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Three-dimensional Kinematics and Electromyography of the Lower Limb of Male and Female Elite Soccer Players Performing an Unanticipated Cutting Manoeuvre

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THREE-DIMENSIONAL KINEMATICS AND ELECTROMYOGRAPHY OF THE LOWER LIMB OF MALE AND FEMALE ELITE SOCCER PLAYERS PERFORMING AN UNANTICIPATED CUTTING MANOEUVRE

By
MÉLANIE BEAULIEU, B.Sc.

THESIS

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THREE-DIMENSIONAL KINEMATICS AND ELECTROMYOGRAPHY OF THE LOWER LIMB OF MALE AND FEMALE ELITE SOCCER PLAYERS PERFORMING AN UNANTICIPATED CUTTING MANOEUVRE

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ABSTRACT

Purpose: The purpose of this study is to compare the time-frequency characteristic, using non-linearly scaled wavelets, the amplitude and the timing of the electromyography (EMG) signal, as well as the three-dimensional (3D) kinematics of the lower limb of female and male elite soccer players performing an unanticipated cutting manoeuvre. **Methods:** Fifteen female and 15 male elite soccer players performed a series of the cutting manoeuvre during which EMG of eight muscles of the right leg, 3D kinematics of the hip, knee and ankle, as well as ground reaction forces were recorded. To create an unanticipated condition, the participants executed one of three tasks, which were signalled to them with an illuminated target board. All variables were compared between genders by means of one-way ANOVAs. **Results:** Female participants performed the cutting task with greater knee valgus and ankle pronation angles, as well as smaller hip internal rotation and ankle external rotation angles, than did the male group. Women also displayed different muscle activation patterns, such as an earlier semitendinosus (ST) onset, greater peak rectus femoris (RF) activity, greater lateral gastrocnemius (LG) and tibialis anterior (TA) activity at initial contact (IC) and greater LG activity during the entire motion. Furthermore, men executed the cutting manoeuvre with higher frequency components for the quadriceps and higher frequencies at IC for the biceps femoris (BF). These higher frequencies dominated the signal earlier in time for the BF and later for the TA in women. **Conclusion:** Gender differences in lower limb kinematics were observed, possibly exposing the female anterior cruciate ligament (ACL) to higher strain. Women also exhibited neuromuscular control strategies that may assist in explaining the gender bias in ACL injury rates. The frequency at which one contracts a muscle to sustain joint stability may be of greater importance than the amount of muscle activity. **Key Words:** Anterior cruciate ligament, Knee Injury, Gender, Wavelet, Neuromuscular Control, Kinematics.

INTRODUCTION

In the literature, studies [2,3,37,44,47,79] have clearly demonstrated that women do injure their ACL at a greater rate than do men in noncontact situations. Most ACL injuries seen in female athletes occur by means of two main injury mechanisms: a plant-and-cut movement or a one-legged landing [9,34,53]. In such situations, the hip is most often internally rotated and adducted, the knee is in valgus and slight flexion (20-30°) and the foot is pronated, thus causing an external rotation of the tibia [9,36]. This position puts the ACL at risk of injury due partly to the fact that in full knee extension, all fibres of the ACL are under tension. Furthermore, the ACL is the principal structure that limits anterior tibial translation and is a secondary structure in controlling varus and valgus forces [17,35]. Hence, a knee in valgus position and near complete extension as well as a rotated tibia causes strain of the ACL.

Although much attention has been given to uncovering the cause of such gender discrepancy with regards to noncontact ACL injuries, the exact origin of this divergence has yet to be determined. This attention, however, have led to the elaboration and discussion of several contributing factors. These can be classified as being one of four types: anatomical, hormonal, neuromuscular and biomechanical factors. Researchers that have assessed anatomical factors in men and women have measured such variables as the quadriceps-angle (Q-angle), the size of the ACL and intercondylar notch and knee joint laxity. In general, results seem to reveal that women tend to have a greater Q-angle [31,70], a smaller ACL [1] and intercondylar notch width [12,64] – although not always accounting for gender differences in body size, as well as greater knee joint laxity [6,32,33,59], thus possibly making women, more than men, susceptible to an ACL injury. There are, however, inconsistencies in the literature [1,42,52] pertaining to the results, as well as the methods used to obtain them. This suggests that insufficient evidence exists to conclude that anatomical factors are solely responsible for the increase rate in ACL injuries in women.

Results have also been inconsistent among studies that have investigated hormonal contributing factors of ACL injuries. Of the studies which have examined the effect of the phases of the menstrual cycle on ACL injury incidence, some results reveal that a woman may be at a predisposed risk of ACL injury during her follicular phase [7], some found this increased risk to be during the ovulatory phase [76] and others during the luteal phase [67]. Thus, researchers have not attained a consensus. Furthermore, some believe that the female sex hormones (i.e., estrogen, progesterone, relaxin) increase the laxity of ligaments [15], yet various researchers [6,11,27] have noted a lack of change in knee laxity with regards to the menstrual phases during which fluctuation of these hormones occur. Other changes that have also been observed with the menstrual cycle are postural sway, knee joint kinaesthesia and muscle strength [25,62], although other studies have revealed contradicting results [24,27]. Hence, it appears that perhaps the menstrual cycle may play a role in the gender discrepancy in ACL injuries. This role is, however, not yet confirmed nor clearly determined.

Although gender differences have been demonstrated at the anatomical and hormonal levels, which may bring an explanation as to why women are more susceptible to anterior cruciate ligament injuries than men, differences with regards to neuromuscular control is most interesting as it offers the greatest potential for intervention and thus prevention of this type of injury. It has been said that women tend to be *ligament-dominant*; therefore they rely more on their knee ligaments, as oppose to their musculature, to absorb a considerable portion of the ground reaction forces. They also display a *quadriceps imbalance* in relation to their hamstrings. Hence, several studies have revealed that women display a greater quadriceps-to-hamstrings strength ratio [1,21,33,46,68,74], as well as a quadriceps activation preference during dynamic activities [66]. Furthermore, women exhibit a *leg dominance*, which means that their dominant limb often demonstrates greater strength and coordination [29]. Other studies have revealed gender differences with regards to neuromuscular behaviours, such as timing and amplitude of the hamstrings and quadriceps. The relationship between these two groups of muscles and the ACL is crucial as hamstring activation acts as an agonist to the ACL to decrease anterior tibial translation with respect to the femur [43,45,51,58]; whereas activity of the quadriceps increases ACL strain when the knee flexes from full extension to approximately 30-45 degrees of flexion and subsequently decreases with further flexion [43,58]. For instance, in a study evaluating hamstring activity with respect to sagittal plane tibiofemoral forces during a deceleration task, it was found that the male participants displayed a better synchronisation of their peak semitendinosus activation in relation to the peak tibiofemoral force, as well as the activation onset with IC [13]. It has also been demonstrated that women's muscle response offers less protection to their ACL in comparison with their male counterparts [75,77]. Accordingly, investigations demonstrated a different neuromuscular control in women in comparison with men.

Moreover, numerous studies have explored biomechanical, both kinematic and kinetic, gender differences during tasks that are representative of the most common mechanisms of ACL injury – cutting manoeuvre and jump landing task. Although some results revealed a lack of gender difference with regards to knee kinematics [13,38,56,66], several studies have demonstrated that women execute the former tasks with larger knee valgus angles [21-23,28,40,46,49,50] and smaller knee flexion angles [14,39,46,49,60] than men. Other differences that have been found include decreased knee internal rotation, hip flexion and internal rotation and greater foot pronation [23,49,60] in women. Other researchers, however, have failed to show a kinematic difference at the hip between men and women [13,14,22,38,40]. This disagreement among researchers might be explained by the diversity among the studies' methodologies. In general, researchers seem to agree that women do perform cutting and landing tasks with greater knee valgus angles, which is presumably the result of differences at another level, such as those observed in the neuromuscular control.

Many studies [13,16,19,46,59,66,74,80] have examined gender differences with regards to neuromuscular control and ACL injuries by means of EMG measurements. All of these studies, however, have made such measurements by means of an anticipated movement, such as a cutting manoeuvre or a drop-jump landing. To fully comprehend the mechanism of an ACL injury, it is advantageous to study a movement similar to that of the actual environment (i.e., game-like situation). In other words, better representative data might be acquired from participants performing a cutting manoeuvre while having to react to a stimulus beforehand, just like one does in competition when reacting to an opponent or a projectile. The studies [23,56] that have examined the gender discrepancy that exists among ACL injury rates using a simulated competition-like environment investigated kinematic and/or kinetic variables and disregarded muscle activation patterns. There is therefore a need to study lower limb muscle activation patterns during an unanticipated manoeuvre, as well as the timing of these patterns. Few studies [13,66] have examined this timing characteristic of the EMG signal between genders. Although it is important to quantify and compare the amplitude of muscle activity between genders, it is equally important to consider the timing of this activity and its relation to other biomechanical parameters. For instance, it is believed that a strong contraction of the hamstrings will increase protection to the ACL, but this contraction must be present in time of need – when the ACL is experiencing large strain. Furthermore, to our knowledge, no published studies targeting ACL injuries and its gender discrepancy examined the time-frequency characteristics of the lower limb muscle activation by means of wavelets. Researchers, however, have performed such an analysis utilizing non-linearly scaled wavelets as they compared female and male runners [72]. The advantage to using the wavelet transform is that it provides a more precise frequency analysis in time, in that it gives a variable resolution (i.e., window), as opposed to the Fourier transform, which provides a fixed resolution (i.e., window). Hence, by using a variable resolution, the size of the window can be adjusted according to the magnitude of the frequency [26,71].

Consequently, the purpose of this study is to compare the time-frequency characteristic, using non-linearly scaled wavelets, the amplitude and the timing of recruitment of the EMG signal, as well as the three-dimensional kinematics, of the lower limb of female and male elite soccer players performing an unanticipated cutting manoeuvre. Based on previous research, which shows lower limb kinematic differences between genders, we hypothesized that the women would display less knee and hip flexion, greater knee abduction, knee external rotation and hip internal rotation angles, as well as greater ankle pronation angles during the plant-and-cut manoeuvre. As studies have revealed that women display a quadriceps activation preference, we also hypothesized that the female athletes would exhibit less hamstrings activation, as well as greater quadriceps activation, than the male athletes. Furthermore, it has been demonstrated that EMG mean frequency is dependant of the conducting velocity during motor unit recruitment, which might identify recruitment control strategies employed by various muscles. Consequently, it was predicted that the male athletes would produce higher mean frequencies and intensities of the EMG signals.

METHODS

Subjects. Fifteen female (age: 21.1 ± 3.6 years; height: 168.3 ± 5.3 cm; mass: 62.4 ± 4.9 kg; soccer experience: 13.7 ± 4.3 years) and 15 male (age: 22.9 ± 3.7 years; height: 178.2 ± 8.0 cm; mass: 75.1 ± 6.7 kg; soccer experience: 15.8 ± 3.3 years) elite soccer players participated in the present study. At the time of data collection, all participants were competing at the university/collegiate or premier level, with the exception of one male athlete who had formerly played at the elite level, but was currently competing at a slightly lower level. Furthermore, all athletes were right-leg dominant and free from any current or past lower extremity injuries, with a minimum of seven years of soccer playing experience. As speculation exists that the phase of the menstrual cycle may have an effect on the laxity of the ACL, thus the susceptibility to ACL injuries, the group of female participants was tested between day 2 and day 11 – during the follicular phase – of their menstrual cycle. Informed written consent, approved by the Health Sciences and Science Research Ethics Board of the University of Ottawa, was obtained from each participant.

Instrumentation. A seven-camera (MX-13) motion analysis system (Vicon Peak, Oxford, UK) was used to capture, at 200 Hz, five successful unanticipated cutting manoeuvres performed by the participant. The cameras were strategically placed so that every marker was seen by a minimum of two cameras at all times. To calculate hip, knee and ankle joint angles in the sagittal, frontal and transverse planes, the plug-in-gait (PIG) model was used in Workstation software (version 5.1, Vicon Peak, Oxford, UK). The PIG model uses a modified Helen Hayes marker set, which involved placing reflective markers (14 mm diameter) on the following anatomical landmarks: anterior superior iliac spines (ASIS), posterior superior iliac spines (PSIS), lateral thigh, lateral epicondyle of the knee, lateral shank, lateral malleolus, posterior calcaneus and second metatarsal head. Additional markers were placed on the centre of the patellas and the tibial tuberosities to measure the participants' right quadriceps-angles (Q-angle) – the angle between the line that connects the ASIS of the pelvis and the patella and the line that connects the tibial tuberosity and the patella – while they stood in a neutral static position. Various anthropometric measurements (i.e., height, weight, leg length, knee width and angle width) were also noted and subsequently used, in conjunction with the markers, to calculate the location of the joint centers.

In addition to 3D kinematic data, EMG data were collected with an eight-channel EMG system (Bortec AMT-8, Bortec Biomedical Ltd.) at 1000 Hz. Pairs of surface electrodes (Kendall Meditrace ® 133, Ag/AgCl) were placed over the belly of the following muscles of the right lower limb: vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), biceps femoris (BF), semitendinosus (ST), medial gastrocnemius (MG), lateral gastrocnemius (LG) and tibialis anterior (TA). Prior to electrode application, the skin area on which these electrodes were placed was shaved, if necessary, with a new disposable razor and cleaned with an alcohol swab. The wires of the electrodes were secured to the subject's skin with tape to minimize motion artifact. The portable unit located on a belt worn around the participant's waist was subsequently connected to the main amplifier (gain = 1000).

Furthermore, a force platform (AMTI, Model OR6-6-2000, Watertown, MA, USA) was embedded in a walkway for it to be flush with the flooring to determine the beginning and end of the cutting motion's stance phase. The same investigator performed all of the anthropometric measurements, as well as the marker and electrode placements.

Protocol. All the participants wore tight-fitting shorts, a sports bra (women only) and their own indoor soccer shoes. To allow for comparison of EMG amplitudes between genders, EMG data were normalized to the data acquired during maximal voluntary isometric contractions (MVIC). The athletes performed three MVICs against a fixed resistance for each movement for a period of five seconds: knee flexion, knee extension, ankle dorsiflexion and ankle plantar flexion. For the former two movements, the knee of the participant was positioned at 60° of knee flexion to be consistent with prior research [30]. For ankle dorsiflexion and ankle plantar flexion, the ankle was positioned at 15° and -10° of plantar flexion, respectively, with the knee at 90° of flexion. The literature [41,61] shows that these positions are optimal for maximal strength production of the ankle plantar and dorsiflexors.

Each athlete then completed a practice session that included several anticipated and unanticipated trials of each of the three tasks to familiarize his/herself with the experimental setup, as well as to reduce the effect of targeting the force platform. The athlete performed 15 trials; five trials of each task were randomly performed. The tasks consisted of a 45° cutting manoeuvre, a straight ahead run and a run-stop. The latter two tasks were catch tasks so as to present the athletes with three options. Consequently, the cutting manoeuvre became an unanticipated task. Specifically, the 45° cutting manoeuvre consisted of an approach run, followed by a plant-and-cut manoeuvre at a 45° angle with the right foot on the force platform. The area on the walkway was outlined with a black rubber mat to designate the path that the athlete was to undergo. As for the straight ahead run, the participants continued the approach run through the experimental set-up, with a change in neither direction nor speed. During the run-stop task, the participants stopped the approach run with their right foot on the force platform.

As the athletes approached the force platform, they triggered a photoelectric cell located 2 m prior to the force platform that, in turn, triggered an illuminated target board, which was positioned 3 m ahead of the force platform (Figure 1). This target board randomly illuminated with an orange (cut), green (straight run) or red (run-stop) light, indicating to the athletes which task to perform. Each participant was given approximately 1.0-1.5 minutes between trials to reduce the potential effects of fatigue. Only successful trials were kept. A cutting trial was deemed successful if the participant performed the manoeuvre when the target board illuminated with an orange light, approached the force platform with a speed of 4.0-5.0 m/s, made the initial ground contact with the force platform and changed direction at a 45° angle. Cutting trials during which the participant modified his/her stride length (i.e., stutter-step) to make contact with the force platform were also discarded. Two other photoelectric cells, positioned 1 m apart, were located 0.5 m prior to the force platform to monitor approach locomotor speed.

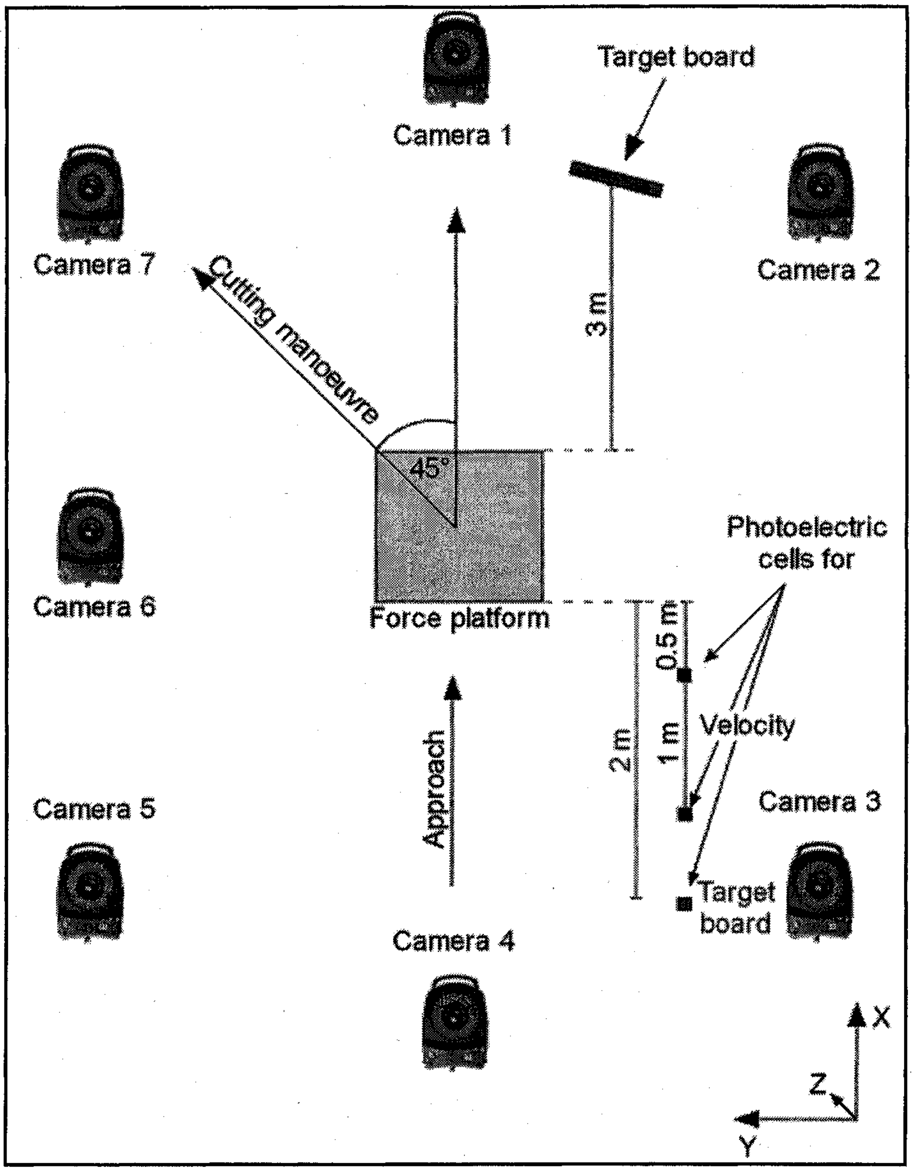

Figure 1: Experimental set-up (not at scale).

Data Analysis. Three-dimensional kinematics and electromyography data of each participant were analyzed for five successful unanticipated cutting trials. The cycle of interest of the cutting trial (i.e., "cutting cycle") was defined as the combination of the pre-stance and stance phases of the right lower limb. This former phase was characterized as the last portion of the swing phase – the time from peak right knee flexion angle to initial ground contact (IC) – prior to the stance phase during which the participant executed a change in direction. This cycle was applied to time normalize the data and to thus enable averaging across trials within and between participants.

The raw kinematic data were filtered using a General Cross Validatory (GCV) quintic-order spline [78]. A kinematic model was defined from a standing static trial and lower limb anthropometric measurements for quantification of ankle, knee and hip flexion/extension, abduction/adduction and internal/external rotation angles during the "cutting cycle". From these data, peak angular values during the stance phase, angular values at IC and range of angles during the "cutting cycle" were obtained for each trial of a participant. The data of the five trials were then averaged for each individual.

From the raw EMG data, the onset was determined for each muscle for each trial with a double-threshold detector by means of a custom MATLAB® (The Mathworks, Inc. USA) program. This detector of the onset of a muscle contraction operates on the raw myoelectric signal from which a first threshold is determined using the noise-to-signal ratio. If at least "r_o" out of the successive samples are above the first threshold, the presence of the signal is acknowledged [10]. The second threshold, represented by "r_o" was set at 1. A false alarm probably was set at 0.05. The timing of the onset was reported as a percentage of the "cutting cycle" in relation to IC. A negative percentage indicates that the onset occurred prior to IC. A positive percentage indicates an onset occurring post IC. Processing of raw EMG was accomplished using another custom MATLAB® program. These raw data were baseline corrected, rectified and smoothed with a critically damped filter (cutoff frequency of 6 Hz) to generate a linear envelope of the EMG signal (LEEMG). From the LEEMG data, the timing of the peak muscle activity was reported as a percentage of the "cutting cycle" in relation to IC, as well as this peak's amplitude normalized to the participant's EMG_{MVIC}. Using this EMG_{MVIC}-normalized data, the integral was acquired for the pre-stance and stance phases.

By means of this same custom MATLAB® program, the short time mean frequency (STMNF) and the total intensity (TI) of the pre-stance and stance phases of muscle activation were obtained. The EMG signal was first decomposed in time and frequency using 11 non-linearly scaled wavelets, whose centre frequencies, cf_j, where j=0,1,...,10, were pre-defined [71]. The power/intensity of the EMG signal in each of the 11 wavelet frequency bands was obtained with the method proposed by von Tscharner [71], where $P_{j,n}$ represents the power for wavelet j at time t_n. Based on another method presented by von Tscharner [72], the STMNF (Equation 1) was obtained by

$$STMNF_n = \frac{\sum_{j=0}^{10} cf_j \cdot P_{j,n}}{\sum_{j=0}^{10} P_{j,n}} \quad (1)$$

and the TI (Equation 2) of the EMG signal was obtained by

$$TI_n = \frac{TI_n'}{MT} \quad (2)$$

where $TI_n' = \sum_{j=0}^{10} P_{j,n}$, and $MT = \max(TI_n')$. After the STMNF and TI were obtained, these data were time normalized to the "cutting cycle" and averaged for each participant. From the averaged STMNF data, values at IC, as well as the integrals for the pre-stance and stance phase of the "cutting cycle", were compared between the female and male soccer players. As for the TI data, total intensity at IC and the timing of the peak, as a percentage of the "cutting cycle" in relation to IC, were reported.

Statistical Analysis. One-way ANOVAs were used to determine if a significant difference exists between genders with regards to the Q-angle, the 3D ankle, knee and hip kinematic variables. As for the EMG variables, one-way ANOVAs were also performed.

Statistical significance was established at alpha (α) < 0.05. All statistical analyses were performed using SPSS software (version 11.5, Chicago, IL). Using data from a pilot study, total sample size was estimated to be 38 athletes for a minimal statistical power of 80% using G*Power Software (version 2.0) [18]. In spite of this, 30 participants were included in the present study due to the greater homogeneity of this group of participants, thus potentially reducing variability in the data, as well as time constraints caused by the complexity and length of the testing session. Furthermore, past studies have demonstrated a count of 30 participants to be adequate to obtain statistically significant results [8,40,50,66].

RESULTS

Although kinematic and EMG data were analyzed for 30 elite soccer players, data from 32 participants were originally collected. Due to malfunctioning of the EMG system, the testing session of participant 1 was ceased without sufficient data collected. Data for participant 6 were found to be inadequate once 3D data reconstruction was performed which was most likely due to an accidentally moved camera(s). For these reasons, data from participant 1 and 6 were excluded from the analysis.

It was our objective to obtain five successful unanticipated cutting trials for each athlete. This was, however, not achieved for two of the participants. For participant 24, one trial was forced to be excluded because the kinematic data were not available for the entire cycle of interest; markers were not in the field of view of at least two cameras at the beginning of the cutting movement. Moreover, only three trials were included in the analyses for participant 3. Two trials were excluded as the cutting movement was found to be performed at an angle inferior to 45°.

As previously described, a successful cutting trial consisted of a cut performed at a 45° angle when the target board illuminated with an orange light, with an approach speed of

4.0-5.0 m/s and with initial ground contact with the force platform. Due to the difficulty of performing this task successfully for a number of five times, the participants required 30 trials on average to do so, ranging from 14 to 51 total trials executed in a testing session.

Q-angle. The quadriceps-angle of the male and female participants standing in an anatomically neutral position was compared. Although the mean angle of the women (mean: 6.96 ± 4.07°) was slightly higher than the men's mean angle (mean: 6.18 ± 4.02°), no significant difference was found ($p > 0.05$).

Kinematics. Hip, knee and ankle three-dimensional joint angles were compared between male and female elite soccer players performing an unanticipated cutting manoeuvre at IC, at the peak joint angles and for the range of motion (ROM) of the cutting cycle. Means and standard deviations for hip positions are presented in Table 1. Men and women exhibited similar hip joint kinematics in both the sagittal and frontal planes ($p > 0.05$), as well as similar hip ROM in the transverse plane ($p > 0.05$). The female participants, however, did perform the cutting task with decreased hip internal rotation at IC ($p=0.013$, $\eta^2=0.20$) and decreased peak hip internal rotation ($p=0.023$, $\eta^2=0.17$) (Figure 2).

Table 1: Means (standard deviations) of hip kinematics, in degrees, between men and women performing an unanticipated cutting task.

Joint	Variable	Men	Women	p-value
At IC	Flexion (+) / Extension (-)	53.25 (7.66)	51.86 (5.26)	0.568
	Adduction (+) / Abduction (-)	-17.61 (7.30)	-13.95 (7.28)	0.179
	Internal (+) / External (-) rotation	8.80 (14.37)	-3.65 (11.23)	0.013*
Peak	Flexion (+)	56.51 (6.79)	55.79 (5.14)	0.746
	Adduction (+)	-12.83 (8.33)	-9.44 (4.35)	0.174
	Internal rotation (+)	14.96 (13.78)	3.87 (11.36)	0.023*
ROM†	Flexion (+) / Extension (-)	66.77 (8.18)	65.54 (8.91)	0.698
	Adduction (+) / Abduction (-)	22.50 (6.06)	23.14 (7.36)	0.795
	Internal (+) / External (-) rotation	21.75 (5.96)	22.73 (5.43)	0.642

† Range of motion (ROM).
* Significant difference between genders ($p < 0.05$).

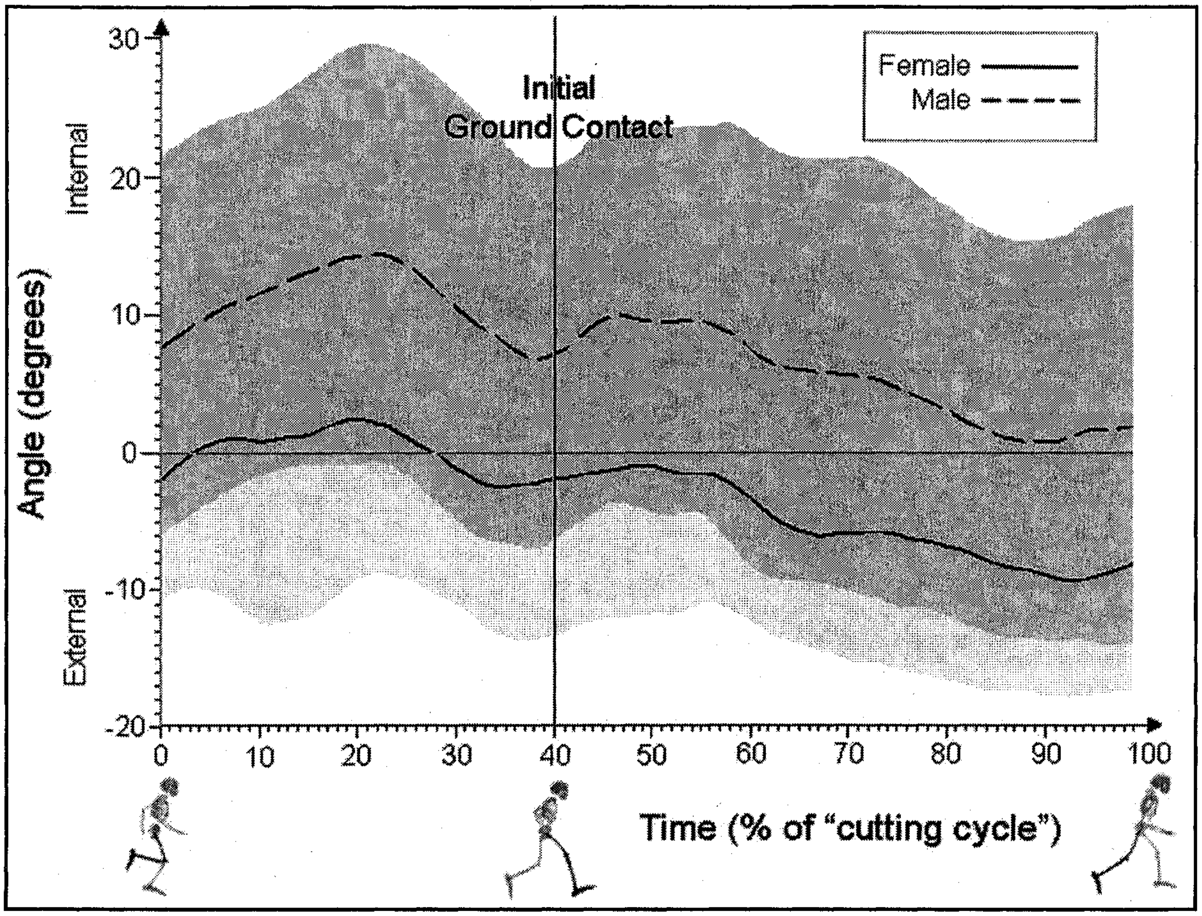

Figure 2: Average (and standard deviation, shaded) hip motion in the transverse plane time-normalized to the "cutting cycle" during an unanticipated cutting task for female and male elite soccer players.

Means and standard deviations for knee positions are presented in Table 2. Men and women exhibited similar knee joint kinematics in both the sagittal and transverse planes ($p > 0.05$), as well as similar knee ROM in the frontal plane ($p > 0.05$). The female participants, however, did perform the cutting task with greater knee valgus angles at IC ($p=0.050$, $\eta^2=0.13$) and greater peak knee valgus angles ($p=0.011$, $\eta^2=0.21$) (Figure 3).

Table 2: Means (standard deviations) of knee kinematics, in degrees, between men and women performing an unanticipated cutting task.

Joint	Variable	Men	Women	p-value
	Flexion (+) / Extension (-)	15.60 (6.11)	17.95 (6.76)	0.326
At IC	Varus (+) / Valgus (-)	1.28 (6.22)	-2.98 (5.10)	0.050*
	Internal (+) / External (-) rotation	0.17 (9.27)	-2.70 (7.26)	0.354
	Flexion (+)	57.36 (5.01)	57.94 (7.28)	0.799
Peak	Valgus (-)	-5.26 (11.28)	-15.31 (8.84)	0.011*
	Internal rotation (+)	22.91 (6.92)	19.81 (5.99)	0.200
	Flexion (+) / Extension (-)	91.14 (15.55)	94.47 (15.05)	0.556
ROM†	Varus (+) / Valgus (-)	22.04 (7.15)	22.05 (4.19)	0.996
	Internal (+) / External (-) rotation	30.32 (8.41)	28.63 (5.51)	0.519

† Range of motion (ROM).
* Significant difference between genders ($p < 0.05$).

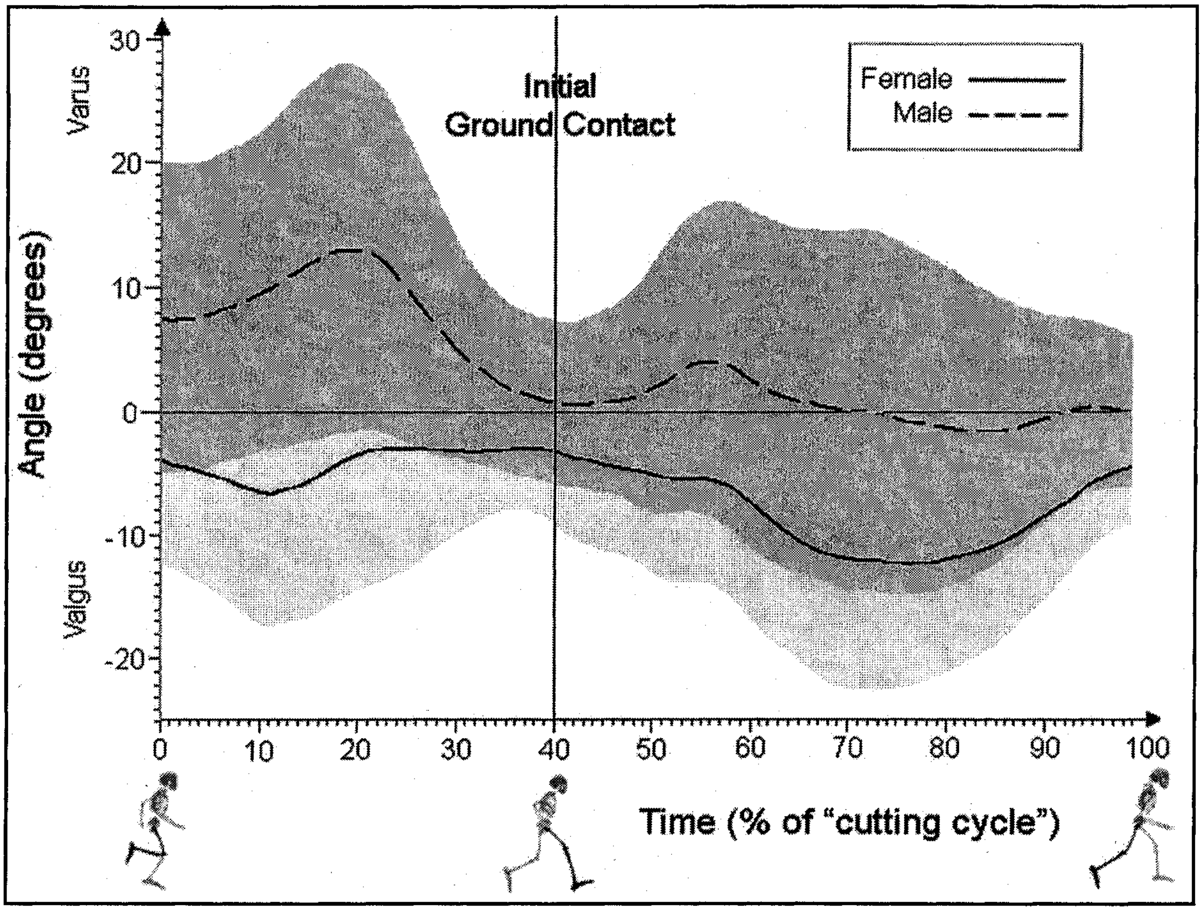

Figure 3: Average (and standard deviation, shaded) knee motion in the frontal plane time-normalized to the "cutting cycle" during an unanticipated cutting task for female and male elite soccer players.

Means and standard deviations for ankle positions are presented in Table 3. Men and women exhibited similar ankle joint kinematics in the sagittal plane ($p > 0.05$), as well as similar ankle ROM in the frontal and transverse planes ($p > 0.05$). The female participants, however, did perform the cutting task with greater ankle pronation at IC ($p=0.041$, $\eta^2=0.14$) and greater peak ankle pronation ($p=0.018$, $\eta^2=0.18$), than did the male participants (Figure 4). The former group also displayed decreased ankle external rotation at IC ($p=0.025$, $\eta^2=0.17$) and decreased peak ankle external rotation ($p=0.039$, $\eta^2=0.14$) (Figure 5).

Table 3: Means (standard deviations) of ankle kinematics, in degrees, between men and women performing an unanticipated cutting task.

Variable	Motion	Men	Women	p-value
At IC	Dorsi (+) / Plantar (-) flexion	2.12 (16.20)	3.05 (8.49)	0.845
	Supination (+) / Pronation (-)	2.87 (3.43)	0.72 (1.81)	0.041*
	Internal (+) / External (-) rotation	-12.96 (12.24)	-4.00 (8.08)	0.025*
Peak	Dorsiflexion (+)	28.90 (7.85)	24.83 (6.09)	0.123
	Pronation (-)	1.74 (3.19)	-0.75 (2.13)	0.018*
	External rotation (-)	-25.87 (10.17)	-18.74 (7.76)	0.039*
ROM†	Dorsi (+) / Plantar (-) flexion	47.10 (8.94)	45.31 (5.32)	0.511
	Supination (+) / Pronation (-)	6.47 (2.69)	7.41 (2.77)	0.352
	Internal (+) / External (-) rotation	26.41 (5.36)	30.29 (7.01)	0.099

† Range of motion (ROM).

* Significant difference between genders ($p < 0.05$).

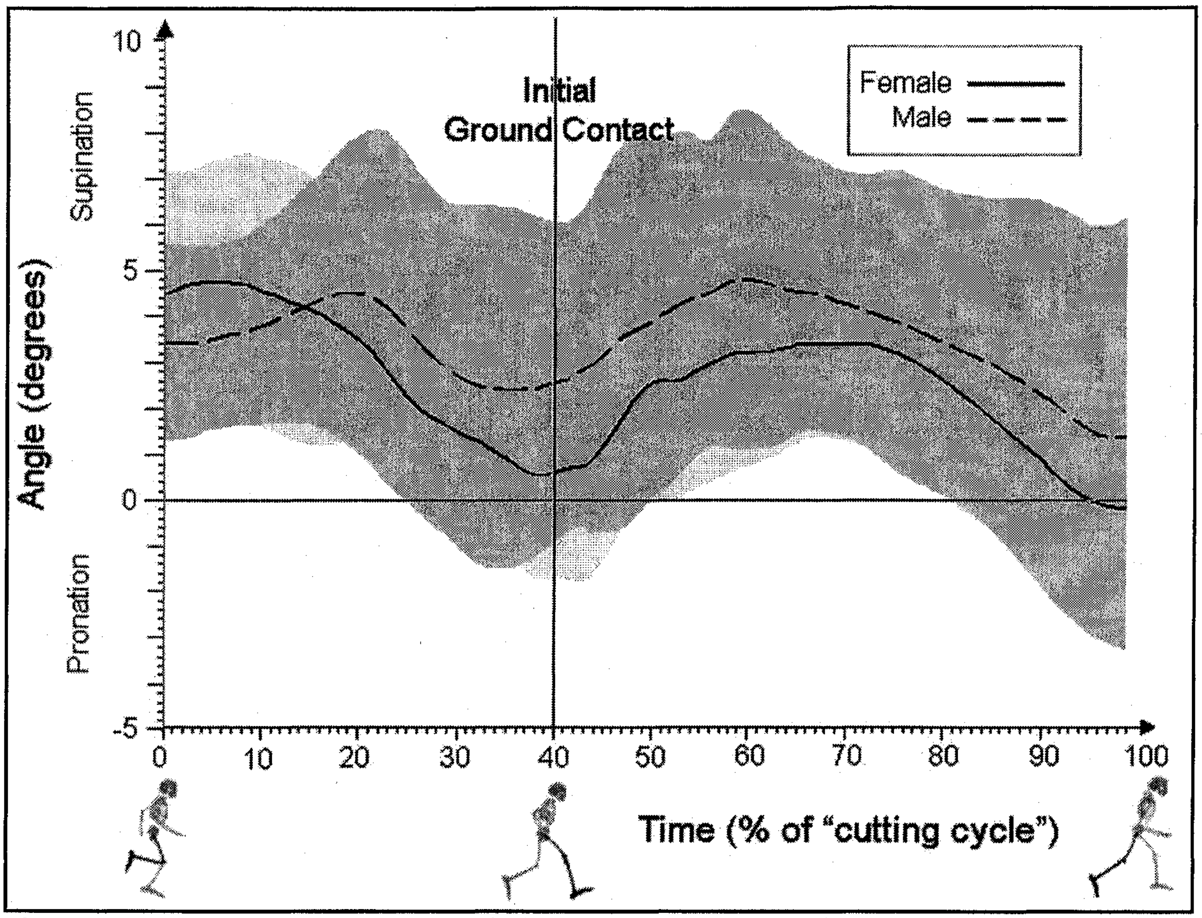

Figure 4: Average (and standard deviation, shaded) ankle motion in the frontal plane time-normalized to the "cutting cycle" during an unanticipated cutting task for female and male elite soccer players.

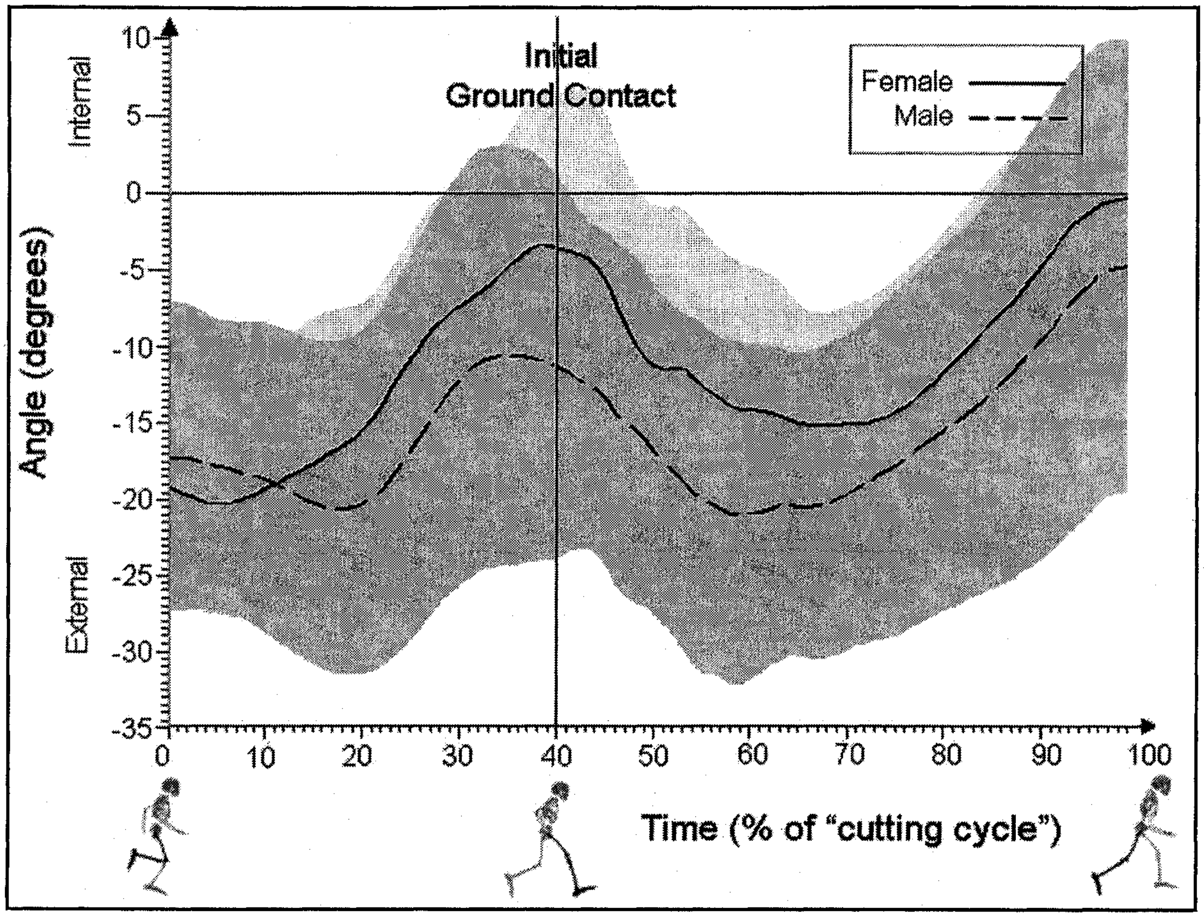

Figure 5: Average (and standard deviation, shaded) ankle motion in the transverse plane time-normalized to the "cutting cycle" during an unanticipated cutting task for female and male elite soccer players.

Electromyography. Right lower limb muscle activity was compared between male and female elite soccer players performing an unanticipated cutting manoeuvre for its timing, amplitude and time-frequency characteristics of the cutting cycle. No gender differences were found with regards to the timing and amplitude variables for the VM, VL, BF and MG ($p > 0.05$). It was found, however, that the onset of the ST occurred significantly sooner for the female athletes (mean: -30.64 ± 7.99%) in comparison with the male athletes (mean: -24.31 ± 8.77%) in relation to IC ($p=0.048$, $\eta^2=0.13$) (Figure 6). A negative value indicates that the event occurred prior to IC. It was also found that women exhibited significantly higher peak RF ($p=0.014$, $\eta^2=0.196$) and LG ($p=0.009$, $\eta^2=0.22$) activity than did men. At

IC, the female soccer players displayed greater TA activity than the male players (p=0.039, η^2=0.14). This former group of athletes also performed the unanticipated cutting task with significantly greater LG activity, as revealed by higher integral values of the LEEMG before (p=0.033, η^2=0.15), as well as after (p=0.004, η^2=0.26), IC. These significant gender differences are illustrated in Figure 6.

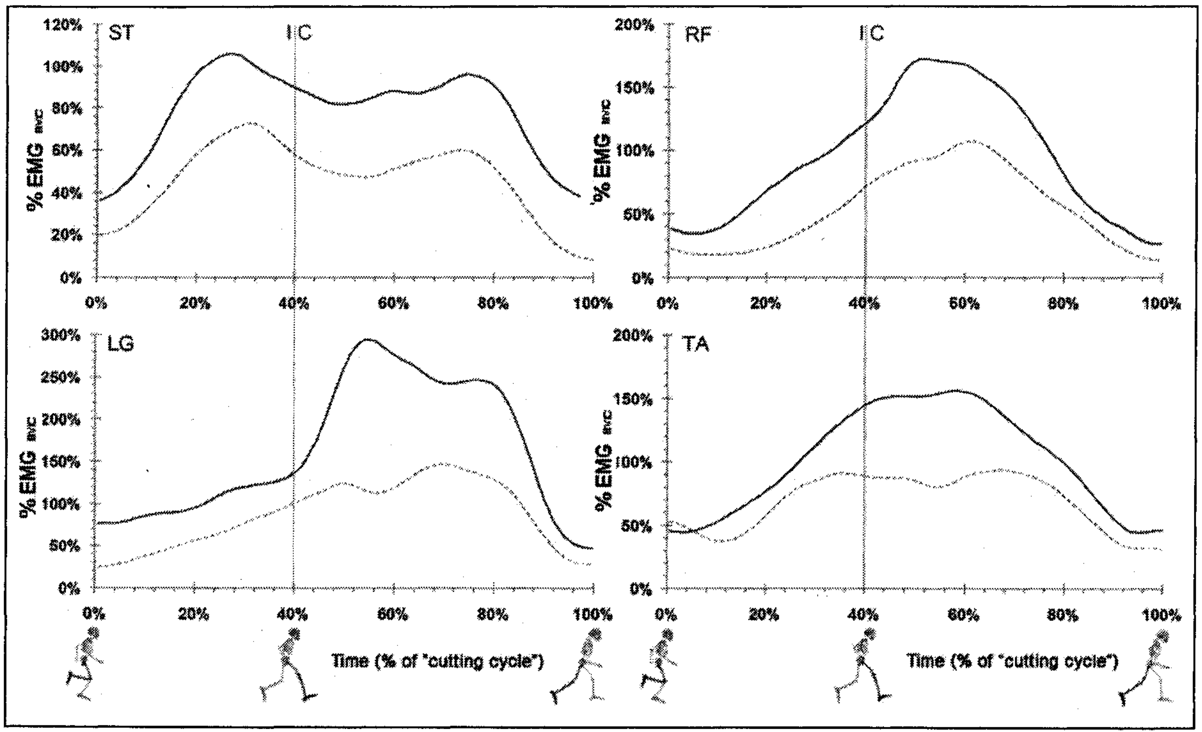

Figure 6: Average activity of the ST, RF, LG and TA time-normalized to the "cutting cycle" during an unanticipated cutting task for female (solid line) and male (dash line) elite soccer players.

As for the time-frequency analysis of the EMG signal by means of non-linearly scaled wavelets, no statistically significant gender differences were found for the ST, MG and LG ($p > 0.05$).

The quadriceps muscle group (Figure 7) showed the highest intensities after IC. The highest frequency components were seen at IC in the case of the vastii muscles and after IC for the RF. These high frequencies were maintained for approximately 30-40% of the cycle. The higher frequencies were, therefore, present at relatively a low total intensity before IC and maintained while the total intensity peaked following IC. These patterns were seen equally for the female and male soccer players, although the men did exhibit higher frequency components at IC for the VL (p=0.011, η^2=0.21) and VM (p=0.010, η^2=0.21), as well as during the stance phase of the "cutting cycle" for the VL (p=0.002, η^2=0.29), RF (p=0.025, η^2=0.17) and VM (p=0.005, η^2=0.25) than did the women.

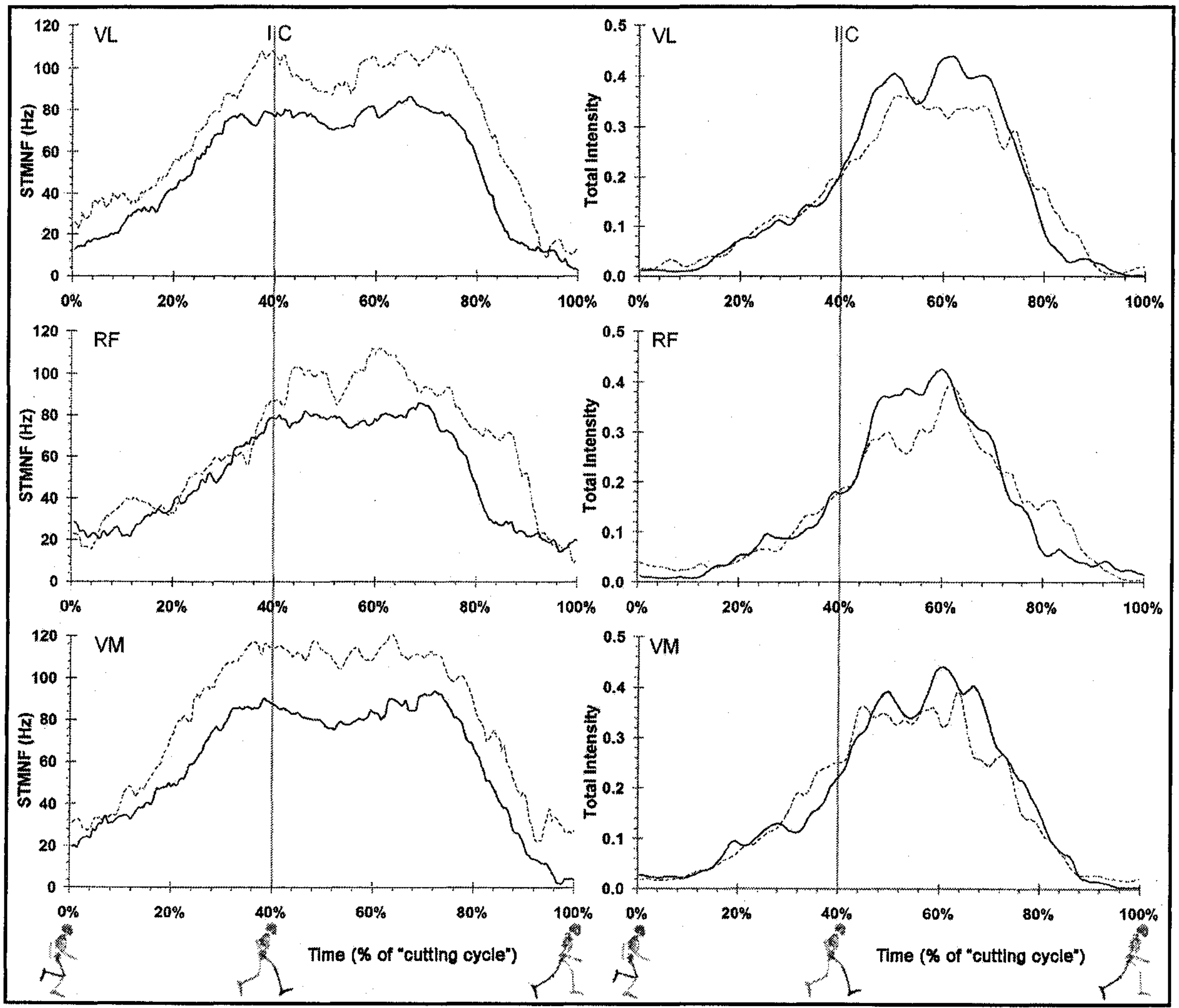

Figure 7: Average STMNF (left side) and TI (right side) of the VL, RF and VM time-normalized to the "cutting cycle" during an unanticipated cutting task for female (solid line) and male (dash line) elite soccer players.

For the hamstrings muscle group (Figure 8), the STMNF is characterized by a peak in high frequencies prior, as well as after IC. The male athletes, however, do not seem to display this decrease in frequency immediately after IC for the BF, as did the female athletes.

For this reason, the men recorded significantly higher frequency components at IC than the women for the BF ($p=0.034$, $\eta^2=0.15$). The peak TI somewhat mirrored the peak frequencies observed prior to IC. In other words, these higher frequency components dominated the pre-stance phase where the TI peaked prior to IC; although, this peak TI occurred significantly sooner for the women than the men for the BF ($p=0.026$, $\eta^2=0.16$). Following IC, the high frequency components observed were paralleled by an increase in TI, but to a lesser extent than the peak observed prior to IC. Hence, the higher frequency components were less dominant after than before IC.

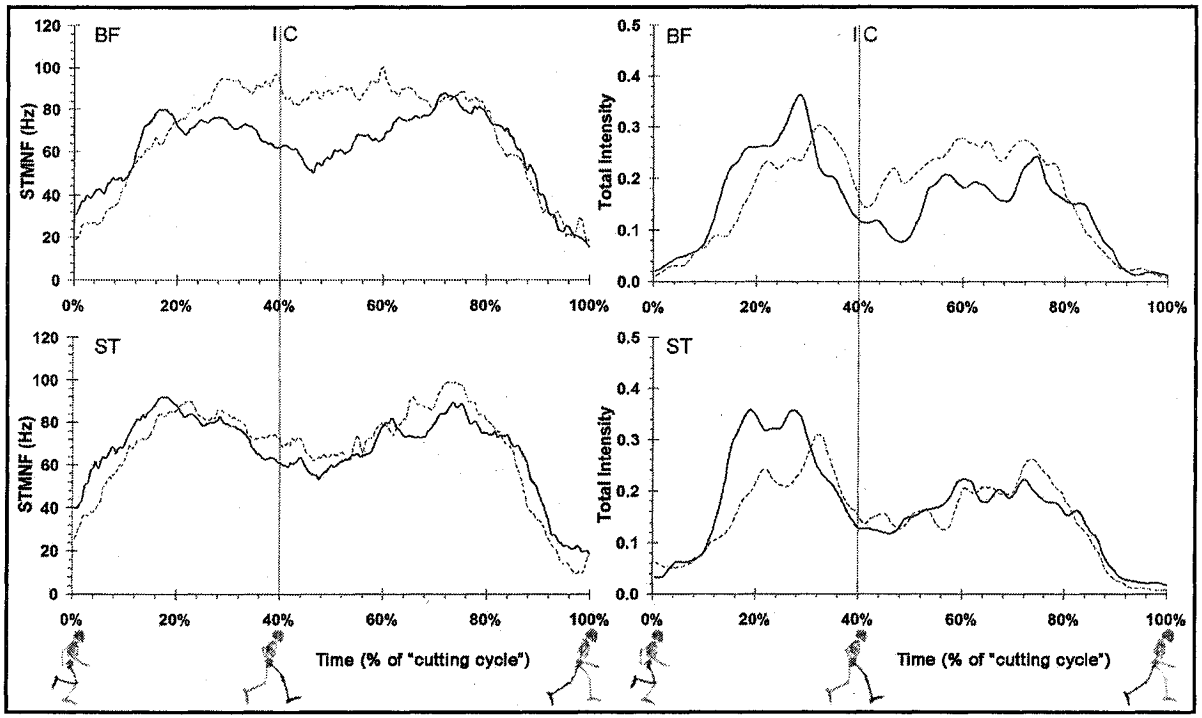

Figure 8: Average STMNF (left side) and TI (right side) of the BF and ST time-normalized to the "cutting cycle" during an unanticipated cutting task for female (solid line) and male (dash line) elite soccer players.

The MG and LG (Figure 9) displayed its highest frequency components after IC, as the athletes were approaching the propulsion portion of the stance phase, which was mirrored by a similar increase in TI. Consequently, the lower frequencies were seen at low intensity prior to IC, while the higher frequencies dominated the EMG signal at approximately 80% of the “cutting cycle”. The women, however, seemed to maintain the higher frequency components of the signal for a longer period time for the LG, although no significant gender differences were found for the gastrocnemius muscles ($p > 0.05$). As for the TA, it was found to be very active with high frequency components present for approximately the middle 60% of the cycle, with a small decrease in frequency 20% after IC. While the male soccer players' TI increased to its peak prior to IC and thereafter progressively decreased, the female players' TI continued to gradually increase until it reached its peak approximately 20% after IC. As a result, the women's TI peak occurred significantly later than did the men's peak ($p=0.003$, $\eta^2=0.28$).

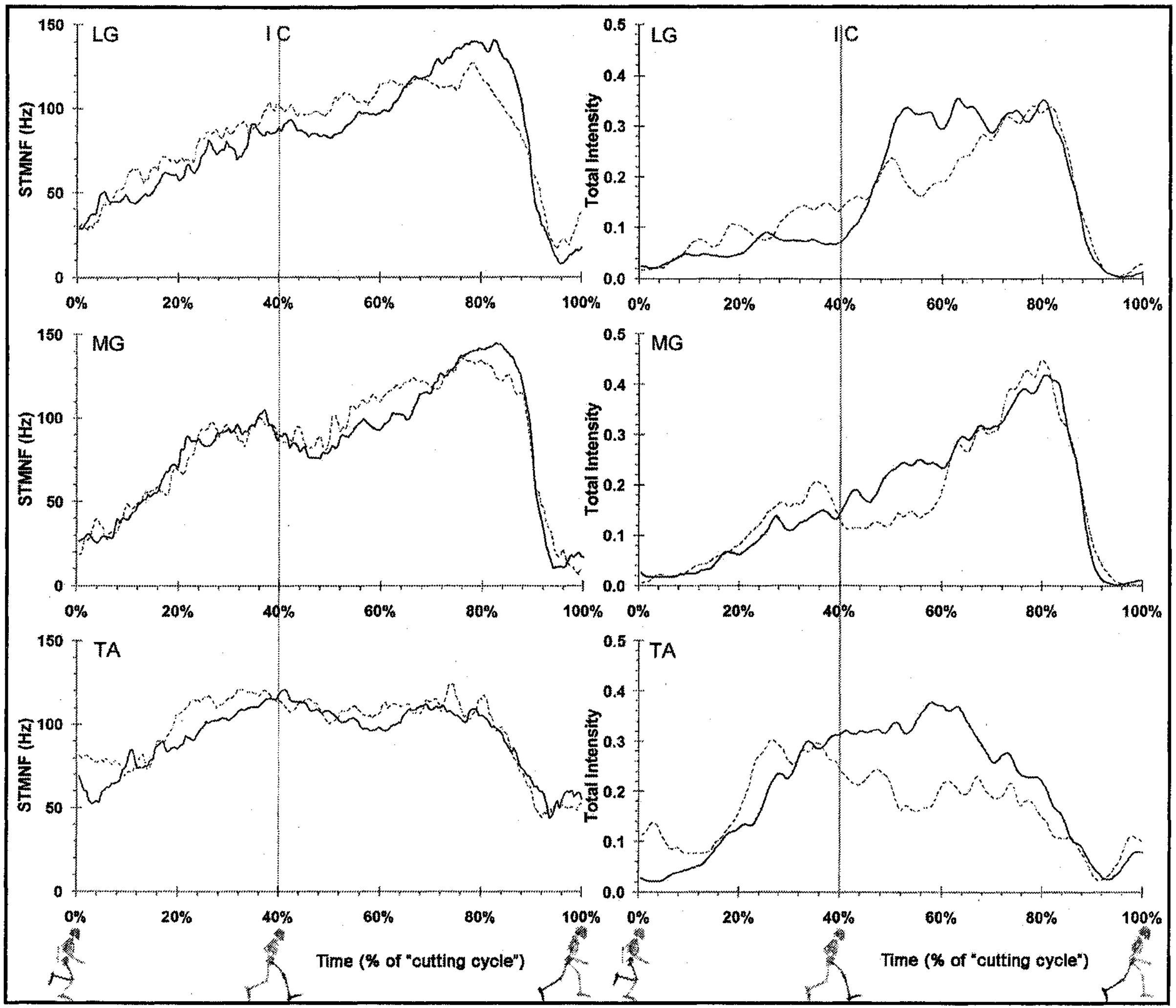

Figure 9: Average STMNF (left side) and TI (right side) of the LG, MG and TA time-normalized to the "cutting cycle" during an unanticipated cutting task for female (solid line) and male (dash line) elite soccer players.

A summary of the statistically significant gender differences for the EMG variables is presented in Table 4.

Table 4: Means (standard deviations) of statistically significant EMG variables between men and women performing an unanticipated cutting task.

Variable	Muscle	Men	Women	p-value
Timing of onset (% of cycle)	ST	-24.31 (8.77)	-30.64 (7.99)	0.048
Peak activity (% EMG_{MVIC})	RF	120.71 (91.59)	215.95 (107.41)	0.014
	LG	190.58 (135.27)	373.41 (215.30)	0.009
LEEMG at IC (% EMG_{MVIC})	TA	88.98 (61.57)	141.94 (72.15)	0.039
LEEMG Integral pre-IC	LG	0.1053 (0.0685)	0.1812 (0.1118)	0.033
LEEMG Integral post-IC	LG	0.3048 (0.2154)	0.5635 (0.2305)	0.004
STMNF at IC (Hz)	VL	99.34 (21.08)	79.00 (19.97)	0.011
	VM	112.78 (25.97)	88.83 (21.38)	0.010
	BF	89.20 (41.12)	61.75 (24.14)	0.034
STMNF Integral post-IC	VL	47.72 (13.62)	34.65 (6.49)	0.002
	RF	47.49 (17.02)	35.58 (9.59)	0.025
	VM	54.00 (14.78)	38.55 (12.60)	0.005
Timing of peak TI (% of cycle)	BF	-7.12 (5.54)	-12.35 (6.64)	0.026
	TA	1.61 (14.27)	20.33 (16.66)	0.003

DISCUSSION

Much research has been undertaken to gain insight on the gender bias with regards to noncontact ACL injuries by means of lower limb kinematic analyses of subjects performing a cutting manoeuvre [23,39,46,49,50,56,66]. Few, however, have done so while the participants performed unanticipated cutting tasks, which better represent a typical noncontact ACL injury environment, as oppose to performing this manoeuvre in an anticipated manner [23,56]. Of these, none have performed a neuromuscular control analysis by means of EMG. Furthermore, to our knowledge, no studies to date have executed a time-frequency analysis using wavelets with regards to ACL injuries and gender differences. For this reason, the present study was carried out to compare muscle activation patterns and lower limb kinematics between female and male elite soccer players performing an unanticipated cutting manoeuvre. Significant kinematic gender differences were found in all three joints. Differences were also found with regards to muscle activation patterns displayed by the athletes.

Mean Q-angle data were found to be similar to those reported previously by Moul [52], both in terms of mean angles measured and lack of significant gender differences. Other results, however, revealed a gender bias with regards to Q-angle measurements, as well as greater angle values in comparison with results of the present study [31,70]. This discrepancy with the literature could be attributed to the methods utilized to measure the angle and in the characteristics of the participants. In the present study, the participants' Q-angle was measured with a precise motion analysis system while other studies simply used a goniometer to obtain measurements of physically active individuals, not necessarily elite athletes. Furthermore, participants of the present study were measured in a shod condition, which could potentially explain the lower Q-angle values obtained.

Kinematics. The findings of the current investigation support our hypothesis that women display less hip internal rotation angles than men. Both genders performed the stance phase of the cutting task with initial hip internal rotation, followed by an external rotation. Indeed the shape of the curves was similar between genders. The position of the mean hip rotation curve of the female group, however, was shifted toward external rotation in comparison with the male group (Figure 2). Of the few studies that have assessed 3D hip kinematics during a cutting manoeuvre, McLean et al. [49] found similar results in terms of the movement patterns, as well as in terms of peak internal hip rotation angles. Conversely, we had to reject our hypothesis that women would display less hip flexion. No significant gender differences were found for hip motion in the sagittal, as well as in the frontal plane, although the female athletes tended to display, on average, lower hip flexion and abduction angles. Consequently, the transverse plane movement of the hip might play a more important role in placing strain on the ACL in comparison with sagittal and frontal plane hip kinematics.

Results found for knee kinematics support our hypothesis that women display greater knee abduction angles during the cutting manoeuvre, than men. The female athletes displayed greater knee abduction angles at IC and greater peak knee abduction angles (Figure 3). Similar results were found by several groups of researchers [23,46,49,50] who also assessed kinematics of the knee during a cutting task. All the female participants in the current study exhibited peak frontal plane knee angle in a valgus position, whereas six of the 15 male participants remained in knee varus throughout the stance phase. With such greater knee abduction angles, these female athletes are placing greater strain on their ACL, as this passive structure plays a role in controlling movement of the knee in the frontal plane [35]. Moreover, our hypothesis stating that the female participants were expected to perform the cutting manoeuvre with less knee flexion and greater knee external rotation motion is rejected, as no significant gender differences were found with regards to those kinematic variables. Results from several studies confirm the results found in the present investigation [23,50,56,66]; others, however found differences when comparing knee motion in the sagittal and transverse planes between genders [39,46,49]. These differences might be attributed to variation in the methodology utilized. For instance, Malinzak and colleagues [46] tested recreational female athletes in an anticipated cutting condition who were found to display lower knee flexion angles than their male counterparts. These recreational athletes might have a lower muscular capacity to control knee motion such that they rely further on passive tissues (i.e., ligaments) to absorb a considerable amount of the ground reaction forces. In addition, McLean et al. [49] and James et al. [39] had their participants perform the cutting task at a 30°-40° angle and 60° angle, respectively, as oppose to the 45° that was used in the present study, as well as in most other studies. As stated by another study conducted by McLean and collaborators [48], "sagittal plane [knee] biomechanics cannot injure the ACL during sidestep cutting". Consequently, motion of the knee in the frontal and the transverse planes might bear more importance on an individual's risk to sustain a noncontact ACL injury.

As opposed to the knee joint, no published studies to our knowledge has investigated motion at the ankle joint in all three planes and few have done so solely in the frontal plane while assessing a cutting task [23,49]. Results found in the present investigation do coincide with past research as well as support our hypothesis that the female group would execute the unanticipated cutting manoeuvre with greater ankle pronation angles in comparison with the male group (Figure 4). Both studies that have examined frontal plane ankle kinematics during a cutting task also found the women to display greater ankle pronation angles. The participants of the current study did, however, display a smaller range of ankle motion in the frontal plane, as opposed to the literature. This deviation might be due to differences in footwear and/or differences in the population participating in these studies. McLean et al. [49] did not describe the characteristics of its population, whereas Ford et al. [23] assessed a young population of basketball players (i.e., middle and high school). Gender differences were also found in the transverse plane – the female athletes performed the cutting task with less ankle external rotation than the male athletes (Figure 5). This finding seems counterintuitive as one would expect the ankle to be more externally rotated given that the knee is in a greater valgus position and the ankle in greater pronation. Since the participants were tested in a shod condition and skin reflective markers were used, some of these markers were placed on the shoe. It is, therefore, possible that the exact motion of the foot inside the shoe was not accurately measured, as observed by Reinschmidt et al. [57]. This method, however, is commonly used in the literature as it is more important for participant to perform athletic manoeuvre with proper footwear. It is also worth mentioning that 3D kinematic motion of the hip, knee and ankle were within anatomical limits, as described in the literature [54].

Electromyography. The results for the present study support, in part, our hypothesis that women would perform an unanticipated cutting task with greater normalized quadriceps activity than their male counterparts. Although no significant gender differences were found for the VM and VL, women did execute the cutting task with greater peak RF activity (Figure 6). This increased quadriceps activation has also been reported by others who have assessed various athletic tasks, such as cutting and single-leg squatting [46,66,80]. Such muscle activation patterns may place the ACL at risk of injury since activity of the quadriceps, which insert on the proximal anterior portion of the tibia (i.e., tibial tuberosity), causes an anterior tibial-femoral shear force, thus straining the ACL – a passive structure that is mainly responsible for limiting anterior translation of the tibia in relation to the femur [43,58]. Although it is believed that these sagittal plane forces are not large enough to be solely responsible for an ACL injury [48], this greater quadriceps activity may increase risk of injury if combined with other neuromuscular and/or kinematic factors (i.e., increase knee valgus motion).

It was predicted that the male elite soccer players would exhibit greater normalized hamstrings activity given that this activity acts as an agonist to the ACL to decrease anterior tibial translation with respect to the femur, bearing in mind women's higher susceptibility to ACL injuries than men. This, however, was not found among the results for the current investigation. No significant differences were found in the level of activation of the hamstrings, although it does not appear to be so in Figure 6 (ST), which illustrates the female group activating their medial hamstrings up to 100% of their EMG_{MVIC}, in comparison with the male group who only achieved 70%. This lack of gender significance might be caused by the high variability inherent to the EMG signal, seeing as relatively high standard deviation values were obtained for the LEEMG's integral, and also by the choice of normalization method [4]. Similar results were found among other studies examining gender differences pertaining to cutting, landing and walking tasks. While some researchers [19,66] found no significant gender differences in the level of hamstring activity, others [16,59,63] found it to be significantly greater in women. In contrast, Malinzak et al. [46] did find hamstring activity to be less in a female group performing a cutting task than a male group; however, recreational athletes were compared as opposed to elite athletes. This difference in level of play might be linked to a distinction in one's ability to achieve knee stability by means of hamstring activation. Hence, this greater medial hamstring activity seen in the present study's female group of athletes – though not statistically significant – might be a compensatory mechanism to offset increased knee joint laxity found in women [6,32,33,59], seeing as the participants of the present study have successfully avoided injury while competing at an elite level. In other words, these athletes have achieved functional joint stability. Alternatively, it is also possible that the women had a decreased capacity to generate a maximum contraction, which indicates that they are using a greater percentage of this maximum contraction to maintain joint stability. With time, this increased level of hamstring activity may cause fatigue, which may lead to injury.

With regards to hamstring muscle activation patterns, it was also found that the female soccer players exhibited a medial hamstring onset further in time to IC than the male players, both occurring prior to IC. Cowling and Steele [13] found similar results during abrupt landings. As they explained, this delayed hamstrings onset exhibited by the male group may perhaps provide a peak muscle activity that better coincides with the peak anterior tibio-femoral shear force that is generated immediately after IC, thus better protecting the ACL against such force given that the hamstrings are known to be agonists to the ACL. It is thus suggested that the male participants of the present study exhibited neuromuscular control of their medial hamstring that may be more protective to the ACL than the female group.

In comparison with studies that have examined hamstring and quadriceps activity during cutting and landing tasks, few have done so for the gastrocnemius and none for the tibialis anterior [13,59]. Of these studies, no significant gender differences were found for this lower leg muscle group. Conversely, the current investigation found that the women executed the cutting task with greater lateral gastrocnemius and tibialis anterior activity (Figure 6). This discrepancy with the literature might be once again due to methodological differences. While the participants of the present study performed an unanticipated cutting manoeuvre, the other studies assessed anticipated landings. Furthermore, results from previous studies have associated contraction of the gastrocnemii with stability of the knee joint by resisting anterior tibial translation [55,65]. Others, however, have proven that this group of muscles might in fact oppose ACL functionality by producing strain on this structure [20]. If the gastrocnemii do indeed provide knee joint stability, this increased activity could indicate a compensatory mechanism exhibited by the female athletes, similar to the women's increased hamstrings activity. If the opposite holds true, this greater lateral gastrocnemius activation may place an increased strain on the ACL, placing it at a larger risk of injury. Consequently, the role of the gastrocnemii is unclear and thus needs further investigation. Although, the role of the tibialis anterior is not directly related to the knee joint or the ACL's functionality, it can be directly associated with the ankle joint – capable of affecting the knee joint as part of the entire kinematic chain of the lower limb. To our knowledge, no published study has investigated its role in ACL injuries and gender differences, with the exception of the present one. It was found that female elite soccer players performed the cutting trials with greater TA activity, as opposed to the male players (Figure 6). These high EMG_{MVIC} values obtained (i.e., nearly 300% of EMG_{MVIC}), as seen in Figure 6, may be a result of a lack of ability to produce a true maximum contraction or the choice of normalization method [4]. Originating on the lateral aspect of the tibia and inserting on the medial aspect of the foot (i.e., cuneiform, first metatarsal), this superficial muscle plays a main role in dorsiflexion, as well as a secondary role in supination of the foot. As discussed earlier, the female participants of the current investigation performed the cutting task with greater foot pronation. No significant gender difference, however, was present for ankle plantar/dorsiflexion angles. More information is therefore necessary to clearly explain this difference in TA activity between the male and female participants.

Regarding the time-frequency analysis of the EMG signal, it was found that the female participants generally performed the cutting manoeuvre at lower frequencies of muscle activation, which supports the last hypothesis that men would produce higher mean frequencies. This was especially true for the quadriceps, as well as the lateral hamstring (Figure 7 & 8). Although no published studies, to our knowledge, have executed a time-frequency analysis using wavelets with regards to ACL injuries and gender differences, White and colleagues [74] have explored this gender bias topic comparing mean power frequency by means of fast Fourier transformation analysis. As mentioned earlier, the wavelet analysis is known to be a more powerful frequency analysis tool. Nonetheless, these researchers found no significant differences for both the quadriceps and the hamstrings between the male and the female group of participants, who executed bouts of isokinetic flexion and extension exercises, although the hamstrings' mean frequency tended to be greater for the men. Had these participants performed a more dynamic activity, such as the one performed in the present study, results might have been able to significantly discriminate between genders. Consequently, the variation between the results of our study and the latter may be a result of the type of activity that was assessed, as well as the frequency analysis method utilized. It remains, however, that similarities are present between the results of both studies. Both parties observed an increased mean frequency in the hamstrings of the male athletes as opposed to the female athletes. It appeared that similar results were also found if one visually examined STMNF diagrams published in paper by von Tscharner and Goepfert [72]. Although not specifically assessed, nor stated in the study's results, it appeared that the male group of runners contracted their hamstrings and quadriceps at higher mean frequencies. Furthermore, STMNF and TI patterns were found to be similar between genders, with some exceptions, and to those found in the literature [72]. A decrease in high frequency components at IC was observed in women with regards to the BF, as the men maintained these high frequencies. These high frequency components dominated the EMG signal closer in time to IC in comparison with the female athletes. Since the literature illustrates that as faster motor units are recruited, higher frequencies emerge from the EMG power spectra [69,73], these gender differences might be to the advantage of the men with regards to ACL injury risk. As the hamstrings are known agonists to the ACL, their activation at higher velocities and closer in time to IC – when highest strain is placed on the ACL – may suggest a more efficient preparation to anterior tibial translation, and in turn a better protection against ACL rupture.

Although efforts were made to mimic a typical noncontact ACL injury environment, an illuminated target board is not a direct replacement for a defender or projectile. There needs to be a balance, however, between internal and external validity. In other words, there needs to be a balance between the degree to which variability is reduced to increase the certainty that the independent variable causes a change or lack of change and the capacity to generalize the results. A defender could have been utilized to force the participants to perform a cutting task, though this present investigation's strong internal validity would have been reduced thus diminishing its overall validity. In addition, to further reduce the effect of variability of the EMG signal, data from a greater number of trials and participants could have been utilized, thus possibly exposing gender differences that were otherwise concealed by high variability. Furthermore, as with most studies obtaining kinematic measurements, skin markers were used to estimate the underlying skeleton's movement, thus influencing the accuracy of the measurements. It was been found that skin markers provided an overestimation of the movement of the skeleton [5]. It is assumed, however, that potential error cause by skin motion artifact is affecting both men and women in a similar manner. To obtain a better overall representation of the cutting manoeuvre and thus gain a more thorough understanding of how gender differences relate to noncontact ACL injuries, future investigation may replicate a similar protocol with the addition of a kinetic analysis, by means of inverse dynamics, of the lower limb. Such a kinetic analysis may help researchers gain insight on the effect of muscle activation patterns and its link with lower limb kinematics.

CONCLUSION

The results of this study confirm that women execute a cutting task with greater knee valgus angles than men. Other kinematic gender differences that may be detrimental to one's ability to minimize strain on the ACL were observed, such as greater rotations at the hip and pronation angles of the foot in the female athletes. Furthermore, the male group displayed neuromuscular control strategies that may be more protective to the ACL. They contracted their quadriceps less and delayed medial hamstring onset such as to better synchronize its activity with peak anterior tibio-femoral translation, thus minimizing strain on the ACL. The female group, however, displayed strategies that may also assist in achieving functional joint stability given that these women have succeeded in avoiding ACL injury. Even though the female athletes did appear to contract their hamstrings to a greater extent, the male athletes activated this group of muscle at higher frequencies, which might indicate a more efficient neuromuscular control strategy. It may be possible that it is the frequency at which one activates a muscle to sustain joint stability that is important and to a lesser degree the magnitude of activity. Further investigation is needed to better understand the role of the frequency components of muscle activation in joint stability and injuries.

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APPENDIX A

THESIS PROPOSAL

CHAPTER I: INTRODUCTION

As demonstrated by previous studies (Arendt & Dick, 1995; Arendt, Agel, & Dick, 1999; Ireland & Wall, 1990; Lindenfeld, Schmitt, Hendy, Mangine, & Noyes, 1994; Malone, Hardaker, Garrett, Feagin, & Bassett, 1993; Mihata, Beutler, & Boden, 2006; Zelisko, Noble, & Porter, 1982), women injure their anterior cruciate ligament (ACL) two to eight times more frequently than their male counterparts in noncontact situations, especially in sports involving many jumping/landing and planting/cutting tasks, such as soccer, basketball and volleyball (i.e., "high risk" sports).

Most ACL injuries seen in women athletes occur by means of two main injury mechanisms: a plant-and-cut movement or a one-legged landing (Boden, Dean, Feagin, & Garrett, 2000; Hutchinson & Ireland, 1995; Olsen, Myklebust, Engebretsen, & Bahr, 2004). In such situations, the hip is most often internally rotated and adducted, the knee is in valgus and slight flexion (20-30°) and the foot is pronated, thus causing an external rotation of the tibia (Boden et al., 2000; Ireland, 2000b). This so-called position of no return puts the ACL at risk of injury due partly to the fact that in full knee extension, all fibres of the ACL are under tension. Furthermore, the ACL is the principal structure that limits anterior tibial translation and is a secondary structure in controlling varus and valgus forces (Dye & Vaupel, 2000; Inoue, McGurk-Burleson, Hollis, & Woo, 1987). Hence, a knee in valgus position and near complete extension as well as a rotated tibia causes strain of the ACL.

Although much attention has been given to uncovering the cause of such gender discrepancy with regards to noncontact ACL injuries, the exact origin of this divergence has yet to be determined. However, three types of contributory factors have been identified. The most simplistic factor is anatomical in nature. A study conducted by Anderson, Dome, Gautam, Awh and Rennirt (2001) revealed that the male ACL is relatively greater in size in comparison with women. Furthermore, women's greater Q-angle and smaller intercondylar notch are anatomical factors that are thought to possibly predispose them to a higher risk of noncontact ACL injuries (Arendt, 2001).

A second factor pertains to hormonal differences between genders. Wojtys, Huston, Boynton, Spindler and Lindenfeld (2002b) have found that a significantly greater than expected percentage of ACL injuries occurred during the ovulatory phase and a less than expected percentage occurred during the luteal phase of the menstrual cycle. The expected percentages used in this study were calculated by dividing the length (in days) of a specific phase by the total length of the cycle. Similar results were found by Beynnon and colleagues (2006) among female recreational alpine skiers. By dividing the menstrual cycle into two rather than three phases – the preovulatory (combination of follicular and ovulatory) and postovulatory (luteal) phases, it was found that skiers in the former phase were more likely to sustain a tear to their ACL. Moreover, female sex hormones – estrogen, progesterone, relaxin – have been reported to increase ligamentous laxity and decrease neuromuscular performance, thus they may decrease passive and active knee stability resulting in an increased risk of injury (Hewett, 2000). Others (Beynnon et al., 2005; Hertel, Williams, Olmsted-Kramer, Leidy, & Putukian, 2006), however, have observed a lack of change in knee joint laxity and neuromuscular control over the duration of the menstrual cycle. It is also believed that oral contraceptives stabilise hormone levels during menstrual cycle and may stabilise the knee joint. Hence, women who use oral contraceptives may be less susceptible to athletic musculoskeletal injuries compared with non-users (Arendt, 2001).

The third factor is currently the most complex and explored – neuromuscular. Women are subject to display neuromuscular behaviours that predispose them to noncontact anterior cruciate ligament injuries. Hewett, Myer and Ford (2001) adequately summarize the neuromuscular contributory factors with the so-called "three-way neuromuscular imbalance": (1) Females tend to be *ligament-dominant*; therefore they allow knee ligaments, instead of their musculature, to absorb a considerable portion of the ground reaction forces. Accordingly, various studies have demonstrated that women execute landing and cutting tasks with lower angles of knee flexion (Colby et al., 2000; Decker, Torry, Wyland, Sterett, & Richard Steadman, 2003; James, Sizer, Starch, Lockhart, & Slauterbeck, 2004; Malinzak, Colby, Kirkendall, Yu, & Garrett, 2001; McLean, Lipfert, & van den Bogert, 2004b; McLean, Neal, Myers, & Walters, 1999; Salci, Kentel, Heycan, Akin, & Korkusuz, 2004; Sell et al., 2006; Yu et al., 2005) and greater knee valgus angles (Ford, Myer, & Hewett, 2003; Ford et al., 2006; Ford, Myer, Toms, & Hewett, 2005; Hewett, Myer, & Ford, 2004; Kernozek, Torry, Van Hoof, Cowley, & Tanner, 2005; Malinzak et al., 2001; McLean et al., 2004b; McLean et al., 1999; Sell et al., 2006) than men. (2) Women display a *quadriceps imbalance* in relation to their hamstrings. Hence, several studies have revealed that women display a quadriceps activation preference (Colby et al., 2000; Cowling & Steele, 2001; Malinzak et al., 2001; Sell et al., 2006; White, Lee, Cutuk, Hargens, & Pedowitz, 2003). (3) Women also exhibit a *leg dominance*, which means that their dominant limb often demonstrates greater strength and coordination. Furthermore, it has been demonstrated that EMG mean frequency is dependant of the conducting velocity during motor unit recruitment (Solomonow et al., 1990; Wakeling & Rozitis, 2004), which might identify a recruitment control strategies employed by various muscles.

Of the three types of factors, the neuromuscular factors seem to be more convincing in explaining the gender discrepancy with regards to noncontact ACL injuries. Furthermore, neuromuscular factors have a possibility for modification to reduce a woman's risk of sustaining an ACL injury, as opposed to anatomical factors. For this reason, additional research is needed to determine the exact cause of this increased risk experienced by women. By doing so, prevention programs can be developed to reduce this risk, and thus reduce this gender divergence with regards to ACL injuries.

Consequently, the purpose of this study is to compare the time-frequency characteristic, using non-linearly scaled wavelets, the amplitude and the timing of recruitment of the electromyography (EMG) signal, as well as the three-dimensional kinematics, of the lower limb of female and male elite soccer players performing an unanticipated cutting manoeuvre. Hence, the independent variable is gender, while the dependant variables are lower limb neuromuscular and three-dimensional (3D) kinematic variables. Specifically, the neuromuscular variables are the following: time-frequency characteristic, timing of muscle contraction onset and peak in relation to initial foot-contact (IC), amplitude of muscle activity as a percentage of maximum voluntary isometric contraction (MVIC) at the time of peak and IC, integrals of the linear envelop EMG (LEEMG) of the semitendinosus (ST), biceps femoris (BF), vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), medial (MG) and lateral gastrocnemius (LG) and tibialis anterior (TA) during the pre-stance and stance phases. Three-dimensional kinematic variables were also measured. The range and maximum values for ankle, knee and hip flexion/extension, external/internal rotation and abduction/adduction during the pre-stance and stance phases, as well as, the values for the above-mentioned movements at IC, are dependant variables. These variables were calculated by means of an unanticipated cutting manoeuvre. Specifically, the athletes approached a force plate, triggered a stimulus (i.e., a light indicating the movement that the athlete must perform) at 1.5 metres from the force plate and thus executed the appropriate movement. The participant executed a straight ahead run, a 45° cutting manoeuvre or a jump stop.

Relevancy

Although many studies have been undertaken, no exact cause for the gender discrepancy found in noncontact anterior cruciate ligament injury rate has yet been determined. Many factors have indeed been identified, including a gender difference in neuromuscular control of the lower limb. This latter factor, however, needs further investigation. Though relative muscle activation and its timing have been examined, the time-frequency characteristic has yet to be explored. Therefore, by performing a time-frequency analysis by means of the non-linear scaled wavelets, new information regarding the neuromuscular control strategies of men and women was acquired.

Hypothesis

It is believed that there exists a significant difference between genders with respect to neuromuscular control, which is thus observed in kinematic data. Various studies have demonstrated that women execute plant-and-cut and landing tasks with lower angles of knee flexion (Colby et al., 2000; Decker et al., 2003; James et al., 2004; Malinzak et al., 2001; McLean et al., 2004b; Salci et al., 2004; Sell et al., 2006; Yu et al., 2005), greater knee valgus angles (Ford et al., 2003; Ford et al., 2005; Hewett et al., 2004; Kernozek et al., 2005; Malinzak et al., 2001; McLean et al., 2004b; Sell et al., 2006) and smaller internal rotation angles (McLean et al., 2004b) than men. It has also been shown that women display smaller hip flexion angles and greater hip internal rotation and ankle pronation angles. Hence, it was predicted that the women would display less knee and hip flexion and greater knee abduction and external rotation and hip internal rotation angles, as well as greater ankle pronation angles, at IC during the plant-and-cut manoeuvre. As studies have revealed that women display a quadriceps activation preference (Colby et al., 2000; Cowling & Steele, 2001; Sell et al., 2006; White et al., 2003), women were predicted to exhibit less hamstrings activation, as well as greater quadriceps activation, than the male athletes. Furthermore, it has been demonstrated that EMG mean frequency is dependant of the conducting velocity during motor unit recruitment (Solomonow et al., 1990; Wakeling & Rozitis, 2004), which might identify recruitment control strategies employed by various muscles. Consequently, it was hypothesized that the male athletes would produce higher mean frequencies and intensities of the EMG signals.

Definitions

For the purpose of this study, an elite soccer player was considered to be an individual with a minimum of five years of soccer experience who is playing at the university/collegiate or premier level. In addition, the term "abduction/adduction" was used to describe a motion in the frontal plane, as well as "valgus/varus", which is occasionally used by other authors. These terms were therefore applied interchangeably in the present study. It is also important to note that the wavelet transform is a set of "mathematical functions that cut up data into different frequency components, and then study each component with a resolution matched to its scale" (Graps, 1995).

CHAPTER II: REVIEW OF LITERATURE

The anterior cruciate ligament (ACL) is one of four major ligaments in the knee. An injury to this passive tissue is one of the most common and traumatizing injury to the knee in sports, especially in female athletes. Thus, to examine research that has been done on ACL injuries, as well as their methodology and their findings, a review of literature is needed. By summarizing past research, gaps in literature will arise, consequently creating a need for further investigation. Of note, the topics of ACL injury rates, role of the ACL and its supporting tissues, mechanisms of ACL injuries, their contributing factors, the effect of maturation and development, prevention program initiatives, and methodological flaws and concerns will be tackled, thus justifying the need for further research.

Anterior Cruciate Ligament Injury Rates

It has been stated in many studies that women tend to injure their anterior cruciate ligament two to eight times more frequently than men (Harmon & Ireland, 2000; Huston, Greenfield, & Wojtys, 2000; Lephart, Abt, & Ferris, 2002). Conversely, others agree on a four to six fold increase in women (Hewett, 2000; Hewett et al., 2001). Nonetheless, the literature shows that women are more susceptible to ACL injuries in comparison with men. In 1985, Gray, Taunton, McKenzie, Clement, McConkey and Davidson conducted a study at the British Columbia Sports Medicine Clinic, in Canada, among 76 female and 151 male basketball players. Over a 30-month period, 19 ACL ruptures were seen in the female athletes, in comparison with only four among the male athletes. The ACL injury rate was therefore 25.0% and 2.6%, respectively, making women more than nine times more affected by this injury than men. However, the authors of this study did not account for exposure time. It is thus possible, yet unlikely, that the women participants were spending more time on the basketball court than the male participants, making this former group more likely to sustain an injury. Nevertheless, it can be concluded that this study showed a higher rate of ACL ruptures among women basketball players than their male counterparts.

Ireland and Wall (1990) also studied ACL injury rates in basketball. Among female and male players that were participating in the United Stated Olympic trials, six out of 64 (9.4%) women and two out of 80 (2.5%) men underwent ACL reconstructions. These women were thus nearly four times more prone to this injury. Yet, Malone and his colleagues (1993) found female intercollegiate basketball players to be more than eight times more likely to sustain an ACL injury than male players while conducting a telephone survey, pertaining to the past five years, among sports medicine practitioners from 29 institutions of the National Collegiate Athletic Association (NCAA), in the United States. This group of researchers also analyzed data collected by the NCAA Injury Surveillance Report for the 1988-89 and 1989-90 athletic seasons. These data revealed an ACL injury rate 6.19 times higher for women in comparison with men. However, it was not mentioned in either study (Ireland & Wall, 1990; Malone et al., 1993), yet again, if the authors accounted for the exposure time of the athletes to the basketball court. Nonetheless, the athletes were competing at the same level, which might yield similar exposure times.

Similar results to the Ireland and Wall (1990) study were found among Texas high school basketball players. Messina, Ferney, and DeLee (1999) concluded that the risk of ACL injury among the female athletes was also nearly four times higher in comparison with the male athletes. Accounting for exposure time, the girls experienced 0.091 ACL injuries per 1000 player-hours as opposed to 0.024 per 1000 player-hours among the boys. While conducting a retrospective study of all ACL injuries verified at hospitals of a selected region in Norway from 1982 to 1991, Bjordal, Arnly, Hannestad and Strand (1997) found that female soccer players had an incidence rate of 0.10 injuries per 1000 game hours – significantly higher than that of male soccer players (injury rate of 0.057). Hence, these female athletes were nearly two times more at risk than the male athletes.

Between 1989 and 1998, two five-year studies were conducted by the collaboration of researchers at the University of Minnesota and the NCAA to determine the injury rate of female and male soccer and basketball players (Arendt & Dick, 1995; Arendt et al., 1999). In the earlier study, it was found that female soccer players were three times more likely to sustain a noncontact ACL injury than the male players, whereas the female basketball players were more than four times at risk of such an injury, in comparison with the male basketball players. The second study yielded similar results, though the above-mentioned rate slightly decreased. Between 1994 and 1998, the interuniversity female soccer players injured their ACL nearly three times more often than their male counterparts. In the sport of basketball, this discrepancy was nearly three-fold. In a recent study (Agel, Arendt, & Bershadsky, 2005) aimed at determining whether the magnitude of this gender discrepancy with regards to ACL injuries has changed over time, the group of researchers from the University of Minnesota examined the NCAA Injury Surveillance System database for injuries relating to soccer and basketball ACL injuries from 1990 to 2002. It was found that women were still more susceptible to ACL injuries in comparison with men. With regards to noncontact ACL injuries, female basketball and soccer players were involved more than three times and nearly five times more than male players, respectively. Similarly, Mihata and colleagues (2006) found no significant change in rate of ACL injury in male or female soccer and basketball players during a 15-year period (between 1989 and 2004).

Hence, it has clearly been demonstrated in the literature that female athletes sustained anterior cruciate ligament injuries at a higher rate than male athletes in the sports of basketball and soccer. To comprehend this gender discrepancy in ACL injury rates, it is fundamental to identify the role of this ligament and of its supporting active tissues.

Role of the Anterior Cruciate Ligament and its Active Supporting Tissues

As a major ligament in the knee, the role of the anterior cruciate ligament is to primarily restrain anterior tibial translation, and secondarily to control varus and valgus motion (Inoue et al., 1987). It is also imperative to acknowledge that in complete knee extension, all fibres of the ACL are tight. As the knee flexion angle increases, the fibres loosen (Dye & Vaupel, 2000). Furthermore, as an agonist to the ACL, the hamstring muscle group – comprised of the semitendinosus, semimembranosus, and the long and short heads of the biceps femoris – reduces anterior tibial translation as it is activated, thus decreasing ACL strain (Li et al., 1999; MacWilliams, Wilson, DesJardins, Romero, & Chao, 1999; More et al., 1993; Renstrom, Arms, Stanwyck, Johnson, & Pope, 1986). Conversely, the activation of the antagonist muscle group, the quadriceps (i.e., vastus medialis, vastus lateralis, vastus intermedius, rectus femoris), produces a tibial anterior translation, which increases when the knee flexes from full extension to approximately 30-45 degrees of flexion and subsequently decreases with further flexion (Li et al., 1999; Renstrom et al., 1986). In a recent study conducted by Withrow, Huston, Wojtys and Ashton-Miller (2006) , during which one-legged jump landings were simulated from cadaveric specimens, the increase in ACL strain was found to be proportional to the increase in the force generated by the quadriceps. It is important to note that these researchers accounted for the role of the hamstrings and gastrocnemius muscle groups. In addition, Renstrom and colleagues found that strain in the ACL was significantly higher during simultaneous hamstring and quadriceps activation than during passive normal knee flexion from full extension to 30 degrees. Hence, as hamstring activation is used to counterbalance the anterior action of the quadriceps on the ACL, strain is nevertheless present in this ligament, but at a lower extent than if the quadriceps were acting alone.

Mechanisms of Anterior Cruciate Ligament Injuries

The anterior cruciate ligament can be ruptured various ways. The simplest way is by receiving a direct blow to the knee, which places a greater amount of force on the ACL with which it can cope. In such a case, the cause of injury becomes apparent. A more complex ACL rupture occurs in a noncontact situation, when forces exceeding the ACL's capacity originate from the individual sustaining the injury, as opposed to originating from a foreign body. This second type of injury mechanism is of interest as one investigates the gender discrepancy with regards to ACL ruptures that exists in athletics.

Manoeuvres. Although Fayad, Parellada, Parker and Schweitzer (2003) found the pivot shift manoeuvre to be the most common mechanism of injury, with 67 and 60% of the female and male participants, respectively, rupturing their ACL while executing this movement, Olsen, Myklebust, Engebretsen and Bahr (2004) found the plant-and-cut manoeuvre to be the most common. Of the ACL injuries that the latter group observed on tape from Norwegian or international competitions of women's handball, 60% resulted from this manoeuvre, which was accompanied by a forceful valgus and an external or an internal rotation while the knee was near full extension. They also found the one-legged jump shot landing, also complemented by a forceful valgus and an external rotation with the knee close to full extension, to be the another main mechanism of ACL injury, with a 20% presence rate. Similarly, Boden and collaborators (2000) found, by means of questionnaire and video analysis, that the majority of the noncontact ACL injuries were sustained at foot strike with the knee close to full extension while the athletes were executing either a change of direction which followed a rapid deceleration (51%) or a landing (44%). The literature therefore reveals that one of the main mechanisms of noncontact ACL injuries among athletes is the cutting manoeuvre, closely followed by the landing.

Kinematics. It is therefore not astonishing that the movements most frequently utilized in ACL injury related studies investigating kinematic, kinetic and/or electromyographical differences between genders are the cutting and landing manoeuvres. Among the studies examining the kinematics of the plant-and-cut movement, most researchers have found that women tend to perform the stance phase of this motion with a greater degree of knee valgus in comparison with men (Ford et al., 2005; Malinzak et al., 2001; McLean et al., 2004b; McLean et al., 1999). Others (Pollard, Davis, & Hamill, 2004; Sigward & Powers, 2006), however, have found similar knee joint kinematics between female and male collegiate soccer players. It was suggested that this might be due to the participants' high skill level and years of exposure to cutting activities, in comparison with the participants of other studies (Malinzak et al., 2001; McLean et al., 1999), for which knee kinematics of less experienced individuals was assessed. It was also found that women performed this movement with less knee flexion (James et al., 2004; Malinzak et al., 2001; McLean et al., 2004b), greater foot pronation angles (Ford et al., 2005; McLean et al., 2004b) and less hip flexion and knee and hip internal rotation (McLean et al., 2004b).

Similar results were found in studies for which lower limb kinematics were assessed while participants performed either a one or two-legged landing. Several researchers concluded that women landed from a drop-jump with greater knee valgus angles (Ford et al., 2003; Ford et al., 2006; Hewett et al., 2004; Kernozek et al., 2005) and diminished knee flexion angles (Decker et al., 2003; Salci et al., 2004), as opposed to men. Conversely, Fagenbaum and Darling (2003) reported greater knee flexion angles among females varsity basketball players. This disagreement among authors might be explained by the studies' methodology. Women landing with smaller knee angles, in contrast to men, performed a two-legged drop, whereas those demonstrating greater angles executed a one-legged drop-jump. Furthermore, Cowling and Steele (2001), as well as Jacobs and Mattacola (2005), also obtained different results when examining one-legged landing manoeuvres. The latter groups observed no significant differences for knee angles between genders. This discrepancy with the literature can possibly be accounted by the fact that a drop-jump landing was not studied, but rather a deceleration landing and a horizontal hopping task. These latter types of task might not put enough strain on the knee to solicit gender differences. Notably, Cowling and Steele did not report the speed at which the participants were moving prior to the deceleration landing, possibly because this variable was not monitored. This being the case, much variability would be introduced in the data, thus perhaps explaining the lack of difference found between male and female participants. Interestingly, Hewett et al. (2005b) screened 205 female athletes of "high-risk" sports (soccer, basketball and volleyball) by means of a biomechanical evaluation of a two-legged drop-jump prior to their seasons. Of this group, seven soccer players and two basketball players subsequently sustained ACL injuries. Results showed that the injured women, compared to the uninjured women, performed the landing task with greater knee abduction angles at initial ground contact, greater peak knee abduction angles and smaller peak knee flexion angles during the landing. No differences, however, were observed at IC for knee flexion angle. Hence, dynamic valgus measures might be able to predict ACL injuries in women.

Additionally, several studies (Cowling & Steele, 2001; Decker et al., 2003; Ford et al., 2006; Jacobs & Mattacola, 2005; Kernozek et al., 2005; Salci et al., 2004) have monitored the movement of the hip during landing tasks. Of those, Salci and collaborators noted that women landed from a two-legged drop-jump with less hip flexion angles than men. Contrarily, most studies (Cowling & Steele, 2001; Decker et al., 2003; Ford et al., 2006; Jacobs & Mattacola, 2005; Kernozek et al., 2005) revealed no difference in hip flexion angles between their female and male participants while the latter executed a one- and two-legged landings.

Although researchers have primarily employed the plant-and-cut and landing manoeuvres as means of assessing gender differences with regards to lower limb kinematics, others have examined these variables through stop-jump tasks, gait, and the single-legged squat. Following a visual cue for the jump direction, high school basketball players participating in a study conducted by Sell and colleagues (Sell et al., 2006) performed a reactive stop-jump task with reduced knee flexion and greater knee valgus angles. In addition, during both normal and perturbed gait, Hurd, Chmielewski, Axe, Davis and Snyder-Mackler (2004) found that women, as opposed to men, displayed greater hip and knee excursion in the frontal and transverse planes. No such differences were found in the sagittal plane. Knee excursion was defined as the joint movement during loading, which was characterised as the time from IC to peak knee flexion. Hence, it can be concluded that women exhibited greater range of motion of knee valgus/varus as well as internal/external rotation. Furthermore, in a study examining ankle, knee and hip angles during a single-legged squat, Zeller, McCrory, Kibler and Uhl (2003) found that the female participants executed this movement with greater ankle dorsiflexion, ankle pronation, hip adduction, hip flexion and hip external rotation, as well as less trunk lateral flexion. It was thus concluded that the women had a decreased ability to maintain a varus knee position, in comparison to their male counterpart. By doing so, the female is in a more valgus position, consequently placing greater strain on the ACL.

Kinetics. Research has also investigated kinetics of the lower limb during plant-and-cut and landing tasks. McLean, Huang and van den Bogert (2005b) discovered that collegiate-level female basketball players performed an anticipated cutting task with greater peak valgus moments. Sigward and Powers (2006) found similar results among collegiate-level female soccer players, who also displayed greater knee valgus moments, as well as reduced knee flexor moments, during a similar task. Such increased moments at the knee, in comparison with male athletes, is shadowed by an increased strain on the ACL, as this structure plays a secondary role in controlling knee motion in the frontal plane.

Among the few that have examined these variables during a landing manoeuvre, Kernozek et al. (2005) revealed that women performed a two-legged drop-jump landing with greater knee valgus moments than men. Decker and colleagues (2003), however, found no gender differences during such a task with regards to peak hip, knee and ankle joint moments. Nonetheless, they found that women exhibited greater peak powers from the knee extensors, which, as stated earlier, increases strain on the ACL.

Furthermore, Chappell, Yu, Kirkendall and Garrett (2002) found that, during three various stop-jump tasks (i.e., forward, vertical and backward jumps), women displayed greater proximal anterior shear forces and greater knee extension and valgus moments. Hence, the female participants revealed knee kinetics that are more stressful to their ACL, in comparison with the male participants. In addition, in a study utilizing a randomly cued cutting manoeuvre, Pollard et al. (2004) found similar results as Decker et al. (2003), who studied kinetics of landing. No differences were found between male and female collegiate soccer players when hip abduction, hip external rotation, knee adduction and knee external rotation moments were compared. It was, however, found that prescreened female soccer and basketball players with subsequent ACL injury displayed greater peak knee abduction moments and peak hip flexion moments during a two-legged drop-jump in comparison with female athletes that remained uninjured (Hewett et al., 2005b). Consequently, results showed that knee abduction moment was a good predictor of ACL injury.

Although several authors have reported no gender difference in lower limb kinematics and kinetics, numerous researchers have demonstrated such a gender difference, thus placing women at a higher risk of anterior cruciate ligament injuries in comparison to men. Generally, women seemed to perform landing and cutting motions with smaller knee flexion angles, greater foot pronation, knee valgus, knee external rotation and hip flexion angles and greater peak knee extension moments and powers, anterior shear forces and valgus moments. Additionally, McLean, Huang, Su and van den Bogert (2004a) did conclude that “sagittal plane biomechanics cannot injure the ACL during sidestep cutting”. These researchers manipulated musculoskeletal models (generated from data obtained from 10 male and 10 female athletes), which simulated cutting manoeuvres. While applying random perturbations at IC and quadriceps and hamstrings activations levels, anterior translation forces originating from the sagittal plane never exceeded 2000 N – the criterion for an ACL injury to take place. However, valgus forces did reach values high enough to rupture the ligament, this occurring more frequently in women, as opposed to men. It is therefore more likely that a valgus load would cause injury to the female ACL.

Contributing Factors to Anterior Cruciate Ligament Injuries

The numerous studies that have been undertaken with regards to anterior cruciate ligament injuries and women, especially from a noncontact mechanism, have led to the elaboration and discussion of several contributing factors. These can be classified as being one of three types: anatomical, hormonal and neuromuscular factors.

Anatomical. Researchers that have assessed anatomical factors in men and women have measured such variables as the quadriceps-angle (Q-angle), the size of the ACL and the intercondylar notch and knee joint laxity. It has been found that women tend to have a greater Q-angle than men (Hsu, Himeno, Coventry, & Chao, 1990; Moul, 1998; Tillman, Bauer, Cauraugh, & Trimble, 2005). Hence, women display a different static posture. Furthermore, it has been shown that the female anterior cruciate ligament is smaller than that of the male ACL, even after accounting for gender differences in body size (Anderson et al., 2001). It was, however, found that intercondylar notch width was similar in men and women – results, which are supported by others (LaPrade & Burnett, 1994). In contrast, Shelbourne, Davis and Klootwyk (1998) found that, controlling for height and weight, women had significantly smaller intercondylar notch widths than men. Charlton, St John, Ciccotti, Harrison and Schweitzer (2002) also found the notch width and the size of the ACL to be smaller in women, as opposed to men. Nevertheless, seeing that they did not control for gender differences in height and weight, the differences found were most likely due to the latter. There is, therefore, contradicting statements in the literature with regards to ACL size and intercondylar notch width and gender differences.

Another anatomical factor frequently assessed is knee joint laxity, which has been found to be greater in women (Beynnon et al., 2005; Hsu, Fisk, Yamamoto, Debski, & Woo, 2006; Huston & Wojtys, 1996; Rozzi, Lephart, Gear, & Fu, 1999), thus possibly making women, more than men, susceptible to an ACL injury. Blackburn, Riemann, Padua and Guskiewicz (2004) found similar results as their female participants displayed greater knee flexor extensibility. In contrast, the male participants demonstrated greater active and passive knee flexor stiffness. Nonetheless, the researchers did not control for gender differences in weight and height; therefore this study's conclusion possibly contradicts the findings of the above-mentioned studies. Interestingly, Boden and colleagues (2000) found that a group of female and male ACL-injured patients had significantly greater hamstring flexibility in comparison with a group of age-matched healthy controls. It seems that this increase in flexibility may lead to a reduction of the hamstrings' passive protection of the ACL. Due to this discrepancy in the literature, insufficient evidence exists to conclude that anatomical factors are responsible for the increase rate in ACL injuries in women.

Hormonal. One the most core and obvious differences between men and women appears at the reproductive system, which greatly involves hormones. It is thus not surprising that various studies (Beynnon et al., 2005; Beynnon et al., 2006; Carcia, Shultz, Granata, Gansneder, & Perrin, 2004; Deie, Sakamaki, Sumen, Urabe, & Ikuta, 2002; Friden, Hirschberg, & Saartok, 2003a; Friden et al., 2003b; Hertel et al., 2006; Wojtys et al., 2002b) have examined the phases of the menstrual cycle in relation to women's susceptibility to ACL injuries to perhaps explain this ACL injury gender discrepancy. It is believed that the female sex hormones (i.e., estrogen, progesterone, relaxin) increase the laxity of ligament and decrease neuromuscular performance, possibly by its effect on ligament collagen; therefore passive and active knee stability may be decreased (Hewett, 2000). As oral contraceptives are known to stabilise hormonal levels during the menstrual cycle, they may, in turn, stabilise the knee joint, either passively or actively. Hence, women who use oral contraceptives may be less susceptible to athletic musculoskeletal injuries compared with non-users.

In a study aimed at exploring the relationship between the rate of ACL injuries and the phases of the menstrual cycle, Wojtys et al. (2002b) found that more ACL injuries than expected were found during ovulation and fewer than expected during the luteal phase. The expected percentage rates of injury were calculated by dividing the length the phase by the total length of the cycle. Similar results were found by Beynnon and colleagues (2006) among female recreational alpine skiers. By dividing the menstrual cycle into two rather than three phases – the preovulatory (combination of follicular and ovulatory) and postovulatory (luteal) phases, it was found that skiers in the former phase were more likely to sustain a tear to their ACL with an odds ration of 3.22. Other researchers have explored the association between anatomical and neuromuscular factors and the menstrual cycle. Specifically, several (Beynnon et al., 2005; Carcia et al., 2004; Hertel et al., 2006) concluded that measures of knee laxity was not significantly affected by the day of the menstrual cycle. Deie et al. (2002) found, however, that joint laxity did vary according to the menstrual cycle. When evaluating tibial anterior displacement at 89 N, results were significantly higher during both the luteal phase and the ovulatory phase, in comparison with the follicular phase. At 134 N, anterior displacement was also greater during the luteal phase than the follicular phase. Hence, conclusions on phases of the menstrual cycle and its role in passive knee stability cannot be made as discrepancy exists in the literature. Investigating active knee stability with regards to the menstrual cycle, Fridén et al. (2003a) reported similar muscle strength and muscle endurance results between menstrual cycle phases in moderately trained women. Part of these results was confirmed by Hertel and colleagues (2006) who also reported a lack of change in quadriceps and hamstring strength with the menstrual cycle. Nevertheless, it was found that postural sway and knee-joint kinaesthesia varied during the menstrual cycle (Friden et al., 2003b), which conflicts with recent results (Hertel et al., 2006) that showed no change in postural control over the menstrual cycle. It was also noticed that women with premenstrual syndrome (PMS) displayed a greater amount of postural sway and a greater threshold for perception of passive motion of the knee joint, in comparison with women without PMS. Interestingly, a study (Warden, Saxon, Castillo, & Turner, 2006) examining the effect of estrogen fluctuation on the mechanical properties of the ACL in rats reported no such hormonal effect on the ACL. Hence, it appears that perhaps the menstrual cycle may play a role in the gender discrepancy in anterior cruciate ligament injuries. This role is, however, not yet confirmed nor clearly determined. It is thus imperative to control for this variable in future studies.

Neuromuscular Control. Although gender differences have been demonstrated at the anatomical and hormonal levels, which may bring an explanation as to why women are more susceptible to anterior cruciate ligament injuries than men, differences with regards to neuromuscular control is most interesting as it offers the greatest potential for intervention and thus prevention of this type of injury. It has been demonstrated on numerous occasions that women displayed neuromuscular behaviours that predispose them to noncontact anterior cruciate ligament injuries. These behaviours are effectively summarized by the so-called "three-way neuromuscular imbalance" (Hewett et al., 2001): Women tend to be *ligament-dominant*, to display a *quadriceps imbalance* and to exhibit a *leg dominance*.

Illustrating this first imbalance –that women are inclined to allow their knee ligaments, instead of their lower limb muscles, to absorb a substantial portion of the ground reaction forces, numerous studies (Ford et al., 2003; Ford et al., 2006; Ford et al., 2005; Hewett et al., 2004; Kernozek et al., 2005; Malinzak et al., 2001; McLean et al., 2005b; McLean et al., 2004b; McLean et al., 1999) have demonstrated that women perform landing and cutting tasks with greater valgus motion than men. By therefore relying predominantly on passive tissues, as opposed to active ones, women display greater knee motion in the frontal plane.

As for the quadriceps imbalance, several studies (Anderson et al., 2001; Ford et al., 2003; Huston & Wojtys, 1996; Malinzak et al., 2001; Soderman, Alfredson, Pietila, &

Werner, 2001; White et al., 2003) have shown that women have lower relative hamstring to quadriceps activation ratio than that of men. It has also been showed that women perform some dynamic movements, such as cutting tasks, with greater quadriceps activity (Sigward & Powers, 2006), which places greater strain on the ACL. In addition, Hollman, Deusinger, Van Dillen and Matava (2003) evaluated relative hamstring activity during a closed-chain knee extension and revealed that women displayed lower values than men. In contrast, DeMont and Lephart (2004), as well as Sell et al. (2006), found that women displayed higher medial hamstring activity during downhill walking and running at a 15% decline and during a jump landing, respectively. This discrepancy with the literature may well be due to the simplistic characteristic of the task for which hamstring activation was evaluated by Hollman and colleagues. Fagenbaum and Darling (2003) also found results diverging from the literature, as the female and male varsity college basketball players participating in their study displayed similar knee muscle activation patterns. Nonetheless, it appears that a quadriceps imbalance is present among women.

Furthermore, Ford et al. (2003) have adequately demonstrated this leg dominance that women commonly exhibit. During a two-legged drop vertical jump, high school female basketball players displayed a significant difference between their dominant and non-dominant side with regards to peak valgus knee angles. It was also found that women who subsequently injured their ACL revealed leg-to-leg differences in knee abduction moments during a two-legged landing task, in comparison with uninjured women who did not display such differences (Hewett et al., 2005b). Consequently, previous research generally supports the "three-way neuromuscular imbalance" described by Hewett and colleagues (2001). Although this "three-way neuromuscular imbalance" adequately summarizes women's neuromuscular control behaviours that may predispose them to anterior cruciate ligament injuries, other studies have demonstrated other relevant behaviours. For instance, in a study (Cowling & Steele, 2001) evaluating hamstring activity with respect to sagittal plane tibiofemoral forces during a deceleration task, it was found that the male participants displayed a better synchronisation of their peak semitendinosus activation in relation to the peak tibiofemoral force, as well as the activation onset with IC. In other words, the men's peak and onset medial hamstring activations were closer in time to the peak tibiofemoral force and to IC, respectively. Furthermore, Wojtys, Huston, Schock, Boylan and Ashton-Miller (2003) directed a 80-N impulse force to the lateral portion of the forefoot. When muscle activity was present, the peak internal rotation of the shank was greater in women than in men, which indicated a smaller increase in knee stiffness in women and thus less muscle protection. As mentioned earlier, hamstring activation acts as an agonist to the ACL to decrease anterior tibial translation with respect to the femur. In a study designed to compare between genders the amplitude of this decrease in translation with hamstring muscle activation, Wojtys, Ashton-Miller and Huston (2002a) revealed that women's muscle response decreased anterior tibial translation to a lesser extent than that of men. Women, therefore, displayed behaviours less protective to their ACL in comparison with their male counterparts. Zeller and colleagues (2003) also demonstrated ACL-detrimental behaviours in women as the latter group displayed greater activation of the rectus femoris during a single-legged squat, in comparison with men. Additionally, women, as opposed to men, exhibited a decreased medial-to-lateral quadriceps ratio during a manoeuvre that reproduced a high ACL injury risk position (Myer, Ford, & Hewett, 2005a). This behaviour is said to possibly contribute to "dynamic valgus", which positions the ACL in a vulnerable position since this ligament is said to be a restraint to valgus forces. Accordingly, the literature demonstrates a diminished neuromuscular control in women in comparison with men.

Effect of Human Maturation and Development

This gender discrepancy, however, seems to emerge with maturation. For example, a study conducted by Yu and collaborators (2005) revealed that kinematic gender differences during a stop-jump task surfaced only after the age of 12 and subsequently increased with age. Hewett et al. (2004) found similar results among young soccer and basketball players. It was concluded that after maturation, women executed a landing task differently than do men – with greater valgus motion at the knee and reduced knee flexor torque. Since the hamstring muscle group acts as an agonist to the ACL, this decrease in torque might place women's ACLs at a greater risk of injury than those of men. Another group of researchers (Hass et al., 2005) published results demonstrating a change in kinematic and kinetic characteristics upon puberty in women. During a landing task, post-pubescent women displayed reduced knee flexion at initial ground contact, increased frontal plane knee joint forces and reduced knee extensor moments. Furthermore, a gender difference in knee laxity was observed between mature boys and girls (14-18 yrs old), whereas none was present between the immature groups (10-14 yrs old) (Ahmad et al., 2006). Leg muscle strength was also showed to differ upon maturation. For instance, Barber-Westin et al. (2006) found that maximum hamstring strength was achieved at age 11 in females and 14 in males, which possibly translated in the greater increase in hamstring strength with maturity in boys (179 %) in comparison with girls (27 %) found by Ahmad et al. The latter group of researchers also found that mature girls demonstrated a greater quadriceps-to-hamstrings strength ratio than did the mature boys, as well as the immature girls and boys. In other words, following onset of puberty, quadriceps strength increased at a greater rate than did the hamstrings strength among girls, which could perhaps translate into greater strain on the ACL during dynamic tasks. Consequently, maturation effects lower body mechanics and neuromuscular characteristics, which put mature women at a greater risk of sustaining an ACL injury.

Time-Frequency Analysis

Another interesting aspect of muscle activation not commonly mentioned is its frequency components. In fact, studies utilizing a time-frequency analysis aimed at comparing neuromuscular control between genders during high ACL injury risk manoeuvres have yet been produced. However, Wakeling and Rozitis (2004) have demonstrated that as faster motor units are recruited, higher frequencies emerge from the EMG power spectra. Similarly, Solomonow, Baten, Smit, Baratta, Hermens, D'Ambrosia and Shoji (1990) found that an increase in average velocity during motor control recruitment was the major source of an EMG median frequency increase. Consequently, it might be believed that men would display higher hamstring EMG frequencies to better work in synergy with the ACL. In other words, men most likely possess higher recruitment velocities to be able to react faster to an anterior tibial translation, and in turn better protect their ACL against rupture.

Wavelet Transform. To precisely measure such frequencies, the wavelet analysis procedure has recently been applied to EMG (Boyer & Nigg, 2004; Lauer et al., 2005; von Tscharner, 2000; von Tscharner & Goepfert, 2003; von Tscharner, Goepfert, & Nigg, 2003; von Tscharner, Gopfert, Wirz, & Friederich, 2004). The wavelet transform may be used as a time-frequency analysis of the intensities in time, such as the method developed by von Tscharner (2000). Furthermore, in a study (Beck et al., 2005) aimed at comparing the discrete wavelet transform and the fast Fourier transform in determining centre (mean or median) frequency during fatiguing isokinetic movement of the biceps brachii, it was found that the Fourier based methods are acceptable for the determination of EMG centre frequency.

ACL-Hamstring Reflex Arc

It has long been suggested that neural pathways exists between the anterior cruciate ligament mechanoreceptors and the hamstring muscle group (Krogsgaard, Dyhre-Poulsen, & Fischer-Rasmussen, 2002). Recently, several studies (Dyhre-Poulsen & Krogsgaard, 2000; Friemert et al., 2005; Tsuda, Okamura, Otsuka, Komatsu, & Tokuya, 2001) have examined this possibility in the human being. Specifically, Dyhre-Poulsen and colleagues (2000) inserted wire electrodes in the ACL and measured muscle activity of the hamstrings (i.e., semitendinosus, long head of the biceps femoris). No muscle activity was found when a single stimulus was administered to the ACL. Muscle activity was, however, recorded with a latency of 95 milliseconds, when the ACL was stimulated during a minimum of two occasions, at an interstimulus interval of five milliseconds. Furthermore, as the participants were asked to contract their muscles around the knee, an inhibition of these was observed following ACL stimulation. During active extension and flexion, ACL stimulation inhibited the activity of the knee extensors and flexors, respectively. Additionally, gastrocnemius activity was inhibited during both active extension and flexion. Tsuda et al. (2001) obtained similar findings when the ACL was electrically stimulated. Following this stimulation, participants displayed increased activity of the hamstrings, thus indicating the presence of a reflex arc between the ACL and the hamstring muscles group. Further indicating the presence of this reflex arc, the hamstrings were no longer activated following injection of lidocaine (local analgesia) in the knee, which produced an interruption of the intraarticular sensation and the mechanoreceptors in the ACL. Despite the evidence of an ACL-hamstrings reflex arc, its latency is not short enough to activate the muscles to prevent a tear in the ligament (Krogsgaard et al., 2002). Nonetheless, this information could be used in the development of complex motor programs to control neuromuscular coordination. Although the latency of the ACL-hamstring reflex arc has yet to be compared between women and men, a difference may exits. This difference may be reflected in the results of studies examining gender differences with regards to neuromuscular control (i.e., three-way neuromuscular imbalance). This, however, has yet to be verified, though neuromuscular prevention training programs have been conceived and applied to various athletic populations

Intervention, Training Programs and Prevention

As results from studies have demonstrated some differences across genders with regards to muscle activity patterns, several researchers (Hewett, Lindenfeld, Riccobene, & Noyes, 1999; Hewett, Stroupe, Nance, & Noyes, 1996; Hurd, Chmielewski, & Snyder-Mackler, 2006; Lephart et al., 2005; Myer, Ford, McLean, & Hewett, 2006; Myer, Ford, Palumbo, & Hewett, 2005b; Myklebust et al., 2003), without necessarily knowing the exact fundamental causes of this gender discrepancy, have elaborated prevention programs aimed at increasing women's neuromuscular control. For example, Hewett et al. (1996) conducted a study aimed at determining the effect of a jump training program on the biomechanics of landing between trained and untrained women and a group of men acting as a control group. Results revealed that the training program was successful in reducing peak landing forces and knee adduction and abduction moments during landings. The program also increased hamstring-to-quadriceps muscle peak torque ratios and hamstring muscle power. Consequently, this jump training program modified factors that otherwise place individuals at risk of ACL injuries. In fact, this program was later evaluated in terms of changes in rates of ACL injury incidence. Results showed that the jump training program decreased the incidence of ACL injury in soccer, basketball and volleyball players (Hewett et al., 1999). Moreover, the rate of incidence of the trained group of women was reduced to that of an untrained group of men. Hence, this training program was successful in eliminated the gender discrepancy, which exists with regards to ACL injuries. Similarly, a neuromuscular training program successfully reduced the rate of ACL injuries among elite (Division I, Norway) team handball players (Myklebust et al., 2003). A recently published study (Myer et al., 2005b) also revealed successful results in women following a six-week neuromuscular training program. In comparison to a control group, women who completed the program displayed a greater knee flexion-extension range of motion and smaller knee valgus and varus torque values during a two-legged drop-jump. These biomechanical modifications improved protection to the ACL. Similarly, other studies (Hurd et al., 2006; Lephart et al., 2005; Myer et al., 2006) have also yielded positive results in women following a neuromuscular training program. Specifically, activity of the gluteus muscle group and hip and knee flexion angles were increased when examined during perturbed gait. Furthermore, reduced knee valgus angles, increased hamstring activity, better timing of hamstrings onset activity, increased knee stiffness and normal quadriceps-to-hamstrings ratio was observed post-training during a jump landing. Accordingly, the success of these neuromuscular training programs provides some evidence that the gender divergence in rates of ACL injuries lies within differences with regards to the neuromuscular facet.

Measurements of Neuromuscular Control

Indeed, many studies (Blackburn et al., 2004; Colby et al., 2000; Cowling & Steele, 2001; DeMont & Lephart, 2004; Fagenbaum & Darling, 2003; Malinzak et al., 2001; Myer et al., 2005a; Sigward & Powers, 2006; White et al., 2003; Zeller et al., 2003) have examined gender differences with regards to neuromuscular control by means of EMG measurements, as mentioned above. However, all of these studies have made such measurements by means of an anticipated movement, such as a cutting manoeuvre or a drop-jump landing. To fully comprehend the mechanism of an ACL injury, it is advantageous to study a movement similar to that of the actual environment (i.e., game-like situation). In other words, better representative data might be acquired from participants performing a cutting manoeuvre while having to react to a stimulus beforehand, just like one does in competition when reacting to an opponent or a projectile. The studies (Ford et al., 2005; Hurd et al., 2004; Pollard et al., 2004) that have examined the gender discrepancy that exists among ACL injury rates using a simulated competition-like environment investigated kinematic and/or kinetic variables and disregarded muscle activation patterns. There is therefore a need to study lower limb muscle activation patterns during an unanticipated manoeuvre.

In conclusion, the literature undoubtedly demonstrates that women do in fact injure their ACL at a higher rate than do men. Consequently, many studies have examined the possible factors associated with this discrepancy. Although much inconsistency exists in the literature, it has been repeatedly shown that women generally performed landing and cutting manoeuvre with smaller knee flexion angles and greater knee valgus angles, which are associated with a high ACL injury risk position. This, however, does not explain the reasons why women displayed such angles. An electromyographical assessment may well compliment kinematics to shed light on the source of lower limb biomechanical differences between men and women. Hence, many studies have investigated gender differences with regards to muscle activation patterns. Yet again, much discrepancy exists in the literature. Nonetheless, results from many studies support the proposed three-way neuromuscular imbalance displayed by women. In spite of this, these studies have made lower limb electromyographical evaluations while their participants performed anticipated manoeuvres, which do not represent a typical noncontact ACL injury environment. Furthermore, no studies targeting ACL injuries and its gender discrepancy examined the time-frequency characteristics of the lower limb muscle activation. As a result, a study evaluating the gender discrepancy that exists in the rate of noncontact ACL injuries by means of three-dimensional lower limb kinematics complemented by an electromyographical analysis during an unanticipated cutting manoeuvre is much needed. As light is shed on this situation, further prevention programs may be developed to reduce the rate of noncontact ACL rupture among women.

CHAPTER III: METHODOLOGY

This section describes the procedures of the study. It therefore provides a detailed description of the participants, the data collection procedures, the protocol and the data processing and analysis procedures. Specifically, the procedures for participant selection and its reasons will be described, as well as the participants' characteristics necessary to this study. The protocol will be thoroughly presented. Data collection procedures will be given as to how the data was obtained. Finally, data processing and analysis procedures will also be given and described.

Participants

Using data from a pilot study, total sample size was estimated to be 38 athletes for a minimal statistical power of 80% using G*Power Software (version 2.0, (Erdfelder, Faul, & Buchner, 1996)). In spite of this, 30 participants was included in the present study due to the greater homogeneity of this group of participants, thus potentially reducing variability in the data, as well as time constraints caused by the complexity and length of the testing session. Furthermore, past studies have demonstrated a count of 30 participants to be adequate to obtain statistically significant results (Blackburn et al., 2004; Kernozek et al., 2005; McLean et al., 1999; Sigward & Powers, 2006). Hence, participants consisted of 15 female and 15 male elite soccer players. The latter is a sport which has high rates of noncontact anterior cruciate ligament injuries, especially among women. Moreover, the participants were over 18 years of age, but less than 35 years of age, healthy (i.e., no injury or history of injury to the lower extremity, especially the knee), right-leg dominant and competing at the university/collegiate or premier level with a minimum of five years of soccer experience. As speculation exists that the phase of the menstrual cycle may have an effect on the laxity of the ACL, thus the susceptibility to ACL injuries, the group of female soccer players were tested during the follicular phase of their menstrual cycle (i.e., day 1-12). By controlling this hormonal factor, it was not able to account for possible, or lack of, gender differences.

Participants with the above-mentioned characteristics were selected from various elite soccer communities on a volunteer basis. Prior to the start of the study, the participants were informed of the nature of the study and its procedures and design. Upon signing a consent form, the participants began their involvement with the study. It was also explained to these athletes that complete anonymity was to be maintained throughout the entire study and that they had the liberty to withdraw at any time.

Data Collection Procedures

Measurement of control variables. A seven-camera (MX-13) high-speed motion analysis system (Vicon Peak, Oxford, UK) was used to measure the participant's right Q-angle – the angle between the line that connects the ASIS of the pelvis and the patella and the line that connects the tibial tuberosity and the patella. Data were collected for three seconds with the athlete standing in a neutral static position with reflective markers placed on the anterior superior iliac spine (ASIS), the patella and the tibial tuberosity of their right limb (Figure A-1).

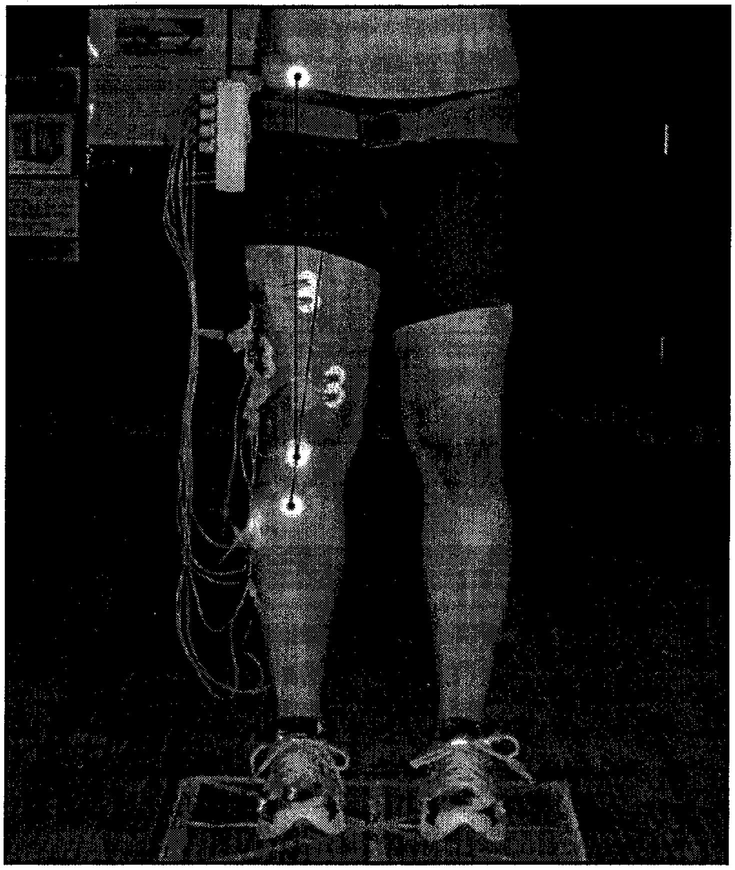

Figure A-10: Static measure of the Q-angle.

Motion recordings. A seven-camera (MX-13) high-speed motion analysis system (Vicon Peak, Oxford, UK) was used to capture, at 200 Hz, a three-dimensional view of the participant performing the cutting task. They were strategically placed so that every marker was seen by a minimum of two cameras at all times (Figure A-2).

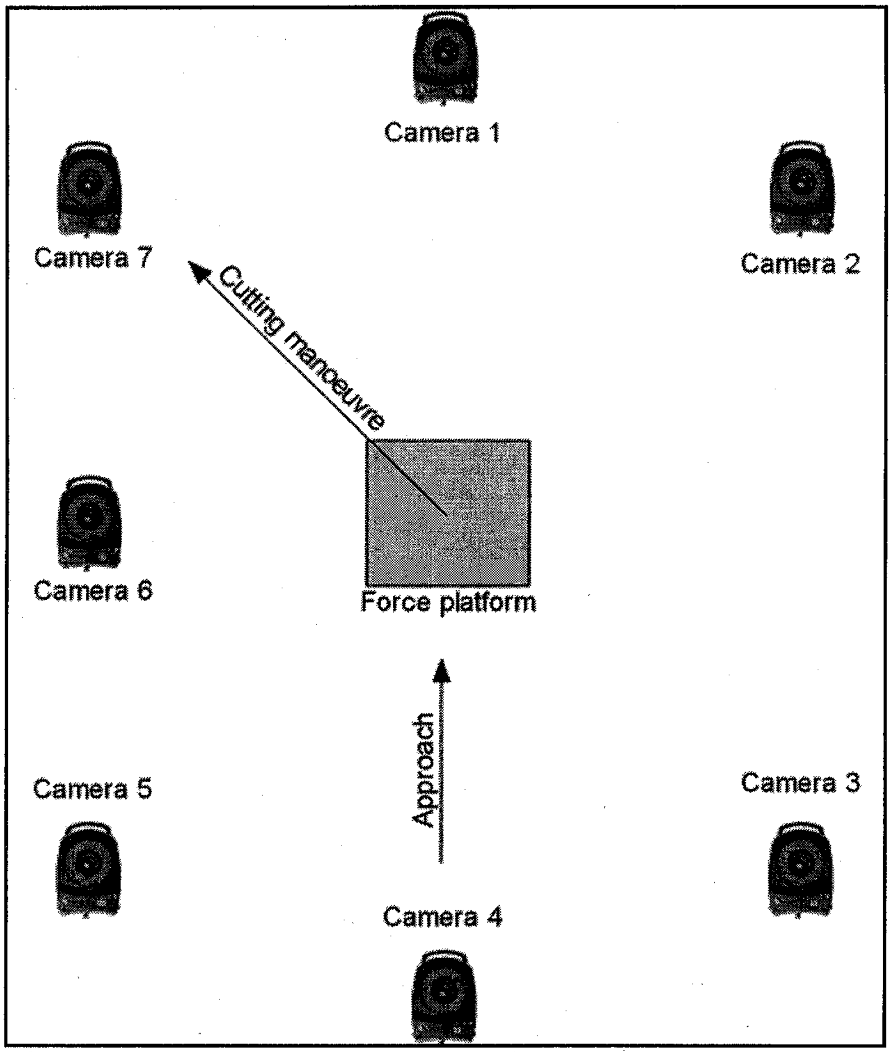

Figure A-11: Camera set-up (not at scale).

To calibrate the filming volume where the movement would occur, a static calibration was performed followed by a dynamic calibration. The static calibration consisted of recording 20 frames of a stationary L-shape frame equipped with four 1.4-cm reflective markers (Figure A-3). Meanwhile, the dynamic calibration consisted of recording the researcher waving a T-shape wand – equipped with three 1.4-cm reflective markers positioned on the spacer bar (Figure A-4) – within the filming volume for approximately 60 seconds. The wand wave thoroughly covered the volume captured by the cameras while enabling a maximum number of cameras to view the wand. This calibration procedure is important to define a global coordinate system, as well as to calculate the location of the cameras with respect to one another.

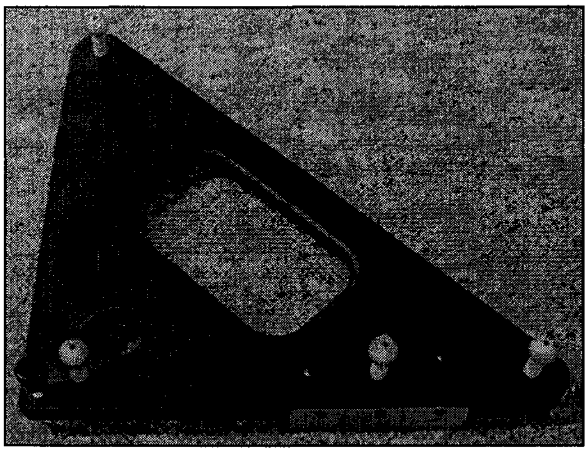

Figure A-12: L-shaped frame used for static calibration.

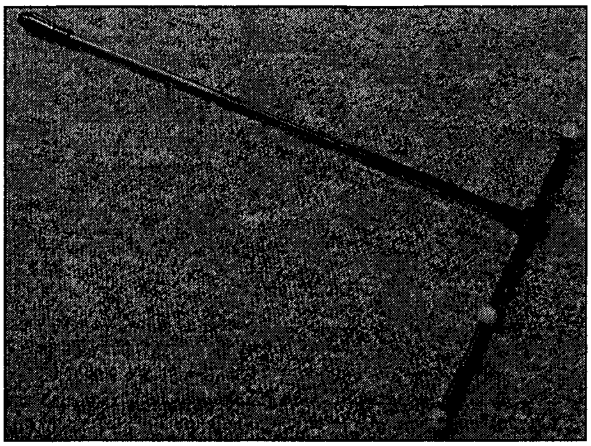

Figure A-13: The wand used for dynamic calibration.

Prior to the experimental protocol, 39 reflective markers were placed on the participant by the investigator to measure ankle, knee and hip flexion/extension, abduction/adduction and internal/external rotation. As a modified Helen Hayes marker set was used to obtain three-dimensional kinematic data, reflective markers were placed on the following anatomical landmarks of the body (Figure A-5): (1) right and (2) left temple, (3) right and (4) left back of the head, (5) spinous process of the 7th cervical vertebrae, (6) spinous process of the 10th thoracic vertebrae (7) jugular notch (where clavicles meet sternum), (8) xiphoid process of the sternum, (9) middle of right scapula, (10) right and (11) left shoulder (acromio-clavicular joint), (12) right and (13) left lateral upper arm, (14) right and (15) left elbow (lateral epicondyle), (16) right and (17) left forearm, (18) right and (19) left lateral wrist (20) right and (21) left medial wrist, (22) slightly proximal of the head of the second metacarpal on the dorsum of the right and (23) left hand, (24) right and (25) left ASIS, (26) right and (27) left posterior superior iliac spine (PSIS), (28) right and (29) left lateral thigh, (30) right and (31) left knee (lateral epicondyle), (32) right and (33) left lateral shank, (34) right and (35) left lateral malleoli, (36) right and (37) left posterior calcaneus, and the (38) second metatarsal head of the right and (39) left foot.

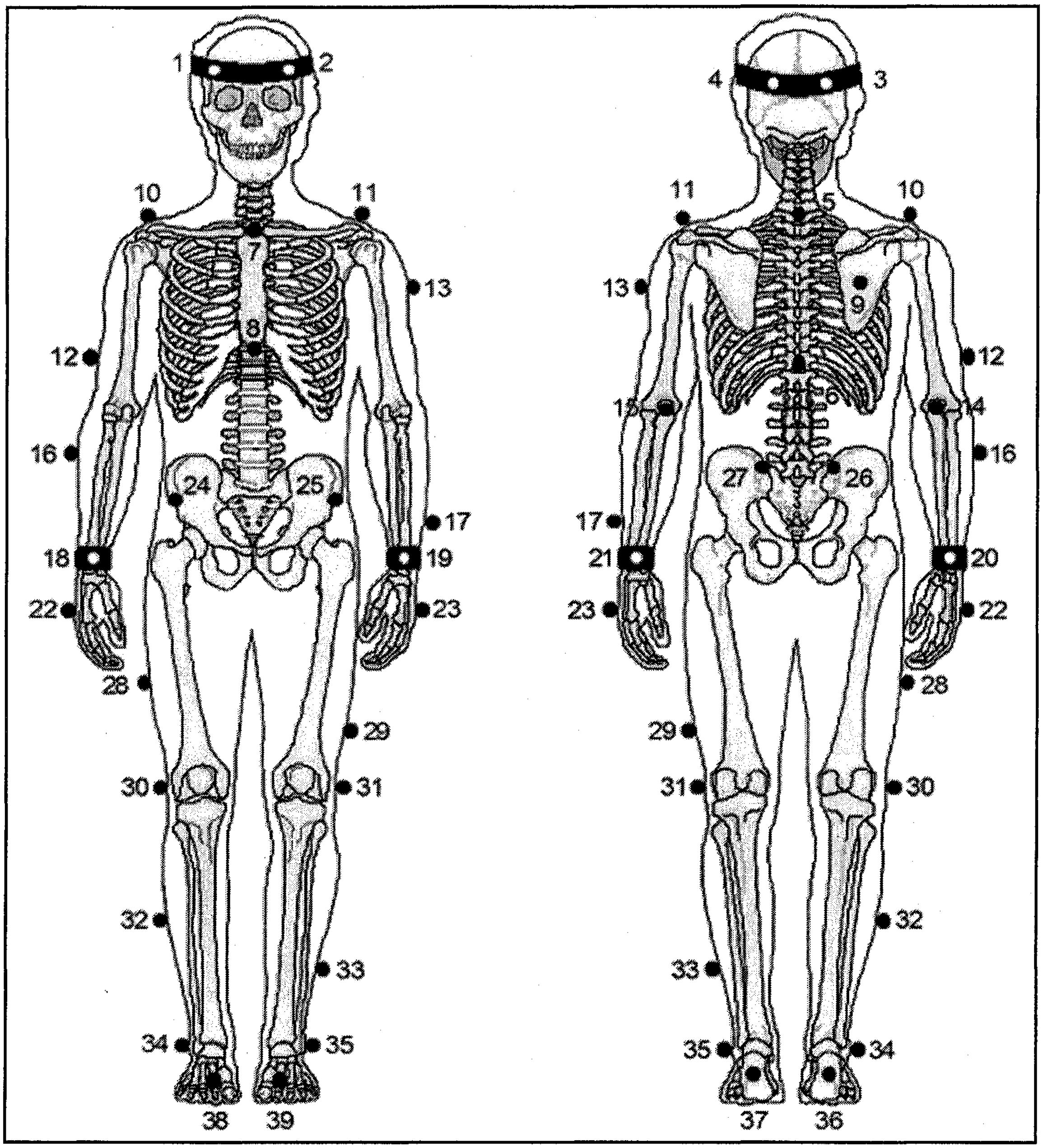

Figure A-14: Marker placement for the modified Helen Hayes marker set: left – anterior view; right – posterior view.

Various anthropometric measurements of the participant were also noted and subsequently used to calculate joint angles (Table A-1). For the capture of the static trial, the participant was asked to stand in an anatomically neutral position with his/her arms abducted at approximately a 90 degree angle, elbows flexed at a 90 degree angle and hands in a prone position (Figure A-6).

Table A-5: Anthropometric measurements of the participants needed to calculate joint angles.

Measurement Name	Measurement Description
Mass (kg)	Weight of the participant
Height (cm)	Height of the participant
Leg length (cm)	Distance between the ASIS and the medial malleolus when the leg is fully extended
Knee width (cm)	The medio-lateral width of the knee across the line of the knee axis when the participant is in a standing position
Ankle width (cm)	The medio-lateral distance across the malleoli

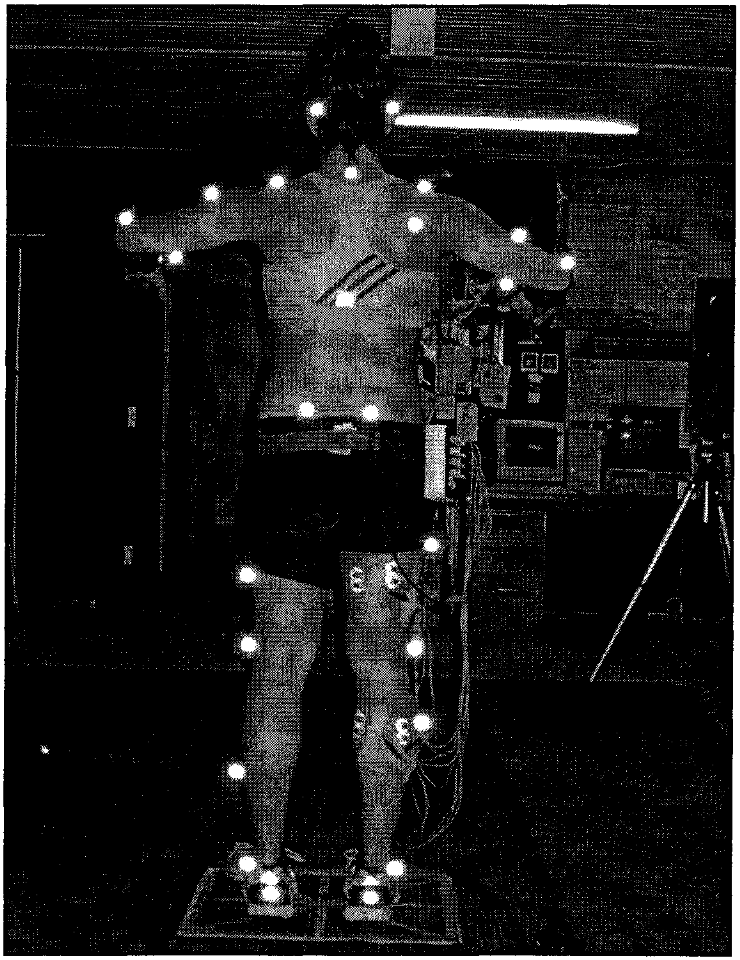

Figure A-15: Capture of the static trial.

Electromyography. In addition to 3D kinematic data, electromyography data were collected with an eight-channel EMG system (Bortec AMT-8, Bortec Biomedical Ltd.) at 1000 Hz. Pairs of surface electrodes (Kendall Meditrace ® 133, Ag/AgCl) were placed over the belly of the following muscles of the right lower limb, with its centres located 2.3 cm apart: TA, MG, LG, VL, VM, BF, ST and RF. A reference electrode (i.e., ground electrode) was placed on the patella. The activity of those muscles was recorded during the pre-stance and stance phases of an unanticipated cutting task. Prior to electrode application, the skin area on which these electrodes were placed was shaved, if necessary, with a new disposable razor and cleaned with an alcohol swab. Once electrode placement was completed, the wires were clipped to the electrodes and plugged into the portable unit located on a belt worn around the participant's waist. This portable unit was subsequently connected to the main amplifier.

Prior to the experimental protocol, the participant's maximum voluntary isometric contractions (MVIC) was then measured. The athlete performed three maximal isometric contractions against a fixed resistance for each movement: knee flexion, knee extension, ankle dorsiflexion and ankle plantar flexion. For the former two movements, the knee of the participant was positioned at 60° of knee flexion to be consistent with prior research (Hewett et al., 1996). For ankle dorsiflexion and ankle plantar flexion, the ankle was positioned at 15° and -10° of plantar flexion, respectively, with the knee at 90° of flexion. The literature (Koh & Herzog, 1995; Sale, Quinlan, Marsh, McComas, & Belanger, 1982) shows that these positions are optimal for maximal strength production of the ankle plantar and dorsiflexors.

Ground reaction forces. The ground reaction forces were also measured during the stance phase of the cutting manoeuvre. A force platform (AMTI, Model OR6-6-2000, Watertown, MA, USA) was embedded in a walkway for it to be flush with the flooring. This measure was used to determine the IC and the toe-off events of the athlete's right foot with the ground.

As the video, the EMG and the force platform data were collected with Workstation software (Vicon Peak, Oxford, UK), this setup allowed for synchronization of kinematic, kinetic and EMG data.

Protocol

Each participant scheduled a three-hour session that was convenient for both the participant and the investigator. Since it has been shown that the phase of the menstrual cycle may have an effect on a woman's neuromuscular performance, every female athlete scheduled this session during her follicular phase. This phase was chosen as it is easily identifiable.

Upon the arrival of a participant, the latter read and signed the consent form and provided information necessary to the study, such as age, athletic background (soccer experience and current level of play), day of menstrual cycle (women only) and use of oral contraceptives (women only). Additionally, height, mass and Q-angle were measured. Each athlete then completed a practice session that included several anticipated and unanticipated trials of each of the three tasks to familiarize his/herself with the experimental setup. The athlete then performed 15 trials; five trials of each task were randomly performed. The tasks consisted of a 45° cutting manoeuvre, a straight ahead run and a run-stop. The latter two tasks were catch tasks so as to present the athletes with three options. Consequently, the cutting manoeuvre became an unanticipated task. Specifically, the 45° cutting manoeuvre consisted of an approach run, followed by a plant-and-cut manoeuvre at a 45° angle with the right foot on the force platform. The area on the walkway to the side of the force platform was outlined with a black rubber mat to designate the path that the athlete was to undergo. As for the straight ahead run, the participant continued his/her approach run through the experimental set-up, with a change in neither direction nor speed. During the run-stop task, the participant stopped the approach run with his/her right foot on the force platform.

As the athlete approached the force platform, he/she triggered a photoelectric cell located 2 m prior to the force platform that triggered an illuminated target board, which was placed 3 m ahead of the force platform (Figure A-7). The target board randomly illuminated with an orange (cut), green (straight run) or red (run-stop) light, indicating to the athletes which task to perform (Figure A-8). Each participant was given approximately 1.0-1.5 minutes between trials to reduce the potential effects of fatigue. Only successful trials were kept. A cutting trial was deemed successful if the participant performed the manoeuvre when the target board illuminated with an orange light. Furthermore, the participant had to approach the force platform with a speed of 4.0-5.0 m/s, make the initial ground contact with the force platform and change direction at a 45° angle (Figure A-9). Two other photoelectric cells, positioned 1 m apart, were located 0.5 m prior to the force platform to monitor approach locomotor speed.

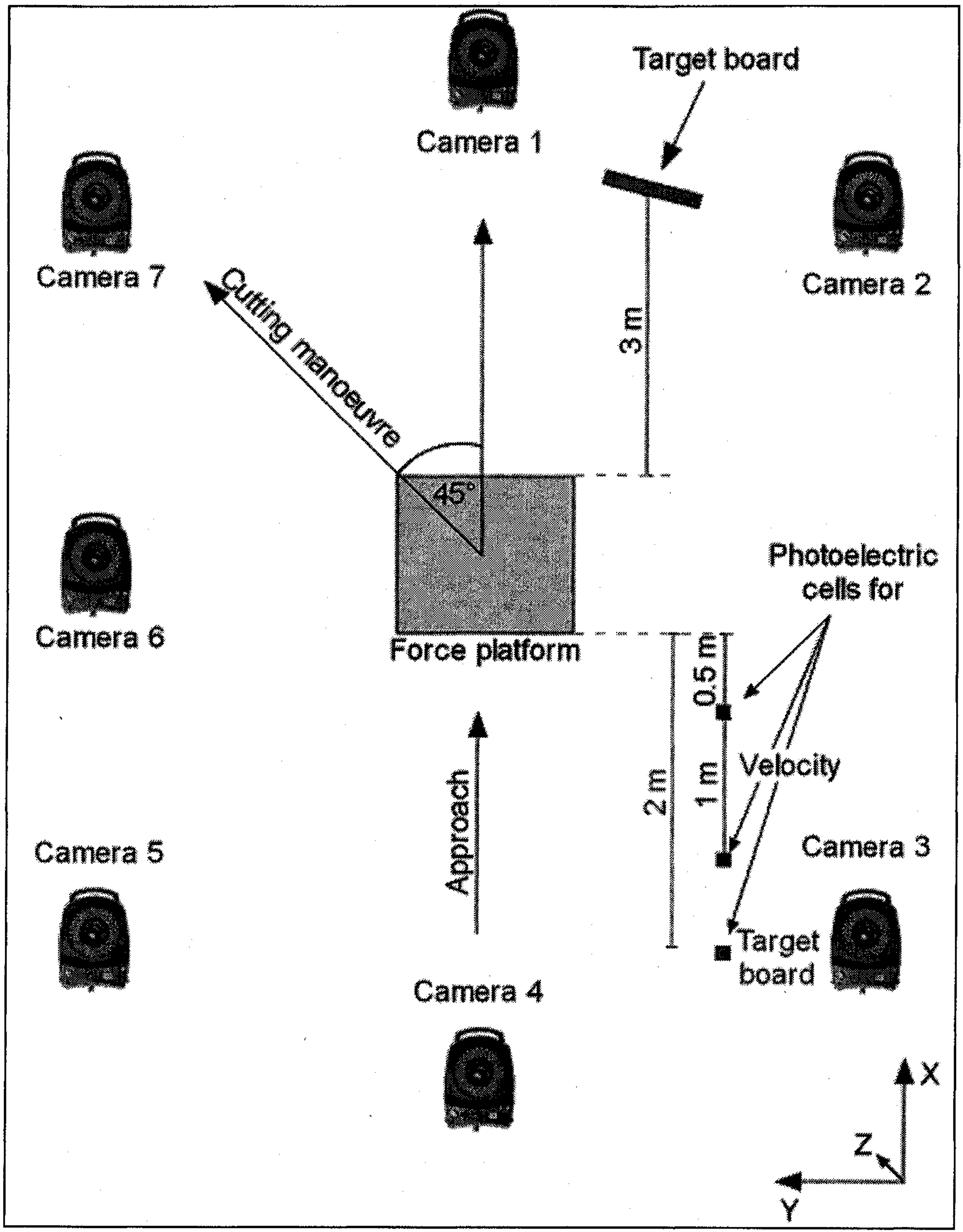

Figure A-16: Experimental set-up (not at scale).

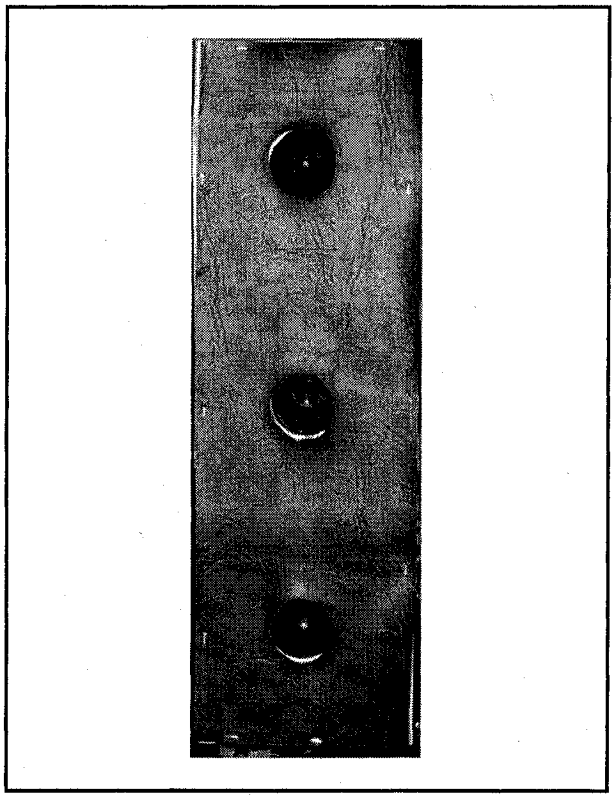

Figure A-17: Target board used to indicate to the participants which task to perform.

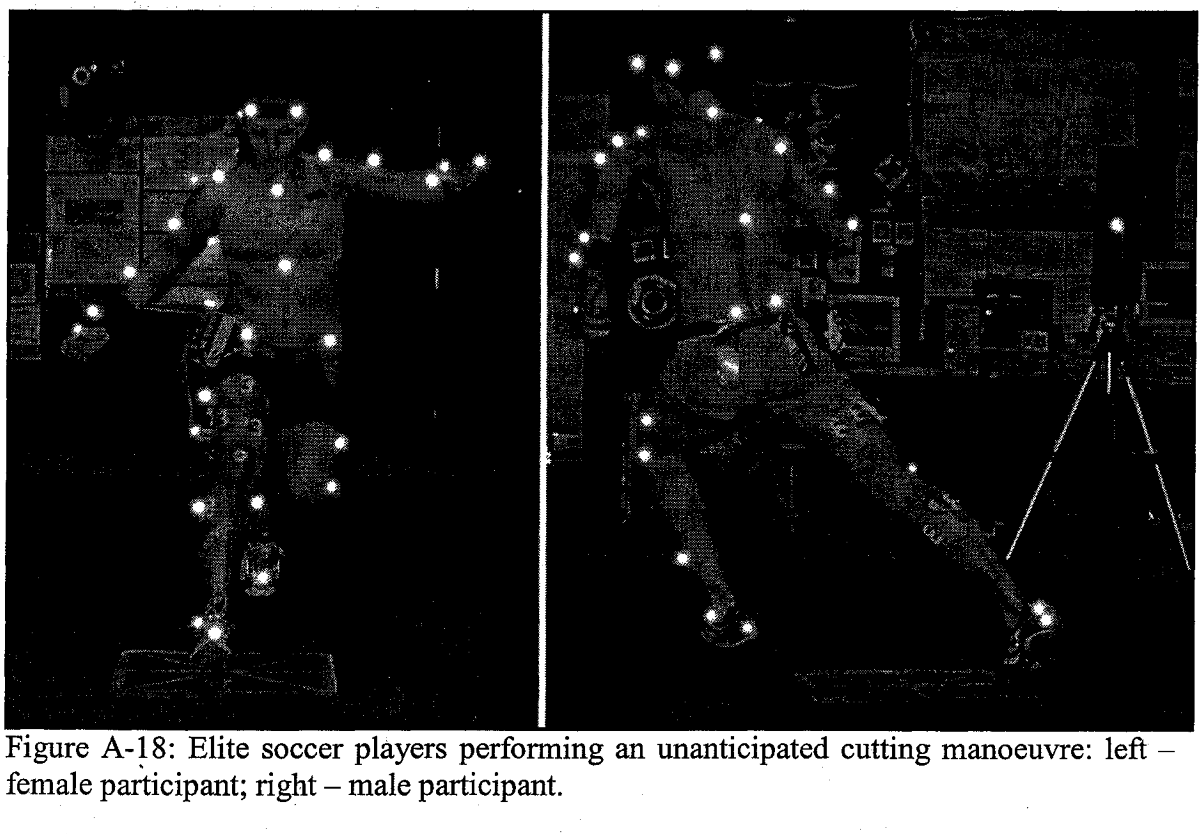

Figure A-18: Elite soccer players performing an unanticipated cutting manoeuvre: left – female participant; right – male participant.

Data Processing and Analysis Procedures

Three-dimensional kinematics and electromyography data of each participant were analyzed for five successful unanticipated cutting trials. The cycle of interest of the cutting trial (i.e., "cutting cycle") was defined as the combination of the pre-stance (i.e., preparation) and stance phases of the right lower limb. This former phase was characterized as the last portion of the swing phase – the time from peak right knee flexion angle to IC – prior to the stance phase during which the participant executed a change in direction. This cycle was applied to time normalize the data and to thus enable averaging across trials within and between participants.

3D Kinematic analysis. To calculate the three-dimensional coordinates of the markers, as well as to perform further analyses on the kinematic data, Workstation software (Vicon Peak, Oxford, UK) was used. Once acquired, these coordinates were filtered using Woltring's spline smoothing code (Woltring, 1986). Specifically, a General Cross Validatory (GCV) quintic order spline was used to smooth each marker's three-dimensional trajectory. Subsequently, the PlugIn Gait model was implemented for quantification of ankle, knee and hip flexion/extension, abduction/adduction and internal/external rotation angles during the "cutting cycle". From these data, peak angular values during the stance phase, angular values at IC and range of angles during the "cutting cycle" were obtained for each trial of a participant. The data of the five trials were then averaged for each individual. By doing so, we were able to determine if 3D kinematic data of the "cutting cycle" differed significantly between genders during an unanticipated cutting manoeuvre.

Electromyographic analysis. From the raw EMG data, the onset was determined for each muscle for each trial with a custom MATLAB® (The Mathworks, Inc. USA) program. The onset of each trial for a participant was determined, as opposed to the onset of the group of trials, due to the variability of the movement. It was noticed in a pilot study, during which the onset of lower limb muscle activity was determined during a one-legged drop-jump landing, that the activation timing patterns were too variable to be able to determine a single onset for each participant. As the cutting task may be compared to a landing task as they are both not cyclic in nature, unlike the gait pattern, it can be hypothesized that the muscle activation timing patterns during a cutting manoeuvre may also include much variability. Consequently, the process for detecting the onset of a muscle contraction in the custom MATLAB® program consisted of first selecting a portion of the cutting trial during which the muscle is not active to determine the noise level and a portion during which the muscle is active to determine the activation level. In turn, a threshold was determined. Muscle activation onset was then identified when the signal was two standard deviations above the threshold (Bonato, D'Alessio, & Knaflitz, 1998). The timing of the onset was then reported as a percentage of the "cutting cycle" in relation to IC with the ground. A negative percentage indicated that the onset occurred prior to IC. A positive percentage indicated an onset occurring post IC.

Raw EMG was processed using another custom MATLAB® program. These raw data were baseline corrected, rectified and smoothed with a critically damped filter (cutoff frequency of 6 Hz) to remove low frequency noise (i.e., movement artifact) and to generate a linear envelope of the EMG signal (LEEMG). From the LEEMG data, the timing of the peak muscle activity was reported as a percentage of the "cutting cycle" in relation to IC, as well as this peak's amplitude normalized to the participant's MVIC. This MVIC-normalized EMG data were obtained by dividing the EMG signal by the MVIC value for each muscle. Using this MVIC-normalized data, its integral was acquired for the pre-stance and stance phases.

Most importantly, the short time mean frequency (STMNF) and the total intensity (TI) of the pre-stance and stance phases of muscle activation were obtained by means of a custom MATLAB® program. The EMG signal was first decomposed in time and frequency using 11 non-linearly scaled wavelets, whose center frequencies, cf_j, where j=0,1,...,10, were pre-defined (von Tscharner, 2000). The power/intensity of the EMG signal in each of the 11 wavelet frequency bands were obtained with the method proposed by von Tscharner (2000), where $p_{j,n}$ represents the power for wavelet j at time t_n. Based on another method presented by von Tscharner and Goepfert (2003), the STMNF (Equation 1) was obtained by

$$STMNF_n = \frac{\sum_{j=0}^{10} cf_j \cdot p_{j,n}}{\sum_{j=0}^{10} p_{j,n}} \quad (1)$$

and the TI (Equation 2) of the EMG signal was obtained by

$$TI_n = \frac{TI_n'}{MT} \quad (2)$$

where $TI_n' = \sum_{j=0}^{10} p_{j,n}$, and $MT = \max(TI_n')$. After the STMNF and TI were obtained, these data were time normalized to the "cutting cycle" and averaged for each participant. From the averaged STMNF data, its value at IC, as well as its integral for the pre-stance and stance phase of the "cutting cycle", were compared between the female and male soccer players. As for the TI data, total intensity at IC and the timing of the peak, as a percentage of the "cutting cycle" in relation to IC, were reported.

Table A-2 contains a summary of the EMG variables compared between genders in the present study.

Table A-6: EMG variables compared between genders.

Variable	Unit
Timing of onset	% of "cutting cycle" in relation to IC
Timing of LEEMG peak	% of "cutting cycle" in relation to IC
Amplitude of LEEMG peak	% of MVIC
Amplitude at IC	% of MVIC
LEEMG Integral	
pre-stance phase	None
stance phase	None
Wavelet analysis	
STMNF at IC	Hz
STMNF integral pre-stance phase	None
STMNF integral stance phase	None
TI at IC	None
Timing of TI peak	% of cutting cycle in relation to IC

Statistics. Statistics were accomplished using the SPSS software (version 11.5). The values obtained for each variable were imported in the SPSS software to determine if there was a significant difference between the female and male athletes by ways of ANOVA analyses. Specifically, one-way ANOVAs were used to determine if a significant difference exists between genders with regards to the Q-angle, the 3D ankle, knee and hip kinematic variables. As for the EMG variables, one-way ANOVAs were also performed. Statistical significance was established at alpha (α) < 0.05.

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APPENDIX B

HEALTH SCIENCES AND SCIENCE RESEARCH ETHICS BOARD APPROVAL

COMITÉ D'ÉTHIQUE DE LA RECHERCHE EN SCIENCES DE LA SANTÉ ET SCIENCES

ATTESTATION D'APPROBATION ÉTHIQUE

La présente attestation certifie que le Comité d'éthique de la recherche en Sciences de la Santé et Sciences de l'Université d'Ottawa a examiné la demande d'approbation éthique pour le projet intitulé ***Three-Dimensional Kinematics and Electromyography of the Lower Limb of Male and Female Athletes Performing an Unanticipated Cutting Manoeuvre (dossier H 06-05-04)*** présentée par Mlle Mélanie Beaulieu qui est supervisée par le Dr Mario Lamontagne, tous deux de l'École des sciences de l'activité physique. Le Comité d'éthique a déterminé que la demande respectait les principes éthiques établis par l'Énoncé de politique des trois conseils et par les règles de procédure des Comités d'éthique de l'Université d'Ottawa. Le Comité d'éthique a donc accordé une catégorie 1a (approbation) à ce projet. La présente attestation est valide pour un an à partir de la date indiquée ci-dessous.

Rita D'Alessandro Responsable de l'éthique en recherche Pour le Dr Daniel Lagarec, Président du CÉR en Sciences de la Santé et Sciences	8 juillet 2005 Date