the following:  
Hildebrand, F.B. (1974). Introduction to Numerical Analysis, 2nd Edition, pp.111  
Kreyszig, Erwin (1983).J Advanced Engineering Mathematics, 5th Edition, pp.793  
Yakowitz, Sydney and Szidarovsky, Ferenc (1989). An Introduction to Numerical Computations, 2nd Edition,  
pp.185*}  
  
{*****Now Calculates Absolute Velocity and Acceleration*****}  
  
FrameTimeLength=1/$SamplingRate
```



```

LVel#Point=((Point[-2]-(8*Point[-1])+(8*Point[1])-Point[2])/(12*FrameTimeLength))/1000
LAccel#Point=((LVel#Point[-2]-(8*LVel#Point[-1])+(8*LVel#Point[1])-
LVel#Point[2])/(12*FrameTimeLength))

Abs#Point#Vel
sqrt((LVel#Point(1)*LVel#Point(1))+(LVel#Point(2)*LVel#Point(2))+(LVel#Point(3)*LVel#Point(3))) =
Abs#Point#Acc
sqrt((LAccel#Point(1)*LAccel#Point(1))+(LAccel#Point(2)*LAccel#Point(2))+(LAccel#Point(3)*LAccel#Point(3))) =

Abs#Point#Velkph=Abs#Point#Vel*3.6
Max#Point#Vel=MAX(Abs#Point#Velkph)

output(LVel#Point,LAccel#Point,Abs#Point#Vel,Abs#Point#Acc,Abs#Point#Velkph, Max#Point#Vel)
param(FrameTimeLength)

endmacro

macro ANGVELACC(Angles)

{ *When called, this macro calculates the angular velocity in rad/s and the angular acceleration in rad/s^2
at a joint, using numerical differentiation. For numerical differentiation, reference one of the following:
Hildebrand, F.B. (1974). Introduction to Numerical Analysis, 2nd Edition, pp.111
Kreyszig, Erwin (1983). Advanced Engineering Mathematics, 5th Edition, pp.793
Yakowitz, Sydney and Szidarovsky, Ferenc (1989). An Introduction to Numerical Computations, 2nd Edition,
pp.185* }

FrameTimeLength=1/$SamplingRate
pi=3.1415927

Scalar#Angles={Angles(1),Angles(2),Angles(3)}

Rad#Angles=Scalar#Angles*pi/180
AVel#Angles=((Rad#Angles[-2]-(8*Rad#Angles[-1])+(8*Rad#Angles[1])-
Rad#Angles[2])/(12*FrameTimeLength))
AAccel#Angles=((AVel#Angles[-2]-(8*AVel#Angles[-1])+(8*AVel#Angles[1])-
AVel#Angles[2])/(12*FrameTimeLength))

output(AVel#Angles,AAccel#Angles)
param(FrameTimeLength)

endmacro

macro FORCEVECTOR(FP)
If ExistAtAll( FP )
    F_#FP = FP(1)
    M_#FP = FP(2)
    C_#FP = FP(3)
    P_#FP = C_#FP
    OUTPUT ( P_#FP, F_#FP )
EndIf
endmacro

macro REVERSEORDER(AR)
AR = <3(AR),2(AR),1(AR)>
endmacro

macro DRAWBONE(Bone,BoneLabel)
{ *Outputs segment definition markers in Polygon format* }

```

```

LL = Bone#Size
DD = LL/10
WW = DD
BoneLabel#O = 0(Bone)+LL*Bone#Shift*Attitude(Bone)
BoneLabel#P = BoneLabel#O+LL*3(Bone#Scale)*3(Bone)
BoneLabel#A = BoneLabel#O+DD*1(Bone#Scale)*1(Bone)
BoneLabel#L = BoneLabel#O+WW*2(Bone#Scale)*2(Bone)
OUTPUT(BoneLabel#O,BoneLabel#P,BoneLabel#A,BoneLabel#L)
endmacro

{*End of macro section*}
{*Initialisations*}

{*Set Deadband, except for static trials*}

    If $Static<>1 Deadband = $Deadband EndIf

    Gorigin = {0,0,0}
    Global = [Gorigin,{1,0,0},{0,0,1},xyz]

mm = 14/2

{*KINEMATICS*}

{*Pelvis, Sacrum, and Hips*}

    Replace4(LASI,RASI,RPSI,LPSI)

    SACR = (LPSI+RPSI)/2

    PELF = (LASI+RASI)/2
    PELF = PELF+$MarkerDiameter*(SACR-PELF)/(2*DIST(PELF,SACR))

{*Definition of Pelvis segment*}

    Pelvis = [PELF,LASI-RASI,PELF-SACR,yzx]

    LATD = $LASisTrocanterDistance
    RATD = $RASisTrocanterDistance

{*Calculation of LHJC & RHJC from ASIS Trochanter Distance based on Davis III et al.*}

    C = $LegLength*0.115-15.3
    InterASISDist=DIST(LASI,RASI)
    aa = InterASISDist/2
    mm = $MarkerDiameter/2
    COSBETA = 0.951
    SINBETA = 0.309
    COSTHETA = 0.880
    SINTHETA = 0.476
    COSTHETASINBETA = COSTHETA*SINBETA
    COSTHETACOSBETA = COSTHETA*COSBETA

    LHJC = {C*COSTHETASINBETA - (LATD + mm) * COSBETA,
    -C*SINTHETA + aa,
    -C*COSTHETACOSBETA - (LATD + mm) * SINBETA}*Pelvis

    RHJC = {C*COSTHETASINBETA - (RATD + mm) * COSBETA,

```

```
C*SINTHETA - aa,
-C*COSTHETACOSBETA - (RATD + mm) * SINBETA}*Pelvis

Pelvis = (LHJC+RHJC)/2 + Attitude(Pelvis)

If $Static==1 Then { *Save pelvis size as parameter* }
    $PelvisSize = DIST(LHJC,RHJC)
EndIf
PARAM($PelvisSize)

PelvisSize = $PelvisSize
PelvisScale = {1.2,1,1}
PelvisShift = {0,0,0}

{ *Sacrum (dummy; to establish relative pose of spine)* }
SAC0 = PELF + $PelvisSize*{-1,0,0}*Attitude(Pelvis)
Sacrum = SAC0+Attitude(Pelvis)

SacrumSize = PelvisSize/2
SacrumScale = {1,1,1}
SacrumShift = {0,0,0}

{ *Femura* }

LFemurD=[LKNE,LHJC-LKNE,LTHI-LKNE,zxy]
RFemurD=[RKNE,RHJC-RKNE,RKNE-RTHI,zxy]

LKJC=$LKJCPR*LFemurD
RKJC=$RKJCPR*RFemurD

{ *Definition of Femur segment* }

LFemur=[LKJC,LHJC-LKJC,LTHI-LKJC,zxy]
RFemur=[RKJC,RHJC-RKJC,RKJC-RTHI,zxy]

LHipJoint = LHJC+Attitude(Pelvis)
RHipJoint = RHJC+Attitude(Pelvis)

LFemurSize = DIST(0(LFemur),0(LHipJoint))
LFemurScale = {1,1,1}
LFemurShift = {0,0,0}

RFemurSize = DIST(0(RFemur),0(RHipJoint))
RFemurScale = {1,1,1}
RFemurShift = {0,0,0}

{ *Tibiae* }

LTibiaD=[LANK,LKJC-LANK,LTIB-LANK,zxy]
RTibiaD=[RANK,RKJC-RANK,RANK-RTIB,zxy]

LAJC=$LAJCPR*LTibiaD
RAJC=$RAJCPR*RTibiaD

{ *Definition of Tibia segment* }
```

```
{*LTibia=[LANK,LKJC-LAJC,LTIB-LAJC,zxy]
RTibia=[RANK,RKJC-RAJC,RAJC-RTIB,zxy]*}
```

```
LTibia=[LAJC,LKJC-LAJC,LTIB-LAJC,zxy]
RTibia=[RAJC,RKJC-RAJC,RAJC-RTIB,zxy]
```

```
LTibiaSize = DIST(0(LTibia),0(LFemur))
LTibiaScale = {0.93,0.93,0.93}
LTibiaShift = {0,0,-0.01}
```

```
RTibiaSize = DIST(0(RTibia),0(RFemur))
RTibiaScale = {0.93,0.93,0.93}
RTibiaShift = {0,0,-0.01}
```

```
{*Foot (and Toes) Segments*}
```

```
LFootD = [L5MT,LAJC-L5MT,LAJC-LKJC,zyx]
RFootD = [R5MT,RAJC-R5MT,RAJC-RKJC,zyx]
```

```
L2MT=$L2MTPR*LFootD
R2MT=$R2MTPR*RFootD
```

```
{*Definition of Foot segment*}
```

```
LFoot = [L2MT,LAJC-L2MT,LAJC-LKJC,zyx]
RFoot = [R2MT,RAJC-R2MT,RAJC-RKJC,zyx]
```

```
LFootSize = 0.76*$LFootLength
LFootScale = {1,1,1}
LFootShift = {0.13,0,0}
```

```
RFootSize = 0.76*$RFootLength
RFootScale = {1,1,1}
RFootShift = {0.13,0,0}
```

```
OUTPUT(RHJC,LHJC,RKJC,LKJC,RAJC,LAJC, L2MT, R2MT)
```

```
{*Draw Bones, Muscle Attachments & Lengths*}
{*=====*
```

```
DrawBone(Pelvis,PEL)
DrawBone(Sacrum,SAC)
DrawBone(LFemur,LFE)
DrawBone(RFemur,RFE)
DrawBone(LTibia,LTi)
DrawBone(RTibia,RTi)
DrawBone(LFoot,LFO)
DrawBone(RFoot,RFO)
```

```
{*Joint Angles*}
```

```
If $Static == 1 Then
    Anatomy = [0(Global),3(Global),(SACR-PELF),zyx]
Else
    Progress = (PELF[7] + PELF[6] + PELF[5] + PELF[4] + PELF[3]
    - PELF[-7]- PELF[-6]- PELF[-5]- PELF[-4]- PELF[-3])/5
    Anatomy = [0(Global),3(Global),-Progress,zyx]
```

EndIf

```
{*Hips: Pelvis >> Femora (VCM)*}
  LHipAngles = <Pelvis,LFemur,yxz>
  RHipAngles = -<Pelvis,RFemur,yxz>(-1)

{*Knees: Femora >> Tibiae (VCM)*}
  LKneeAngles = <LFemur,LTibia,yxz>(-1)
  RKneeAngles = -<RFemur,RTibia,yxz>

{*Ankles: Tibiae >> Feet (VCM)*}
  LAA = -<LTibia,LFoot,yxz>
  LAnkleAngles = <-90 - 1(LAA),-3(LAA),-2(LAA)>
  RAA = -<RTibia,RFoot,yxz>
  RAnkleAngles = <-90 - 1(RAA),3(RAA),2(RAA)>
```

{*Velocities*}

```
PELC = (PELF+SACR)/2
LINVELACC (PELC)
LINVELACC (LHJC)
LINVELACC (RHJC)
LINVELACC (LKJC)
LINVELACC (RKJC)
LINVELACC (LAJC)
LINVELACC (RAJC)
LINVELACC (L2MT)
LINVELACC (R2MT)
```

BReplace4(B1, B2, B3, B4)

```
BALL = (B1 + B2)/2
```

```
LINVELACC (BALL)
```

OUTPUT(BALL)

```
ANGVELACC(LHipAngles)
ANGVELACC(RHipAngles)
ANGVELACC(LKneeAngles)
ANGVELACC(RKneeAngles)
ANGVELACC(LAnkleAngles)
ANGVELACC(RAnkleAngles)
```

OUTPUT(LHipAngles,RHipAngles,LKneeAngles,RKneeAngles,LAnkleAngles,RAnkleAngles)

```
{*Kinetics*}
{*=====*
```

```
BodyMass =($BodyMass(3))/9.81
Output (BodyMass)
```

```
AnthropometricData
AnthroFemur 0.1416 0.5905 0.329 0.162
AnthroTibia 0.0433 0.5541 0.249 0.103
AnthroFoot 0.0137 0.5585 0.245 0.124
```

EndAnthropometricData

Pelvis = [Pelvis, 0.142*BodyMass, {0,0,0}, {0,0,0}]

LFemur = [LFemur, Pelvis, LHJC, AnthroFemur]

RFemur = [RFemur, Pelvis, RHJC, AnthroFemur]

LTibia = [LTibia, LFemur, LKJC, AnthroTibia]

RTibia = [RTibia, RFemur, RKJC, AnthroTibia]

LFoot = [LFoot, LTibia, LAJC, AnthroFoot]

RFoot = [RFoot, RTibia, RAJC, AnthroFoot]

{*Force Vectors*}

{*=====*

ForceVector(ForcePlate1)

ForceVector(ForcePlate2)

{*Decompose Reactions, Mormalise, Adjust Polarities, Recompose, Re-decompose!*}

{*=====*

{*CALCULATED IN LCS OF EACH SEGMENT*}

FP1 = |ForcePlate1(1), ForcePlate1(2), ForcePlate1(3)|

ForceThreshold=20

LHF = 1(REACTION(LFemur))/BodyMass

LHF = {1(LHF), 2(LHF), -3(LHF)}

LHM = 2(REACTION(LFemur))/BodyMass

LFemurR = |LHF, LHM, 3(REACTION(LFemur))|

LHipForce = 1(LFemurR)

LHipMoment = 2(LFemurR)

RHF = 1(REACTION(RFemur))/BodyMass

RHF = {1(RHF), -2(RHF), -3(RHF)}

RHM = 2(REACTION(RFemur))/BodyMass

RHM = {-1(RHM), 2(RHM), -3(RHM)}

RFemurR = |RHF, RHM, 3(REACTION(RFemur))|

RHipForce = 1(RFemurR)

RHipMoment = 2(RFemurR)

LKF = 1(REACTION(LTibia))/BodyMass

LKF = {1(LKF), 2(LKF), -3(LKF)}

LKM = 2(REACTION(LTibia))/BodyMass

LKM = {1(LKM), -2(LKM), 3(LKM)}

LTibiaR = |LKF, LKM, 3(REACTION(LTibia))|

LKneeForce = 1(LTibiaR)

LKneeMoment = 2(LTibiaR)

RKF = 1(REACTION(RTibia))/BodyMass

RKF = {1(RKF), -2(RKF), -3(RKF)}

RKM = -2(REACTION(RTibia))/BodyMass

RTibiaR = |RKF, RKM, 3(REACTION(RTibia))|

RKneeForce = 1(RTibiaR)
RKneeMoment = 2(RTibiaR)

LAF = 1(REACTION(LFoot))/BodyMass
LAF = {-3(LAF),2(LAF),-1(LAF)}
LAM = 2(REACTION(LFoot))/BodyMass
LFootR = |LAF,LAM,3(REACTION(LFoot))|
LAnkleForce = 1(LFootR)
LAnkleMoment = 2(LFootR)

RAF = -1(REACTION(RFoot))/BodyMass
RAF = {3(RAF),2(RAF),1(RAF)}
RAM = 2(REACTION(RFoot))/BodyMass
RAM = {-1(RAM),2(RAM),-3(RAM)}
RFootR = |RAF,RAM,3(REACTION(RFoot))|
RAnkleForce = 1(RFootR)
RAnkleMoment = 2(RFootR)

OUTPUT(LHipForce,RHipForce,LKneeForce,RKneeForce,LAnkleForce,RAnkleForce)
OUTPUT(LHipMoment,RHipMoment,LKneeMoment,RKneeMoment,LAnkleMoment,RAnkleMoment)

{*Joint Powers (W/kg)*}
{*=====*

LHipPower = POWER(Pelvis, LFemur)/BodyMass
RHipPower = POWER(Pelvis, RFemur)/BodyMass
LKneePower = POWER(LFemur, LTibia)/BodyMass
RKneePower = POWER(RFemur, RTibia)/BodyMass
LAnklePower = POWER(LTibia, LFoot)/BodyMass
RAnklePower = POWER(RTibia, RFoot)/BodyMass

OUTPUT(LHipPower,RHipPower,LKneePower,RKneePower,LAnklePower,RAnklePower)