AN EXAMINATION OF LOWER EXTREMITY SEX DIFFERENCES IN CONTINUOUS RELATIVE PHASE DURING A DROP JUMP AND TWO DIFFERENT UNPLANNED CUTTING MANEUVERS

A Thesis
Presented to
the Faculty of Plymouth State University

In Partial Fulfillment
of the requirement for the Degree
Master of Science

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by
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May 2007

PLYMOUTH STATE UNIVERSITY

SCHOOL OF GRADUATE STUDIES

May 2007

We recommend that the master's thesis

prepared under our direction by Arnau Galobardes i Tuneu

entitled AN EXAMINATION OF LOWER EXTREMITY SEX DIFFERENCES IN CONTINUOUS RELATIVE PHASE DURING A DROP JUMP AND TWO DIFFERENT UNPLANNED CUTTING MANEUVERS

be accepted as fulfilling the research requirement for the degree of Master's of Science in Athletic Training

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Dedication

To both of you, because giving me what you had never dreamt was, and still is, your first priority.

To you, for being the good reference that any brother needs while growing as a human being.

To all seven of you, because no matter where I am on the planet, true friendship remains.

And because the following words do not only represent the hopes of a nation but should also represent the hopes of any scientist, friend or lover…

Ara Mateix	Right now
…Posem-nos dempeus altra vegada	…Let's stand upon our feet again
i que se senti la veu de tots	and let the voices of us all
solemnement i clara.	be heard, solemn and clear.
Cridem qui som	Let's cry out who we are
i que tothom ho escolti.	and let the world attend to it.
I en acabat, que cadascú es vesteixi	And then, let everybody choose the
com bonament li plagui,	clothes that each prefers, and
i via fora!, que tot està per fer	go out there!, for all is to be done
i tot és possible.	and everything is possible.

Miquel Martí i Pol

Acknowledgements

I would like to gratefully acknowledge the enthusiastic supervision of Dr.King during this project. None of this would have been possible without her tremendous job and amount of time spent during the preparation of this paper. Margie, thanks for helping me make my dream come true :)

I thank Dr.Swartz for accepting to sit on the thesis committee without hesitation. For the same reason I thank Dr.Hamill. From now on, you have to know that “You’ll never walk alone”.

Núria Cardellach Ramirez and Jordi Roca Vila are thanked for their help with computational assistance and programming during data processing.

I would like to say thank you to Darin A. Padua for data collection and processing guidance.

Monika Bhuta from Innovative Sports Training is thanked for technical support.

I thank Jean P. Boucher for statistical guidance.

Thanks to Jasmine Tyler for her writing assistance and for her patience with a writer whose English is not his native tongue.

Graduate and undergraduate students of the athletic training program at Plymouth State University are thanked for participating in the pilot testing and for peer reviewing my writings.

None of this would have been possible without the participation of the men’s and women’s 2006-2007 basketball teams from Plymouth State University.

MOLTES GRÀCIES A TOTS

THANKS ALL OF YOU

May 2007 A.G.T

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An Examination of Lower Extremity Sex Differences in Continuous Relative Phase during a Drop Jump and Two Different Unplanned Cutting Maneuvers

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ABSTRACT

Objective: To determine whether there is a sex difference in Continuous Relative Phase (CRP) and its variability during a drop jump and two different unplanned cutting maneuvers. ***Design and Setting:*** A repeated measures one session design was used. A 2 x 3 mixed factorial (sex by task) ANOVA was performed on the subjects' means for CRP for five deemed acceptable trials for each task yielding the Mean Absolute Relative Phase (MARP). The standard deviation was calculated to reflect between trial variability resulting in the Deviation Phase (DP) variable. Based on the stance phase, a 2 x 3 repeated measures ANOVA (sex, task) was analyzed for two CRP coordinative relationships: knee rotation and foot inversion/eversion (K_{rot}-$Foo_{in/ev}$); hip abduction/adduction and foot inversion/eversion ($H_{abd/add}$-$Foo_{in/ev}$). ***Subjects:*** Seven males and six females (*N* = 13) non-injured collegiate basketball athletes participated in the study. ***Measurements:*** The MotionMonitor™ (Innovative Sports Training, Chicago, IL) was used to obtain kinematic data used in the data processing to obtain CRP. Subjects performed a drop jump and two different unplanned 45° cutting maneuvers (freely moving their arms and grabbing a ball respectively).

Results: No significant ($H_{abd/add}$-$Foo_{in/ev}$ $p = .736$; K_{rot}-$Foo_{in/ev:}$ $p = .793$) differences were found between sex in any of the coordinative relationships for MARP nor for DP. No significant ($H_{abd/add}$-$Foo_{in/ev}$ $p = .304$; K_{rot}-$Foo_{in/ev:}$ $p = .053$) differences were found between tasks in any of the coordinative relationships for the for DP. ***Conclusions:*** While for the K_{rot}–$Foo_{in/ev}$ relationship the more complex the tasks were, the more variability subjects showed, this phenomenon was not observed for the $H_{abd/add}$-$Foo_{in/ev}$ relationship. Upon closer review, it was revealed that there was increased variability seen in the women in the least complex of the tasks, Task A (drop jump). This may be the manifestation of the suggested lack of neuromuscular control of the hip and core muscles resulting in the large variability observed. In this instance, variability may be counter productive and a predisposing factor for injury.

An Examination of Lower Extremity Sex Differences in Continuous Relative Phase during a Drop Jump and Two Different Unplanned Cutting Maneuvers

Results focusing in biomechanical lower extremity gender differences observed in laboratory motor tasks have been reported within the literature. While some authors (Bello, 2004; Ciolek, 2002; Willson et al., 2006; Zeller et al., 2003) found gender differences in their results, others did not (Barber-Westin et al., 2006; Noyes et al., 2005; Pollard et al., 2004a). Traditional explanations to these gender differences include anatomical factors (Chandrashekar et al., 2005; Horton & Hall, 1989; Lombardo et al., 2005; McClay Davis & Ireland, 2003; Teitz et al., 1997), and neuromuscular factors (Barber-Westin et al., 2006; Chappell et al., 2005; Ciolek, 2002; Garrison et al., 2005; Hewett, 2000; Hewett et al., 1996; McClay Davis & Ireland, 2003; Noyes et al., 2005; Rozzi et al., 1999; Shultz et al., 2001; Zeller et al., 2003).

All the studies that obtained kinematic data focused on the function of a single joint. Dynamical Systems Theory offers an innovative approach for human motion analysis. One of its tools, continuous relative phase, is a unique measure because it compresses four variables (proximal and distal segments’ displacement and velocities) into one measure (Stergiou, 2004). This approach allows the study of inter-joint coordination and its variability and this methodology has been proposed as an alternative to the traditional explanations for the gender differences in anterior cruciate ligament (ACL) injury rates (Pollard et al., 2004b; Pollard et al., 2005). In one of these studies, Pollard et al. (2005) found gender differences in variability using joint coupling analysis while previous analysis using single joint assessment of the same sample of participants (Pollard et al., 2004a) did not.

In order to analyze human motion, different motor tasks have been used in laboratory conditions. The single leg squat test (DiMattia et al., 2005; Zeller et al., 2003), the vertical jump test (Bello, 2004; Brosky et al., 1999; Ernst et al., 2000; Petschnig et al., 1998; Shetty & Etnyre, 1989), the drop jump test (Barber-Westin et al., 2006; Noyes et al., 2005), stop-jump tasks (Chappell et al., 2005), gait analysis (Byrne et al., 2002; Chmielewski et al., 2005; Kurz & Stergiou, 2002), running analysis (Hamill et al., 1999; Heiderscheit et al., 1999, 2002; Kurz & Stergiou, 2002; Stergiou et al., 2001a; Stergiou et al., 2001b), obstacle clearance tasks (Stergiou et al., 2001a; Stergiou et al., 2001b), shooting in basketball (Liu & Burton, 1999), and cutting tasks (Besier et al., 2003; Besier et al., 2001a; Besier et al., 2001b; Ciolek, 2002; Pollard et al., 2004a; Pollard et al., 2004b; Pollard et al., 2005) have been used.

Several other tasks under the denomination of functional tests, such as the single-leg hop for distance (Bandy, 1992; Barber et al., 1990; L.A. Bolgla et al., 2002; Brosky et al., 1999; Docherty et al., 2005; Groves, 1994; Noyes et al., 1991; Petschnig et al., 1998; Wilk et al., 1994; Yildiz et al., 2003) are currently being used in clinical conditions as a return to play criteria.

Different authors (Balagué i Serre, 2005; Bandy, 1992; Pollard et al., 2005) have identified that one limitation of some of the currently administrated tasks and tests may be the fact that these tasks and tests do not parallel the situations that the athletes are facing in the real sports competition.

Besier et al. (2001a) found kinematic differences in a cutting task when the motion to perform was preplanned (similar to most of the laboratory tasks and tests) compared to an unplanned motion (similar to real sport situations).

Olsen et al. (2004), after reviewing ACL videotaped injuries in female team handball players, found that of the 19 injuries in the attacking phase, seven were out of balance and in 12 cases athletes suffered some form of perturbation (being out of balance, being pushed or held by an opponent or trying to evade a collision with an opponent). These injury situations do not mimic the tasks usually proposed in laboratory conditions.

Additionally, most of these laboratory based tasks and tests are not administered under fatigued conditions and fatigue might be an important factor for injury risk during athletic participation.

Different authors (Brosky et al., 1999; Shetty & Etnyre, 1989) have suggested that arm motion may modify the results found in the tasks and tests where arm motion is restricted by crossing the arms on the chest or by placing the hands on the waist.

Another weakness of these tasks and tests may be the level of instructions given in order to perform the tasks. Noyes et al. (2005), in an attempt to avoid knee injuries and during a training protocol, made athletic trainers instruct the subjects of their study to keep the heels directly under the hips with toes and knees pointed forward at all times during landing and take off when jumping. However, from a Dynamical Systems point of view, Munhall & Kelso (1985) suggested the need to guide research by the ability to detect patterns in the data rather than by the direct comparison of models. Therefore, they suggested that treatment interventions in sports medicine should not be directed towards the achievement and maintenance of an “ideal” motor pattern.

After reviewing the literature, it became apparent that Dynamical Systems Theory and its tools might be a useful approach to analyze biomechanical lower extremity sex differences. Study of the variability of joint coordination to account for biomechanical lower extremity sex differences might be an alternative to the traditional explanations for the disparity of ACL injuries rates between males and females, that include anatomical and neuromuscular factors, and that until now have shown varied and contradictory results.

The purpose of the present study was to examine lower extremity sex differences in joint coordination during one of the tasks that has been traditionally used in laboratory conditions, a drop jump, and two different unplanned cutting maneuvers. A cutting task, and specifically a sidestepping task, has been identified to be a main mechanism of ACL injuries (Boden et al., 2000; Olsen et al., 2004). Additionally, Arendt & Dick (1995) reported a greater incidence of ACL injuries in females compared to males. Therefore, in this study, it was anticipated that biomechanical sex differences would be present in the cutting tasks.

METHOD

The purpose of this study was to examine lower extremity sex differences in continuous relative phase during a drop jump and 2-different unplanned cutting maneuvers. A kinematic analysis was performed with the MotionMonitor™ (Innovative Sports Training, Chicago, IL). The MotionMonitor™ is composed by a software program (designed by Innovative Sports Training Inc.), an analog to digital (A/D) board, and the Flock of Birds™ (Burlington, VT) as hardware. The Flock of Birds™ is an electromagnetic motion tracking system. Each subject was asked to perform a 90-minute training session, and 24-72 hours later, a 60-minute one-time testing session. In both sessions each subject performed a series of drop jumps and 2-different unplanned cutting maneuvers.

Subjects

Following Institutional Review Board (IRB) approval (Appendix C), a total of seven male (age = 21.2 ± 1.3 years; height = 182.1 ± 7.5 cm; weight = 79.7 ± 8.4 kg) and six female (age = 19.6 ± 1.2 years; height = 170.1 ± 8.2 cm; weight = 80.4 ± 15.9 kg) non-injured volunteers participated in the study. Subjects were collegiate basketball athletes from a New England Division III university. With the data obtained from the subject sport, fitness, and injury history questionnaire (Appendix D), subjects were excluded from the study if they presented any of the following: any history of surgical interventions in the lower back or lower extremities; any previous history of injury in the lower back or lower extremities, within the last three months, that had required absence from practice or play or alternative conditioning for more than three days; any current injury of the lower back or lower extremities that would have required medical attention.

Each subject was also required to read and sign an informed consent document (Appendix C) before participating in the study.

Testing Instruments

Kinematic Assessment

The MotionMonitor™ and the Flock of Birds ™ Systems

To obtain kinematic data, the MotionMonitor™ (Innovative Sports Training, Chicago, IL) was used as software program. The MotionMonitor™ integrates the Ascension (Burlington, VT) system, “Flock of Birds™” as hardware. The Flock of birds™ is an electromagnetic tracking device based on direct current.

Electromagnetic Sensors

Eight electromagnetic sensors were used to digitize the subject and measure the following: foot inversion/eversion, knee rotation, and hip abduction/adduction. Data was collected at a sampling rate of 100 frames per second.

Video Cameras

Two video cameras were placed next to the testing area. The cameras were focused on the subjects’ feet during the two different unplanned cutting tasks and were used to confirm acceptable trials by identifying appropriate foot placement while performing the tasks.

Kinetic Assessment

4060-NC Bertec Force Plate

A non-conductive 4060-NC Bertec force plate (40 x 60 cm.) made from a resin impregnated wood, and specifically designed to be used in environments requiring measurement of magnetic fields, was used to identify the stance phase of the tasks performed by the subjects.

The Testing Area (Appendix F)

The landing area, which consisted of the 4060-NC Bertec force plate, was located within a 319.5 x 122 cm. wooden platform which was raised (15.24 cm.) from the floor level. The distance from one edge of the wooden platform to the center of the landing area was 208 cm. while the distance from the other edge to the center of the landing area was 111.5 cm. Next to the wooden platform, two exiting wooden platforms (122 x 122 cm. and both raised 15.24 cm.) were placed in order to provide a safety exiting area to perform all the tasks. One of the edges of each of these two exiting platforms was positioned in contact with the largest edges of the wooden platform. The distance from one edge of each exiting platform related to the smallest edges of the wooden platform was 233 cm.

Additionally, two diagonal cutting alleys were drawn on the three wooden platforms taking as reference the center of the landing area. These two alleys were 30 cm. wide and two imaginary lines divided each of the alleys in two equal parts. These two imaginary lines had their origin on the middle of the landing area and described an angle of 45º in relation with the largest edge of the landing area.

The transmitter (30.5 x 30.5 x 30.5 cm.) was positioned on a 44 cm. high plastic podium, with the center of the transmitter located at 96.5 cm. of the center of the landing area.

Functional Tasks

Use of the Step for All the Tasks

A 13 cm. height step served as the starting position for the three tasks. The step was placed on the wooden platform in front of the landing area. The distance from the center of the step to the center of the landing area depended on the subjects’ anthropometric measures.

Use of the Photoelectric Switch for Tasks B and C

Between the step and the landing area, one photoelectric switch (MicroDetectors®, Italy) created a photoelectric field. The photoelectric switch and its mirror were placed between the starting position and the wooden platform at a distance of 15 cm. from the starting position. Photoelectric switch and mirror were separated by 302 cm. They were placed at a height corresponding to the midpoint of the thigh for each subject. The photoelectric switch was connected by an electric cable to an electric switch. From the switch, two electric cables were separately connected to two different 100W color bulbs (blue and amber). The bulbs were placed on the wall, at 225 cm. horizontally from the center of the landing area and at 110 cm. of height from the floor level. Both bulbs were separated by 120 cm.

Use of a Volleyball for Task C

For setting up the subjects in the starting position according to their anthropometric characteristics and to complete task C, one volleyball (diameter = 20 cm.) attached by Velcro® to a retractable rope was suspended above the surface of the wooden platform. The ball was placed between the subjects starting position and the landing area. The horizontal distance between the center of the ball and the center of the landing area was 40 cm. and its height depended on the subjects anthropometric characteristics.

Procedures

Training Session

Arrival at the Human Performance Laboratory

Each subject was asked to participate in a 90-minute training session, and 24-72 hours later in a 60-minute one-time testing session. Upon their arrival at the Human Performance Laboratory for the training session, the subjects were required to fill out a short sport, fitness, and injury history questionnaire (Appendix D) and an informed consent form (Appendix E). Subjects were required to wear a pair of athletic low top shoes, shorts, t-shirt and socks. The investigator then measured and recorded subjects’ descriptive data (age, height, weight, sex, and limb dominance).

Establishing the Vertical Height of the Ball

Each subject stood in front of the descending trajectory of the volleyball with the right shoulder flexed at 180° and the right elbow extended. The ball attached to the rope by Velcro® was lowered with a pulley mechanism until the moment that the center of the ball coincided with the olecranon process of each of the subjects' elbow.

Establishing Subjects' Horizontal Distance from the Ball

The subjects were placed on the step with the right shoulder flexed at 90°, the elbow extended, the forearm pronated, the wrist extended and the fingers flexed. The horizontal distance of the step was adjusted until the distal end of the third metacarpal bone was placed in the same vertical plane as the forward edge of the ball.

Height of the ball and distance from the step to the center of the landing area were recorded for each subject to be replicated during the testing session.

Warm-up

The subjects completed a 5-minute stationary bike warm-up on a Compu Trainer Pro® device.

Sensors Set-Up

Seven electromagnetic sensors were assigned to 7-different landmarks. The sensors were attached with double side tape on the skin and were secured with elastic tape. The seven landmarks for each sensor were: #2, L5-S1 spinous processes; #3, midpoint of the left thigh on its lateral aspect; #4, midpoint of the right thigh on its lateral aspect; #5, midpoint of the gastrocnemius muscle belly on its lateral aspect on the left leg; #6, midpoint of the gastrocnemius muscle belly on its lateral aspect on the right leg; #7, midpoint of the dorsal aspect of the left foot; #8, midpoint of the dorsal aspect of the right foot. It is important to note here that the sensors on the feet were also supported by the tongues and laces of the shoes. Finally, the stylus was attached to sensor #1 and was used to digitize the location and orientation of virtual joint centers and segment axes relative to the world coordinate axes and create a three-dimensional diagram of the subject. For this purpose, each subject adopted an anatomical neutral position, standing on the surface of the landing area, facing the positive y-axis.

The height of the subject was measured by digitizing the top of the head with the stylus. The feet, ankles, and knees were digitized using the centroid method. This method consists of digitizing two points on equal and opposite sides of the joint. The hips were digitized using the Leardini (1999) method, circumducting the hip through 6 different positions. The knees were digitized to the medial and lateral joint line. The ankles were digitized to the medial apex of the medial malleolus and lateral apex of the lateral malleolus. The feet were digitized to the distal phalanx of the first toe.

Tasks to Perform

At the beginning of the training session, the order in which the subjects practiced the three tasks (tasks A, B, and C) was randomly selected. Then, and following this order, a 15 minute instructional-period was used to provide verbal instructions and demonstrations of the drop jump and the two unplanned cutting tasks (tasks B, and C). During the 15-minute instructional period, and before practicing the drop jump, the subjects viewed a short video clip demonstrating the drop jump from the sagittal plane providing the subjects a reference model for task performance. In addition to the visual information, instructions to the subjects related to the drop jump were:

“start with a two foot take-off, land with both feet within the limits of the landing area bending your knees as shown in the video clip. Then jump up as high as you can and land on the landing area with both feet at the same time. Keep both of your hands at your waist during the whole maneuver”. Then the subjects were allowed to practice four trials of the drop jump.

For the unplanned cutting tasks, four trials of each task were performed starting the maneuver and landing with the right lower extremity and then four more trials for each task were performed starting the maneuver and landing with the left lower extremity. However, and for learning purposes, in this 15-minute instructional period instead of performing unplanned tasks, the subjects performed planned tasks, two of them being sidestepping maneuvers while the other two were crossover maneuvers. No video clip reference model was supplied for the cutting maneuvers. Instructions for tasks B and C included: “start with a one-foot take-off, land within the limits of the landing area with the same foot that started the approach maneuver. Initiate the cutting maneuver with your other foot in the appropriate direction, stepping within the limits of the corresponding cutting alley. The phase from the moment you first make contact with the landing area until the end of the maneuver has to be performed as fast as possible, as a sport situation”. Additionally, and for task C, other instructions included: “on your way to the landing area, grab the volleyball with both hands, bring it down and keep it in both hands during the rest of the maneuver”. After this 15-minute instructional-period, the subjects self elected which foot (right or left) they preferred to start the unplanned cutting maneuvers and land on the landing area for the rest of the training session and for the test session. The foot elected was recorded.

Then, and following the same previously randomly selected order each task was practiced during 10 minutes with unlimited number of trials. At this time, the unplanned cutting maneuvers were introduced utilizing the signal bulbs.

Task A (Drop Jump). Subjects stood on the step placing their hands at their waist and with both feet centered to the landing area. Subjects were asked to drop from the step using a two foot take-off, land onto the landing area with both feet simultaneously and perform a vertical maximum jump to finally land on the landing area with both feet simultaneously. Subjects were asked to keep their hands on their waist throughout the whole task.

Task B (cut and free upper extremity motion). Subjects were placed in the same start position as for task A (Drop Jump). Then the investigator connected the photoelectric switch. The subjects initiated an approaching maneuver towards the landing area with a one-foot take-off (the one self-selected during the instructional period) and targeted and landed on the landing area with the same foot that started the approaching maneuver. When the photoelectric field was cut by the subjects approaching the landing area, one of the two bulbs placed on the field of vision of the subjects was illuminated. The investigator was able to manipulate via the electric switch, which of the two bulbs was going to be illuminated prior to each approaching maneuver.

After landing on the landing area with the self-selected foot, the subjects had to perform a cutting maneuver through one of the two alleys marked on the wooden platforms. Illumination of the right bulb indicated the need to perform a right cutting maneuver. Illumination of the left bulb indicated the need to perform a left cutting maneuver. During the next stance phase of the maneuver the subjects had to step within the limits of the alley with their other foot. If a subject self-selected the right foot to perform the maneuver, then illumination of the right bulb indicated the need to perform a cutting maneuver consisting of a crossover task while illumination of the left bulb indicated the need to perform a cutting maneuver consisting of a sidestep task. If a subject self-selected the left foot to perform the maneuver, then illumination of the right bulb indicated the need to perform a cutting maneuver consisting of a sidestep task while illumination of the left bulb indicated the need to perform a cutting maneuver consisting of a crossover task.

Task C (cut and grab the ball). Procedures were exactly the same as in task B with the exception that now the subjects were instructed to grab the volleyball which was hanging from the ceiling with both hands, bring it down and keep it in both hands during the rest of the maneuver.

Testing Session

Between 24 and 72 hours after the training session, the subjects came back to the Human Performance Laboratory for the 60-minute one-time testing session. The protocol followed was composed by the same warm-up and the same sensor set-up as for the training session. The starting position of each subject and the height of the volleyball were placed according to the measurements taken in the training session.

The three tasks to be performed were the same used during the training session and the order in which they were performed was randomly selected for each subject. For the two unplanned cutting maneuvers, the foot elected during the 15-minute instructional period of the training session to start the unplanned cutting maneuvers and to land on the landing area was used for the same purposes.

Before data recording, and for each task, subjects were asked to execute 2-practice trials. Subjects then performed the maneuvers and kinematic and kinetic data was recorded. Subjects executed 6-testing trials for the drop jump and 18-testing trials for each of the other two unplanned cutting tasks (nine trials directing the subjects to the right and nine more directing the subjects to the left).

For the unplanned cutting-task trials, the investigator was able to manipulate the direction of the unplanned cutting maneuver (right or left) using the electric switch without subjects’ knowledge. The order, in which the directions of the 18 trials of the two unplanned cutting-maneuvers was performed, was randomly selected by the investigator prior to the subjects' arrival at the Human Performance Laboratory. The investigator randomly selected the order for each unplanned cutting task and for each subject individually. Each task was relatively short in duration and anaerobic in nature. However, to avoid fatigue as a confounding factor, each subject was given 30 seconds of rest between each trial and three minutes between each task.

An acceptable trial for task A consisted of landing inside the limits of the landing area, jumping vertically and landing again inside the limits of the landing area. Hands had to be kept on the waist during the whole maneuver. For tasks B and C, subjects needed to step inside the limits of the landing area, follow the correct direction indicated by the signal light, and step with the other foot inside the limits of the alley. For task C, subjects had to grab the volleyball which was hanging from the ceiling with both hands, bring it down and keep it in both hands during the rest of the maneuver.

For task A, B, and C the investigator visually identified the correct performance of the tasks. For tasks

B and C, video analysis post-intervention was used to determine if the subjects moved within the alley limits.

Data Processing

The digitized kinematic data was obtained from the MotionMonitor™ for the lower extremity (right or left) elected by the subject to perform tasks B and C during the training session. For task A, the same leg was examined. The whole stance phase and 3 frames before and after the stance phase identified with the kinetic data obtained from the force plate were digitized. For task A, the stance phase analyzed corresponded to the phase in which subjects landed on the landing area for the first time and not after performing the vertical jump. Kinematic data was smoothed and filtered using a Butterworth filter set at 10 Hz.

Creation of the Phase Plots

Phase plots were calculated for the following joint angles: foot inversion/eversion, knee rotation, and hip abduction/adduction. Each phase plot was achieved by plotting the joint's angular position (θ) on the horizontal axis versus its angular velocity (ω) on the vertical axis.

Normalization of the Phase Plots

Before calculation of the phase angles, each phase plot for each of the trials performed by the subjects was normalized using a normalization method in which the following equations were used:

Horizontal axis (angle):

$$\theta_i n = \frac{2 * [\theta_i - (\max \theta_i + \min \theta_i)]}{\max \theta_i - \min \theta_i}$$

(θ = segment angle; i = data point within the stance phase)

Vertical axis (angular velocity):

$$\omega_i n = \frac{\omega_i}{548.505327}$$

(ω = segment angular velocity; i = data point within the stance phase)

The normalization process was conducted in order to adjust for amplitude differences in the range of motion of the three joints analyzed (hip abduction/adduction, knee rotation, and foot inversion/eversion) and to center the phase plot about an origin (Hamill et al., 2000).

After the normalization process, the phase plots had four quadrants being -1.0 and 1.0 the minimum and maximum values. The axis where angular velocity was plotted was normalized based on the maximum absolute velocity value of the multiple strides from all trials, tasks, subjects, and joint motions analyzed. This value corresponded to 548.505327 degrees/sec. This process placed zero velocity at the origin.

Calculation of the Phase Angles

To calculate the phase angle for each data point of the cycle, the phase plot trajectories were transformed from Cartesian (x,y) to polar coordinates, with a radius (*r*) and phase angle (Φ). The phase angle (Φ) was defined as the angle between the right horizontal and a line drawn from the origin to a specific data point (θ, ω) (Hamill et al., 1999), and was calculated as follows:

$$\Phi = \tan^{-1} \frac{\omega(t)}{\theta(t)}$$

(ω = angular velocity; θ = angular displacement at the time point (t) of the trajectory of the stance phase)

The phase angles were calculated for foot inversion/eversion, knee rotation, and hip abduction/adduction.

Calculation of the Continuous Relative Phase (CRP)

The CRP was defined as the difference between the normalized phase angles of two segment motions throughout the stance cycle.

$\mathrm{CRP}(t) = \Phi_{\text{distal segment}}(t) - \Phi_{\text{proximal segment}}(t)$

CRPs were calculated from the normalized phase plots for hip abduction/adduction and foot inversion/eversion ($H_{abd/add}$ - $Foo_{in/ev}$); knee rotation and foot inversion/eversion (K_{rot} – $Foo_{in/ev}$).

Calculation of the CRP Rescaled to % of Stance Phase

Using a polynomial procedure, each CRP profile was interpolated to 100 data points. This allowed for further trial comparison.

Calculation of the Approaching and Exiting Speeds

Data obtained from the sensor placed on the subjects' L5-S1 spinous processes (sensor #2) allowed for post-intervention calculation of the speed at which subjects where moving at the data point in which they made contact with the force plate (approaching speed), and at the data point in which they lost contact with the force plate (exiting speed). These speeds were obtained by summing the linear velocities of the X, Y, and Z vectors provided by sensor #2.

Statistical Analysis

Analysis for tasks A, B, and C was performed on the lower extremity elected by the subject to perform tasks B and C during the training session. Five deemed acceptable trials for the drop jump (Task A) and five deemed acceptable trials where the subjects performed a sidestepping task for each of tasks B and C were analyzed. The cross over trials for each of tasks B and C was not included in this analysis.

Calculation of the Mean Absolute Relative Phase (MARP)

Each CRP profile for each coupling relationship was interpolated to 100 data points using a polynomial procedure. Ensemble curves were calculated from each coupling relationship for each subject in each trial to be analyzed as the mean from five deemed acceptable trials CRP curves for each task. These five trials were randomly selected whenever more than five deemed acceptable trials where collected. The MARP was calculated by averaging the absolute values of the ensemble curve points for the stance cycle.

$$\text{MARP} = \sum_{i=1}^{N} \frac{[\Phi\text{relative phase}]}{N}$$

N = number of points in the relative phase mean ensemble; Φ relative phase = the relative phasing relationship between two segments (Stergiou, 2004)

Calculation of the Deviation Phase

The variability of CRP was calculated as the standard deviation of each point on the ensemble curve and was quantified by calculating the average standard deviation over the complete CRP curve points for the stance cycle. The DP was calculated as follows:

$$\text{DP} = \frac{\sum_{i=1}^{N} [\text{SD}_i]}{N}$$

N = number of points in the relative phase mean ensemble; SD = the standard deviation of the mean ensemble at the ith point (Stergiou, 2004).

Statistical Test

To determine the presence of a sex effect, a 2 x 3 mixed factorial (sex by task) analysis of variance (ANOVA) with the task as repeated factor was performed on the subjects’ means for the Mean Absolute Relative Phase (MARP) and for the Deviation Phase (DP). MARP and DP statistical analysis was performed for each coordinative relationship (knee rotation and foot inversion/eversion; hip abduction/adduction and foot inversion/eversion) during the stance cycle of the tasks. Sex significant differences were established at $p < 0.05$.

To determine sex differences in the speeds at which subjects performed tasks B and C, a 2 x 2 mixed factorial (sex by task) analysis of variance (ANOVA) with the task as repeated factor was performed on the subjects' means for the approaching and exiting speeds.

RESULTS

Descriptive Statistics

A total of seven males (age = 21.2 ± 1.3 years; height = 182.1 ± 7.5 cm; weight = 79.7 ± 8.4 kg) and six females (age = 19.6 ± 1.2 years; height = 170.1 ± 8.2 cm; weight = 80.4 ± 15.9 kg) non-injured collegiate basketball athletes participated in the current study. In Tables 1, 2, 3, and 4 the descriptive statistics are presented for the Mean Absolute Relative Phase (MARP) for the hip abduction/adduction and foot inversion/eversion ($H_{abd/add}$-$Foo_{in/ev}$); MARP for the knee rotation and foot inversion/eversion (K_{rot}–$Foo_{in/ev}$); Deviation Phase (DP) for the $H_{abd/add}$-$Foo_{in/ev}$; and DP for the K_{rot}–$Foo_{in/ev}$ CRP coordinative relationships in tasks A (drop jump), B (cut and free arm motion), and C (cut and grab the ball). The descriptive statistics for the approaching speeds for the males and females groups in tasks B and C are presented in Table 9.

Trial Reliability

Five trials of each task from each subject were used for further analysis. Trial reliability was analyzed by calculating intra-class coefficients (ICC) using repeated measures ANOVAs.

The results obtained showed good trial reliability. Excepting for the ICC value in task A for the $H_{abd/add}$-$Foo_{in/ev}$ CRP coordinative relationship (ICC = 0.99), all the other tasks and CRP coordinative relationships showed the highest level of trial reliability (ICC = 1).

Mean Absolute Relative Phase (MARP)

The results of the 2 x 3 mixed factorial ANOVA comparing sex and task for the MARP in the $H_{abd/add}$-$Foo_{in/ev}$ and in the K_{rot}–$Foo_{in/ev}$ CRP coordinative relationships in tasks A, B, and C are presented in Tables 5 and 6 respectively. No significant ($H_{abd/add}$-$Foo_{in/ev:}$ $p = .736$; K_{rot}–$Foo_{in/ev:}$ $p = .793$) differences were found between sex in any of the CRP coordinative relationships. Significant ($H_{abd/add}$-$Foo_{in/ev:}$ $p = .003$; K_{rot}–$Foo_{in/ev:}$ $p = .000$) MARP differences were found between tasks in each of the two CRP coordinative relationships.

Deviation Phase (DP)

The results of the 2 x 3 mixed factorial ANOVA comparing sex and task for the DP in the $H_{abd/add}$-$Foo_{in/ev}$ and in the K_{rot}–$Foo_{in/ev}$ CRP coordinative relationships in tasks A, B, and C are presented in Tables 7 and 8 respectively. No significant ($H_{abd/add}$-$Foo_{in/ev:}$ $p = .581$; K_{rot}–$Foo_{in/ev:}$ $p = .882$) differences were found between sex in any of the CRP coordinative relationships. No significant ($p = .304$) DP differences were found between tasks in the $H_{abd/add}$-$Foo_{in/ev}$ CRP coordinative relationship. For the K_{rot}–$Foo_{in/ev}$ CRP coordinative relationship, no significant ($p = 0.053$) DP differences were found between tasks.

Approaching and Exiting Speeds

The results of the 2 x 2 mixed factorial ANOVA comparing sex and task for the approaching and exiting speeds at which the subjects performed tasks B and C are presented in Tables 10 and 11 respectively. No significant differences were found between sex (p = .222), nor between tasks (p = .171), in the exiting speed at which subjects performed tasks B and C. No significant (p = .654) differences were found between sex in the approaching speed at which subjects performed tasks B and C. No significant (p = .343) differences were found between tasks in the exiting speed. Significant differences (p = .043) were found in the approaching speed (task by sex) for tasks B and C.

DISCUSSION

The purpose of the present study was to examine lower extremity sex differences in Continuous Relative Phase (CRP) during a drop jump and two different unplanned cutting maneuvers. CRPs for the hip abduction/adduction and foot inversion/eversion ($H_{abd/add}$-$Foo_{in/ev}$), and for the knee rotation and foot inversion/eversion (K_{rot}–$Foo_{in/ev}$) CRP coordinative relationships were calculated for each of the trials performed by the seven male and six female collegiate basketball athletes who composed the two groups of this study. For each subject, CRPs from five deemed acceptable trials for each of the three tasks were used to obtain Mean Absolute Relative Phase (MARP) and Deviation Phase (DP) values. No significant sex differences were found for MARP and DP for any of the two CRPs coordinative relationships ($P < 0.05$). While no significant task differences were found for the DP in the $H_{abd/add}$-$Foo_{in/ev}$ CRP coordinative relationship ($P < 0.05$), for the K_{rot}–$Foo_{in/ev}$ CRP coordinative relationship the value obtained ($p = .053$), although not statistically significant, suggested a trend that warranted further discussion.

Significant task differences were found for the MARP in each of the two CRPs coordinative relationships ($P < 0.05$). MARP scores are reflective of limb segmental coordination. It was not unexpected that limb segmental coordination was found to be different across the 3 different tasks therefore no further analysis was pursued.

Innovations in the Current Study

Continuous Relative Phase (CRP) represents the phasing relationship or coordination between the actions of two interacting segments or joints at every point during a specific time period (Byrne et al., 2002; Stergiou et al., 2001a). Peters et al. (2003) pointed that one main issue in utilizing CRP is how it is interpreted. The authors suggested that the interpretation of CRP information should be limited to describing the relationship between the individual phase-planes of two signals, and should not be used to describe a relationship in their original time series data.

Within the literature, CRP analysis has been used in different studies with different purposes: to analyze intralimb coordination tasks (Carson et al., 1995; Scholz & Kelso, 1989), postural tasks (Bardy et al., 1999; Marin et al., 1999), lifting tasks (R. Burgess-Limerick et al., 2001), gait (Byrne et al., 2002), running (Hamill et al., 1999; Heiderscheit et al., 1999; Kurz & Stergiou, 2002), obstacle clearance (Stergiou et al., 2001a; Stergiou et al., 2001b), one legged hopping (van Uden et al., 2003), and to analyze a lateral step down task (Rienmann et al., 2004). To our knowledge, no study has attempted to analyze a drop jump or a cutting task using the CRP methodology.

However, to our knowledge in only one study (Pollard et al., 2005), interjoint coordination was used to kinematically analyze a cutting task. In this study, to analyze interjoint coordination Pollard et al. (2005) used a modification of the vector coding technique and not the CRP analysis used in the present study. The authors obtained the following joint couplings: thigh rotation and leg rotation, thigh abduction/adduction and leg abduction/adduction, hip abduction/adduction and knee rotation, hip rotation and knee abduction/adduction, knee flexion/extension and knee rotation, and knee flexion/extension and hip rotation coordinative relationships. Conversely, in the current study, hip abduction/adduction and foot inversion/eversion, and knee rotation and foot inversion/eversion coordinative relationships were analyzed. Therefore, although a similar cutting task was used, the coordination relationships analyzed in the current study were different than those used by Pollard et al. (2005).

Rationale for Task Selection

Anterior cruciate ligament (ACL) injuries have become one of the biggest impairments among the athletic population due to its consequences. More than six months (mean = 6.2 months) away from competing at full capability if a patellar tendon graft reconstruction is the treatment of choice (Shelbourne & Gray, 1997) is a clear example.

In the current study, the rationale for analyzing the chosen coordinative relationships was based on the fact that they were thought to maintain a relationship with one of the most common mechanism of injury of the ACL: a plant and cut movement pushing off to change direction toward the medial side of the knee axis (Olsen et al., 2004). The association between task selection and ACL injury mechanism was already studied by Cross et al. (1989) when 11 male subjects performing a sidestepping cutting maneuver were analyzed with a triaxial electrogoniometer. In the current study, task B (cut and free arm motion) was designed for its resemblance to the most common ACL injury mechanism.

In an attempt to address the growing current of thought which states that the controlled laboratory conditions do not mimic the adversities that the athletes are facing on the field (Balagué & Torrents, 2005; Bandy, 1992; Buekers et al., 1999; Pollard et al., 2005), in the current study two different actions were undertaken. Firstly, task C (cut and grab the ball) was designed with the objective of paralleling a real sport situation encountered in many sports such as basketball or team handball. Secondly, and in order to address some issues encountered within the literature related to the low predictive value of the results obtained when planned tasks are analyzed (Besier et al., 2003; Besier et al., 2001a;

Brosky et al., 1999; Pollard et al., 2004a; Pollard et al., 2004b; Pollard et al., 2005), two bulb signals were introduced in tasks B and C to transform the planned cutting tasks into unplanned maneuvers.

The other task analyzed in the current study, task A (drop jump), is a task that has been used in several studies (Barber-Westin et al., 2006; Noyes et al., 2005) to identify possible explanations for the gender differences in ACL injury rates. However, the drop jump does not possess many similarities with the main mechanism of injury of the ACL and its resemblance to a real sport situation might be considered as low. Additionally some confounding factors such as the fact that not always both feet land at the same time, can make this task difficult to analyze.

In the current study, a 13 cm. height step was used as starting position. This height was relatively lower than the height of 30 cm (Barber-Westin et al., 2006; Noyes et al., 2005), of 25,45,65,85, and 105 cm (Torrents Martín, 2005), or 60 cm (Russell et al., 2006) used in other studies in which the drop jump task was analyzed. The main goal of using a smaller step was bifold. Firstly, and for further task comparison, it was attempted that subjects started from the same position for all three tasks.

Secondly, a 14 cm height step is close to any height that people face in the daily activities such as going downstairs. Therefore, anthropometric differences might be buffered with this height selection.

In this study, the distance of the step to the landing area was based on individual anthropometric measures. The mean distance from the step to the middle of the landing area was 85.64 ± 6.63 cm for the male group and 83.5 ± 3.39 cm for the female group. This distance was longer than the 20 cm reported by Torrents Martín (2005) while in other studies (Barber-Westin et al., 2006; Noyes et al., 2005) this distance was not reported.

Finally, another inherent weakness to the task design for the drop jump was that subjects were requested to keep their hands on the waist during the whole maneuver instead of allowing them to freely move their upper extremity.

Results Discussion

Several epidemiology studies have emphasized the differences in ACL injury rates between genders (Agel et al., 2005; Arendt & Dick, 1995; Bjordal et al., 1997; Motohashi, 2004). For this reason in the current study a sex comparison was conducted between males and females.

Continuous Relative Phase and its variability were the variables analyzed.

A Trend towards Statistical Significance for the DP in the K_{rot}–$Foo_{in/ev}$ CRP Coordinative Relationship

In the current study subjects were tested while performing three different tasks that were differently constrained. Task A (drop jump) was characterized by being a planned maneuver. In task B (cut and free arm motion) task constraints came from the bulb signals indicating the required direction of cutting. In task C, not only the bulb signals but also grabbing a ball hanging from the ceiling increased the complexity of the task. No statistical significant differences existed between tasks in the DP variable ($P < 0.05$) for the $H_{abd/add}$-$Foo_{in/ev}$ CRP coordinative relationship ($P < 0.05$). However, in the K_{rot}–$Foo_{in/ev}$ coordinative relationship the value of statistical significance between tasks in the DP variable ($p = .053$) revealed a trend towards the level of significance. Upon closer look at the means, it was observed that task A (drop jump) presented the lowest value when compared to tasks B and C. This might be explained by the fact that the drop jump is a controlled task as opposed to a real sport situation such as tasks B and C. This adds more evidence to the low levels of external validity that some laboratory tasks present.

Table 12 presents the DP values for the male and female groups during tasks A, B, and C for the two CRP coordinative relationships analyzed. From Table 12 it can be observed that the variability (represented by DP) for the K_{rot}–$Foo_{in/ev}$ CRP coordinative relationship was larger in task C (DP = 34.85 ± 13.36) than the other two tasks. Task B values were larger than Task A (DP = 31.28 ± 12.63 and 22.03 ± 16.24 respectively). These values represented 10.24% less variability in the K_{rot}–$Foo_{in/ev}$ CRP coordinative relationship in task B compared to task C, and 36.79% less variability in task A compared to task C. In other words, the more constrained and complex the tasks were, the more variability the subjects showed.

Conversely this phenomena did not occur in the $H_{abd/add}$-$Foo_{in/ev}$ CRP coordinative relationship. In this relationship, higher levels of task complexity did not demonstrate increased levels of variability. As shown in Table 12 and similar to the K_{rot}–$Foo_{in/ev}$ CRP coordinative relationship, when the male and female data was combined, DP values were higher in task C (DP = 38.77 ± 12.88) than in task B (DP =

29.46 ± 11.22). Subjects showed 24.01% less variability in task B compared to task C. Contrary to what was shown in the K_{rot}–$Foo_{in/ev}$ CRP coordinative relationship, the DP values in task B (DP = 29.46 ± 11.22) were lower than the values showed in task A (DP = 34.08 ± 19.90). This finding was in large part due to the increased variability demonstrated by the females (DP = 39.61 ± 23.23) compared to their male counterpart (DP = 28.55 ± 16.61). The DP value for Task A for the female group (DP = 39.61 ± 23.23) was even higher than the result in task C for the females (36.13 ± 10.08).

Overall for the $H_{abd/add}$-$Foo_{in/ev}$ CRP coordinative relationship, males and females showed 12.1% less variability in task A (DP = 34.08 ± 19.90) than in task C (DP = 38.77 ± 12.88), and 24.01% less variability in task B (DP = 29.46 ± 11.22) than in task C (DP = 38.77 ± 12.88). However, when compared individually, females showed 9.63% more variability in task A than in task C while males showed 31.04% less variability in task A than in task C.

Theoretically, it seems logical that the more complex a task is the more variability the subjects should show in its accomplishment. From the results of the current study, and because of the fact that this postulate was only accomplished for the K_{rot}–$Foo_{in/ev}$ and not for the $H_{abd/add}$-

$Foo_{in/ev}$ CRP coordinative relationship, the reason for this phenomena might be the presence of the hip abduction/adduction joint motion in the second of these CRP coordinative relationships. Within the literature it has been demonstrated that females display a knee valgus pattern throughout a squat activity (Zeller et al., 2003), in the landing phase of a drop vertical jump (Ford et al., 2003), and in the landing phase of a single leg vertical jump landing task (Bello, 2004). An increased knee valgus to a flexed knee has been reported to increase the force on the ACL (Markolf et al., 1995). This knee valgus pattern has been associated with neuromuscular control deficiencies. Apparently, females show weakness in hip abduction, hip external rotation, and in core muscles, and this may predispose them to athletic injury (Leetun et al., 2004). This lack of neuromuscular control at the knee, which may actually be derived from the hip and core muscles may explain the increased variability of the $H_{abd/add}$-$Foo_{in/ev}$ CRP coordinative relationship in task A (drop jump) for the female group seen in this study.

Additionally, and based on a qualitative assessment by plotting CRP variability over the stance phase, a visual inspection of Figure 1 revealed that compared to males, in task A females showed high variability levels in between the 20 and 55% of the stance phase for the $H_{abd/add}$-$Foo_{in/ev}$ CRP coordinative relationship. This section of the graph may approximately coincide with the flat foot to maximum knee flexion part of the drop jump, which is the part from which results are usually reported within the single joint analysis literature.

Further analyzing these sex differences in CRP variability in task A for the $H_{abd/add}$-$Foo_{in/ev}$ CRP coordinative relationship, while the traditional perspective considers variability as pathology, performance decrements, and/or non-expert dynamics, Dynamical Systems considers variability as healthy, functionality, and/or expert dynamics (Van Emmerik & Van Wegen, 2002). However, in the present study, the level of variability shown by the female group in task A for the $H_{abd/add}$-$Foo_{in/ev}$ CRP coordinative relationship might be associated with pathology, and specifically with ACL injury risk. This issue might be related to the concept reported by Van Emmerik et al. (2002) who clarified that the high levels of variability considered as expertise do not attempt to assume that variability is beneficial or that represents healthy status in all circumstances.

Broderick & Newell (1999) observed that movement patterns of the less skilled subjects bouncing a ball in their study were more variable than those of the more skilled. This made the authors suggest that when comparing states of skill it is necessary to specify what is more, or less variable. Buekers (2000) also noted that at later stages of learning, the variety of movements should be reduced, shifting from “variation in variable situations to variation in specific situations” (p. 487).

A main question from the results in the current study is how to interpret the high levels of variability in the $H_{abd/add}$-$Foo_{in/ev}$ CRP coordinative relationship in the female group for task A. If higher variability is desirable in order to avoid injuries regardless of the characteristics of this variability, what has been suggested within the literature related to a predominant knee valgus pattern while landing in female as a possible reason for the gender differences in injury rates (Bello, 2004; Ford et al., 2003) should be reconsidered. On the other hand, a lack of stability in the motion pattern due to an undesirable lack of neuromuscular control might keep a relationship to the high levels of variability found in task A.

Future research should clarify if the $H_{abd/add}$-$Foo_{in/ev}$ coordinative relationship is uniquely responsible for the quantity of variability demonstrated, or if the source of the variability is the hip joint itself. Further analysis of other CRP coordination relationships would determine if the same patterns would be observed if hip abduction/adduction was coupled with other joint motions different than the foot. The relevance of these hypothetical findings could support the idea of the need to consider the study of interjoint coordination rather than the traditional single joint analysis.

No Significant Sex Differences

No significant differences ($P < 0.05$) were found between sex in the MARP and DP variables in any of the CRP coordinative relationships analyzed. Different reasons could explain the non significance of these results. First of all the small size of the two groups (7 male, 6 females) should be considered. Pollard et al. (2005), within a Dynamical Systems background and thereafter studying variability, although using a variation of the coding technique to obtain interjoint coordination instead of using the CRP as it was in the current study, found significant gender differences in a group of healthy soccer players composed by 12 males and 12 females while performing an unplanned sidestepping task. Conversely, Heiderscheit et al. (1999) did not find significant gender differences after assessing variability in the CRP of 32 healthy subjects while running over ground and who were divided in four groups (males with high Q angle, females with high Q angle, males with low Q angle, and females with low Q angle).

Another possible explanation for the lack of significant sex differences could come from the part of the stance phase analyzed. In some of the studies within the literature that used a Dynamical Systems background to analyze the variability of different joint coordinative relationships, authors (Hamill et al., 1999; Heiderscheit et al., 1999) opted to analyze different and relevant intervals of the entire stance phase. Reviewing the graphics of the group variability along the whole stance phase might be the reference to decide which intervals could reveal statistical significance.

In the present study, the graphs of the sex differences for the whole stance period and for both the $H_{abd/add}$-$Foo_{in/ev}$ and the K_{rot}–$Foo_{in/ev}$ CRP coordinative relationships in tasks

A, B, C, and for all the tasks matched are shown in Figures 1, 2, 3, and 4 respectively.

Observation of these figures reveals that the graphic pattern found by Hamill et al. (1999) in which subjects showed more variability at the beginning of the stance phase while running followed by a decreased variability along the stance phase, was not obtained in the current study. However, and regarding the first part of the stance phase (approximately 10-15%) of the present study, upon qualitative assessment of the graphs, it can be observed that female tended to show less variability than did male. This is especially prominent in the K_{rot}–$Foo_{in/ev}$ graphics for tasks B and C (Figures 2 and 3 respectively). Further data processing and quantitative statistical analysis would reveal if significant sex differences actually existed in this first part of the stance phase of the current study.

Different authors (Hamill et al., 1999; Heiderscheit et al., 2002) have suggested that the increased variability in the first part of the stance phase is indicative of flexibility of the system. This flexibility would allow the system to explore the environment (the ground in this case), and would give the system the ability to overcome a possible perturbation. Once the surface is known, a stable pattern would develop for the rest of the stance phase. A possible explanation for why the subjects in the present study did not show this pattern might be related to the inherent characteristics of the tasks analyzed. Since Kugler's et al. (1980) work about Dynamical Systems application in the motor learning field, different authors have used CRP to analyze different tasks, ranging from interjoint coordination (Kelso, 1984) to running (Hamill et al., 1999; Heiderscheit et al., 1999). Compared to running, the cutting tasks analyzed in the current study present a different level of complexity. The cutting tasks (task B and c) were unplanned tasks and additionally, in task C, subjects had to grab a ball hanging from the ceiling, which increased even more the complexity of the task. Thereafter, the high levels of variability in the middle and final part of the stance phase in the cutting tasks of the current study might be due to inherent complexity of the tasks.

Neuronal networks in the spinal cord, known as spinal central pattern generators, have been proposed to be present in human locomotion (Hultborn & Nielsen, 2007). Studies have reported that an alternating electromyography activity might be observed in the lower limb in patients with complete spinal cord lesion when placed on a moving treadmill (Wernig & Muller, 1992). Pre-locomotor infants as young as one month, when supported over a moving surface, have demonstrated stepping movements (Corbetta & Vereijkew, 1999). These findings could suggest that while human locomotion is generated by spinal networks, the unplanned cutting tasks in the present study would require cognitive control in order to be achieved. This would support the high levels of variability along the entire stance phase during the achievement of these more complex tasks.

Comparing task complexity levels, in between the running task analyzed by Hamill et al. (1999) and the two unplanned cutting tasks analyzed in the present study, we could place the drop jump which was also analyzed in this study. The drop jump is a planned task similar to running. Thereafter the pattern consisting of increased variability at the beginning of the stance phase reported by Hamill et al. (1999) should be observed. In the present study there was a trend towards this pattern in task A (drop jump), especially in the K_{rot}–$Foo_{in/ev}$ CRP coordinative relationship (Figure 1). However, from this graphic we can not only observe that there was an increasing variability at the beginning of the stance phase but also at the end, which was more evident for the female group. This finding might by coincident with Hamill et al. (1999), who reported that the tibial rotation-foot inversion/eversion coupling in their study was the only one which displayed a slight increase in variability as toe-off approached.

We consider that in the current study, and for the K_{rot}–$Foo_{in/ev}$ CRP coordinative relationship in task A, the increase of variability in the last part of the stance phase might be supported by the same interpretation for which different authors (Hamill et al., 1999; Heiderscheit et al., 2002) have explained the increased variability in the first part of the stance phase. While in a running task the transition of the system from foot ground contact to the swing phase might not reveal much variability, the same part in a drop jump task where the complexity of jumping is higher than just swinging might cause the increasing in the levels of variability.

In the current study, high levels of trial reliability were showed by the ICC calculations. Although these results were influenced by the large values of the between subject mean square obtained with the ANOVAs analyzes, the trial mean square values were lower when compared to the error mean square values obtained, which would also indicate good trial reliability. Thereafter, each subject performed each task consistently but there were substantial differences in task performance between each subject. Additionally the fact that the coefficient of variation values obtained across gender and tasks (Table 13) ranged approximately from 25 to 54% further supports the notion that each subject performed each task differently when compared to the other subjects. All these findings might explain why significant sex differences between the two groups were not found. The within subject variance was too large to observe any between group differences. These findings could be explained by the nature of the tasks selected in the current study.

An additional finding in the current study related to the level of complexity of the tasks corresponded to the significant differences ($p = .043$) of the approaching speed (task by sex) during tasks B and C. Table 9 presents the descriptive statistics for the approaching speed in tasks B and C for both males and females. While for the male group an increasing in task complexity (from task B to task C) signified an almost negligible increase in approaching speed (0.86%), the female group decreased their approaching speed (2.11%) when they were more constrained with the ball (task C). In other words, the males approached the landing area in a similar fashion while with the same increasing in task complexity the female group moved more slowly. Although the main goal of the current study was not to address these issues, this finding might be taken in consideration when injury prevention programs are designed. If females tend to reduce their approaching speed when the complexity of the task increases, this might be due to their inability to neuromuscularly resolve a more complex task without decreasing the approaching speed. Training programs that included such situations might improve females’ abilities to satisfactorily overcome these situations and therefore reduce their injury risk.

Suggestions for Future Research

Krosshaug et al. (2007) pointed the need to continue the development of task protocols that simulate the situations that athletes encounter during a game. In the present study this was accomplished by testing two unplanned cutting tasks (tasks B and C), and by introducing the action of grabbing a ball while performing task C. More closely simulating sport situations will produce results that will show the way subjects are typically moving on the field, which should be the first aim of any study involving athletes. By making subjects move following strict task models which do not allow for their individual characteristics, researchers might not obtain valid results. The inherent internal validity of the project may limit the external generalizability of the findings. Ideally, laboratories should be taken to the fields and not athletes to the laboratories. However with the currently available technology, field testing compromises internal validity of the research project. Therefore, continued qualitative and quantitative evaluations of human movements in various environments will be required.

The fact that various authors (Hamill et al., 1999; Heiderscheit et al., 1999) have divided the stance phase in different parts in order to analyze the relevant events that surround the stance phase seems a crucial element in CRP analysis. Pollard et al. (2005) used a variation of the vector coding technique to quantify joint coordination in order to test their subjects while performing three unplanned tasks. One of the three tasks performed was a sidestepping maneuver. The authors decided to analyze the first 40% of the stance phase, which was based on the fact that two critical events would be observed during this phase: first, a knee flexion from 0 to 40° and second, a deceleration of the cutting maneuver would occur (Pollard et al., 2004b).

It is our belief that if the goal is to understand the disparity in ACL injury rates between males and females it would be important to focus on the part of the stance phase considered being crucial in an ACL injury. Different studies within the literature have tried to describe the mechanisms related to ACL injuries analyzing videos of real injury situation (Boden et al., 2000; Krosshaug et al., 2007; Olsen et al., 2004). Krosshaug et al. (2007) suggested that the estimated time of injury in basketball players ranged from 17 to 50 milliseconds after initial ground contact. However the validity of this information should be taken with care because the exact moment of ACL disruption is impossible to determine (Boden et al., 2000; Krosshaug et al., 2007; Olsen et al., 2004). Therefore, besides their importance to document the events that surround an ACL injury, video analysis might present some limitations in the interpretation of ACL injury mechanisms.

In order to investigate the events that surround an ACL injury from another point of view, authors (Bahr & Krosshaug, 2005; Boden et al., 2000; Fauno & Wulff Jakobsen, 2006; Gray et al., 1985; Olsen et al., 2004) have attempted to interview the protagonists of the situation: the injured athletes. However within these studies, description of the exact moment of the injury during the entire stance phase reported by the athletes’ experience are usually missing or the level of description is limited. Additionally, another limitation of interviews is that they consist of a subjective reporting of the injury and that they might be biased by not exactly remembering the event (Krosshaug et al., 2007).

It is our thought that if our aim is to prevent ACL injuries in male and female athletes, analyzing the sex differences in injury rates is the starting point. More specific data surrounding the exact moment of the injury provided by the injured athletes could narrow our search in the understanding of the mechanism of the injury and would allow researchers to focus on specific parts of the stance phase. Observations from clinical practice suggest that injured athletes, when questioned shortly after the event, can usually report with great detail the events surrounding their injury and this may be considered as valuable information. In the current study, although no significant sex differences were found during the entire stance phase, from Figures 2 and 3 it can be observed that female constantly displayed less variability in the first part (10-15%) of the stance phase of the cutting tasks (Task B and Task C). To find out if this event has any relationship with the disparity in ACL injury rates between males and females, future studies should focus in the study of this part of the stance phase and establish any possible relationship with data obtained from more specific ACL injury questionnaires.

Overall, it is still unknown why an ACL injury occurs during a sidestepping maneuver, a type of maneuver which has been performed innumerable times during any athlete’s career without causing any injury. If lack of variation is indicative of an injury state, individuals showing lower variability might suffer an overuse injury (Hamill et al., 1999). External perturbations applied to a less neuromuscularly flexible individual may result in repetitive microtrauma to the ligaments (Pollard et al., 2005). Thereafter if these hypotheses were demonstrated, the possibility that an acute ACL injury might occur due to an overuse process rather than a single event should be considered. In the present research, and within a Dynamical Systems background, study of the variability of the interjoint coordination was performed to stress these suggestions. More studies will be needed to obtain a more accurate insight on theses suggestions.

While much of the research to discover the crucial events surrounding the gender bias in ACL injury rates has been focusing on the knee joint, others (Lephart et al., 2002; Pollard et al., 2007) have attempted to analyze the hip joint. Bahr et al. (2005) suggested that to understand the causes of any particular injury type, a complete description of the mechanism of injury needs to include a description of the whole body and joint biomechanics at the time of injury. In the present time, consideration of the use of the modeling tools of the Dynamical Systems for data processing and analysis should be considered to account for these suggestions. For this reason the design of the current study was based on the analysis of the variability of the Continuous Relative Phase over the stance phase during a drop jump and two different unplanned cutting maneuvers. It is hoped that this and future studies using a Dynamical Systems approach will continue to add to the body of knowledge and eventually reveal the causal mechanism in the ACL mystery.

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Table 1

Descriptive Statistics for MARP for the $H_{abd/add}$*-*$Foo_{in/ev}$ *Coordinative Relationship for Males and Females in Tasks A, B, and C*

Task		*M*	*sd*	*N*
Task A				
	Male	65.60	33.31	7
	Female	89.32	48.84	6
Task B				
	Male	114.05	38.81	7
	Female	107.77	29.02	6
Task C				
	Male	107.12	36.68	7
	Female	107.22	22.41	6

Table 2

Descriptive Statistics for MARP for the K_{rot}–$Foo_{in/ev}$ Coordinative Relationship for Males and Females in Tasks A, B, and C

Task		*M*	*sd*	*N*
Task A				
	Male	131.16	27.79	7
	Female	129.16	44.14	6
Task B				
	Male	86.00	45.57	7
	Female	80.69	22.89	6
Task C				
	Male	94.07	39.22	7
	Female	88.55	16.76	6

Table 3

Descriptive Statistics for DP for the $H_{abd/add}$*-*$Foo_{in/ev}$ *Coordinative Relationship for Males and Females in Tasks A, B, and C*

Task		*M*	*sd*	*N*
Task A				
	Male	28.55	16.61	7
	Female	39.61	23.23	6
Task B				
	Male	27.94	12.97	7
	Female	30.98	9.71	6
Task C				
	Male	41.40	15.23	7
	Female	36.13	10.08	6

Table 4

Descriptive Statistics for DP for the K_{rot}*–*$Foo_{in/ev}$ *Coordinative Relationship for Males and Females in Tasks A, B, and C*

Task		*M*	*sd*	*N*
Task A				
	Male	21.95	16.89	7
	Female	22.10	17.04	6
Task B				
	Male	31.24	17.16	7
	Female	31.32	5.43	6
Task C				
	Male	36.27	13.08	7
	Female	33.43	14.77	6

Table 5

2 x 3 Mixed Factorial ANOVA Comparing Sex to Task for the MARP in the $H_{abd/add}$*-*$Foo_{in/ev}$ *Coordinative Relationship*

Source	*ss*	*df*	*ms*	*F*	*p*
Between Groups	376253.338	1			
Sex (A)	331.614	1	331.614	.120	.736
Error	30397.247	11	2763.386		
Within					
Task (B)	8681.614	2	4340.807	7.946[a]	.003
A x B	1614.282	2	807.141	1.478	.250
Error	12017.611	22	546.255		
Total	398566.845	27			

[a] Table *F* (.05) (4, 22) = 4.62

Table 6

2 x 3 Mixed Factorial ANOVA Comparing Sex to Task for the MARP in the K_{rot}–$Foo_{in/ev}$ Coordinative Relationship

Source	*ss*	*df*	*ms*	*F*	*p*
Between Groups	400231.161	1			
Sex (A)	177.238	1	177.238	.072	.793
Error	26989.188	11	2453.563		
Within					
Task (B)	16213.647	2	8106.824	13.618[a]	.000
A x B	25.246	2	12.623	.021	.979
Error	13097.006	22	595.318		
Total	429567.06	27			

[a] Table *F* (.05) (4, 22) = 6.76

Table 7

2 x 3 Mixed Factorial ANOVA Comparing Sex to Task for the DP in the $H_{abd/add}$*-*$Foo_{in/ev}$ *Coordinative Relationship*

Source	*ss*	*df*	*ms*	*F*	*p*
Between Groups	45090.063	1			
Sex (A)	83.776	1	83.776	.324	.581
Error	2844.654	11	258.605		
Within					
Task (B)	559.354	2	279.677	1.258[a]	.304
A x B	430.983	2	215.492	.969	.395
Error	4892.629	22	222.392		
Total	50973.029	27			

[a]Table *F* (.05) (4, 22) = 3.62

Table 8

2 x 3 Mixed Factorial ANOVA Comparing Sex to Task for the DP in the K_{rot}*–*$Foo_{in/ev}$ *Coordinative Relationship*

Source	*ss*	*df*	*ms*	*F*	*p*
Between Groups	33480.727	1			
Sex (A)	7.288	1	7.288	.023	.882
Error	3500.783	11	318.253		
Within					
Task (B)	1132.205	2	566.103	3.370[a]	.053
A x B	18.861	2	9.430	.056	.946
Error	3695.336	22	167.970		
Total	38327.129	27			

[a] Table *F* (.05) (4, 22) = 3.16

Table 9

Descriptive Statistics for the Approaching Speeds for Males and Females in Tasks B and C

Task		*M*	*sd*	*N*
Task B				
	Male	1.98	0.10	7
	Female	2.04	0.12	6
	Total	2.01	0.11	13
Task C				
	Male	2.00	0.15	7
	Female	2.00	0.13	6
	Total	2.00	0.13	13

Table 10

2 x 2 Mixed Factorial ANOVA Comparing Sex to Task for the Approaching Speeds in Tasks B and C

Source	*ss*	*df*	*ms*	*F*	*p*
Between Groups	104.149	1			
Sex (A)	.007	1	.007	.212	.654
Error	.341	11	.031		
Within					
Task (B)	.001	1	.001	.980[a]	.343
A x B	.006	1	.006	5.225	.043
Error	.012	11	.001		
Total	104.168	14			

[a] Table *F* (.05) (2, 11) = .980

Table 11

2 x 2 Mixed Factorial ANOVA Comparing Sex to Task for the Exiting Speeds in Tasks B and C

Source	*ss*	*df*	*ms*	*F*	*p*
Between Groups	199.356	1			
Sex (A)	.066	1	.066	1.673	.222
Error	.435	11	.040		
Within					
Task (B)	.025	1	.025	2.144[a]	.171
A x B	.004	1	.004	.356	.563
Error	.127	11	.012		
Total	199.512	14			

[a] Table *F* (.05) (2, 11) = 2.144

Table 12

Deviation Phase (DP) Values for the Male and Female Groups during Tasks A, B, and C for the $H_{abd/add}$-$Foo_{in/ev}$ and for the K_{rot} – $Foo_{in/ev}$ Coordinative Relationships

CRP and Task		*M*	*sd*
$H_{abd/add}$ - $Foo_{in/ev}$			
A	Male	28.55	16.61
	Female	39.61	23.23
	Total	34.08	19.90
B	Male	27.94	12.97
	Female	30.98	9.71
	Total	29.46	11.22
C	Male	41.40	15.23
	Female	36.13	10.08
	Total	38.77	12.88
K_{rot} – $Foo_{in/ev}$			
A	Male	21.95	16.89
	Female	22.11	17.04
	Total	22.03	16.24
B	Male	31.24	17.16
	Female	31.32	5.43
	Total	31.28	12.63
C	Male	36.27	13.08
	Female	33.43	14.77
	Total	34.85	13.36

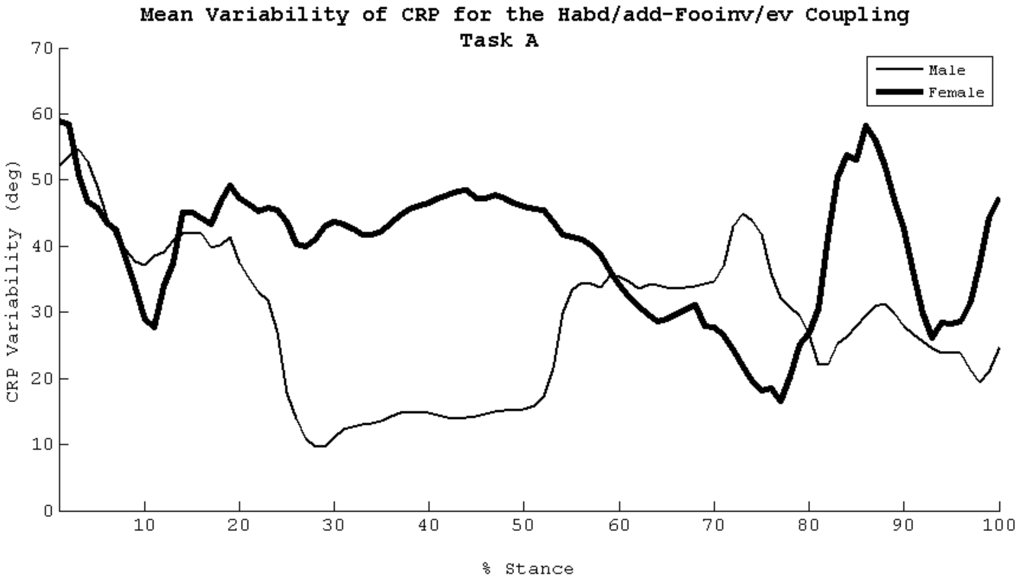
Table 13

Coefficient of Variation Values Obtained Across Sex and Tasks for the MARP in the $H_{abd/add}$ *-* $Foo_{in/ev}$ *and for the* K_{rot} *–* $Foo_{in/ev}$ *Coordinative Relationships*

CRP and Task		*CV (%)*
$H_{abd/add}$ - $Foo_{in/ev}$		
A	Male	50.78
	Female	54.68
	Total	53.86
B	Male	34.03
	Female	26.93
	Total	30.04
C	Male	34.24
	Female	20.90
	Total	27.71
K_{rot} – $Foo_{in/ev}$		
A	Male	21.19
	Female	34.17
	Total	26.59
B	Male	52.99
	Female	28.37
	Total	42.56
C	Male	41.69
	Female	18.93
	Total	32.68

Figure Caption

Figure 1. Mean Variability of CRP for the $H_{abd/add}$-$Foo_{in/ev}$ and K_{rot}–$Foo_{in/ev}$ Coordinative Relationships in Task A


Mean Variability of CRP for the Habd/add-Fooinv/ev Coupling
Task A
Male
Female
CRP Variability (deg)
0
10
20
30
40
50
60
70
10
20
30
40
50
60
70
80
90
100
% Stance

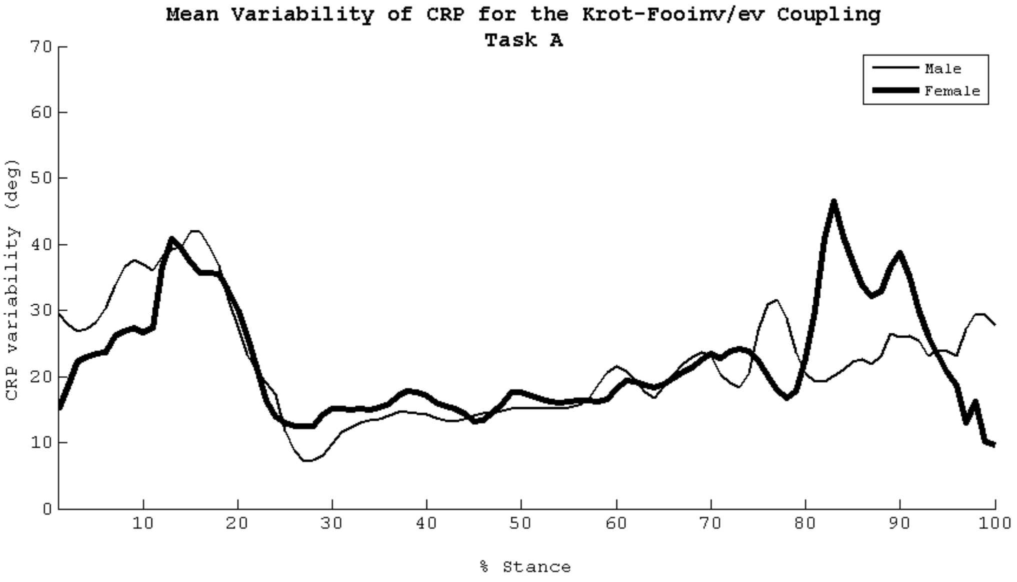
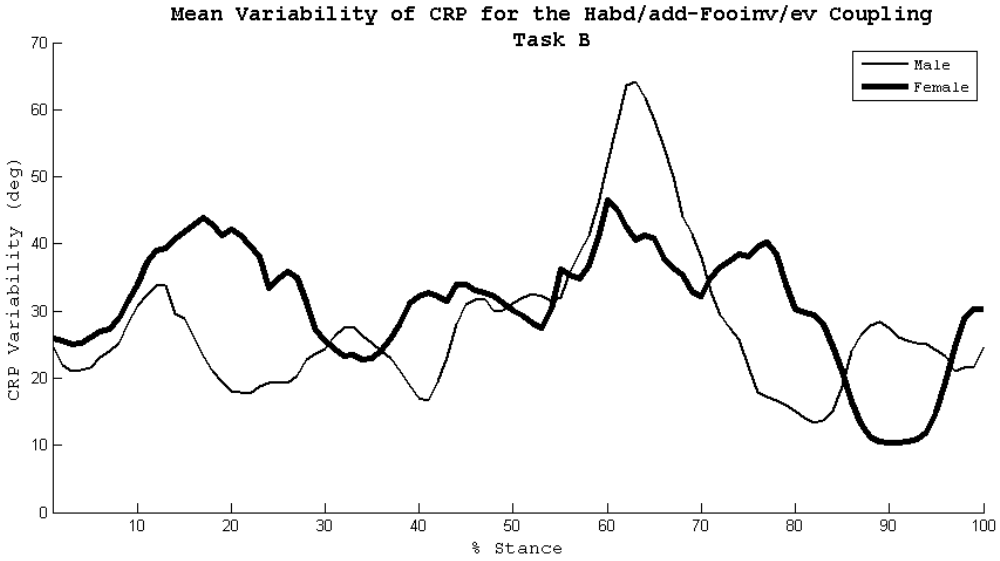

Mean Variability of CRP for the Krot-Fooinv/ev Coupling
Task A
Male
Female
CRP variability (deg)
0
10
20
30
40
50
60
70
10
20
30
40
50
60
70
80
90
100
% Stance

Figure Caption

Figure 2. Mean Variability of CRP for the $H_{abd/add}$-$Foo_{in/ev}$ and K_{rot}–$Foo_{in/ev}$ Coordinative Relationships in Task B


Mean Variability of CRP for the Habd/add-Fooinv/ev Coupling
Task B
Male
Female
CRP Variability (deg)
% Stance
0
10
20
30
40
50
60
70
10
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30
40
50
60
70
80
90
100

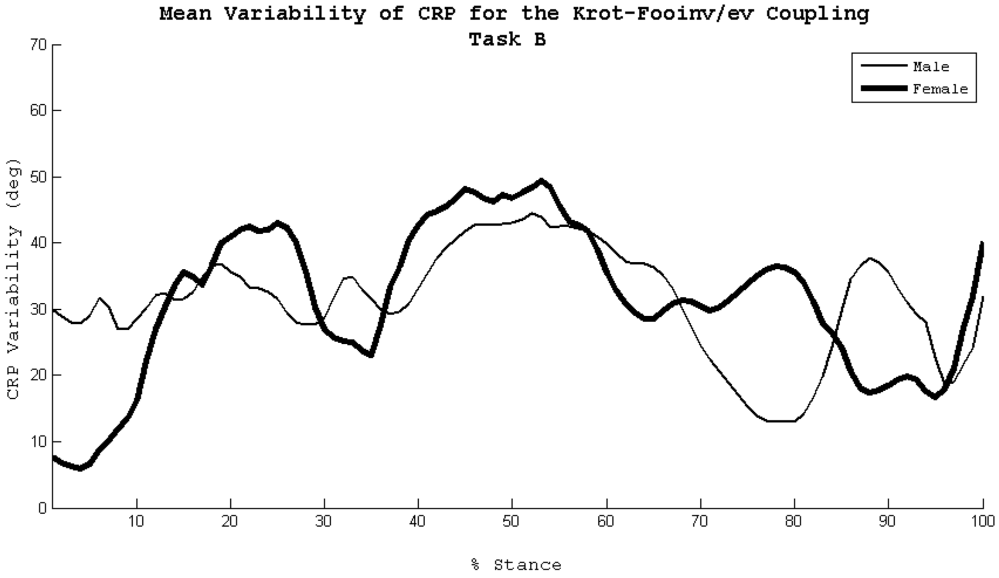

Mean Variability of CRP for the Krot-Fooinv/ev Coupling
Task B
Male
Female
CRP Variability (deg)
% Stance
0
10
20
30
40
50
60
70
10
20
30
40
50
60
70
80
90
100

Figure Caption

Figure 3. Mean Variability of CRP for the $H_{abd/add}$-$Foo_{in/ev}$ and K_{rot}–$Foo_{in/ev}$ Coordinative Relationships in Task C

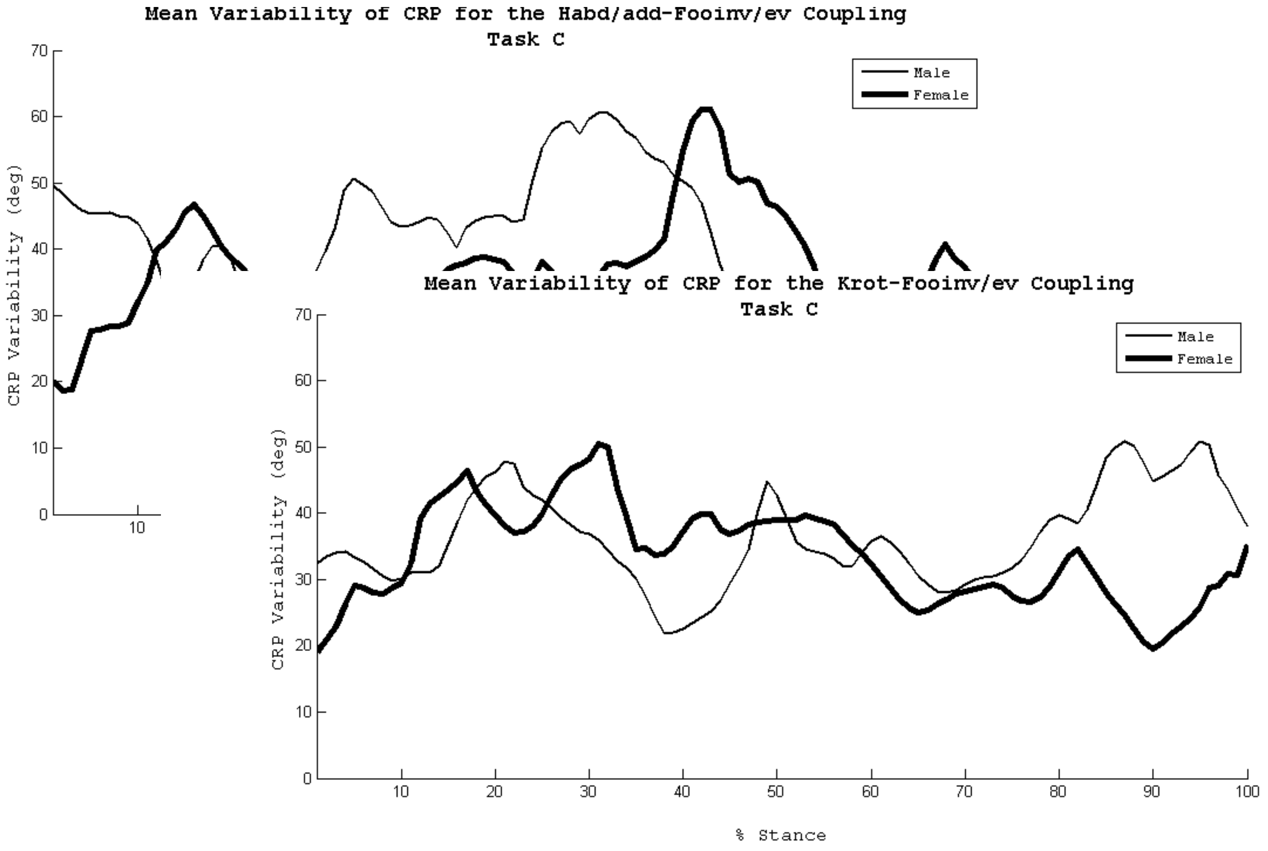
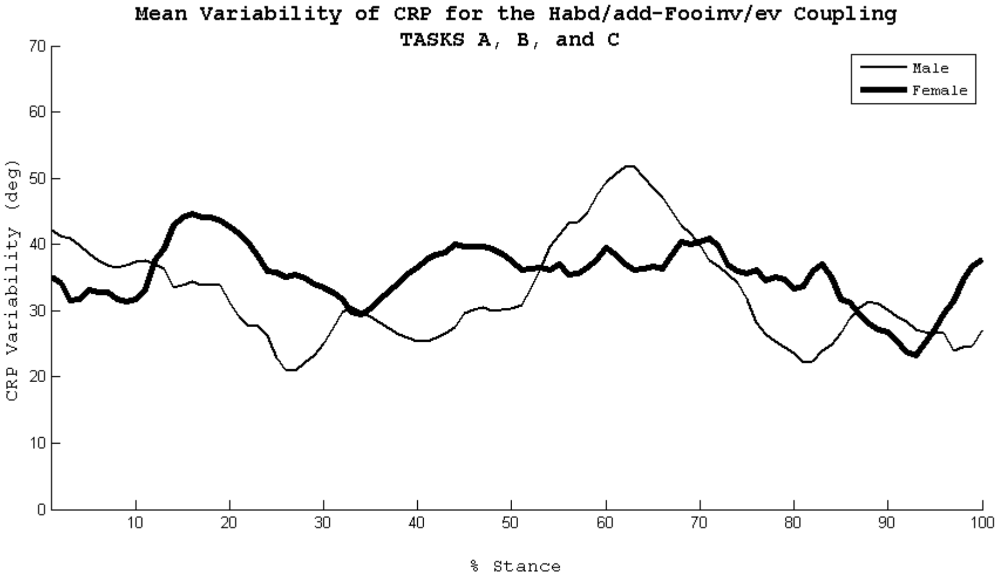
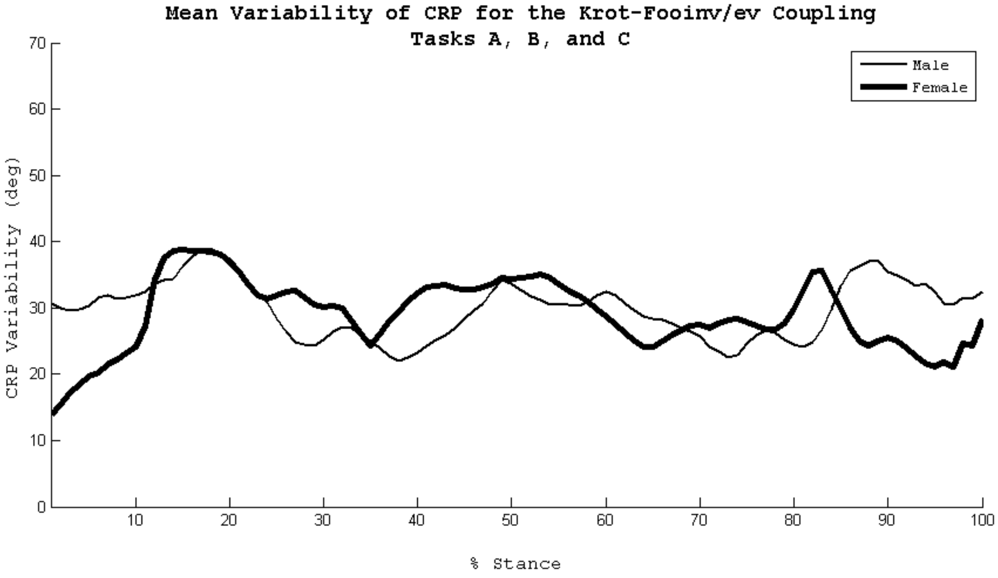

Mean Variability of CRP for the Habd/add-Fooinv/ev Coupling
Task C
Male
Female
CRP Variability (deg)
70
60
50
40
30
20
10
0
10
Mean Variability of CRP for the Krot-Fooinv/ev Coupling
Task C
Male
Female
CRP Variability (deg)
70
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
90
100
% Stance

Figure Caption

Figure 4. Mean Variability of CRP for the $H_{abd/add}$-$Foo_{in/ev}$ and for the K_{rot}–$Foo_{in/ev}$ Coordinative Relationships in tasks A, B, and C Matched Together


Mean Variability of CRP for the Habd/add-Fooinv/ev Coupling
TASKS A, B, and C
Male
Female
CRP Variability (deg)
% Stance
0
10
20
30
40
50
60
70
10
20
30
40
50
60
70
80
90
100


Mean Variability of CRP for the Krot-Fooinv/ev Coupling
Tasks A, B, and C
Male
Female
CRP Variability (deg)
% Stance
0
10
20
30
40
50
60
70
10
20
30
40
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80
90
100

APPENDIX A

RESEARCH DESIGN

Within the literature, examination of biomechanical lower extremity gender differences has revealed contradictory results. While some authors (Bello, 2004; Ciolek, 2002; Willson et al., 2006; Zeller et al., 2003) found gender differences in their studies, others did not (Barber-Westin et al., 2006; Noyes et al., 2005; Pollard et al., 2004a). Additionally, in all these studies, the way in which data has been processed and analyzed has only focused on a single joint analysis.

Dynamical Systems Theory offers an innovative approach for human motion analysis. One of its tools, continuous relative phase, is an unique measure because it compresses four variables (proximal and distal segments’ displacement and velocities) into one measure (Stergiou, 2004). This approach allows the study of inter-joint coordination and its variability, which has been proposed as an alternative to the traditional explanations of anatomical and neuromuscular gender differences (Pollard et al., 2004b; Pollard et al., 2005).

Statement of the Problem

The purpose of the current study was to examine sex differences in continuous relative phase values for two selected lower extremity couplings. To obtain the corresponding continuous relative phase couplings, a kinematic assessment tool, the MotionMonitor™, was used to measure hip abduction/adduction, knee rotation, and foot inversion-eversion while the subjects performed a drop-jump and two different unplanned cutting maneuvers. A total of seven male (age = 21.2 ± 1.3 years; height = 182.1 ± 7.5 cm; weight = 79.7 ± 8.4 kg) and six female (age = 19.6 ± 1.2 years; height = 170.1 ± 8.2 cm; weight = 80.4 ± 15.9 kg) non-injured volunteers participated in the study. Subjects were collegiate basketball athletes from a New England Division III university.

Definition of Terms

The following definitions were used within the context of the current research study.

Non-Injured

A non-injured subject in this study was defined as a subject with no history of surgical interventions in the lower back or lower extremities, no previous history of injury in the lower back or lower extremities within the last three months that had required absence from practice or play, or alternative conditioning for more than three days, and with no current injury of the lower back or lower extremities that would have required medical attention.

Dominant Limb

The dominant limb was defined as the leg with which the subjects reported that they would be more likely to use when kicking a ball (Fagenbaum & Darling, 2003).

Landing Area

The 60 x 40 cm. area in which the subjects of the present study had to land on during the drop jump and the two different unplanned cutting maneuvers. The lading area consisted of a 4060-NC Bertec force plate.

Exiting Platforms

Each of the two 122 x 122 cm. wooden platforms which were used to step on after the unplanned cutting maneuvers.

Cutting Alleys

The two alleys that were drawn on the wooden, and exiting platforms. Taking as reference the center of the landing area, these two alleys were 30 cm. wide and two imaginary lined divided each of the alleys in two equal parts. These two imaginary lines had their origin on the middle of the landing area and described an angle of 45º in relation with the largest edge of the landing area.

Starting Position

The position on a 13 cm. height step from where all subjects started the drop jump and the two different cutting maneuvers. The step was placed on the 319.5 x 122 cm. and 15.24cm raised wooden platform. The distance from the center of the step to the center of the landing area depended on the subjects' individual anthropometric measures. Relative to the landing area, all subjects kept a centered foot positioning before starting each task.

Unplanned Task

An unplanned task was defined as a task in which the subject had no knowledge of the outcome to be performed prior to the start of the task.

Cutting Maneuver

A cutting maneuver was defined as changing the direction of travel while moving.

Sidestep Task

A sidestep task was defined as a cutting maneuver consisting of planting the self-selected foot on the landing area, pivoting on this planted foot externally rotating the hip while using the other leg as the swing leg to step within the limits of the corresponding cutting alley.

Crossover Task

A crossover task was defined as a cutting maneuver consisting of planting the self selected foot, pivoting on this planted foot internally rotating the hip while using the other leg as the swing leg to cross over the planting foot and step within the limits of the corresponding cutting alley.

Training Session

The 90-minute session where the subjects were instructed on how to perform, as well as allowed to practice, the drop jump and the two different unplanned cutting maneuvers.

Instructional Period

The 15-minute part of the 90-minute training session where the subjects were instructed on how to perform the drop jump and the cutting tasks.

Practice Period

The 40 minute part of the 90-minute training session where the subjects were allowed to practice an unlimited number of trials for each task for a total of 10 minutes.

Self-Selected Foot

The foot (right or left) elected during the instructional period, with which the subjects preferred to start the unplanned cutting maneuvers and land on the landing area during the two different unplanned cutting maneuvers.

Testing Session

The 60-minute session where the subjects were tested while performing the drop jump, and the two different unplanned cutting maneuvers.

Task A (drop jump)

The drop jump was defined as the movement pattern with an individually prescribed start with the subject leaving the step using a two feet take-off, landing within the limits of the landing area with both feet simultaneously flexing the knees as shown in a video projection, and performing a vertical maximum jump to finally land on the landing area with both feet simultaneously. The continuous movement had to take place with the trunk straight and the hands at the waist.

Task B (cut and free upper extremity motion)

Task B was defined as an unplanned cutting maneuver with and individually prescribed start with the subject leaving the step with a one-foot take-off (the one self-selected during the instructions-period), landing on the landing area with the same foot, and performing a cutting maneuver (sidestepping or crossover depending on the bulb lit) for finally stepping with the other foot within the limits of the alley, performing the maneuver as fast as possible, as a sport situation.

Task C (cut and grab the ball)

Task C was operationally defined as in task B with the exception that subjects were instructed to grab a volleyball with both hands, bring it down and keep it in both hands during the rest of the maneuver.

Stance Phase

The weight-bearing phase of the gait cycle, beginning with the initial contact with the surface, and ending when the contact was broken (Starkey & Ryan, 2002, p.307).

Knee Rotation

Knee rotation was defined as the quantity of angular displacement on the transverse plane of the shank relative to the transverse plane of the thigh.

Foot Inversion

Foot inversion was defined at the subtalar joint as a combination of supination, adduction, and plantar flexion (Norkin & White, 2003, p.270). Foot inversion was measured by evaluating the foot segment relative to the tibial segment on the frontal plane of motion.

Foot Eversion

Foot eversion was defined at the subtalar joint as a combination of pronation, abduction, and dorsiflexion (Norkin & White, 2003, p.272). Foot eversion was measured by evaluating the magnitude of angular motion of the foot segment relative to the tibial segment on the frontal plane of motion.

Hip Abduction/Adduction

Norkin & White (2003) defined hip abduction/adduction as “the motion which occurs in a frontal plane around an anterior-posterior axis” (p.198-200). Hip abduction/adduction was measured by evaluating the magnitude of angular motion of the thigh segment relative to the sacrum segment in the frontal plane.

Approaching Speed

Approaching speed was defined as the speed at which subjects where moving when they made contact with the landing area. Approaching speed consisted of the linear speed of the sacrum center of mass relative to the world.

Exiting Speed

Exiting speed was defined as the speed at which subjects where moving when they lost contact with the landing area. Exiting speed consisted of the linear speed of the sacrum center of mass relative to the world.

Continuous Relative Phase (CRP)

Continuous Relative Phase represented the phasing relationships or coordination between the actions of two interacting segments at every point during a specific time period (Stergiou et al., 2001b). Specifically, in this study joint couplings were calculated for hip abduction/adduction and foot inversion/eversion, and knee rotation and foot inversion/eversion.

Mean Absolute Relative Phase (MARP)

The mean absolute relative phase was defined as the average of the absolute values of the ensemble curve points for the stance cycle of five deemed acceptable trials for each subject and task.

Deviation Phase (DP)

Deviation phase was defined as the standard deviation of each point on the ensemble curve and was quantified by calculating the average standard deviation over the complete CRP curve points for the stance cycle of five deemed acceptable trials for each subject and task.

Deemed Acceptable Trial

An acceptable trial for task A consisted of landing inside the limits of the landing area, jumping vertically and landing again inside the limits of the landing area. Hands had to be placed on the waist during the whole maneuver. For tasks B and C, subjects needed to step inside the limits of the landing area, follow the correct direction indicated by the signal light, and step with the other foot inside the limits of the alley. For task C, subjects had to grab the ball that was hanging from the ceiling, bring it down, and keep it in both hands during the rest of the maneuver.

Delimitations

This research was delimited by the following factors:

1. Subjects were volunteer collegiate athletes from a small Division III university in the New England area of the United States of America.

2. Subjects were healthy and non-injured.

3. Subjects self selected which foot (right or left) they preferred to start the unplanned cutting maneuvers and land on the landing area after the instructional period of the training session. This foot was used for the rest of the training session and for the test session.

4. Subjects were tested with the same tasks.

5. The MotionMonitor™ and two video cameras were the only equipment to measure kinematic data.

6. The 4060-NC Bertec force plate was the only equipment to measure kinetic data.

7. Rest was given between trials and tasks to minimize testing subjects under fatigue conditions.

Limitations

The following limitations should be considered for further interpretation of the results of this research:

1. Subjects were volunteers.

2. The unplanned cutting tasks were limited to a 45° sidestepping and to a 45° crossover unplanned cutting maneuvers.

3. The drop jump might not have been a functional task for all the subjects.

4. For the two cutting tasks, no video instructions were given regarding the performance of the tasks.

5. Approaching and exiting speed for the two cutting maneuvers could not be consulted during intervention.

6. Continued performance of the drop jump and the two different unplanned cutting maneuvers might have caused a learning effect.

7. Performance of the drop jump and the two different unplanned cutting maneuvers might have caused fatigue.

8. Subjects had a wide range of abilities; therefore no attempt was made to control the degree of athletic ability.

9. The researcher assumed that subjects were honest reporting their previous injury history.

10. The researcher assumed that the subjects used their maximal effort and abilities to complete the drop-jump and the two different unplanned cutting maneuvers.

11. The researcher calibrated all equipment prior to data collection.

Research Hypotheses

The following hypotheses were tested in this study:

1. No significant mean absolute relative phase (MARP) difference was expected between males and females in any of the CRPs calculated for task A (drop-jump).

2. No significant mean absolute relative phase (MARP) difference was expected between males and females in any of the CRPs calculated for task B (cut and free arm motion).

3. No significant mean absolute relative phase (MARP) difference was expected between males and females in any of the CRPs calculated for task C (cut and grab the ball).

4. No significant deviation phase (DP) difference was expected between males and females in any of the CRPs calculated for task A (drop-jump).

5. No significant deviation phase (DP) difference was expected between males and females in any of the CRPs calculated for task B (cut and free arm motion).

6. No significant deviation phase (DP) difference was expected between males and females in any of the CRPs calculated for task C (cut and grab the ball).

APPENDIX B

REVIEW OF LITERATURE

Due to the disparity of the incidence in knee ligamentous injury between genders (Arendt & Dick, 1995), researchers have tried to identify the causal factors for the increased injury rates detected in women. To test these gender differences, different tasks and functional tests are currently being used in laboratory settings. However, the validity of some of these tasks and tests as well as the approach to data collection, processing and analysis may present some limitations. Dynamical Systems Theory (DST) and its computational tools may provide an innovative approach able to address some of these limitations.

To address the above mentioned issues, this literature review has been organized as follow: (1) Dynamical Systems Theory; (2) research study designs used to assess lower extremity human motion; (3) gender differences in lower extremity biomechanics; (4) Continuous Relative Phase, an innovative tool from the Dynamical Systems Theory to measure human motion; (5) the MotionMonitor™ and the Flock of Birds™ as a measurement tool; and (6) summary.

Dynamical Systems Theory (DST)

Theoretical Introduction

The 20th century was characterized by the appearance of novel and different theories which suggested considering the organisms in a more holistic fashion and in relationship to their environment.

The Dynamical Systems approach, which was developed over a long period of time, emerged due to influences coming from Thermodynamics, Gestalt’s Psychology, Quantum Physics, the General Systems Theory, and from the Synergetic of Cognition (Torrents Martín, 2005). All these theories considered that the properties of a given system (biological, chemical, etc.) cannot be determined or explained by the sum of its component parts alone (holism). This is in contrast to the classical perspective of reductionism which asserts that the nature of complex things is reduced to the nature of sums of simpler or more fundamental things.

Another influence to the emergence of Dynamical Systems that considers holism came from Cybernetics, which is the study of communication and control typically involving regulatory feedback in living organisms, machines, and organizations, as well as their combinations. The conceptual framework of feedback in cybernetics considers multidirectional channels of communication rather than the more simplified unidirectional concept of sensory input affecting the output (Torrents Martín, 2005). Figure 5 reflects this concept. This is opposed to the model in which only the input affects the output (Figure 6). So from a Cybernetics point of view, the Central Nervous System (CNS) is not just an isolated organ that receives inputs from the senses and that downloads outputs to the muscles, it is an inter-relationship of regulatory feedback.

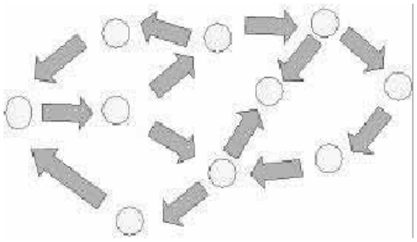


Figure 5

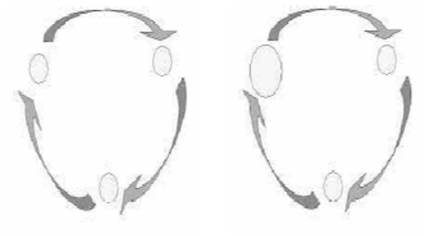


Figure 6 (Torrents Martín, 2005)

Other influences to the emergence of Dynamical Systems were summarized by Torrents Martín (2005) starting with the mathematician Jules Henry Poincaré, who proposed a new approach which emphasized the qualitative instead of the quantitative prediction. Poincaré contemplated the possibility of chaos, stating that the behavior of the complex systems such as the weather, have nothing to do with the ideal pendulums of the classic physics. However chaos hides an internal order, so even though any phenomena will not be able to be predicted exactly, general tendencies in the behavior of the systems can be found. Another theoretical current was developed by Thom in 1975. It was the Catastrophe Theory which defines catastrophe as the disappearance of a determined equilibrium and the appearance of a new one.

Finally, the Dynamical System concept can be considered as a theoretical mathematical formalization used to model physical phenomena whose state changes over time. A dynamical system is any process that moves or changes over time and the mathematical models used to describe the swinging of a clock pendulum, the weather, the stock exchange, or the number of salmons that will survive the trip from the ocean to a specific river to spawn are examples of dynamical systems. Dynamical Systems Theory, the mathematics that arrange the chaos, “is an explicit theory of change, devoted to/focused on the capture, study, and understand structural and behavioral transitions occurring in, amongst others, living systems" (Corbetta & Vereijkew, 1999, p.508).

Dynamical Systems Theory is currently being applied in multiple disciplines such as mathematics, physics, or psychology. The current thinking about the Dynamical Systems Theory applied to human movement is considered to be derived from the works of a Russian author, Nikolai Alexandrowitsch Bernstein, who in order to express his ideas found source of inspiration from some of the systemic theories above mentioned.

One of the most important problems that authors have found to interpret and follow Bernstein's ideas is the fact that his work was not translated into English until 1967 (Torrents Martín, 2005). For Bongaardt & Meijer (2000), the development of Bernstein's work should be analyzed by movement science specialists who first of all are familiar with the contemporary issues, that have a mastery of Russian language, and that have access to all his written work. The language barrier in the popularization of Bernstein's work is proved when from Bernstein's more than 140 publications , only 24 have been published in, or translated into English or German (Bongaardt & Meijer, 2000).

Bernstein’s Biography

Bongaardt & Meijer (2000), described Bernstein’s life in three different periods:

The first period (1920-1930). Nikolai Alecksandrovitsch Bernstein was born in Moscow in 1896. In the Russia of 1918, Lenin challenged scientists to increase labor efficiency and to formulate the correct methods of labor, which included the elimination of redundant and inefficient movements. When Bernstein entered the field of movement, it started to be evident that progress in this field would depend upon the further development of measurement techniques. Thus, the innovations in Bernstein’s first period were focused on technological aspects rather than on movement concepts.

The second period (1930-1948). At the end of the 1920s, it was unclear which of the schools in neuropsychology would gain the dominance within the Soviet Union. Bekhtereev, Pavlov, and Kornilov’s model of brain functioning, were the aspirants to gain this dominance. Pavlov, who had already received the 1904 Nobel Prize for his work on the mechanisms of digestive secretion gained it. Most of Bernstein’s articles in this period contain a rejection of Pavlov’s simplistic mechanistic approach. The core of Bernstein’s argument appears to be that as far as Pavlov failed to understand the organization of movement, he consequently failed to understand the brain.

By 1935, Bernstein (influenced by the Andronov and Chakin’s Theory of Oscillations) concluded that successive movements of cyclical nature never exactly repeat themselves. But this conclusion was considered incompatible with the neo-Pavlovian theory of the conditioned reflex, which states that reflexes explain the human functioning.

The third period (1954-1966). During the last years of his life, Bernstein’s central concern was the use of mathematical models as approach to understand movement. In 1966 he came to realize that Cybernetics was insufficiently equipped to deal with all relevant aspects of life.

From all this biography, in their conclusion remarks, Bongaardt & Meijer (2000) highlighted the fact that it would be relatively easy to conclude that Bernstein, throughout his life, was inconsistent because his work was mainly mechanistic in the 1920s, dynamic in the 1930s and 1940s, cybernetic and thus mechanistic again in the 1950s, and finally, naturalistic with regard to planning and thus dynamic again in the 1960s. The authors stated that even Pavlov might have been a source of inspiration into

Bernstein, but he spent much energy attacking Pavlov’s theories. However, the changes in his approach may be more of a reflection of the evolution of his thought processes.

Bernstein’s Ideas about the Development and Control of Voluntary Movement

The idea of a sensory input yielding either a direct reflex output (peripheral control) or a conscious action (central control) was the basis of the 19th century psychophysiology. In the field of motor control, this traditional view has evolved into a distinction between (inflexible) peripheral control processes and (adaptive) central control processes (Reed, 1982).

Reed (1982) stated that as early as the 1930s, there was considerable evidence against any strictly periphalist account of motor control. This is why in the 1950s the periphalist account of motor control was replaced by the motor program concept, which is a central process for the control of movement, a central command pattern for generating a given pattern of movement (Reed, 1982).

Reed (1982) stated that Bernstein criticized the central program theory giving three different arguments: (1)an individual’s body is a mechanical system, with mass, and subject to gravity and inertial forces; (2) during the course of any movement, the amounts of force acting on the body will change, as potential and kinetic energy interchange; (3)the trajectory of any part of the body cannot be calculated without some updated information about the changes in forces occurring because of that movement itself (Reed, 1982). For all these reasons, Bernstein rejected the possibility of a central program system.

Bernstein and the main concept of his work: Dexterity.

In Bernstein’s book “Dexterity and its Development”, edited and translated into the English language by Latash et al. (1996), Bernstein suggested that dexterity was one of four entities that characterize “psychophysical capacities”. These capacities were (1) force, (2) speed, (3) endurance, and (4) dexterity. For Bernstein, dexterity is the most complex capacity and the main role in dexterity is played by the central nervous system. Dexterity refers to quickness, agility, flexibility and skillfulness of our body. Bernstein formally defined dexterity applied to any movement as “the ability to solve a motor problem correctly, quickly, rationally, and resourcefully” (M. L. Latash et al., 1996, p.242). For Bernstein, resourcefulness is the nucleus of motor dexterity and movement resourcefulness stands in a direct relation to accumulated motor experience. Demand for dexterity is not in the movements themselves but in the surrounding environmental conditions, which can increase the complexity of a simple motor task. Bernstein considered dexterity special because it is a universal and very versatile physical capacity, because it is accessible and not an inborn capacity so it can be improved, and because it differs from other physical capacity like force or endurance because dexterity, related to movement, is an accumulation of experiences. For Bernsetin, dexterity in each person is qualitatively different and unique so this is why it is the only psychophysical capacity that is not able to be quantitatively measured.

Bernstein's model of voluntary movement. Bernstein defined coordination as "overcoming excessive degrees of freedom of our movement organs, that is, turning the movement organs into controllable systems" (M. L. Latash et al., 1996, p.41). By movement organ Bernstein was referring to any anatomical structure involved in the accomplishment of a movement. In other words, for Bernstein the problem of movement coordination consisted of controlling excessive degrees of freedom.

Bernstein, stated that the sensory organs must continuously send signals to the brain about the progress of the movement and thus enable the brain to introduce, without delay, required changes (corrections). For Bernstein, just one redundant degree of freedom means an infinite freedom of choice of movements.

For Bernstein (1967), the term redundant degrees of freedom refer to the total amount of degrees of freedom available to perform a coordinated activity. It is important however to state that for Bernstein, the available degrees of freedom exceed the number of degrees of freedom needed to accomplish the task. For Bernstein, when learning a new task, an initial solution to reduce the unmanageable number of degrees of freedom to a manageable number, is to “freeze out” a portion of the degrees of freedom. This can be done by keeping the joint angles or the whole body “rigidly, spastically fixed”. After this first period of freezing degrees of freedom and progressing to learn the new task, Bernstein postulated a first stage of release in which the restrictions are gradually lifted and the degrees of freedom become incorporated into larger functional units (named coordinative structures). Finally, in a second stage this organization becomes more economical in the sense that passive forces (reactive, frictional, inertial) become incorporated. This second stage is achieved in concordance with the efficiency of muscular (active) forces. Overall, passive and active forces contribute to exploit all the possibilities in a movement.

Related to the second stage of release, Broderick & Newell (1999) stated that it is one of Bernstein’s central insights because as far the passive forces can not be predicted, no movement can be completely pre-programmed.

Davids et al. (1999) added that an important characteristic of a coordinative structure is that if one of the component parts introduces an error into the common output, and in order to minimize this error, the other components automatically vary their contribution to movement organization.

Hierarchical organization of the movement systems. For Bongaardt & Meijer (2000), Bernstein distinguished in the brain an exact representation of what will later occur at the periphery. After this, a meditating process of integration of the central signal and sensory information would occur. Finally the locomotor apparatus would produce the outcome movement.

Bernstein distinguished four broad levels of control in the construction of movements: the level of tone, the level of synergies, the level of space, and the level of action (M. Latash, 2000, p.115). The level of tone is the level of tonic muscular force. In the level of synergies muscles and joints work together to form coordinated movements. The level of space deals with movement in the space adjacent to the body. The level of action is the highest controlling mechanism that takes part in all movements that require action sequences, adaptations and solutions to the problems encountered during movement.

Reviewing Bernstein's Ideas about how Degrees of Freedom are Released when Learning a new Skill

Vereijken et al. (1992) stated that the ideas of Bernstein about skill acquisition, and how the release of degrees of freedom process is achieved, had not been subjected to empirical verification. Since Vereijken's et al. (1992) statement, different studies within the literature have tried to review, assess, and confirm some of the ideas postulated by Bernstein's model of voluntary movement, movement coordination, degrees of freedom, and how these degrees of freedom are released when learning a new task. While some of these studies have supported some of the ideas exposed by Bernstein (Buchanan & Kelso, 1999; Vereijken et al., 1992), others have rejected them (Broderick & Newell, 1999). Finally, a whole new discussion is still open suggesting that maybe the disagreement among Bernstein’s followers may originate with some misinterpretation of his original ideas (Bongaardt & Meijer, 2000; M. Latash, 2000).

Supporting Bernstein’s ideas. Vereijken et al. (1992) tested five males (20 to 32 years old) with no previous experience with skiing, or with this ski apparatus specially designed by the investigators. Subjects were tested on a task consisting in the making of slalom like ski movement on the specially designed ski apparatus. Kinematic data from hip, knee, and ankle angles were taken. Amplitude and frequency of the platform movements were also measured.

Results revealed that subjects were moving the platform in an average amplitude that increased over trials, with the largest increase seen on the first day of training. Initially subjects started to move the platform at a high frequency but very small amplitude. The increase in amplitude at the end of the first training day was accompanied by a large drop in frequency. Over the rest of the days, subjects gradually increased the frequency again with a simultaneous further increase in amplitude. At the early phases of learning, the joint angles of the lower limbs and torso displayed little movement. Individual degrees of freedom were released rapidly over the early trials and on the contrary, the couplings between body angles changed gradually over the entire practice period. In their discussion, the authors stated that traditionally, learning has been viewed as the process of reducing variability in performance, but in contrast, the acquisition of coordination can be regarded as the search for optimal movement strategies within the biological workspace. The results found in this study would agree with Bernstein’s model of voluntary movement when learning a new skill.

Buchanan & Kelso (1999) suggested that recruitment and suppression processes occur at many levels in the nervous system. The authors tested seven right-handed subjects (four men and three women) in two different experiments. In experiment one, subjects swung four different pendulums with motion of the forearm constrained or unconstrained. Pendulums were single hand-held and were moved forward and backward in the sagittal plane abducting and adducting the wrist maintaining a 1:1 relationship with a metronome. In experiment 2, the subjects swung paired pendulums (with forearms constrained and unconstrained) in either an in-phase (pendulums were swung symmetrically directions) or an anti-phase (pendulums were swung anti-symmetrically) coordinative mode as movement rate was increased. The pendulum pair was moved in the same way as for experiment 1 following a 1:1 relationship with the metronome. In both experiments, subjects closed their eyes and the metronomes frequency increased every 10 cycles.

Results in experiment 1 showed that pendulum motion changed form planar (2d) to elliptical (3D) and forearm motion (produced by elbow flexion-extension) was recruited with increasing movement rate for cycling frequencies typically above the pendulum’s frequency. Elliptical pendulum motion was observed regardless of the length-mass characteristics of the pendulums, but only for frequencies above pendulum’s Eigen frequency (the frequency at which the pendulum would naturally move).

Pendulum length-mass characteristics had little influence on the amplitude of wrist motion, even though wrist amplitude decreased significantly as frequency increased above the pendulums’ Eigen frequency. It was interesting that the decrease in wrist amplitude occurred over the same frequency range at which another degree of freedom was recruited, namely, forearm motion produced by elbow flexion-extension. As in the single pendulum case, in experiment two, pendulum motion changed from planar to elliptical, and forearm motion was recruited with increasing cycling frequency. Also, not only was forearm motion recruited, but it could be suppressed, then recruited again. Related to Bernstein ideas, results from experiment two clearly demonstrated that the CNS spontaneously recruits and suppresses degrees of freedom in a flexible fashion in order to achieve task specific goals.

Rejecting Bernstein’s ideas. Broderick & Newell (1999) observed the coordination patterns of people of different ages and skill levels bouncing a ball. The authors analyzed the relative increase and decrease of degrees of freedom with learning and the order of progression in the changing organization of those degrees of freedom with development and learning.

Results from the coordination patterns revealed that the movement patterns of the less skilled subjects were more variable than those of the more skilled. This made the authors suggest that the central concern about Bernstein’s view of movement coordination about the release of degrees of freedom while learning movement might be inexact. Broderick & Newell (1999) stated that to chart behavior, careful language use is necessary when describing comparative states of skill, and thereafter we need to specify always what is more or less variable. For the authors, expertise means greater constraint on movement while allowing for the possibility of greater adaptation. From this rationale, and in the comparisons of states of skill, the same terms can describe the same behavior in contradictory ways. The authors argued that if Bernstein’s first stage on release of degrees of freedom were the case we would not expect to see a gradual diminution of variability associated with increasing skill level as their results showed.

Broderick & Newell (1999) concluded that Bernstein himself and those following him had very little to say about how coordination is acquired. Rather, the problem was seen to be how coordination is accomplished, given that the organism is already at some level or state of coordination.

Have Bernstein's ideas been misinterpreted? Bongaardt & Meijer (2000) asked themselves if the disagreement among Bernstein's followers arise from the structure of his work itself or from incomplete exploitation of his thinking.

Latash (2000) also stated that even though in English the meaning of the word "redundancy" is opposed to "abundance", the Russian word *izbytochnost* used by Bernstein in his original writings can mean "redundancy" or "abundance", depending on the context. "Isn't it amazing that a whole direction of research developed based on an imprecise translation of a single word?!" (Latash, 2000, p.261). In order to suggest that the problem of motor redundancy proposed by Bernstein has been inadequately formulated, Latash (2000) suggested that there is no motor redundancy in human movements but there is motor abundance. This suggestion was based on the results of a study conducted by Bernstein in 1924 analyzing blacksmiths movements with a hammer showing that the variability of the tip of the hammer across a series of trials was smaller than the variability of the trajectories of individual joints of the subject's arms concluding that the joints were not acting independently but correcting each others' errors.

For Latash (2000), this observation already suggests that the CNS does not try to find a unique solution for the problem of kinematic redundancy. The CNS uses the apparently redundant set of joints to assure more accurate (less variable) performance of the movements. For the author, even though Bernstein viewed the elimination of the redundant degrees of freedom as the most essential problem of motor control, it is unclear whether he seriously implied an elimination of biomechanical degrees of freedom because the only way to eliminate a biomechanical degree of freedom is to perform a major surgery. For Latash (2000), the principle of abundance appears when many more elements than the necessary to produce a movement participate in it and these elements should not be viewed as a source of problems for the nervous system but as a useful resource that requires proper organization.

Dynamical Systems Theory Applied to the Sports and Physical Activity Fields

Related to sport and physical activities, Dynamical Systems Theory has already been applied in different fields. In all these applications, the consideration of organisms as non-linear systems is a crucial concept that characterizes this new approach.

Applications of the Dynamical Systems Theory applied to the sports field include the study of the learning processes of sport skills (Buekers et al., 1999), the analysis of sport tasks (Broderick & Newell, 1999; Liu & Burton, 1999; Stergiou et al., 2001a; Stergiou et al., 2001b), the study of the interactions between athletes during sport situations (McGarry et al., 2002), or applications related to sport physical conditioning methods (Balagué & Torrents, 2000, 2005; Schoellhorn, 2000; Torrents Martín, 2005).

Dynamical Systems Theory Applied to Movement Coordination

Movement is an inherent characteristic of the human beings. In order to understand and improve learning processes, several different theories have attempted to understand and explain how movement coordination is acquired. From a Dynamical Systems Theory point of view, a different approach to movement coordination has been proposed opposing the traditional motor learning theories. Within this section, different concepts and terminology from DST applied to movement coordination and motor learning are exposed.

Related to the human motion research field, some of these concepts should be taken in consideration when research methods are designed. Sometimes, the task selection used in laboratory conditions do not parallel the actual tasks required for athletic performance. The way the selected laboratory tasks are taught should follow objective parameters and considerations, and the Dynamical Systems approach applied to the movement coordination might offer some of them.

Intrapersonal coordination. Several studies have attempted to analyze how learners coordinate their own movements (intrapersonal coordination) while others have attempted to analyze how subjects coordinate their movements related to other subjects (interpersonal coordination). Since Kugler’s et al. (1980) work about Dynamical Systems application in the motor learning field, a new line of research was developed in this field. Under this approach, Haken et al. (1985) developed a theoretical model (HKB model), using concepts central to the interdisciplinary field of synergetics and non-linear oscillator theory. This model attempts to reproduce what different experimental studies have shown about abrupt phase transitions in human hand movements: that when two limbs (i.e. the index fingers of two hands) are moved in a cyclic manner and the frequency of movement is increased, the original out of phase pattern in which both limbs are moving asymmetrically, is replaced by an in-phase pattern in which both limbs are moving symmetrically (Buchanan & Kelso, 1999; Kelso, 1984). Additionally, this phase relationship between two segments (in phase or out of phase) can be defined in a quantitative manner. An in-phase mode corresponds to 0º while an out of phase mode corresponds to 180º. All the other values between 0º and 180º are possible to be developed, even though their production in a coordinated manner is more difficult to be achieved.

This change on phase transition occurs despite the conscious effort to stay in the starting movement and it can be observed in all people but at different frequencies, and once this critical frequency is passed, it is not possible anymore to switch to the starting movements without reducing the frequency (Schoellhorn, 2000). However, when starting the movement with an in-phase mode, the transition into an out-phase mode is not observed.

Additionally, in-phase and out of phase modes are the only two modes that can be performed in a stable manner.

Kelso (1984) analyzed hand motion at the horizontal plane of the wrist in an asymmetrical mode (flexion of one wrist was accompanied by extension of the other and vice versa). Instructions to the subjects were to commence cycling the hands slowly, and to increase rate of cycling either in response to a verbal cue provided by the experimenter at 15 seconds intervals or by a metronome. In another experiment subjects performed a series of trials under identical instructions but with a resistive load applied to both limbs. Subjects were instructed to choose their preferred frequencies and amplitudes at a comfortable rate.

Results showed that a permanent transition from the original asymmetric to the symmetric in-phase mode was observed. When cycling frequency was increased, one mode became unstable only to disappear and be replaced by another stable mode. Symmetric and asymmetric modes were the only two modes that could be performed in a stable manner, which did not mean that the other phase relations are not possible, but tended to be much more variable.

Interpersonal coordination. Interpersonal coordination, the coordination between subjects, has been assessed in several studies. While intrapersonal coordination is the study of the coordination of ones own movements, interpersonal coordination studies movement relative to another subject’s motion.

Schmidt & O'Brien (1997) tested 20 paired participants that performed a simple rhythmic task swinging pendulums in which they had visual information about each other’s movements but had no goal to coordinate. Subjects seated with arms attached and handheld pendulums that were oscillated parallel to the sagittal plane, approximately about the adduction-abduction axis of the wrist. Two different pendulum lengths were used (0.32m and 0.62m). Each participant pair was asked to oscillate two combinations of the pendulum lengths. In the same length condition, both participants used short pendulums. In the different length condition, one participant used the short pendulum and the other the long pendulum. For the first 12 seconds of each trial, participant pairs were instructed to look straight ahead so they could not see one another and perform the task at a comfortable rate. During the last 12 sec of each trial, participants were told to maintain their preferred tempo from the first half of the trial while looking at the other participants’ moving pendulum.

Results revealed a distribution of relative phase angles that was dominated by values near 0° (in-phase) and 180° (out of phase). The results indicated that with and without information available, the movements of the two participants were at different frequencies and were not frequency-locked when viewing the other person’s pendulum (although they were closest to a 1:1 frequency ratio).

Contextual interference effect. Ideas suggested by the contextual interference effect concept might be taken in consideration when developing research design methods for biomechanical analysis. The way in which tests and tasks to be performed are instructed to the subjects in laboratory settings might deserve special consideration.

Magill & Hall (1990) defined contextual interference effect as a learning phenomenon where interference during practice is beneficial to skill learning. The question to why the simple alteration of the schedule of practice for several different skills should lead to different learning effects, was answered by Magill & Hall (1990) by stating that the contextual interference effect has been shown to occur when several variations of a task must be learned during practice. While performance during practice applying contextual interferences is typically depressed, performance on a later retention or transfer test performance is better than for those practice conditions in which there were lower levels of interference (Magill & Hall, 1990).

Carnahan & Lee (1989) tested 36 right-handed undergraduates divided in three groups: duration group, variable phase group, and constant-phase group. Each group was required to learn three movement timing patterns. For any one movement pattern, subjects were required to knock down three wooden barriers. A computer measured the movement time between the switch of a start button and the first barrier (phase 1), the movement time between the first and second barriers (phase 2) and the movement time between the second and third barriers (phase 3). The goal of both phase groups was to complete each phase of the movement pattern in specified movement times. A transfer test was performed after the tests.

The transfer results of the present study clearly supported the higher order variable hypothesis, which supports that phasing timing training develop a timing skill that is flexible for various types of transfer tasks rather than the contextual interference hypothesis where the difficulty associated with segmental training was sufficient to provide this flexibility for later transfer. This was shown when the constant phase-trained group out-performed the duration-trained group on all of the transfer tests. In addition, no differences between the two-phase-trained groups were found on any of the transfer tests. However, results demonstrated a contextual interference effect for the acquisition because the variable-phase-group experienced more error than the constant-phase group, demonstrating that random practice groups experience poor performance during acquisition when compared with blocked practice groups.

These results were supported by Hall & Magill (1995) when the authors tested their subjects in a tapping task that required a right-handed tap of three small brass plates arranged in a diamond pattern, revealing that the learning benefits of contextual interference are more likely to occur when skill variations are from different classes of movement.

Perception-action coupling. For the same reasons as for the contextual interference effect, the perception-action coupling concept should be taken in consideration when teaching tasks and tests to be performed in a laboratory with biomechanical research purposes. From the ecological psychology of Gibson (1979), the perception-action approach is based on the fact that the human being can not be studied separately from the environment in which he/she functions. Perception and action are interconnected, one depends on the other. For this reason there is no need for the subject to anticipate the occurrence of future events, given the continuous real time update on the status of the actor-environment system with respect to the action undertaken (Buekers et al., 1999).

The term affordance is derived from the ecological psychology, and tries to identify a property of an object that indicates how to interact with this object. For example, the shape of a chair affords sitting. An affordance refers both to properties of the environment and to properties of the organism so the same environment can have different affordances for different organisms (Riccio, 1988).

For Buekers (2000), the learner should be presented with a large number of perception-action couplings. For the author, and in order to be able to adapt to the continuously changing game situations, the presentation of a large number of couplings is essential. Although these perception-action constraints are often presented under the form of verbal instructions, Buekers (2000) proposed a more direct method: the “environmental facilitators”. This methodology could be exemplified when runners learn how to hand off the baton to the next runner within the delimited zone in a relay race. In order to achieve a good performance, this action has to be highly coordinated and the aim is to exchange the baton while both runners are at full speed. A common practice is to place an environmental facilitator such as a towel at a distant point from the exchanging point as reference. When the runner who carries the baton crosses it, the next runner starts to run with the aim to be at full speed at the exchanging point.

Explicit learning. Related to movement coordination, explicit learning is achieved by providing specific instructions on how to perform a movement while implicit learning is the knowledge that is inherent and that does not need specific instructions or explanations to be transmitted. In both cases, there is a selected outcome. It is the process through which this outcome is achieved that is different. For explicit learning, specific step by step instructions are given, influencing the performance of the task to achieve the final outcome. For implicit learning, several opportunities in various environments are created that will allow the subject to “discover” their most efficient way to create the desired outcome movement pattern.

When selecting a task instructional method in laboratory testing, one may want to be aware of the implications of specific task performance instructions (which will enhance internal validity) vs. allowing for self-selected movement patterns which will weaken internal validity by enhancing external validity.

The term Bi-stability can be defined as the capacity of moving in both a symmetric in-phase (0°) mode or in an asymmetric out of phase (180°) mode. Opposite to bi-stability, multi-stable subjects are able to develop their movements throughout all the phase relationships (0 to 180°). However, patterns in between 0 and 180° are much more difficult to achieve in a coordinated manner.

Hodges & Franks (2002) manipulated instructions and demonstrations to make pre-practice behaviors explicit, and informed participants how to build-upon these to perform a novel bi-manual movement. In the first of their experiments, the authors tested bi-stable and multi-stable subjects (who can move in two patterns simultaneous in patterns in-between zero and 180 degrees). In the second experiment, there were two parts. Individuals who could perform additional multi-stable movements were tested. In part one, the task goal for all participants was to learn how to correctly move the arms to produce circle patterns on a computer screen that matched as closely as possible a criterion circle trace. In part two, the goal was to produce 15 circles within a 15 seconds trial by moving in time with an auditory metronome. Circles could be produced by correctly moving the arms in a 90° relative phase coordination pattern where one arm preceded the other by a quarter of a full cycle.

Results from the study showed that instructions directing participants to modify the pre-existing bi-stable patterns (anti phase or in phase) to perform 90° relative phase failed to benefit learning. Hodges & Franks (2002) concluded that it might be better to avoid instructions and demonstrations when learning a novel motor skill with complex response requirements. As long as feedback is provided that relates performance to the task goal and therefore encourages change in performance form trial to trial, the learner might be better left to explore and familiarize him or herself with the task before movement related instructions are given (Hodges & Franks, 2002).

Implicit learning. Beek (2000) stated that implicit learning is superior to explicit learning because implicit appears to be retained longer than explicit. Beek (2000) argued that for the most part, implicit learning is what is present when learning a new skill while explicit learning may even become an exception during the learning process. However the author concluded that suggestions that consider that implicit learning is always superior to explicit learning seem to be too simple. For Beek (2000), one of the complicating factors is that different perceptual-motor skills may be learned differently and may appeal differently to explicit and implicit processes.

Corbetta & Vereijkew (1999) chose to study infants arguing that infants have a comparatively limited prior history and develop a wide range of new fundamental skills in a comparatively short time span. The researchers observed pre-locomotor infants in a qualitative way. They observed the action of catching and the behavior of the infants on cyclical treadmill stepping. Results revealed that subsequent progress in the control of reaching trajectory was achieved by calibrating the forces intrinsic to the movement as a function of the specified goal. When supported over a moving surface, even one-month old infants would make stepping movements. The authors concluded that in these tasks, the behavioral solution did not need to be known by the learner. The exposure to certain environmental conditions could drive, facilitate or alter the formation of specific movement patterns.

Applications of the explicit and implicit learning concepts related to the biomechanics field could be introduced in the way tasks and tests are presented to the subjects. The assessment of explicitly learned tasks predominates within the methodologies used by human movement analysts.

Deliberate practice. Another concept to consider when testing subjects in the laboratories is the deliberate practice concept. In a more quantitative approach the amount of time spent while learning a motor task has been viewed as proportional to the positive outcome obtained. Hence the number of trial selections may play a role in the performance outcome.

Ericsson’s et al. (1993) model of acquisition of expert performance known as the model of deliberate practice, suggests that athletes are made, not born, and that success is a function of the amount of “deliberate practice” one has accumulated.

Starkes (2000) evaluated Belgium athletes in two different sports (soccer and field hockey) and at different level of practice. Subjects had to complete a questionnaire for biographic information concerning the age when practice was first initiated, the highest level attained in the activity, success in competitions, and the number of coaches they have had during their careers. Also the amount of time that subjects had spent practicing for the activity individually and in team practice, in activities related to the skill and in every day activities during a typical week. Results showed that for international players, individual practice time significantly increased from 3 to 18 years into career. Accumulated practice also showed that by 18 years into career, international, national and provincial players had accumulated 10237, 9147 and 6048 practice hours respectively. The authors concluded that only practice, and not talent (based on the level of play), appeared to be important on the road to expertise.

Van Rossum (2000) challenged Starkes (2000) results assessing Dutch field hockey players for the amount of hours in deliberate practice. Results showed that Dutch field hockey players appeared to practice thousands of hours less than the Belgian players studied in Starkes (2000) study even though Dutch field hockey players performed at a much higher level of international excellence. Van Rossum (2000) concluded that the magic number of 10,000 hours proposed by Starkes (2000) of accumulated practice to reach a level of excellence, did not apply for the Dutch field hockey players. For Van Rossum (2000), the fundamental issue might not be the number of hours of accumulated practice necessary to obtain excellence, but how to improve the quality of instruction.

Learning based on individualization vs. learning the “ideal” model. Learning based on an ideal model is a common practice in the motor learning domain. Models are supposed to be ideal movement patterns that produce effective outcomes. However, and from a Dynamical Systems approach, no movement can be repeated twice in the same conditions. Thereafter, the usefulness of reproducing an ideal model to analyze human motion might present some weaknesses.

Latash (2000), addressing Bernstein’s ideas and showing that no movement can be repeated in the same conditions stated:

> Which forces should be produced by each of the six major muscles crossing the elbow joint to generate a certain value of elbow joint torque? Or which motor units should be recruited by the CNS and at what frequencies to produce a certain level of muscle activation? Solving such ill-posed problems is equivalent to solving a system of equations with more unknowns than the number of equations. (p.259)

Balagué & Torrents (2005) theorized that the modern science of sport training is based in the classic science which postulates a causality model. This is why the motor learning in many sport motions is nowadays due to the observation of a model. For the authors it is not necessary anymore that the athlete knows previously the solution for a new motion because the response comes up through a gradual discovery process. The authors continued stating that training does not have to insist only in repetition as the most important factor to increase performance rather than giving to the athlete a wide range of situations that lets the athlete to spontaneously generate changes in coordination that will guide him to the final answer. With similar ideas, Schoellhorn (2000) stated: “When the next movement is different from the last anyway, what can be the ideal movement?” (p.67).

On November 15, 1993, a 72-year-old gentleman named Dr. Amberry entered the Guinness Book of World Records by sinking 2750 shots in a row. The words from this Guinness record man (Amberry, 1996) emphasized the idea of the uselessness of using models as a methodology to improve final outcomes in basketball free shots:

> Never say to yourself, ‘You almost missed it short. Shoot this one longer! Don’t compare your next shot to your previous one. That shot is history. It’s gone. But you can learn from it. If your first shot hit the front of the rim, remind yourself to make a deep knee bend. Don’t make a deeper knee bend. (p. 68-69)

By saying make a deep knee bend and not a deeper, Amberry (1996) pointed the usefulness of using comparative models to master a skill.

Liu & Burton (1999) observed changes in basketball shooting patterns as a function of distance when a basketball was shot. However, these changes in basketball shooting patterns were not observed when the distance from the rim was increased while simulating a shot. In their discussion, the authors stated that many coaches and instructors in basketball teach their players and students to follow a precise movement pattern as a model. However, this research demonstrated that the model should be changed when distances from the basket increases if increasing of the outcome performance the goal is. In this particular study distance was the variable that changed the movement pattern but in a real sport situation such as a basketball game, multiple other variables while shooting a basket have to be taken in consideration. The distance of the opponent, the temperature in the gymnasium, the level of fatigue, or the psychological pressure when a decisive shot is needed to win a game are examples that application of models in movement and coordination do not consider the multiple parameters encountered in a sports situation.

Introducing variations during the learning processes. For Buekers (2000), one of the typical characteristics of an expert is the ability to adapt his motor behavior to the requirements of the game situations.

Buekers (2000) also noted that at later stages of learning, the variety of movements should be reduced, shifting the attention from a more general approach to one in which the demands of one specific discipline prevails, concluding that the learning of techniques in team sports is characterized by a shift from “variation in variable situations to variation in specific situations” (p. 487). An example of this suggestion could be when practicing performance on a basketball shot. While the variation in variable situations could be achieved by throwing heavier basketballs from different distances, variation in specific situation could be exemplified by throwing heavier basketballs from the free shot line.

Dynamical Systems Theory Applied to the Sports Medicine Field

In the past years, motor-control researchers have developed a theoretical framework for using non-linear dynamics within a Dynamical Systems framework that might be applicable to sports medicine (McKeon & Hertel, 2006).

Davids et al. (2003) stated that the implementation of a dynamical systems theoretical interpretation of variability in movement systems, makes evident to re-evaluate the influences of the traditional ‘medical model’ to interpret motor behavior and performance related to injury of the movement systems. For McKeon & Hertel (2006), the functional role of variability might be protective, serving to reduce the repeated stress on tissues, and might allow for greater flexibility in dealing with unexpected perturbations.

Davids (1999) within a Dynamical Systems background, measured posture differences between an ACL-deficient group and a control group. Other studies with a dynamical systems background have focused on ACL-reconstructed subjects (van Uden et al., 2003), while others focused on patellofemoral pain (Hamill et al., 1999). Finally, others (Bardy et al., 1999; Marin et al., 1999; Van Emmerik & Van Wegen, 2002), using the same approach, have assessed posture.

Basic Terminology to Apply Dynamical Systems Theory to the Sports Medicine Field

In order to understand this innovative framework, and to apply it to the research in the sports medicine field, the terminology and concepts of the Dynamical Systems approach need to be understood.

Non-linear systems. Within the literature, several studies (J. A. S. Kelso et al., 1981; Thelen et al., 1996; Torrents Martín, 2005) have demonstrated the non-linear behavior of the human beings as measured from a Dynamical Systems approach.

Kelso et al. (1981) tested two groups of subjects: a single hand group (N=6), that completed the experiments using the index finger of only one hand, and a bimanual group (N=6) that used both, the left and right hand. The task throughout all experiments was to move the index fingers of one or both hands in all cyclical (flexion-extension) manners from the onset of an auditory start signal to a stop signal. For the two-handed task, the movements were always symmetrical (flexion of one hand was accompanied by flexion of the other and the same was valid for extension). Instructions in all the experiments were to move the finger(s) continuously over a 10 second trial in a way that felt most comfortable and required least effort. Movements of the fingers were constrained to a 50° range with an apparatus able to produce torque resistances, first to 50% of maximum torque output available and secondly to 25%. Then, resistances were removed.

Results from the study showed that two-handed movements maintained fixed amplitude and frequency (a stable limit cycle organization) when brief and constantly applied load perturbations were imposed on one hand or the other, regardless of the presence or absence of fixed mechanical constraints (the resistance). The results demonstrated the non-linear behavior of the subjects.

Torrents Martín (2005) compared the temporal series of the forces applied on a force plate when landing during a drop jump from different heights. When the first part of the time series for Fx, Fy, and FZ were analyzed, a high variability was noticed. Then the signal stabilized following a similar pattern in all the jumps for all the subjects. This showed that the analysis of this variable was especially justified in the first part of the contact with the floor and that the subjects followed a coordinative stable pattern but at the same time variable in order to adapt themselves.

Torrents Martín (2005) concluded that when the subjects landed on the platform, high levels of variability in the horizontal force parameter were observed until they stabilized in the vertical axis. Those variations were higher as the distance or height of the jump increased. These results demonstrated the non-linear behavior of their subjects while performing the tasks requested. Stability diminished when the subjects approached the transition zone, showing that the transition into a new pattern is preceded by a period of exploration of new solutions of variability, such as is proposed by the Dynamical Systems approach. Torrents Martín (2005) suggested that this variability is probably needed to avoid injuries.

Thelen et al. (1996) conducted an investigation to provide evidence that one reason why reaching in young infants is unskilled is because the trajectories are still tightly coupled to the energetic and biomechanical constraints of the movement executions. Four normal infants were observed every week from three until 30 weeks of age and once every two weeks thereafter until 52 weeks during two sessions each week. The authors determined trials and portions of trials that were behaviorally interesting such as spontaneous movements performed either in conjunction with a reach or not, and object or goal oriented movements.

The four infants showed several common changes in their reaching skill across the first year. They all had active periods during which reaching speed affected trajectory control and they all showed a stable period marked by a steady kinematic profile. Reaching speeds increased, path straightness decreased primarily during the periods prior to stability. Results also showed several individual differences, specifically in the timing of reach onset, the timing of the active periods and the timing of the transitions to the stable periods. Infants also had individually characteristic speed preferences. Within these preferences they also showed developmental variability, with each infant having an epoch of faster or more variable movements preceded and followed by periods of greater stability. All these data allowed Thelen et al. (1996) to demonstrate the non-linearity of trajectory development.

Overall, evidence has been provided within the literature showing that human beings behave as non-linear systems. This evidence should be taken in consideration in the design of research methods in the sports medicine field.

Motor system variability. The capability in biological organisms to develop a particular task in different manners is a resource of variability in movement. This variability offers flexibility to deal with unexpected changing constraints (McKeon & Hertel, 2006).

Davids et al. (1999), in order to show the importance of variability, stated that motor patterns emerge under different task constraints to achieve stable task outcomes. Lee et al. (1995) showed that an increase in variability when learning novel bi-manual movements was indicative of the search to discover the new movement. This variability preceded their ability to perform the newly required movement.

Instability or transitions. The terms instability and transitions describe alterations and changes from a given state to another state as a function of time. In general, instabilities can emerge from environmental and/or internal modifications that are affecting the behavioral patterns of the movement system (Corbetta & Vereijkew, 1999). Liu & Burton (1999) considered that a transition was referred to an abrupt qualitative change or reorganization of a movement pattern

Liu & Burton (1999) in order to examine the effect of distance of basketball shooting accuracy and more importantly on movement patterns, tested five male and five female (m = 26 years old) with no basketball experience beyond regular physical education. The subjects shot 20 times at each of eight distances from 5 to 40ft (Natural condition). Also they pretended to shoot the ball 5 times at each of the eight distances, for a total of 200 shots each (Pretend condition).

Results showed that shooting accuracy decreased as distance increased for the Natural condition. Related to the stability of shooting patterns at particular distances, the participants showed remarkable stability in all body components across distances and conditions. Related to transitions from one stable component level to another, the most common form of transitions were from ipsilateral to contralateral forward foot position, from high to low hand position, from no trunk rotation to trunk rotation, and from low to high jump. The distances of least stability in the Natural condition occurred at the distance right before the transition 80.0% of the time. However, in the Pretend condition, an abrupt transition without any instability was observed 70% of the time.

The authors concluded that as a player begins to see a drop in shooting accuracy, new shooting pattern alternatives may begin to be used. Higher stability in the pretend condition as compared to the natural condition was explained by the authors as having no feedback related to missed baskets in the Pretend condition, which did not require adjusting any shooting pattern.

Burgess-Limerick et al (2001), in order to describe an example of spontaneous transitions between qualitatively different coordination patterns during a cyclic lifting and lowering task, tested eleven subjects while raising and lowering continuously a 1 kg load. Results showed that two distinct patterns of coordination were evident: a squat technique and a stoop technique. Abrupt transitions from stoop to squat techniques were observed during trials when they were lowering the load and from squat to stoop during lifting the load for trials by nine of the 11 participants, in 55% of the total number of trials (66 of 121 trials).

Constraints. Constraints can be defined as aspects that alter the conditions in which a movement is performed. Byrne et al. (2002) stated that constraints effectively reduce the number of degrees of freedom and simplify the management of the neuromuscular system, with the motor output being shaped by the constraints applied to the system. For Byrne et al. (2002), and from the Dynamical Systems theory point of view, coordinated patterns are assumed to be constructed out of the constraints applied to the neuromuscular system. The author stated that these constraints come from the organism, the environment, and task. Riccio (1988) conducted a research to assess the control of stance. The authors considered three classes of constraints on the control of stance: properties of the surface of support, the properties of the organism and the goals of behavior.

Davids et al. (1999) in order to examine how task, informational, and sensorimotor system constraints influence postural control, tested 15 subjects (8 male and 7 female; mean age = 25 years old, SD = 3) that had sustained an ACL injury with no surgical repair. Subjects were tested at a minimum of 2 weeks after having undergone arthroscopic diagnosis of complete rupture of ACL and the mean time after injury for all the subjects was 25 months (SD = 17). ACL-deficient subjects were matched by gender, age, height, weight, and activity or sporting background with a control group consisting of 15 healthy volunteers.

Informational and task constraints, in the form of vision and type of stance were manipulated on the postural modifying test positions, which consisted of standing on two legs with eyes open, standing on two legs with eyes closed, standing on the injured leg with eyes open, standing on the injured leg with eyes closed, standing on the non-injured leg with eyes open, and standing on the non-injured leg with eyes closed. Results of the study showed that vision was the most important informational constraint on postural control for subjects on the dynamic task, particularly for the ACL-deficient group standing on the injured leg.

Order parameters. The order parameter is a measure able to reflect rhythmic individual components that exist within a system (McGarry et al., 2002). In Dynamical Systems Theory, continuous relative phase is used as an order parameter measurement variable.

Scholz & Kelso (1989) suggested that in cases of motor coordination, the relative phasing among rhythmically moving components may be a relevant collective variable, or order parameter. Stergiou et al. (2001a) used the phasing relationship of limb segments (continuous relative phase) within the same leg as order parameter.

Control parameters. A control parameter is some property that constrains the behavior of a dynamical system. The control parameter could be exemplified by altering the center of gravity of a subject by adding a weight on his ankle. For McGarry et al. (2002), one feature that characterizes a dynamical system is the transition in some order parameter (or collective variable) as a result of scaling in some control parameter.

For Stergiou et al. (2001a), the approach of the Dynamical Systems Theory implies a first step where movement patterns are characterized using the appropriate variables, the order parameters. Then it is important to identify control parameters that move the system through its behavioral states, so when a control parameter reaches a critical threshold a transition to a new coordinative behavior will occur.

Torrents Martín (2005) used the height of a Drop Jump and the distance of a double-legged hop jump as two quantifiable measures adopted as control parameters. Stergiou (2001a) used the height of an obstacle that a runner had to clear as a control parameter.

Intrinsic dynamics. Corbetta & Vereijkew (1999) defined intrinsic dynamics as the spontaneous coordination tendencies or preferred modes of coordination that exist in the movement system at the start of a learning process. In other words, intrinsic dynamics capture the initial state of an organism when faced with a new learning or developmental task, reflecting the history of the system and prior experiences that contribute to form the existing behavioral repertoire.

Traditional Approach Compared to Dynamical Systems Approach in the Sports Medicine Field

Balagué i Serre (2005) proposed the use of the tools from the Dynamical Systems approach combined with computer science to cope with the complexity of human motion. Fischer & Pare-Blagoev (2000) stated that an emerging framework of analysis that addresses the issues of variation is Dynamical Systems Theory, provides important new methodological and theoretical tools for analyzing variation in developmental pathways.

DST emphasizes holism while the traditional view emphasizes reductionism. The traditional approach of human motion analysis has been focusing on analytic assessment measuring single joint analysis rather than focusing on a more global study. Tools from the Dynamical Systems Theory, such as Continuous Relative Phase which is an attempt to couple different joints in a single measure, might be an alternative to the traditional methodology.

For Hamill et al. (2000) it is clear that the actions of the lower extremity are coupled and that these coupling relationships have not been clarified using the traditional spatial models. Additionally, several studies have indicated that the human body as a whole should be reviewed when recalling the mechanisms of injury (Boden et al., 2000; Corbetta & Vereijkew, 1999; Kurz et al., 2005).

Kurz et al. (2005) after comparing an ACL-reconstructed group and a control group while walking and running, stated that the results of their study indicated that changes in both walking and running following ACL reconstruction were not localized at the knee joint, suggesting that these adaptations could be learned during the early stages of post surgical rehabilitation for avoiding knee pain. Another possibility could be that these adaptations could have been learned in between the time of initial injury and surgical intervention.

Boden et al. (2000) after reviewing videotaped ACL injuries observed that in many of the deceleration injury mechanisms, the hip on the injured side was in a neutral position while the trunk was leaning backwards.

Pollard et al. (2005) tested their subjects while performing one unanticipated cutting task. Gender differences in variability using joint coupling analysis were found while previous analysis of the same sample of participants (Pollard et al., 2004a) showed gender differences in one variable (women showed less peak hip abduction than did males) but not in any of the other three variables (hip internal-external rotation, knee abduction-adduction, and knee internal-external rotation angles). Results of this study confirm the usefulness of a kinetic chain analysis rather than a single joint analysis.

DST emphasizes qualitative analysis while the traditional view emphasizes quantitative analysis. In an attempt to conduct qualitative analysis, and so as an alternative to the classical reductionism using only time-discrete data for quantitative analysis, Balagué & Torrents (2005) proposed the use of a holistic process-oriented approach using time series analysis, which measure a variable throughout time. Other tools from the Dynamical Systems such as Continuous Relative Phase, can provide qualitative measures to the scientists.

From the Dynamical Systems point of view a single-subject analysis is preferred to a big sample. The number of subjects needed to conduct a research project was addressed by Munhall & Kelso (1985). The authors, while responding to Corcos et al. (1985) stated that:

> If a presentation on power analysis were to provide significant benefits to those of us studying motor systems (a possibility that we have some doubts about at present), we suspect that a more sophisticated tutorial than that provided by Corcos et al. (1985) will be required. (Munhall & Kelso, 1985, p.494)

Because DST emphasizes a more qualitative analysis, and even a single-subject analysis, utilizing a tool for quantitative research such as power analysis, would not support the Dynamical Systems principles.

Munhall & Kelso (1985) proposed strategies for movement science which included the observation of how constant should we expect biological patterns to be or how might similarity in pattern be appropriately characterized. The authors also stated that nothing of what had been stated identified the difficulty that one encounters in distinguishing error, variation, and lawful behavior but that it should also be clear that power analysis is not the solution to solve these problems.

Other qualitative strategies such as a descriptive video analysis of the mechanism of an ACL injury (Boden et al., 2000; Olsen et al., 2004), reviewed by medical doctors and national team coaches describing the injury mechanisms and playing situations (Olsen et al., 2004), and a questionnaire concerning the events and mechanism of injury that patients reported surrounding an ACL injury (Boden et al., 2000) are some examples of qualitative analysis within the literature.

DST emphasizes the study of variability while the traditional view accepts it as noise. Van Emmerik & Van Wegen (2002) stated that in data obtained from biological systems, there will always be variability within and between measurements. For the authors, this variability can be due to the measurement error or to the inherent dynamics of the system and even though measurement error is attempted to be reduced with filtering techniques, inherent variability of the systems can not be avoided and should not be ignored.

The concept of error is also changed so variability is necessary because it is a consequence of the interaction between complex systems and constraints, which allows the production of movements (Balagué i Serre, 2005). Therefore what previously was considered as error may actually be valuable and an important component in movement analysis.

Variability expresses flexibility of the system to adjust, select or change to new patterns and therefore adapt to changes. While the traditional perspective considers variability as pathology and/or non-expert dynamics, the new approach considers variability as healthy and/or expert dynamics (Van Emmerik & Van Wegen, 2002). Additionally, the functional role of variability might be injury protective (McKeon & Hertel, 2006). However, Van Emmerik & Van Wegen (2002) clarified that with these statements, it is not intended to convey the message that variability is always beneficial or under all conditions reflects healthy functioning.

Overall, even though Dynamical Systems and its computational tools offer an alternative approach to the traditional approach for the study of athletic population, this innovative approach is still used by very few in the sports medicine research field.

Research Study Designs Used to Assess Lower Extremity Human Motion

Current Tasks and Tests Used to Assess Lower Extremity Human Motion

Several studies within the literature and in an attempt to assess lower extremity human motion have used different tests and tasks in order to obtain kinematic and kinetic data. In the following sections, tasks and tests used in laboratory and in clinical settings will be reviewed.

Tasks Used in Laboratory Settings

Laboratory tasks have been used within the literature as a methodology to analyze lower extremity motion. Results from these tasks are supposed to reflect how athletes behave on the field. Under common denominations, some of these tasks have presented variations depending on the purposes of each study.

Single leg squat test. Zeller et al. (2003) used a single legged squat test in order to identify differences in kinematics and electromyographic activity. In this study, a single leg squat test was defined as lowering as far as possible and then returning to a standing position without losing balance. Di Mattia et al. (2005) presented the relationship of the single leg squat test to hip abduction strength. Hip abduction strength, obtained with a handheld dynamometer with subjects in a side-lying position, and hip and knee kinematic data during a Trendeleburg test and a single leg squat were obtained.

Willson et al. (2006) used a 45° single leg squat to compare the orientation of the lower extremity among male and female athletes, to evaluate the association between trunk, hip, and knee strength, and the orientation of the knee joint during this activity. The frontal plane projection angle of the knee was determined using photo editing software.

Vertical jump test. Brosky et al. (1999) used a single leg vertical jump to measure jump height with a Vertec vertical jump apparatus (Sports Imports, Inc., Columbus, Ohio) to obtain data from ACL reconstructed knee subjects. With the same purpose, Ernst et al. (2000) used the single leg vertical jump to measure hip, knee, and ankle extension moments of 20 subjects with ACL reconstruction and 20 matched subjects. Bello (2004) used a single-leg vertical jump-landing task to test 30 recreational athletes. The vertical jump height of the jump task was normalized according to the maximum vertical jump (MVJ) of each subject. A ball was suspending at the 90% MVJ height of each subject and during the task subjects had to grab the ball simulating a basketball rebound. Kinematic data (knee valgus-varus) was obtained in the landing phase.

Petschnig et al. (1998) tested healthy and ACL reconstructed subjects using the one-legged and the two legged vertical jump, obtaining measures from the Jumpergometer (Fitronic, Bratislava), apparatus which measures the contact and flight times during rebound jumps by means of the special contact mattress interfaced to a computer. Shetty & Etnyre (1989) used the vertical jump to observe differences in vertical forces (maximum force, work done, power, release velocity, impact force) testing a motor task which included free upper arm motion compared with a no upper arm motion task.

Drop jump test. Hewett et al. (2005) prescreened 205 female athletes in the high-risk sports of soccer, basketball, and volleyball while performing a drop jump from a 31 cm height box and compared 9 of these athletes who injured their ACL after the analysis with the rest of the group. The authors obtained kinematic data to quantify knee flexion-extension and adduction-abduction, and kinetic data from the vertical ground reaction forces (GRF).

Noyes et al. (2005) used a 30.48 cm height drop jump test in order to discover an athlete’s ability to control lower limb axial alignment. The authors analyzed the absolute centimeters separation distance between the right and left hip and normalized separation distances for the knees and ankles as well as the knee varus-valgus angles. Barber-Westin et al (2006) used a 30 cm height drop jump to conduct a jump-land gender comparison of 1140 athletes (9 to 17 years of age) using the same variables as (Noyes et al., 2005). Torrents Martín (2005) used the drop jump from five different height boxes (25, 45, 65, 85, and 105 cm) which were alternatively placed at 20 cm from the landing area. Russell et al. (2006) used a 60 cm height single-leg drop jump to asses gender differences in knee valgus.

Stop jump tasks. Chappell et al. (2005) designed three stop-jump tasks to investigate the effect of fatigue on knee kinematics. Measurements of the peak proximal tibial anterior shear forces, valgus moments, and knee flexion angles were obtained. Their three tasks consisted in a forward-stop-jump, a vertical-stop-jump and a backward-stop-jump task. The three tasks consisted of a three step approach run followed by a one footed take-off, followed by a two footed landing and a two footed backward, vertical, or forward take-off for maximum height.

Gait analysis. Chmielewski et al. (2005) evaluated their subjects walking across a stationary or moving platform (horizontal translations) before and after perturbation training in order to obtain kinematic (knee flexion angles) and electromyographic data. Byrne et al. (2002), within a dynamical systems background and in order to obtain coordination between the shank and the thigh and between the foot and the shank, compared intralimb gait patterns of the lower extremity coordination between young and elderly women. An added ankle weight was used to provide a second condition for gait analysis. Kurz &

Stergiou (2002) evaluated the effect of ACL reconstruction on lower extremity relative phase dynamics during walking.

Running analysis. Different studies (Stergiou et al., 2001a; Stergiou et al., 2001b) investigated the lower extremity intralimb coordination while running over a level surface. In order to evaluate continuous relative phase of the lower extremity and its variability, Hamill et al. (1999) evaluated their subjects while running at a velocity ranging from 3.60 m◌s^{-1} to 3.8 m◌s^{-1}. Testing their subjects while running too, Heiderscheit et al. (1999) tried to detect Q-angle influences on the variability of lower extremity coordination. Kurz & Stergiou (2002) evaluated the effect of ACL reconstruction on lower extremity relative phase dynamics during running.

Obstacle clearance tasks. Stergiou et al. (2001a) evaluated 10 subjects running over obstacles of different heights (5%, 10% and 15% of the subjects’ standing height) while Stergiou et al. (2001b) placed the obstacles at six different heights (10, 12.5,15,17.5, 20 and 22.5% of the subjects’ standing height). In both studies, lower extremity coordination was assessed.

Cutting tasks. A group of researchers, in three different journal articles (Besier et al., 2003; Besier et al., 2001a; Besier et al., 2001b), in order to investigate the external loads applied to the knee joint designed two sidestepping tasks, one at 30º from the direction of travel and the other task at 60º from the direction of travel. They also included a crossover cut to 30º from the direction of travel and a straight running task. Tape was placed on the floor to indicate the cutting angle required. Subjects were instructed to maintain their running speed as much as possible throughout the task. Infrared timing gates were used to monitor the approach running speed. Subjects were aware of the position of the force plate that they had to step on to ensure that they were performing the tasks at the same position even though they were instructed to look straight ahead when performing each task so that they did not “target” the force plate. External flexion/extension loads, varus/valgus, and internal/external rotation moments applied to the knee joint were obtained.

Ciolek (2002) tested ten male and ten female Division I lacrosse collegiate athletes in a sidestep pivot testing. Every subject was required to carry a lacrosse stick during the test. The subjects had 13 feet to accelerate before they reached the force plate, where they were required to use their right foot to perform the sidestep pivot. The subjects were required to maintain a previously accorded approach speed for the trial to be deemed accepted. A one-foot wide alley way (marked with tape on the ground) was set up just beyond the force plate, to direct the athlete’s placement of their left foot. The alley was set up so the athlete was forced to pivot at an angle between 35-55 degrees. Knee flexion at initial ground contact, maximum knee flexion angle and impact absorption angle were obtained.

A group of researchers (Pollard et al., 2004a; Pollard et al., 2004b; Pollard et al., 2005) used three different tasks, one of which was a 45º cutting (sidestepping) maneuver. To measure approach and exit velocity, four photocells were placed before and after the cutting area. For all trials, it was required that approach speed fall between 5.5. and 6.5 m/s and exit speed fall between 4.5 and 5.5 m/s. A cutting trial was deemed successful if the right foot came in contact with a force platform, if the initial left foot contact following the cutting action was near the designated 45º angle, and if the participant remained within the pathway designated by six cones. Peak hip adduction, hip internal rotation, knee abduction and knee internal rotation angles were measured during the initial 40% of stance.

Sports related tasks. Liu & Burton (1999) kinematically analyzed their subjects shooting from different distances in a basketball court. Broderick & Newell (1999) observed the coordination patterns of people of different ages and skill levels bouncing a ball

Tasks Used in Clinical Sites: Functional Tests

Numerous and varied tasks are currently being used in clinical settings in order to evaluate rehabilitation stages after injury or as a return to play criteria. Commonly known as functional tests, many varieties exist within the literature. Assessing lower extremity function, several types of tests have been found.

One-legged hop test for distance. The one-legged hop for distance test is one of the most common tests used within the literature (Bandy et al., 1994; Barber et al., 1990; L. A. Bolgla & Keskula, 1997; L.A. Bolgla et al., 2002; Brosky et al., 1999; Docherty et al., 2005; Neeb et al., 1997; Noyes et al., 1991; Petschnig et al., 1998; Wilk et al., 1994) . In the one-legged hop for distance, subjects stand on one limb and hop as far as possible landing on the same limb. Distance is then measured. Juris et al. (1997) used the one-legged hop for distance to test their subjects while they placed their hands on the hips while Friden et al. (1998) used it in conjunction with a gradual reduction in visual control by blind folding the non-dominant eye, the dominant eye and both eyes.

One-legged triple hop test for distance. The procedures for this test are the same as for the one-legged hop for distance but three consecutive jumps are performed instead of just one. The one-legged triple hop for distance has been assessed in several studies (Bandy et al., 1994; L. A. Bolgla & Keskula, 1997; Noyes et al., 1991; Petschnig et al., 1998; Risberg & Ekeland, 1994).

One-legged timed hop test. The one-legged time hop test consists of hopping a distance of 6 m on the limb to be tested. Time to perform the test is the variable measured. Even though most of the studies within the literature have used a 6 m distance (Barber et al., 1990; L. A. Bolgla & Keskula, 1997; L.A. Bolgla et al., 2002; Brosky et al., 1999; Noyes et al., 1991; Wilk et al., 1994), others have used distances of 3.05 m (Bandy et al., 1994), or 10 m (Neeb et al., 1997). On the other hand, even though using a 6 m distance, Groves (1994) tested their subjects while hopping the 6 m distance on one leg, changing the direction and returning to the starting point on the other leg.

Crossover triple-hop test for distance. A 6 m length line is used to perform this test. Subjects begin the test by standing on the right side of the line on the limb to be tested. Then subjects hop over to the left side and back over to the right side using only the limb to be tested. Distance after the three hops is then measured. Several authors have used the crossover triple-hop for distance (Bandy et al., 1994; L. A. Bolgla & Keskula, 1997; L.A. Bolgla et al., 2002; Munn et al., 2002; Noyes et al., 1991; Wilk et al., 1994).

Side jump test. Risberg & Ekeland (1994) drew two 6 m long straight parallel lines which were drawn 30 cm apart. Ten marks were made on the outside of one line at 60 cm intervals and the corresponding marks were made on the other line starting at 30 cm from the base line. Subjects jumped from one marking to the other and time to complete the task was measured.

Side hop test. Docherty et al. (2005) instructed their subjects to hop laterally 30 cm and back for a total of 10 repetitions on the same leg. Time to perform the task was then measured.

One-legged vertical jump. Several authors (Bandy et al., 1994; Barber et al., 1990; Brosky et al., 1999) have used he one legged vertical jump to test their subjects. Height reached with one hand has been measured to assess this test.

Lateral step-up. Ross (1997) asked their subjects to stand with the extremity being tested on a 20 cm step first and on a 15 cm height after, with their feet parallel and shoulder width apart. The hip and knee of the extremity being tested were then moved into full extension followed by flexion until the heel of the extremity not being tested touched the floor. Fifty repetitions were asked and time to perform them was recorded. A second testing condition consisted of performing as many repetitions as possible within a 15 s time period.

Figure of 8 test. Risberg & Ekeland (1994) tested their subjects while running a figure of eight (each circle 4 m in diameter) three times. Time to perform the task was recorded in seconds. In a similar test but hopping on a single leg instead of running, Docherty et al. (2005) used a 5 m figure of 8 test.

Up-down hop test. Docherty et al. (2005) used a 20 cm step and instructed their participants to hop vertically up and down on the step for a total of 10 repetitions. Time was the variable measured.

Stairs hopple test. Risberg & Ekeland (1994) tested their subjects while going up and down, on a single leg, over 22 steps (each step was 17.5 cm high) on a staircase. Time was the variable measured.

Stairs running test. Risberg & Ekeland (1994) tested their subjects while running up and down a staircase with two 180° turns and 55 steps in total. Each step was 17.5 cm high. Time was the variable measured.

Shuttle run. A 6 m shuttle run with one limb kept toward the inside of the course during the test for the changes in direction has been used in several studies (Barber et al., 1990; Groves, 1994; Munn et al., 2002).

Carioca test. Groves (1994) used the carioca test which was composed of a lateral grapevine or cross-over step over a total distance of 80 feet. The carioca test involved crossing the right leg over in front of the left leg followed by bringing the left leg back in position parallel to the right leg. The right leg was then crossed behind the left leg and the left leg was brought back to a position parallel to the right. The subject chose to face whichever direction was the most comfortable and was instructed to remain facing that direction for the entire trial. The subject traveled laterally a 40 foot distance then returned to the starting line using the crossover step as described above.

Lower extremity functional test (LEFT). Tabor et al. (2002) designed a comprehensive timed sequence test composed of eight multidirectional skills performed continuously in a standardized 16 steps sequence between targets. Forward run, retro run, side shuttle, carioca, figure 8 run, 45º cuts, 90º cuts and 90º crossover cuts performed on a 10 and on a 30 inches lines are included in the test. The authors emphasized the uniqueness of the LEFT because it incorporates most of the stresses placed on the lower extremity during sport activity.

From all the tasks and tests exposed, it seems evident that no standardized tests exist within the literature and sometimes under the same test denominations different protocols for the same test exist. On the other hand, even though there is a paucity of research supporting their reliability, conflicting evidence on their usefulness could be suspected because the tasks and the conditions in which these tasks are requested do not match the situations that athletes will be facing out on the field.

Limitations of the Tasks and Tests Used in Clinical and Laboratory Settings to Assess Lower Extremity Human Motion

Current tasks and tests used in clinical and laboratory settings, in an attempt to gain on internal validity, might not be testing the subjects in the same conditions that athletes are facing on the field and thereafter their external validity might be severely weakened.

Munhall & Kelso (1985) manifested the need to guide research by the abilities to detect patterns in the data than by the direct comparison of models. For the authors, the “ideal” motor pattern that is usually searched for treatment interventions in sports medicine should not be the aim of rehabilitation programs.

Laboratory Tasks and Functional Tests Are not Similar to Real Sport Situations

For Balagué i Serre (2005), despite the carefully planned and currently administrated tests, important limitations are found related to their low predictive value. For the author, tests are usually closed tasks with rigid protocols and are not reflecting the situations produced during sports competition.

Bandy (1992) proposed that for optimal results, functional tests should be used that are closely related to the actual activity that the athlete will perform during competition. For the author, functional testing gives the clinician additional information on the ability of the athlete to perform at a functional level even though functional testing is not truly sport specific. The author stated that no test replaces what actually occurs in full-contact, full-speed practice or competition.

Buekers et al. (1999) stated that movement patterns found in laboratory settings may be different from patterns that emerge within the context of real sport situations. Pollard et al. (2005) stated that while the results of their study assessing subjects while performing a cutting task clearly demonstrated gender differences in lower extremity coupling variability, the values observed may be different in a field setting. The authors added that additional sources of perturbations, and therefore increased complexity in task organization may alter their results because of the many environmental conditions that are controlled in a laboratory setting.

Laboratory tasks and functional tests are pre-planned. Brosky et al. (1999) stated that an inherent weakness of functional testing is that many of these tests are premeditated, planned, and task oriented while functional activities involving sporting movements are reactive and require automatic responses to ever-changing environmental conditions. The authors stated that sports medicine clinicians need to develop tests that challenge patients to react to unexpected situations and that require automatic postural adjustments. The investigators suggested that clinicians need to practice specificity in testing and emphasized the concept of reactive rehabilitation and testing, a concept that involves automatic stabilization, postural adjustments and/or directional changes by patients in response to visual, auditory or somatosensory feedback provided by the clinician. The authors suggested that reaction training could be as simple as having patients change directions, jump, accelerate, or decelerate in response to a hand gesture, auditory signal, or a tactile cue. This method of evaluating functional performance may more closely to the athletic situations encountered (Brosky et al., 1999).

Additionally Reed (1982) stated that generalizations about movement organization will require experimental testing under different functional circumstances. The author added:

> Because experiments working within a motor systems framework do not test motor function across various functional circumstances, they tend to confirm their hypotheses about triggered reaction. On the information given it would be best not to assume anatomical or mechanical fixity of response (at any level of a system) until direct tests have been made. If such tests reveal that many anatomically specific movement patterns persist despite functional variability, then the present theory will be weakened severely. (p.124)

Besier et al. (2001a) stated that sporting maneuvers are not always anticipated during game situations and usually occur as a sudden reaction to an external stimulus such as avoiding another player or following the bounce of a ball suggesting that pre-planned cutting maneuvers are not a true reflection of the loads applied to the knee joint during a sporting situation. The authors examined the loads at the knee during two sidestepping tasks, a crossover cut and a straight running task. The investigators constructed a target board using a set of light emitting diodes (LEDs) to indicate the desired task under two different conditions: preplanned (PP) and unanticipated (UN). For the UN conditions a LED was turned on so that the subject was required to make the decision on which task to perform just before reaching a force plate.

Results showed that the approach running speed was similar for all trials between UN and PP conditions. A change in speed occurred throughout the performance of the cutting maneuver. Overall, UN condition was performed ~0.15 $\text{m}\cdot\text{s}^{-1}$ slower than the PP condition ($p < 0.05$). External flexion/extension moments at the knee joint were similar between PP and UN conditions; however, the varus/valgus and internal/external rotation moments during the UN cutting tasks were up to twice the magnitude of the moments measured during PP condition. Also although the exact nature of posture strategies was outside the scope of this study, a qualitative analysis of the cutting tasks revealed differences in joint kinematics between UN and PP conditions. These included changes in foot placement on the ground and varying amounts of trunk lean toward the new direction of travel.

The authors published more data obtained from this study in a different journal article (Besier et al., 2003). Measuring EMG, results showed that selective activation of medial/lateral and internal/external rotation muscles and co-contraction of flexors and extensors were used to stabilize the joint under PP conditions, whereas only generalized co-contraction strategies were employed during the UN condition. Net muscle activation during the UN sidestepping tasks increased by 10-20%, compared with an approximately 100% increase in applied varus/valgus and internal/external rotation joint moments.

A group of researchers (Pollard et al., 2004a; Pollard et al., 2004b; Pollard et al., 2005), used three different unanticipated tasks: a 45° cutting (sidestepping) maneuver, a straight-ahead run, and a jump stop task. An illuminated target board triggered by a photocell located 1.5 m from a force platform was used to signal the appropriate task to perform.

Discussing the need to introduce upper limb free motion in functional tests. Brosky et al. (1999) encouraged their subjects while performing 3 functional hop tests (single leg hop for distance, 6 meter timed hop and vertical hop) to move the upper extremity because they believed that upper extremity movement is a normal component of maximal physical efforts providing balance, stability, momentum and postural maintenance and attempts to control this could have a determinant effect on performance and functional relevance.

Shetty & Etnyre (1989) suggested that the use of arm movements during jumping activities can decrease the impact forces on landing and may reduce the potential of injury.

Laboratory tasks and functional tests are not usually applied in fatigue conditions. Athletes, once returned to the field will have to support fatigue conditions and usually in the laboratory tasks and functional tests, these conditions are not accounted for. Studies investigating issues related to fatigue found differences in kinetic and kinematic data (Abian Vicén et al., 2005; Chappell et al., 2005) and in electromyography scores (Ciolek, 2002; Padua et al., 2006) after a fatigue protocol.

Chappell et al. (2005) tested their subjects in different stop-jump tasks after a fatigue protocol which consisted of unlimited repetitions of five consecutive vertical jumps followed by a 30m sprint until the subject reached a state of volitional exhaustion.

Ciolek (2002) evaluated ten male and ten female lacrosse collegiate athletes before and after a fatigue protocol. The protocol setting consisted of four cones set up in a 12 x 12 yard square. The subjects started at the first cone and performed five maximal effort squat jumps. The sequence continued as the subjects performed an “X” pattern between the cones. They were required to sprint between each cone, decelerate and perform a roll dodge (180 degree pivot) upon the arrival at each cone to change direction, and perform two sidestep pivots, one to the right, one to the left, as they sprinted across the diagonals. The entire sequence was repeated an average of six times for females and seven times for males, with a five second rest interval between each sequence until the subject became fatigued. Fatigue was defined when the subject added 3 seconds to their baseline time, recorded earlier.

Abian Vicén et al. (2005), tested subjects while landing on a force plate from 0.75 m of height in two different sessions on different days with two different fatigue programs. The fatigue programs consisted of an exercise bike at 175 W and a plyometric program with 80 jumps.

Evidence Showing the Limitations of the Functional Tests

After injury, isokinetic measurements of the involved leg do not correlate to performance on functional tests when both measurements are compared to the uninvolved leg (Brosky et al., 1999; Noyes et al., 1991; Petschnig et al., 1998; Wilk et al., 1994; Yildiz et al., 2003). Studies within the literature have shown that after injury, results of isokinetic measurements of the involved leg show weakness of this leg compared to the uninvolved while with the same subjects, functional tests are not capable to demonstrate these differences.

Wilk et al. (1994) suggested that the inconsistencies between isokinetic and functional measurements found within the literature might be due to differences in subject population, pathologic condition, testing methodology, equipment, and assessment of test results. The authors measured the relationship between isokinetic concentric testing (180, 300 and 450º·s) and three functional single leg hop tests (hop for distance, timed hop, cross over triple hop). From the 50 patients who had undergone ACL reconstruction tested, 78% were tested six months post surgery. Results showed a positive correlation between isokinetic quadriceps peak torque at 180 and 300º/s and functional testing but the isokinetic peak torque of the hamstrings appeared not to have a positive correlation with functional testing.

Yildiz et al. (2003) determined the relation between isokinetic muscle strength (60 and 180º/s) and functional capacity (one leg standing test, single limb hopping course, one legged hop for distance, triple legged hop for distance, six meter hop for time, cross six meter hop for time) in 30 male recreational athletes diagnosed with chondromalacia patellae (CMP). Results showed a poor correlation between the extensor endurance ratio and the one leg standing test. After an isokinetic exercise program, the improvement in the functional capacity did not correlate with the isokinetic parameters.

Brosky et al. (1999) tested 15 physically active male with unilateral ACL-reconstructed knees with the KT-1000, isokinetic dynamometer (60 and 360º/s) and three functional tests (single-leg vertical jump, single-leg hop for distance, and single-leg 6m hop for time). From the results, the authors suggested that in all the functional tests, an inherent weakness is that they might not be sensitive enough maneuvers to adequately test the strength, power and stability of the knee.

Noyes et al. (1991) assessed the sensitivity of four different types of one-legged hop tests (single hop for distance, timed hop, triple hop for distance and cross-over hop for distance) and isokinetic tests (60 and 300°/s) in non surgical reconstructed ACL injured knees (n=67). All 67 patients performed the single hop for distance and the timed hop (Group 1). A sub portion, consisting of 26 patients, completed all four tests (Group 2). Results in Group 1 showed that when the results of only one test were considered, only 49% to 52% of the patients had abnormal limb symmetry which was related to a low sensitivity rate. However, the percent of abnormal scores increased to 62% when the results of two hop tests were calculated. A relationship was found between limb symmetry scores on the single hop and timed hop tests and low velocity isokinetic quadriceps scores ($P<0.01$); however, the correlation coefficient was low ($r=0.49$) thereby indicating that a highly significant relationship did not exist between these variables.

Petschnig et al. (1998) conducted a study with three groups (group A= 50 healthy subjects, groups B and C = 55 ACL reconstructed knees with similar characteristics in both groups). The investigators tested their subjects at 12.9 (group B) and 53.9 (group C) weeks after surgery using dynamometric isokinetic measurement in a concentric mode (15°/s) and four functional tests (one legged vertical jump, two legged vertical jump, single hop test and triple hop test).

Processing data from functional and isokinetic tests separately showed limb symmetry indices of 95% or more for group A on all functional performance and isokinetic tests, less than 85% on all tests for group B and in group C the index for the vertical jump was the only functional test that fell below the level of 85%. A positive correlation between the jump height on the vertical jump and the peak torque of the quadriceps in two groups (group of healthy subjects and one of the groups with reconstructed ACL) was observed. However, there was no positive correlation with the third group of the study.

Overall, evidence within the literature shows inconsistencies between isokinetic and functional measurements.

Joint compensations, a possible explanation. Isokinetic tests are usually performed on a single joint while functional tests are based on multi-joint analysis. Studies within the literature have addressed these issues and have suggested that maybe compensations coming from the non-involved joints might play a role in compensating for the injured joint (L.A. Bolgla et al., 2002; Ernst et al., 2000).

Bolgla et al. (2002) simulated a knee effusion in the dominant knee of nine healthy subjects. Subjects were divided in two groups of people: group 1, with 30 ml of effusion; group 2, with 60 ml of effusion. Performance of three functional-performance tests (single hop, crossover hop and timed hop tests) before and after the simulated effusion was measured.

Results showed significant change in average test scores after injection only for the timed hop test in subjects receiving a 60 ml injection. The authors hypothesized that non significant differences might have resulted because of compensations from other muscle groups, fluid movement within the joint, and absence of inflammatory process. Specifically, the authors of this study suggested that maybe the no difference was due to the facilitation of soleus and hamstrings contractions after effusion to compensate for the inhibition of quadriceps in functional performance tests.

Ernst et al. (2000) evaluated the extension moments of ACL reconstructed knee subjects (n=20; 14 male and 6 female) and compared them to the uninjured limb. Subjects were examined at a mean of 9.8 months after surgery while performing a single leg vertical jump (VJ) and a lateral step-up (LSU).

Results showed that knee extension moment of the ACL reconstructed extremity was lower than that of the uninjured and matched extremities during the LSU, VJ take off, and VJ landing. However there was no difference in summated extension moments (hip + knee + ankle) among extremities during the LSU and VJ take off while the VJ landing was less than that of the uninvolved and matched extremities. The authors hypothesized that the hip or ankle extensors may compensate for the knee extension moment deficit which could explain why, within the literature, subjects with knee injury tend to score within a normal range during functional tests while they show quadriceps femoris muscle weakness with non weight bearing isokinetic testing.

Lack of sensitivity of the tests, another possible explanation. Apart from joint compensations, the inconsistencies found between isokinetic and functional tests outcome could be also explained by a lack of sensitivity of the functional tests (Docherty et al., 2005; Munn et al., 2002).

Munn et al. (2002) conducted one study in order to determine whether the triple-crossover hop and timed shuttle run were able to discriminate between injured and uninjured limbs in subjects with functional ankle instability. With a sample of university age subjects (n=16) the authors concluded that the triple crossover hop and the shuttle run did not detect functional deficits despite subjects self reported scores indicating functional impairment.

Docherty et al. (2005) conducted a study with 60 participants (42 injured subjects with ankle instability and 18 uninjured) performing the figure 8 hop, the side hop, up-down hop and single hop tests. Even though a significant relationship was found between the functional ankle instability and the side hop and the figure 8 hop tests a relationship did not exist between functional ankle instability and the up-down hop and single hop tests. Interesting from this study is that only the tests that stressed the ligaments responsible of providing ankle lateral instability were sensitive enough to detect this ankle instability.

Limitations of the functional tests. Overall, several authors have discussed the usefulness of the functional tests or at least have suggested the limitations of these tests.

Barber et al. (1990) evaluated the effectiveness of five hopping jumping and cutting type tests in ACL deficient knees. Volunteers with no history of lower extremity injuries or deficiencies (n=43 females, 35 males and 15 elite male soccer players) and patients with ACL deficient knees treated non-operatively (n= 26 males and 9 females) formed the two groups. Subjects performed a one-legged hop for distance, a one-legged timed hop (6 m), a one legged vertical jump, a shuttle run with no pivoting, and a shuttle run (cutting type) with pivoting.

Results showed that the cutting-type tests and the vertical jump test did not detect functional limitations in a reliable manner. In the one-legged hop test, 50% of the patients performed normally even though all reported giving-way episodes with sports. Barber et al. (1990) concluded that:

> Clinicians are advised to use the one legged hop tests as a screening procedure to determine lower limb function. Patients who score abnormally on these tests have significant functional limitations for sport activities. Patients who score normally may still have

> giving-way episodes under uncontrolled sports situations. (p.214)

The importance of these results is that tests keeping a greater resemblance to the athletic activities (cutting tests and vertical jump test) were not able to detect functional limitations accurately.

Noyes et al. (1991) after assessing the sensitivity of four different types of one-legged hop tests (single hop for distance, timed hop, triple hop for distance and cross-over hop for distance) and isokinetic tests (60 and 300º/s) in non-surgical reconstructed ACL injured knees (n=67) stated that clinicians should be aware that patients who score normally on these functional tests may still be at risk for giving way during actual sports situations and activities, suggesting that functional tests should be used in conjunction with other clinical assessment tools (i.e., isokinetic testing, flexibility assessment, etc.).

Laboratory Tasks and Functional Tests Are not Similar to Injury Mechanisms

Olsen et al. (2004) after reviewing ACL videotaped injuries of female team handball players, found that of the 19 injuries in the attacking phase, seven were out of balance and in 12 cases athletes suffered some form of perturbation (being out of balance, being pushed or held by an opponent or trying to evade a collision with an opponent). These injury situations are far away from the tasks proposed in laboratory conditions. Within the literature, several studies have used different tasks and tests that have few similarities with the mechanisms of a possible injury. The Drop Jump test, a common task used in several studies might be an example.

Drop jump vs. cutting tasks in Anterior Cruciate Ligament (ACL) injury assumptions. That functional tests and laboratory tasks are not similar to real sport situations has already been discussed. From this statement, it might be assumed that if tests and tasks are not similar to real sport situations then their resemblance to injury mechanisms might be doubtful. Several studies trying to identify explanations for the gender differences in ACL injuries testing healthy subjects have used the Drop Jump as screening test (Barber-Westin et al., 2006; Noyes et al., 2005). However, if we have a look at the mechanisms of injury of the ACL, we realize that tasks such as the drop jump do not maintain many similarities with the mechanisms of injury of the ACL.

Olsen et al. (2004) conducted a descriptive video analysis research and described the mechanisms of ACL injuries in female handball top level division Norwegian players during 12 seasons (1988-2000). The most common (12 of 20 injuries), a plant and cut movement which occurred in every case with a forceful valgus and external or internal rotation with the knee close to full extension. All but one of the players was pushing off to change direction toward the medial side of the knee axis. The other main injury mechanism (4 of 20 injuries) was a one legged jump shot landing, which occurred with a forceful valgus and external rotation with the knee close to full extension. All occurred to the take off and landing leg (taking off and landing on the same leg). Three injuries occurred when the players were running forward or decelerating without a change of direction (all when landing on 1 foot). The only injury in the defensive phase was due to a direct contact flow to the anterior aspect of the leg by an opponent.

Boden et al. (2000) reviewed 27 videotaped injuries. The position of the leg just before collapse in all of the non-contact injuries was near foot strike with the knee close to full extension. The non-contact injuries were divided into sharp deceleration associated with (40%) or without (27%) a change of direction and landing on one (20%) or two legs (13%).

Alternatives to the drop jump. Tasks more similar to the main mechanism of injury of the ACL, have been administered to test athletic population. Using two sidestepping tasks (one at 30º from the direction of travel and the other task at 60º from the direction of travel) a crossover cut to 30º from the direction of travel and a straight running task, Besier et al. (2001b) found that external flexion/extension loads at the knee joint were similar across tasks; however the varus/valgus and internal/external rotation moments applied to the knee during sidestepping and crossover cutting were considerably larger than those measured during normal running ($p < .05$). Sidestepping tasks elicited combined loads of flexion, valgus, and internal rotation, whereas crossover cutting tasks elicited combined loads of flexion, varus and external rotation.

Improving the Design of the Laboratory Tasks and Functional Tests

Balagué i Serre (2005) stated that thinking after computing is nowadays a common practice and questioned if the results obtained after computer analysis are really helping and solving the main questions posed by sport scientists, coaches and athletes.

In general terms, scientists in the human motion analysis field might lack the clinical experience needed to understand what is really happening when athletes face adversities on the field. Coaches, athletic trainers, or physical therapists, even though they possess this on-field knowledge in their daily professional activities, lack the knowledge and the tools to process data to conduct research. For Buekers (2000), “a coach has to be certain about things he is not certain about, and a scientist has to be uncertain about things he is certain about” (p.489). The author claimed the need for both actors to remain sensitive to the information provided by the counterpart.

For Reed (1982), tests of motor function can no longer be considered complete if a movement is studied under only a single postural condition. The author also stated that:

> Given the major differences in performance, it would be imprudent to generalize about the organization of action on the basis of experimental tests in which postural parameters are not varied. At the very least,

> theorists should be clear about the limitations of their studies (Reed, 1982, p.127).

So overall, when testing athletic population, scientists should possess or acquire the appropriate knowledge about the requirements of the sport developed by the athlete when facing adversities on the field. Knowledge from experts on the specific sport domain such as coaches or players should be obtained in order to design specific methodology to specifically test the subjects.

Also, an in order to account for the individual characteristics of the subjects, tasks and functional tests should not be based on the repetition of an ideal model. More freedom should be given to the subjects in order to reflect their individual and unique motion characteristics.

Challenges in the future will be to increase the external validity of the tasks and tests used in laboratory conditions without decreasing their internal validity. The laboratories should be taken to the fields and not the athletes to the laboratory. In an attempt to gain specificity, and related to functional tests used in clinical settings, sport specific tests should be developed to replace the current functional tests. These tests should include sport specific motion developed in fatigued and unplanned conditions, and instead of basing conclusions on quantitative results, clinicians should base their conclusions, such as return to play criteria, in qualitative results.

Gender Differences in Lower Extremity Biomechanics

Biomechanical Lower Extremity Gender Differences Observed in Laboratory Motor Tasks

Some studies assessing lower extremity gender differences tested healthy subjects and were conducted in an attempt to examine gender differences in Anterior Cruciate Ligament (ACL) injury. Assumptions made in some of these studies suggested that biomechanical factors can be the cause of gender differences in ACL injuries (Barber-Westin et al., 2006; Chappell et al., 2005; McClay Davis & Ireland, 2003; Zeller et al., 2003). However, testing healthy populations and applying the findings to injured populations, stretches the external generalizability of these studies. Even though further research will be needed to support these assumptions, the results obtained from these studies can be useful to review lower extremity gender differences in human motion within healthy population.

Biomechanical Gender Differences during a Squat Task

Zeller et al. (2003) obtained kinematic data from 18 intercollegiate athletes (9 male, 9 female) performing five single-legged squats on their dominant leg. Results showed that women demonstrated significantly more ankle dorsiflexion, ankle pronation, hip adduction, hip flexion, hip external rotation and less trunk lateral flexion than men. These factors were associated with a decreased ability of the women to maintain a varus knee position during the single-leg squat task.

Willson et al. (2006) found that females typically moved toward more extreme frontal plane projection angle (FPPA) of the knee during single leg squats while males tended to move toward more neutral alignment. From the results provided by Zeller et al. (2003) and Willson et al. (2006), it can be concluded that female tend to present higher valgus values while performing a single leg squat.

Biomechanical Gender Differences during a Vertical Jump Task

Bello (2004) used a one-legged vertical jump while grabbing a ball which was hung at 90% height of a previously recorded maximum vertical jump. Fifteen male and fifteen female recreational and collegiate athletes were tested. Results showed that compared to males, females displayed an overall significantly (*p* = .016) greater valgus angle when landing after a vertical jump. The valgus angle at 0.03 seconds before initial contact with the ground and peak valgus angles obtained during the jump-landing were significantly greater than valgus angles at 30º of knee flexion and valgus angles at peak ground reaction force. No significant (*p* = .210) gender differences were found for valgus angle excursion during the jump-landing phase. From the data provided by this study, it is clear that female present higher values of knee valgus when landing after a vertical jump.

Swartz et al. (2005) tested 28 post pubertal subjects (14 men and 14 women) with ages ranging from 19 to 29 years old, and 30 subjects (15 boys, age = 9.63 ± 0.95 years; 15 girls, age = 9.19 ± 1.00 years). Subjects were analyzed while performing a vertical jump to a target (an inflatable ball), set at 50% of their maximum vertical jump height ability. Hip and knee flexion and knee valgus angles were analyzed at initial contact and at the point of peak vertical ground reaction force (VGRF) during landing. No gender differences in knee and hip kinematics were apparent among recreationally active children or adults when landing. Results showed similar knee flexion angles at initial contact for both groups, even though the adults had greater flexion angles for the hip and greater flexion angles for the hip and knee at the point of peak VGRF. Additionally the adults landed with less knee valgus at both initial contact and VGRF than the children. Results of this study suggested that landing patterns change with physical development.

Biomechanical Gender Differences during a Drop-Jump Task

Noyes et al. (2005) tested a young population recording data with videography only of the frontal plane, measuring the distance between hips, knees, and ankles during a drop-jump in 325 female and 130 male athletes (aged 11 to 19). Images from the frame in which the athlete’s toes just touched the ground after the jump off of the starting position, the frame in which the athlete was at the deepest point and the frame that demonstrated the initial forward and upward movement of the arms and the body as the athlete prepared to perform the maximum vertical jump were obtained.

Reflective markers were placed at the greater trochanter and the lateral malleolus of both the right and left legs, and Velcro circles were placed on the center of each patella. The authors analyzed the absolute centimeters separation distance between the right and left hip and normalized separation distances for the knees and ankles. Normalized knee separation distance was calculated as knee separation distance/hip separation distance, and normalized ankle separation distance was calculated as ankle separation distance/hip separation distance. The frontal angle (varus or valgus alignment) of the lower extremities was measured too.

Results showed no statistically significant difference between male and female subjects in the mean normalized knee and ankle separation distance during the landing and takeoff phases revealing both male and female, a valgus alignment appearance. Female athletes only demonstrated significantly higher mean knee and ankle normalized separation distances during the pre-land phase.

Barber-Westin et al. (2006) evaluated jump-landing characteristics in young (9 to 17 years old) athletes (396 females and 140 males). The authors analyzed lower limb alignment during a drop jump using the same protocol of study as Noyes et al. (2005). No difference in the results of the video drop jump data was found when the knee and ankle separation distances (measured in centimeters) were normalized to body height. No age or gender effects existed in limb alignment on the drop jump test.

Russell et al. (2006) assessed sex differences in valgus knee angle during a single-leg drop jump obtaining kinematic measurements. Thirty-two healthy subjects between the ages of 18 and 30 years were assessed at initial contact with the ground and at maximal knee flexion. Results showed that at initial contact, women landed in knee valgus and men landed in knee varus while at maximal knee flexion, both men and women were in a position of knee varus, but the magnitude of varus was less in women than in men.

To summarize the gender differences during landing (after a drop jump or a vertical jump), results from the studies reviewed show that when using normalized measurements and with young population, no gender effects exist in limb alignment on the drop jump test. However, and using a single-leg drop jump, women land in knee valgus while men land in a more knee varus position. Landing patterns after a vertical jump have also been proved to change with physical development (Swartz et al., 2005).

Biomechanical Gender Differences during Cutting Tasks

Ciolek (2002), tested ten male and ten female division I collegiate athletes in a sidestep pivot maneuver (35-55° of the direction of travel). The kinematic variables (knee flexion at initial ground contact, maximum knee flexion angle and impact absorption angle) studied were not found to show statistical differences between genders. However, male subjects consistently had a five degree greater knee flexion angle than females at initial ground contact and maximum knee flexion.

Pollard et al. (2004a) investigated kinematic gender differences testing 12 female and 12 male college soccer players while performing an unanticipated 45° cutting task (sidestep) using the right foot. Peak hip adduction, hip internal rotation, knee abduction and knee internal rotation angles were measured during the initial 40% of stance. The rationale to test the initial 40% of stance was based in the fact that two critical events occur (1) 0-40 ° of knee flexion and (2) deceleration of the cutting maneuver. Results showed that women demonstrated less peak hip abduction than did males, but otherwise, there were no gender differences in selected peak hip and knee joint kinematics and moments.

The same results of this study were analyzed again by Pollard et al. (2005) using different segment and joint couplings based on a Dynamical Systems approach. Results showed that female demonstrated significantly less variability, as measured by the standard deviation of the coupling angles across trials, in four of the six couplings examined. For thigh rotation/leg rotation women demonstrated 32% less variability, 40% less for thigh abduction-adduction/leg abduction-adduction, 46% less for knee flexion-extension/knee rotation, and 44% less for knee flexion-extension/hip rotation. For the other two couplings (hip abduction-adduction/knee rotation, and hip rotation/knee abduction-adduction), although they did not display gender differences, there was a trend toward decreased variability in the women and for example when for the hip rotation/knee abduction-adduction coupling the 35-45% stance phase was analyzed women demonstrated 51% less variability.

To summarize the biomechanical gender differences observed in cutting tasks, it seems to be clear that the greatest gender differences are observed when data is analyzed using a Dynamical Systems approach by coupling joints and segments, and that the studies which utilized the traditional single-joint analysis did not show consistence and significance in biomechanical gender differences during a cutting task.

Rationale for the Biomechanical Gender Differences

Anatomical Factors

Several anatomical knee gender differences have been reported within the literature to explain biomechanical gender differences observed.

Notch size and ACL geometry. Chandrashekar et al. (2005) in a descriptive study with cadavers, found that ACL in women is smaller in length, cross-sectional area, volume, and mass when compared with men. The authors also found that men had larger notches than women and those larger notches were highly correlated to have ACLs with larger masses.

Teitz et al. (1997) compared the notch width index in both knees of 40 male and 40 female patients. Half of the patients in each group had ACL injuries. Results showed that although the female patients tended to have smaller notch width indexes than the male patients, the difference was not statistically significant. There was no difference in notch width index between patients with and without anterior cruciate ligament tears.

Lombardo et al. (2005) examined the relationship between the notch width index and anterior cruciate ligament injury in professional basketball players by using a notch view radiograph. The authors measured the femoral notch and the condylar widths and then calculated the notch width index of 615 male athletes. After a period of 11 years, results showed that the absolute measurement of the notch width did not predict the rate of anterior cruciate ligament injury and a level of critical notch stenosis was not detected.

So as reflected in the literature, results from different studies show different evidence related to femoral notch size and its possible implication to biomechanical gender differences.

Q-angle. The Q-angle has been proposed as a contributing factor to the development of knee injuries (Heiderscheit et al., 1999). Horton & Hall (1989) found larger Q-angles, measured goniometrically, in young adult women compared with young adult men.

Neuromuscular Factors

Gender differences in muscle activation patterns. Shultz et al. (2001) tested 32 females (19 lacrosse and 13 soccer players) while standing in a single-leg, weight-bearing stance Subjects were perturbated by a lower extremity perturbation device to produce a sudden, forward, and either internal or external rotation moment of the trunk and femur relative to the weight-bearing tibia. Surface electromyography to record long latency reflex times of the medial and lateral quadriceps, hamstring, and gastrocnemius muscles was measured. Results showed that even though men and women did not exhibit differences in muscle recruitment order, women tended to activate their quadriceps earlier than men.

Zeller et al. (2003) analyzed the single-legged squat in 18 intercollegiate athletes (9 male and 9 female). Results showed that women presented rectus femoris muscle activation, measured with electromyography (EMG) assessing both the area under the linear envelope and the maximum activation data, statistically greater than men.

Ciolek (2002) found that before and after a fatigue protocol, and in sidestep pivot maneuver, female activated their vastus medially oblique more than males. Female subjects demonstrated a lesser lateral hamstring average muscle activity during preparatory phase for both the non-fatigued and fatigued conditions when compared to male subjects. Other muscles of interest (rectus femoris, medial hamstring) did not reveal significant results.

In the results of a study with healthy soccer and basketball players (n=34; 17 male and 17 female) from a collegiate level, Rozzi et al. (1999) concluded that female athletes demonstrated greater EMG peak amplitude area of the lateral hamstring muscle when landing from a jump. The authors hypothesized that as far as the lateral hamstring muscle protects the knee from anterolateral subluxations, these muscle activation patterns appeared to be learned in an attempt to compensate for inherent joint laxity and proprioceptive deficits. The excessive joint laxity of women appears to contribute to diminished joint proprioception, rendering the knee less sensitive to potentially damaging forces and possibly at risk for injury.

Garrison et al. (2005) tried to focus on the influence of the gluteal muscles stating that the study of these muscles have been largely ignored in the literature in benefit of the quadriceps and hamstring muscles. The authors hypothesized that because women land with greater hip internal rotation (IR), placing the knee in an internally rotated position, they would generate significantly lower EMG values at the peak knee IR moment (measuring gluteus medius, lateral hamstrings and vastus lateralis) compared to men. Results showed that male and female collegiate soccer players displayed similar relative activation patterns of the lower extremity during landing.

After reviewing the literature related to muscle activation patterns, it seems evident that women tend to activate their quadriceps earlier than men when landing, and that the quadriceps activation compared to the hamstring activation, measured with electromyography, is statistically greater than in men.

Gender differences in strength (isokinetic tests). Hewett et al. (1996) tested 12 female high school volleyball players and matched them with nine male subjects. Subjects were isokinetically tested at high-speed (360°/s) in a range of motion of 100° of flexion during 15 isokinetic concentric contractions for each leg. Results showed that female had hamstring-to-quadriceps ratio significantly lower than male (51% versus 65% respectively).

Barber-Westin et al. (2006) analyzed isokinetic concentric hamstring and quadriceps strength at the knee(853 female and 177 males) at 300º/s. Results showed that there was no significant difference between genders in the mean knee extension and flexion peak torques until the age of 14 years. Boys aged 14 to 17 years old had significantly greater normalized for body weight mean extension and flexion peak torques than did age matched girls. However there was no significant difference between genders in the hamstring-quadriceps ration in any age group. For male, hamstring-quadriceps ratios declined significantly from age 9 years (mean = 87%) to 14 years (mean = 72%), after which this value remained constant. In female hamstrings-quadriceps ratios slightly declined with age (from 82% at age 10 years to 70% at age 17 years). This made the authors conclude that there was no relationship between age and quadriceps or hamstrings torque or for the hamstrings-quadriceps ratio.

Lephart et al. (2002) evaluated with an isokinetic device, concentric quadriceps and hamstring peak torque to body mass at 60 degrees/second. After assessing a total of 30 participants female had significantly les peak torque to body mass for the quadriceps and hamstring than males.

Related to gender differences in isokinetic strength levels, it can be summarized that females have less hamstring torque capability and a greater imbalance between quadriceps and hamstring muscle activation.

Gender differences in fatigability. Padua et al. (2006) tested 10 males and 10 females physical active while performing hopping protocols consisting of a 2-legged hopping in place with the hands on the hips while barefoot at two frequencies (self selected rates and at 3.0 Hz). Subjects were tested before and after a fatigue protocol which was induced by repeated squatting at submaximal loads. After fatigue, females demonstrated greater quadriceps-hamstrings coactivation ratios than males. Females used a more quadriceps-dominant strategy than males, showing greater quadriceps activity and a larger quadriceps-hamstrings coactivation ration. Only females showed increased knee flexion at initial contact after fatigue during hopping. Other findings included that after fatigue, both males and females used an ankle-dominant strategy, with greater reliance on the ankle musculature and less on the knee musculature. The authors suggested that changes in muscle activation and coactivation ratios because of fatigue and sex might alter knee joint stability and increase ACL injury risk.

Chappell et al. (2005) tested recreational athletes (n=20; 10 men and 10 women) performing three stop jump tasks before and after completing a fatigue exercise. Results from the study showed that fatigued recreational athletes demonstrated altered motor control strategies. Both male and female subjects had significantly increased peak proximal tibial anterior shear forces as measured by the anterior displacement of the proximal part of the tibia, valgus moments, and decreased knee flexion angles. However, female subjects had significantly greater peak proximal tibial anterior shear force (p = .01, representing a mean 94% increase in the peak proximal tibial anterior shear force for female in comparison to male), significant differences in the knee valgus-varus moment at the peak proximal tibial anterior shear force (p = .03, 96% increase in the knee valgus moment for female and 43% decrease in the knee varus moment for male, and significantly smaller knee flexion angles at the peak proximal tibial anterior shear force (p = .03, decrease of 12% in female and 15% in male). All three measurements were consistent across fatigue state and tasks.

Contrary results but in a different motor task were found by Ciolek (2002), who tested gender differences before and after a fatigue protocol in a sidestep pivot maneuver. Results showed that male had a five degree (non significant at $p < .05$) greater knee flexion angle than female that remained consistent pre and post fatigue protocol so there was no change revealed in the impact absorption angle between the fatigue conditions or gender.

Gender differences in the level of physical conditioning. Hewett et al. (1996) measured the vertical jump height before and after a six week training program between genders. The program included strengthening of the knee with jump training and concentrating on the use of proper technique focusing on correct posture and body alignment, jumping straight up with no excessive side to side or forward-backward movement, soft landings including toe to heel rocking and bent knees, and instant recoil preparation for the next jump. Before training, female had hamstring-to-quadriceps ratio statistically significantly lower than male (51% versus 65% respectively) while after training it increased to an equivalent value. The female subjects (n = 12) decreased abduction and adduction moments at the knee from values similar to those of the male subjects (n = 9) to significantly below that level. Abduction and adduction moments at the knee were the sole significant predictors of peak landing forces, so the authors concluded that a decreased adduction or abduction moment would decrease the risk of femoral condylar lift off from the tibial plateau. Knee flexion and extension moments and knee flexion angles did not increase with training.

Before and after a six week neuromuscular training program, Noyes et al. (2005) tested 62 female athletes. The program consisted of stretching, plyometric jump training and weight training, one hour per day, three days per week on alternating days. Also athletic trainers instructed the athletes to keep the heels directly under the hips with toes and knees pointed forward at all times during landing and take off. After training, statistically significant increases were found in female athletes in the knee absolute separation distance on landing (29 ± 8 cm, $P < .0001$) and in the normalized knee separation distance calculated as knee separation distance/hip separation distance (68% ± 18%, $P < .0001$).

Overall, the literature showed that physical conditioning protocols in female, related to injury patterns, modified kinematic and kinetic measurements in a positive manner.

Continuous Relative Phase: an Innovative Tool from the Dynamical Systems Theory to Measure Human Motion

Hamill et al. (2000) presented discrete and continuous methods as two different approaches that have been used from the dynamical systems perspective to address movement coordination between two bio-physical oscillators such as two segments or two joints. For Hamill et al. (2000), and related to kinematic data, discrete methods evaluate coordination at only one point in each cycle and no further manipulations to the data must be made other than what normally would be done in the calculation of the joint angles. Continuous methods can spatially/temporally evaluate coordination.

Measures such as joint moments, joint angles, ground reaction forces or forces measured by isokinetic dynamometers have provided useful information in kinetic and kinematic data acquisition. In the last sections of this literature review, these traditional measurements have been presented as useful tools to measure human mechanics. However, tools from the Dynamical Systems Theory offer an innovative and different approach. For Stergiou (2004), “tools from DST embrace the idea that the generation of movement patterns is multifactor and that movement involves the coupling of the multiple degrees of freedom present in the human body” (p.93). Continuous Relative Phase (CRP) attempts to measure inter-joint coordination and could be an alternative to the traditional measurements. Thereafter CRP could be an alternative to assess gender differences in lower extremity biomechanics.

Obtaining Continuous Relative Phase (CRP)

Modeling the Human Body

Several studies within the literature have modeled the lower extremities as if they were oscillating pendulums (Hamill et al., 1999; Stergiou et al., 2001a; Stergiou et al., 2001b). From the model proposed by Byrne et al. (2002) in Figure 7, the angular displacement of the segments (thigh, shank, and foot) is measured in the sagittal plane and relative to a fixed horizontal reference:

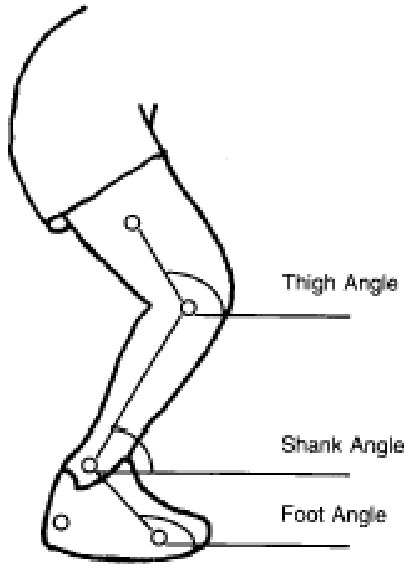


Figure 7 (Byrne et al., 2002)

Obtaining Phase Plots (so Called Phase Portraits or Phase Planes)

Hamill et al. (1999) calculated phase plots for segment and joint angles. Each phase plot consisted of the angle during joint or segment motion (θ) on the horizontal axis with its first derivative, angular velocity of the joint or segment during motion (ω) on the vertical axis.

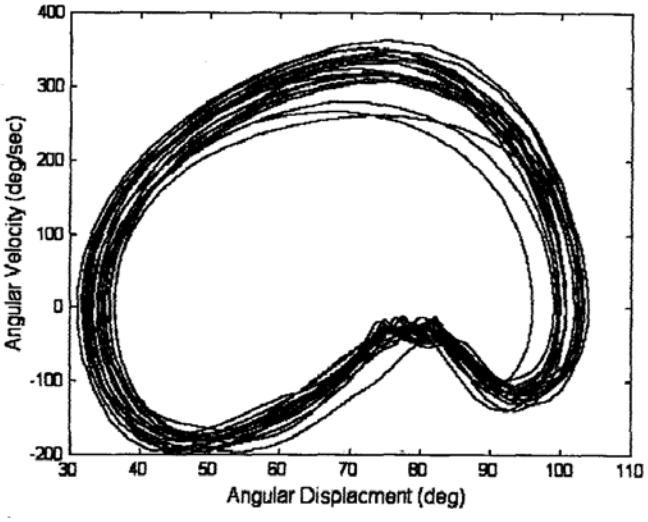


Figure 8 (Stergiou)

Related to Figure 8, a phase plot, Stergiou (2004) indicated that the behavior of the lower extremity segments during the gait cycle conforms to the shape of a limit cycle system that has a closed periodic orbit and that the behavior of the lower extremity segments can be described as a limit cycle oscillator. The author noticed that additionally it is evident that there are slight variations in the path of the trajectory for each gait cycle and that rather than be considered as “biological noise”, these variations from a DST point of view are necessary for the neuromuscular system to adapt to global and local perturbations in gait pattern.

Obtaining Phase Angles

To calculate the phase angle, the phase plot trajectories are transformed from Cartesian (x,y) to polar coordinates, with a radius (*r)* and phase angle (Φ) (Scholz & Kelso, 1989). Hamill et al. (1999) defined the phase angle (Φ) as the angle between the right horizontal and a line drawn from the origin to a specific data point (θ,ω) and was calculated as follow:

$$\Phi = \tan^{-1} \frac{\omega(t)}{\theta(t)}$$

Where ω is the angular velocity and θ is the angular displacement at the time point (t) of the trajectory.

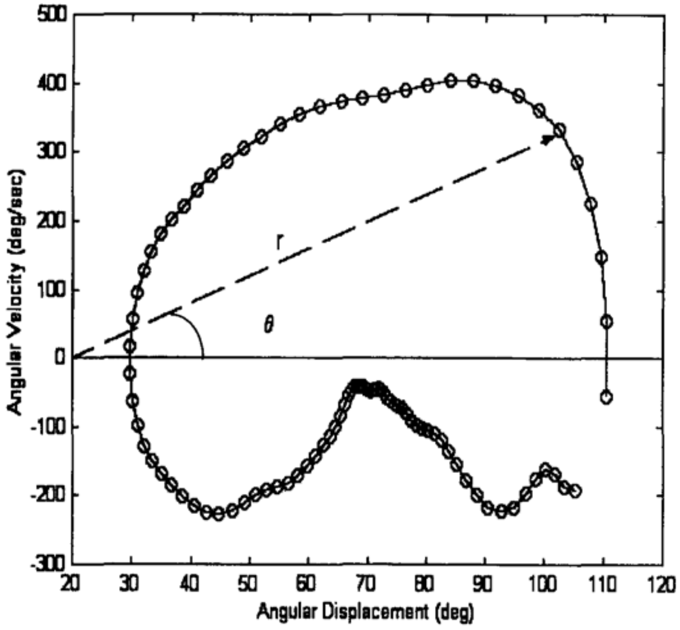


Figure 9 (Stergiou, 2004)

Obtaining Relative Phase (RP)

Relative Phase provided a measure of the interaction or coordination of two segments during a gait cycle (Stergiou et al., 2001a; Stergiou et al., 2001b) and during a bimanual index fingers motion cycle (Scholz & Kelso, 1989). Observation of the relative phase relationship can provide quantitative information on how the segments of a joint or legs are coordinated during gait (Stergiou, 2004, p.96). To calculate relative phase it is needed to subtract the phase angle of the proximal segment from that of the distal segment for each time data point of the time-normalized movement cycle (Hamill et al., 1999; Scholz & Kelso, 1989; Stergiou, 2004).

$$\theta_{\text{relative phase (t)}} = \Phi_{\text{distal segment(t)}} - \Phi_{\text{proximal segment (t)}}$$

$$\theta_{\text{sagittal shank-thigh relative phase}} = \Phi_{\text{shank(t)}} - \Phi_{\text{thigh(t)}}$$

Where $\theta_{\text{relative phase}}$ is the relative phase angle between the distal and proximal segment, $\Phi_{\text{distal segment}}$ is the phase angle of the distal segment, and $\Phi_{\text{proximal segment}}$ is the phase angle of the proximal segment.

The uniqueness of the relative phase measure is that it compresses four variables (proximal and distal segments’ displacement and velocities) into one measure (Stergiou, 2004). Relative Phase values range from 0 to 360°. However, for (Hamill et al., 2000) in the CRP, the redundancy in angles (0° and 360° mean the same thing) generally present the scale in a 0-180° form. Relative phase values that are zero degrees suggest that the two oscillating segments are in phase, while relative phase values that approach 180° are considered out of phase (Hamill et al., 1999; Scholz & Kelso, 1989). A positive value would indicate that the proximal segment has a greater phase angle while a negative value indicates that the distal segment has a greater phase angle (Hamill et al., 1999).

Obtaining Continuous Relative Phase (CRP)

In the Continuous Relative Phase (CRP) measure, the Relative Phase throughout the entire movement cycle is obtained (Hamill et al., 1999). Continuous relative phase (CRP) represents the phasing relationships or coordination between the actions of the two interacting segments at every point during a specific time period (Byrne et al., 2002; Stergiou et al., 2001a). Hamill et al. (1999) in a study where subjects were tested while running, defined the CRP as the difference between the normalized phase angles of two segment motions throughout the stance phase or the entire stride phase.

Phase Plot Normalization

Within the literature different perspectives have been found related to the need to normalize the amplitudes of the phase plot coordinates prior to calculation of relative phase. The rationale for normalizing the phase plot coordinates is based on the assumption that the segment with the largest amplitude will dominate the relative phase measure, providing inadequate results for coordination (R. Burgess-Limerick et al., 1993; Hamill et al., 2000; Hamill et al., 1999). For Hamill et al. (2000), when dealing with intra-limb coordination a normalizing procedure will adjust for amplitude differences in the range of motion of the oscillator and additionally the phase plot will be centered about the origin. From this point of view, normalization of the phase portrait should produce a scalar multiple of the original phase plane trajectory and maintain the dynamic qualities of the segment.

Hamill et al. (1999) suggested that in sinusoidal type movements, the discrete RP and CRP should and do provide similar information regarding coordination changes even though in more complex coordinative patterns, these measures could provide different sources of information. Hamill et al. (2000) suggested that the congruence between CRP and discrete RP disappears as oscillations deviate from being sinusoidal or even in sine waves whose frequencies are other than of 0.5/л Hz. Arguments given by Hamill et al. (1999) supporting this statement included the fact that the continuous relative phase measure includes both continuous spatial and temporal information while the state space is made up from the relative system variables and these are often times unknown.

Peters et al. (2003) conducted an investigation in order to illustrate the need for phase-plane normalization prior to calculating phase angles. In their study, CRP was calculated from test signals with known and different phase and frequency properties. The goal of the study was to compare between the calculated CRP values and the values that theoretically and intuitively should be obtained based on discrete RP measures. When the frequency differences of the test signals were not normalized, the theoretical outcome was not obtained and artifacts in form of low frequency oscillations appeared in the CRP measure. Conversely, when the test signals were normalized the CRP outcome coincided with the theoretical outcome. For the authors, the exact normalization technique used will depend on the research question of interest. Analysis of sinusoidal movement, non-sinusoidal movement, or partial movement should be taken in consideration when choosing the exact normalization technique.

Analysis of Continuous Relative Phase

Discrete Relative Phase (DRP)

In the discrete relative phase measure, the difference in timing of two segments or joints is calculated and divided by the cycle time on one of the segments or joints (Hamill et al., 1999). Discrete relative phase evaluates the local minimum and maximum of the relative phase curve configuration (Stergiou, 2004, p.105).

For Peters et al. (2003) it is incorrect to state that CRP is often interpreted as a higher resolution form of DRP. This was demonstrated when results of their study in which a constant time lag between two identical, non-sinusoidal signals did not produce the intuitive DRP relationship when determined via CRP. For the authors, this lack of intuitive result is caused by the tendency to try to interpret CRP using DRP terminology. DRP provides a comparison of the temporal dispersion of events between two signals while CRP describes their relationship in the phase-plane domain. For Peters et al. (2003) it is incorrect to state that a CRP value near 180° means that the two signals are moving in the opposite directions (out of phase).

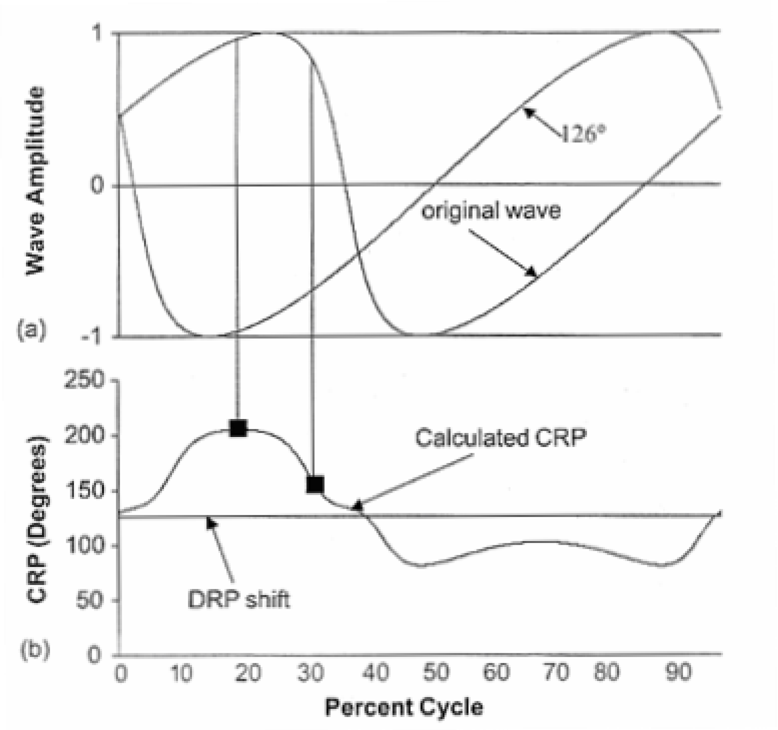


Figure 10 (Peters et al., 2003)

In Figure 10, while the two different waves in the time series showed that the signals were moving “in-phase” in one case and “out-of phase” in the next, these points were equidistant from 180° when the CRP for both waves was calculated. This indicated very different behaviors related to the time-series data.

Mean Absolute Relative Phase (MARP)

This measure is used to quantify and statistically test differences between relative phase curves, obtaining a single number. MARP is calculated from the mean ensemble curve, which is the curve that represents the mean of at least two continuous relative phase curves. MARP is obtained by averaging the absolute values of the ensemble curve points for the designated periods of time (Stergiou, 2004).

$$\text{MARP} = \sum_{i=1}^{N} \frac{[\Phi\text{relative phase}]}{N}$$

Where N is the number of points in the relative phase mean ensemble and Φ relative phase is the relative phasing relationship between two segments.

A low MARP value indicates that the oscillating segments have a more in-phase relationship; a high MARP value indicates that the oscillating segments have a more out-of-phase relationship (Stergiou, 2004, p.103).

Deviation Phase (DP)

Deviation phase of the Relative Phase has been calculated in several studies (Byrne et al., 2002; Hamill et al., 1999; Stergiou et al., 2001a; Stergiou et al., 2001b) providing a measure of stability of the organization of the neuromuscular system.

DP is calculated by averaging the standard deviations of the ensemble relative phase curve points for the designated time periods (Stergiou et al., 2001b). The DP was calculated by Stergiou (2004) as follow:

$$DP = \frac{\sum_{i=1}^{N} [SD_i]}{N}$$

Where N is the number of points in the relative phase mean ensemble and SD is the standard deviation of the mean ensemble at the ith point. A low DP indicates a more stable (less variable) organization of the neuromuscular system; a high DP value indicates less stability in the organization of the neuromuscular system (Stergiou, 2004, p.103).

For Hamill et al. (2000) CRP variability is calculated as the standard deviation on a point by point basis over the complete cycle.

Hamill et al. (1999) after collecting data from their subjects while running and to measure between trial variability of the relative phase, each CRP profile for each coupling relationship was interpolated to 100 data points using a polynomial procedure. Ensemble curves were calculated from each coupling relationship for each subject. These ensemble curves represented the mean from the 10 trials CRP curves performed by the subjects. The variation of CRP was calculated as the standard deviation of each point on the ensemble curve and was quantified by calculating the average standard deviation over the complete profile over the support and swing phases of the stride, and over portions of the support phase.

Studies that Used CRP as a Variable

CRP in Intralimb Coordination Tasks

Scholz & Kelso (1989) tested five adult males while they rhythmically flexed and extended the metacarpophalangeal (MCP) joint of both index fingers. Subjects were asked to move their index fingers rhythmically in one of two patterns of coordination (initial coordination), in phase and out of phase, in synchrony with an audible metronome pulse while maintaining the prescribed pattern of coordination which varied in frequency. Torque perturbations were administered in order to disturb the ongoing coordinative pattern.

Results showed that subjects performed one of two patterns of hand coordination (in phase and out of phase) as the frequency of movement was systematically increased. Moreover, when subjects began a trial in the out-of-phase pattern, a strong and statistically significant increase in relaxation time (time required to return to the same pattern) was observed as the frequency increased prior to the transition, indicating a loss of pattern stability. No transitions occurred when subjects began in the in-phase pattern of coordination.

Carson et al. (1995) tested four subjects while performing rhythmic movements of the ankle and the wrist in time with an auditory metronome, in two modes of coordination, anti-phase and in-phase. Mean relative phase values were calculated and the relative phase value at the midpoint of the transition was also obtained. When movements were prepared in the anti-phase mode and the frequency of the metronome was increased spontaneous transitions to the in-phase mode or to the phase wandering were observed. Contrary, when prepared in the in-phase mode, transitions between in-phase modes or to phase wandering were occasionally observed.

CRP in Postural Tasks

Bardy et al. (1999) studied the coordination of multiple body segments (torso and legs) in the control of standing during a suprapostural task. Ten subjects stood barefoot and were asked to stay oriented to an object depicted on a screen and to follow with the head the fore-aft oscillations of the simulated object (in phase with the fore-aft oscillations). Center of Mass (CM) of the subjects was changed generating three different conditions altering the CM: (a) adding a 10 kg fitness mass attached around the participant’s neck; (b) 5 kg on each knee; (c) normal condition with no manipulation of the CM. Results showed that across the variation conditions, two modes of hip-ankle coordination were observed: in phase and anti-phase. The authors suggested that the assumption that at low frequency and for small amplitudes of sway the body behaves like an inverted pendulum, with no functional motion at the hips may be necessary to reconsider because not only rotations around the ankles but hip motion, were found in all conditions in their experiments.

Marin et al. (1999) stated that while it is widely accepted that a hip strategy may include rotation at the ankles, it is often assumed that in the ankle strategy there is no rotation at the hips. The authors conducted a research with 12 participants in which subjects were asked to track one fore-aft motion of a target with their heads. Three support surface conditions (standard, foam, rollers) were tested.

Results showed that two preferred patterns emerged: close to in-phase (relative phase similar to 0°) and close to anti-phase (relative phase similar to 180°). The non rigid surface produced anti-phase coordination and the roller surface produced in-phase coordination (with one exception) regardless of the amplitude of target or head motion. The results of the experiment were consistent with the view that postural modes emerge from the interaction of body-based, task-based and environment-based constraints and proved appropriate to analyze coordination between the ankles and the hips because ankle and hip strategies each involve movement about both joints.

CRP in Lifting Tasks

Burgess-Limerick et al. (2001) in order to describe spontaneous transitions during a cyclic lifting and lowering task, tested 11 subjects (6 male and 5 female) while subjects raised and lowered a 1 kg. load. In order to measure kinematic data, the authors used Continuous Relative Phase between the ankle and the knee, and the ankle and the hip. Results showed that two distinct patterns of coordination were evident: a squat technique and a stoop technique and abrupt transitions from one pattern to the other were evident when raising and lowering the load.

CRP in Gait

Byrne et al. (2002), compared intralimb gait patterns of the lower extremity coordination between young and elderly women measuring relative phase. Twenty women (10 young, mean age = 24.6 yr., and 10 elderly, mean age = 73.7 yr.) were videotaped during free speed gait and gait perturbed by an ankle weight. Relative phase of the ankle (foot – shank) and the knee (shank – thigh) were calculated. Results showed that young group walked at an average pace of 1.43 m/s., while the elderly group walked at an average pace of 1.24 m/s. Differences in mean absolute relative phase were found between the young and elderly groups for the relationship between the shank and thigh during the braking period of walking. For the elderly group, these two segments were moving more in-phase during this period. The application of the ankle weight significantly increased the deviation in phase for the relationship between the shank and thigh during the baking period of walking which made the authors suggest that an increase in variability, and thus, a less stable relationship between the two segments during this period.

CRP in Running

Kurz & Stergiou (2002) evaluated the effect of ACL reconstruction on lower extremity relative phase dynamics during walking and running. Ten subjects (seven females, three males; mean age = 23.9 years) who had completed knee rehabilitation and had returned to full functional activity after ACL-reconstruction were tested at an average of 3.4 years after surgery and were matched with ten healthy controls (gender and age matched). The subjects were instructed to walk and run on a treadmill at a self-selected pace. Relative phase dynamics were calculated for the foot-shank and shank-thigh coordinative relationships.

Average walking speeds were 1.21 ms^{-1} (SD = 0.19) for the ACL group and 1.23 ms^{-1} (SD = 0.17) for the control group. The average running speeds were 2.26 ms^{-1} (SD = 0.45) for the ACL group and 2.33 ms^{-1} (SD = 0.24) for the control group. Results showed that statistical differences between the groups were noted for the foot-shank relationship ($p < 0.05$) during both running and walking, and for the shank-thigh relationship ($p < 0.05$) during walking. For the authors, changes were related to a loss of sensory information that is usually provided by the ACL and to lower extremity adaptations learned during rehabilitation.

Hamill et al. (1999) conducted an investigation to show that variability of the CRP is an effective manner of discriminating between symptomatic an asymptomatic individuals while running. In their first study, subjects with Q-angles greater than 15° and those with Q-angles less than 15° were compared. In the second study, a comparison of symptomatic individuals with patellofemoral pain and individuals with no pain was undertaken. CRPs were calculated for thigh flexion/extension and tibial rotation, thigh abduction /adduction and tibial rotation, tibial rotation and foot eversion/inversion and femoral rotation and tibial rotation.

Results showed that individuals who were asymptomatic, even though they may have an anatomical aberrant structural problem (i.e. high vs. low Q angles) showed no differences in the pattern of the continuous relative phase or in the variability of the continuous phase. However, patellofemoral pain individuals showed less variability in the continuous relative phase of the lower extremity couplings than did the healthy subjects. The authors suggested that individuals with little variability in the lower extremity CRPs may produce an overuse situation, stressing the same general area of the cartilage producing localized stress in the tissue.

Heiderscheit et al. (1999) tested 32 healthy pain-free subjects with varying Q-angles who were divided into groups based on gender and Q-angle. The subjects included 16 males and 16 females and abnormal Q-angles were defined as greater than 15°. CRP was calculated from thigh flexion/extension and leg rotation, thigh abduction adduction and leg rotation, and leg rotation and foot eversion/inversion.

Results showed that no significant differences were found between genders or high and low Q angle groups for any of the CRP coupling variables (P>0.15). However, significant CRP variability differences were found between the stance intervals of all segment couplings (P<0.05). All subjects revealed distinct CRP variability phases during running. Early stance phase consistently displayed greater variability than the remaining stance. At the heel strike, the increased variability between coupled segments would indicate a flexible system and this allows the system to explore its environment, in this case, the ground surface to maintain external stability. Once the surface is known, a stable pattern can then present itself without compromising the external stability. For the authors, the lack of significant group differences indicate this balance to be unaffected by excessive Q-angles or might be a reflection of the subjects involved (healthy).

CRP in Obstacle Clearance Tasks

Stergiou et al. (2001b) tested ten healthy subjects, (4 male and 6 female) recreational runners (23.5 years) while running over a level surface and over obstacles of six different heights (10, 12.5,15,17.5, 20 and 22.5% of their standing height) In addition, a baseline condition with no obstacle was collected. Relative phase was calculated from a sagittal view for the ankle (foot – leg) and knee (leg – thigh).

Results demonstrated that the increasing obstacle height elicited behavioral changes. The foot and the leg became more independent in their actions, while the leg and the thigh strengthened their already stable relationship. The fact that the foot-leg MARP values significantly increased in both periods with obstacle height indicated that the foot and the leg are moving out of phase or away from each other in the higher obstacles. After obstacle clearance and during pre-landing, leg thigh DP significantly decreased which may suggest that the system actually became more stable at the knee. This might be a knee strategy for obstacle clearance to absorb shock forces. On the contrary, the stance leg-thigh DP increased significantly for the highest obstacle condition. This increased instability can be the result of extremely high impact forces at this level.

Stergiou et al. (2001a) investigated intralimb coordination during running over a level surface and over obstacles. Ten subjects (7 male and 3 female), ran at their self-selected pace under four conditions: over a level surface and over obstacles of different heights (5%, 10%, 15% of their standing height. The phasing relationships between the foot and leg motions in the frontal plane, and the shank and thigh motions in the sagittal plane were used to compare patterns of coordination.

Results showed that the increase in obstacle height resulted in significant changes in impact forces and a more in-phase relationships between the segments during early stance. No changes were observed in the variability of the phasing relationships. This led the authors to conclude that since the impact forces increased, the system has to use some compensatory strategies aimed to reduce forces and potential injury. However, such adaptations probably were not sufficient in the present study because impact forces still increased significantly.

CRP in One-legged Hopping Test

Van Uden et al. (2003) compared seven patients (2 females and five males; 19-40 years old) who had undergone ACL reconstruction (average = 12.1 months; range 7.5 - 14.8 months) to 13 healthy control subjects (2 females and 11 males; 21-40 years old). The relative phase between rotations of knee and ankle was calculated.

The left and right leg in the control group for mean relative phase (MRP) between knee and ankle rotations showed no differences. The difference between the MRP of the operated limb and the non-operated leg in patients approached the level of significance ($p = 0.006$). The standard deviation of the relative phase (SRP) of the operated limb was significantly larger than the pooled SRP of the control group ($p = 0.001$). The SRP of the operated limb in patients was higher than the SRP of the not operated limb ($p = 0.018$). Also, during the swing phase of the hopping cycle, knee and ankle showed more variation in the movement pattern when compared to the ground phase, which for the authors was due to the fact that during the swing phase, the neuromuscular system possesses larger degrees of freedom to control the hopping movement than during the ground phase. The authors concluded that patients with ACL reconstruction one-year post-operative have a different coordination and a less stable movement pattern of the lower extremity during one-legged hopping.

CRP in Lateral Step Down Task

Rienmann et al. (2004), in order to determine the coordination between the pelvis, thigh and shank during lateral step-downs evaluated 31 Division I female athletes (age= 19.7 ± 1.4 yrs). The angular displacements and velocities of the three body segments with respect to the frontal (FP) and sagittal (SP) planes were time normalized across ten trials. Results suggested that the SP thigh-shank coordination exhibits a stable, in-phase pattern. Surprisingly, the SP pelvis-thigh coordination and stability were significantly less than SP thigh-shank coordination. FP coordination was revealed to be relatively unstable compared to SP. Finally, with the exception of the significant FP relationship, stability of the coordination patterns appeared to be independent of each other.

Variation of CRP Used to Measure Intra-Limb Non-Sinusoidal Coordination: A Modification of the Vector Coding Technique

Contrary to Hamill et al. (1999), and due to its limitations to measure non-sinusoidal time series, Heiderscheit et al. (2002) measured joint coordination using a modification of the vector coding technique suggested by Sparrow et al. (1987), from which the orientation to the right horizontal of the resultant vector between two adjacent data points in the stride cycle is calculated as follows:

$$\Phi = \tan^{-1} \frac{(y_{i+1} - y_i)}{(x_{i+1} - x_i)}$$

Where $i = 1,2,\ldots,n$

The justification to use this variation was that with the exception of the sagittal plane motion at the hip, the remaining joint motions of the lower extremity during running are largely non-sinusoidal which may produced inaccurate results if continuous relative phase is used. The authors tested eight women (19 to 36 years old) with a diagnosis of unilateral PFP who were compared to eight asymptomatic women (21 to 38 years old) while running on a treadmill at a fixed (2.68 m/s) and at a preferred speed. Intralimb Couplings were created for thigh rotation/leg rotation and thigh flexion/leg flexion, knee rotation and ankle inversion, knee flexion and ankle inversion, knee flexion and ankle dorsiflexion.

A second objective of this study was to analyze the variability of stride characteristics. Results showed that the PFP group displayed greater stride length variability during running at the preferred speed even though contrary results were found for the fixed speed condition. Across the entire stride cycle, coordination variability for all joint couplings was consistent between the two groups even though about the heel-strike phase, reduced joint coordination variability for the thigh rotation/leg rotation coupling of the PFP group’s injured limb compared to the non-impaired group was found. Also, an increase in the thigh rotation/ leg rotation variability of the non-injured limb during preferred running was concurrent with the decreased variability of the injured limb, suggesting that the intralimb joint coordination of one limb is influenced by the intralimb coordination of the other. The authors concluded that with the exception of the transverse plane rotations at heel-strike, the level of pain experienced by the PFP participants might not be great enough to produce a change in the intralimb coordination patterns.

Pollard et al. (2005) also used a modification of the vector coding technique in order to evaluate gender differences in the variability of various lower extremity segment and joint couplings: thigh rotation and leg rotation, thigh abduction-adduction and leg abduction-adduction, hip abduction-adduction and knee rotation, hip rotation and knee abduction-adduction, knee flexion-extension and knee rotation, knee flexion-extension and hip rotation.

The MotionMonitor™ and the Flock of Birds™ as a Measurement Tool

The MotionMonitor™ (Innovative Sports Training, Chicago, IL) is a software program which integrates the Ascension (Burlington, VT) system, “Flock of Birds™” as hardware.

The Flock of Birds™ is a six degree-of-freedom (x, y, z, axes) motion tracking device that can be used to track the position and angular orientation of two to 14 different sensors with respect to a transmitter using pulsed DC magnetic fields. Each sensor can transmit dynamic linear and angular displacement. The extended range transmitter and the magnetic sensors provide position accuracy up to 0.3 inches/ 0.5 degrees at a five-foot distance from the transmitter and 0.6 inches/ 1.0 degrees at a ten-foot distance from the transmitter. Data can be collected at a 30 to 144 Hz sampling rate.

Before measurements, the world coordinate axes have to be defined and the system has to be calibrated. Also, each of the sensors has to be placed above and below the joint to be measured. Then a third sensor, a “movable” sensor, is used to determine global position of bony landmarks, virtual joint centers, and location and orientation of the segment axes. During movements, the position and orientation of the sensors is continuously recorded.

The Innovative Sports Training Inc. is able to integrate data form Ascension Technology magnetic trackers, Polhemus’ Fastrak, Northern Digital’s Optotrak; Bertec, AMTI and Kistler Forceplates; Noraxon, Run Technologies, Delsys EMG Systems; ATI and AMTI load cells.

The Flock of Birds™ Accuracy

Milne et al. (1996) evaluated the static positional and rotational accuracy and resolution of the Ascension Technology’s “Flock of Birds” tracking system. The effect of different metals by placing cylindrical metal samples at set location to determine the possibility of interference induced by experimental test fixtures or orthopedic implants was also studied. Positional accuracy was evaluated using a custom-manufactured Delrin grid board, with nominal 25 mm spacings. For six axes (+ X, + Y, - Z, and three combinations of X, Y, Z) the receiver was advanced through 25 mm steps over a grid board range of 15-85 cm.

When utilized within its optimal operating range of 22.5-64 cm., the Flock of Birds was found to have positional and rotational errors of less than 2%. The device was found to be sensitive enough to read positional and rotational changes of 0.25mm and 0.1° respectively. These values were equal to or slightly better than the manufacturer’s technical literature which suggests accuracies of 2.5mm Root Mean Square (RMS) and 0.5° RMS averaged over the translational range and resolutions of 0.75 mm and 0.10° at 30.5cm. The device was also found to be insensitive to commonly used orthopedic alloys.

McQuade et al. (2002) developed a dynamic pendulum calibration method to test the performance of the Ascension’s Flock of Birds™ system, using Innovative Sports Inc. MotionMonitor™ data acquisition software. Sensor data using Flock of Birds™ sensors and potentiometer data were collected simultaneously during dynamic pendulum motion at two transmitter distances (30 and 60 cm.) and then were compared. Results showed that the position and orientation errors were velocity-dependent and decreased rapidly as the pendulum slowed during free swing. Angular errors were less than 1 degree Root Mean Square (RMS) for all speeds. The authors concluded that experiments conducted with motions occurring at speeds lower than 250º/sec. will have greater accuracy and that the sensor distance from the transmitter had a minimal influence on accuracy.

Kindratenko (2001) compared the tracking accuracy of the Flock of Birds and the IS-900. The IS-900 combines ultrasound and inertia tracking to achieve a high accuracy and high update rate for large tracking areas. Both systems were installed at two university sites within a large virtual reality designated space called the CAVE. The experiment consisted of moving the tracking sensor on the regularly spaced X-Z grid with known X and Z coordinates. Y coordinate was constant. Results showed that both systems performed well near the center of the CAVE, but the Flock of Birds performed very poorly near the edge of the tracked volume, reporting errors as large as 499 mm in maximum error location when the system was not calibrated and 92 mm when the system was calibrated for the same value in one of the two university settings. In the same university setting, the maximum location error for the IS-900 was only 45 mm.

Results of this experiment consistently show that in a typical CAVE environment, and when operating near the center of the CAVE, the Flock of Birds is significantly less accurate than the IS-900. This is primarily due to the ambient electromagnetic environment that interferes with the Flock of Birds operation.

Studies conducted using the MotionMonitor™

Within the literature, the MotionMonitor™ and the Flock of Birds™ systems, have been proved to be effective in kinematic analysis (Bello, 2004; Ciolek, 2002; Thigpen et al., 2006).

Using both systems, Bello (2004) measured knee valgus angle during a single-leg jump-landing. Thigpen et al. (2006) measured scapular downward rotation, internal rotation, and anterior tipping during the empty-can and the full-can tests. Ciolek (2002) obtained kinematic data from ten male and ten female Division I collegiate lacrosse athletes measuring knee flexion angles at initial ground contact and maximum angle while performing a sidestep pivot.

Summary

Within the literature, different authors have addressed issues related to the low predictive value of the tasks and tests used to measure lower extremity function that are currently being administered in laboratory and clinical settings. For Balagué i Serre (2005), despite the carefully planned and currently administrated tests, important limitations are found related to their low predictive value. For the author, tests are usually closed tasks with rigid protocols and are not reflecting the situations produced during sports competition. Bandy (1992) stated that no test replaces what actually occurs in full-contact, full-speed practice or competition.

Tests and tasks such as the one-legged hop test for distance used by Barber et al. (1990) are pre-planned. Additionally, most of the tests such as the single-legged time hop test used by Wilk et al. (1994) are not administered under fatigued conditions. On the other hand, some of them restrict arm motion, which has been suggested as another possible limitation (Brosky et al., 1999; Shetty & Etnyre, 1989). Also, some of these tests such as the drop jump test, are not similar to the mechanisms that lead to sustain an injury.

Another weakness of these tasks and tests may be the level and type of instructions given in order to perform the tasks. While performance of a strict motor model while testing athletic population is a current methodology, Munhall & Kelso (1985) manifested the need to guide research by the abilities to detect patterns in the data than by the direct comparison of models. Therefore, the usefulness of some of the tasks and tests currently used in laboratory conditions and in clinical settings should be revised and re-analyzed.

Another inherent weakness of the current motion analysis studies may be the way data is processed. A quantitative analysis based on a reductionism view where variability is considered as error, predominates. An alternative approach comes from the Dynamical Systems Theory and its tools. Accepting the non-linear behavior of the human being, considering the human being as a whole (holism), performing a qualitative analysis, and studying the variability as a crucial point to understand human movement are the basis of this alternative approach.

Finally, one of the tools for kinematic analysis that comes from the Dynamical Systems approach is the measure of the variability of the relative phase between two joints or segments (joint coordination). The uniqueness of the relative phase measure is that it compresses four variables (proximal and distal segments’ displacement and velocities) into one measure (Stergiou, 2004).

All this make the study of the variability of joint coordination (Continuous Relative Phase) an alternative method to the traditional measurements such as joint angles, joint moments, EMG, or ground reaction forces. Continuous Relative Phase, a valuable measurement to analyze human motion might thereafter be an alternative to evaluate gender differences in lower extremity kinematics.

APPENDIX C

INSTITUTIONAL REVIEW BOARD FORM

Plymouth State University
Statement Concerning the Use of Human Subjects in Research

Name of Principal Investigator: Arnau Galobardes i Tuneu

Department: Health and Human Performance

Email Address: agalobardes@mail.plymouth.edu

Campus Mailing Address and Phone Number: Principal Investigator

Arnau Galobardes i Tuneu
19 Highland Avenue / Suite 2635
Plymouth, NH 03264
603- 254-4175

Campus Mailing Address and Phone Number: Faculty supervisor

Marjorie A. King PhD, ATC, PT.
Plymouth State University
Department of Health and Human Performance
17 High Street, MSC #22
Plymouth, NH 03264
603-535-3108

1.Title and brief description of project. Include a time line of when you plan to collect data.

Title:

An Examination of Lower Extremity Sex Differences in Continuous Relative Phase and Ground Reaction Forces during a Drop Jump and Two Different Unplanned Cutting Maneuvers.

Description of the Project:

The purpose of this study is to determine the lower extremity sex differences during a Drop Jump and two other different unplanned cutting maneuvers. To achieve this purpose, Continuous Relative Phase and Ground Reaction Forces will be examined. Continuous Relative Phase is a measure to analyze inter-joint coordination. This information will add to the current literature investigating injury sex differences in athletic population. On the other hand, this information will be useful to consider the limitations of the functional tests currently used in the research field.

Each subject will be asked to participate in a 90-minute training session, and 24-72 hours later in a 60-minute one-time testing session. Upon their arrival at the Human Performance Laboratory (Draper and Maynard Building, Room 417) for the training session, the subjects will be required to fill out a short Injury History questionnaire. Subjects will be required to wear a pair of athletic shoes, shorts, t-shirt and socks. The investigator will then measure and record the height and weight for each of the subjects. A 5-minute warm-up protocol on a stationary bicycle will be followed by placement of the 7 movement sensors on the body parts of the subject to be analyzed. Assessments for 3-different maneuvers will include kinematic analysis using the MotionMonitor™ and kinetic analysis using the Bertex™ force plate.

During the first 15 minutes of the 90-minute training session subjects will be instructed to execute 3-different maneuvers. One of the tasks to perform will be a Drop Jump. A Drop Jump is a functional test that has been used in several motion analysis investigations. According to their anthropometric characteristics, subjects will be standing on a step to a determined distance of a force plate placing their hands on their waists. Subjects will be asked to drop from the step using a two foot take-off, land on the force plate with both feet at the same time and perform a vertical maximum jump to finally land on the force plate with both feet at the same time. Subjects will keep their hands on their waists throughout the whole maneuver.

The other two maneuvers will be two different unplanned cutting maneuvers and will only differ one from the other in the upper extremity motion. For the lower extremity motion during the two maneuvers, subjects will be placed in the same position as for the first maneuver described (Drop Jump). Between the step and the force plate, one photoelectric switch will create a photoelectric field. The subjects will initiate an approaching maneuver towards the force plate with a one-foot take-off and will target and land on the force plate with the same foot that started the approaching maneuver. When the photoelectric light field will be crossed by the subjects approaching the force plate, one of the two bulbs placed on the field of vision of the subjects will be lit. The investigator will be able to manipulate which of the two bulbs will be lit prior each approaching maneuver. After landing on the force plate, the subjects will have to perform a 45º cutting maneuver. Illumination of the right bulb will indicate the need to perform a right cutting maneuver. Illumination of the left bulb will indicate the need to perform a left cutting maneuver. The direction of these maneuvers will be directed by two alleys marked on the floor.

Related to the upper extremity movement, subjects will be asked to perform the unplanned cutting maneuvers in 2-different ways:

1. Subjects will be allowed to freely move their upper extremity during the maneuver.

2. Subjects will have to grab a ball that will be hanging between the starting point and the force plate. The height and the distance of the ball will depend on the anthropometric characteristics of each subject.

After this 15-minute instructional-period, the subjects will self select which foot (right or left) they prefer to start the unplanned cutting maneuvers and land on the landing area for the rest of the training session and for the test session. The foot elected will be recorded.

For the rest of the training session, the order in which the subjects will practice the three tasks will be randomly selected. Each task will be practiced during 10 minutes with unlimited number of trials.

Between 24 and 72 hours after the training session, the subjects will come back to the Human Performance Laboratory for the 60-minute one-time testing session. The warm-up protocol and sensors set-up will be the same as for the training session. After the 7-motion analysis sensors have been attached to the subject, the MotionMonitor™ kinematic analysis system will draw a three-dimensional image of the subject and will collect kinematic data. The 3-tasks to be performed will be the same used during the training session and the order in which they will be performed will be randomly selected for each subject. Before each task subjects will be asked to execute 2-practice trials prior to data recording. Subjects will then perform the maneuvers and kinematic and kinetic data will be recorded. Additionally two video cameras will be focused on the subjects' feet during the two different unplanned cutting tasks and will be used to confirm acceptable trials by identifying appropriate foot placement while performing the tasks. Subjects will execute 6-testing trials for the Drop Jump and 18-testing trials for each of the other 2-tasks (9 trials directing the subjects to the right and 9 more directing the subjects to the left). The subjects will be given 30 seconds of rest between each of the practice trials and between each of the test trials. Additionally, a 3-minute period rest will be given between each of the tasks.

Timeline:

Testing sessions will begin during the Fall 2006 Semester and are expected to be completed by the end of Spring 2007 Semester. The timeline for the entire project including the data reduction and statistical analysis will be 12 months.

2. Indicate how informed consent is to be obtained. Provide a copy of the informed consent documents you will use in your research. If your research involves a survey or interview questions, please provide these.

Obtaining Informed Consent:

A consent form will be given to each subject prior to the beginning of the study (see attached). Before signing, subjects will be encouraged to ask questions and state concerns. If for any reason, a subject decides not to participate in the study after reading the consent form, he/she will be able to let the investigator know during this time. Each subject will receive a copy of the consent form.

3-How will confidentiality of subject data be assured as it is collected, and, if it is to be retained, over the length of time that it is to be retained?

How confidentiality will be assured:

Confidentiality will be maintained by coding each participant with a number that will be used for all the documentation. That number will not be associated with their name in any way throughout data collection or analysis. During the data collection, data reduction and discussion processes, data will be kept in a locked file cabinet. This data will be retained for five years in a locked filing cabinet in the Health and Human Performance Graduate Research Office (Draper and Maynard Building Room 405) at Plymouth State University.

Related to the camera recordings, only the lower extremities of the subjects will be recorded and only the investigators of this research will review these recordings.

Additionally, subjects´ final decision on whether to participate or not in the study will not be communicated to any of the captains, teammates, coaches or anyone other than the researcher.

4-List all foreseeable risks which may be encountered by the subjects and the justification for the project in terms of benefits to be realized which might outweigh the risks, and steps taken to reduce any potential risks.

Risks:

Overall, there is the possibility of mild muscle soreness, muscle strains, and ligamentous sprains to the lower extremity and lower back. However these risks have been considered and minimized. A warm-up protocol before each testing or training session is designed to introduce the tasks to the subjects, minimizing injury risk. The level of intensity of the selected tasks mimics movement patterns and typical sporting activities. Therefore, the risk of injury is not expected to exceed the physical demands required during practice or play.

Additionally, all the maneuvers take place on a 320 x 122 cm wooden platform and are typical functional movement patterns for any physically active individual. Also, and for the unplanned cutting maneuvers, two 122 x 122 cm. wooden platforms will be placed next to the 320 x 122 cm. wooden platform to offer a secured exiting area. The tasks take place in controlled environmental conditions in which no actions of other players or other constrains that athletic population usually face on the field while playing are present. Finally, an investigator will be present during the tests to ensure safety during the practice and test sessions.

Benefits:

There is no direct benefit to the participants. However, the results of this study will provide information about lower extremity sex differences in Continuous Relative Phase and Ground Reaction Forces during unplanned cutting maneuvers. The results will also provide information on how to design functional tests. All these findings may be used to develop injury prevention programs and to identify individuals with a higher predisposition to suffer injuries.

5. Describe how you intend to recruit your participants. In addition, describe any incentives that you intend to offer participants for their involvement in your study.

Recruiting Participants:

Forty subjects (20 male, 20 female), athlete students, 18-26 years of age, from the Plymouth State University teams will be recruited for the study. The subjects will be recruited through voluntary participation.

The athletes will not feel obliged to participate in this study because the principal investigator, who will be in charge of the recruitment process, does not have any professional or academic relationship with any of the possible subjects. This is not an academic project for any of the athletes; therefore there will be no issue of grades being affect with or without their participation. Individual meetings with the possible subjects will be scheduled in order to introduce them to the project. These meetings will be outside of the regular time practices or games, therefore there will be no knowledge of participation by the coaches, fellow teammates, captains or faculty members. All these actions during the recruitment process will avoid any bias in playing decisions and grading.

For student project only:

This research has been reviewed and approved by my instructor, who is:

Name: Marjorie King, PhD, PT, ATC

Title: Director of Graduate Athletic Training Education

Signature:

____

APPENDIX D

SUBJECT SPORT, FITNESS AND INJURY HISTORY QUESTIONNAIRE

An Examination of Lower Extremity
Sex Differences in Continuous Relative Phase and Ground Reaction Forces during a Drop Jump and Two Different Unplanned Cutting Maneuvers.

Arnau Galobardes i Tuneu
Plymouth State University
Master's Thesis

Subject ID # ________________ Date: ____________________________________

DOB**:** _________________________ Sex: M F

Dominant Hand: (hand with which you prefer to write)

___ R ___ L

Dominant Leg: (leg with which you prefer to kick a ball)

___ R ___ L

Cite any sport(s) that you participated in during your high school career and write the number of years that you participated in.

Sport	Number of years

Indicate your 2006-2007 season sport(s) participation in the Plymouth State University Teams

___Men's Basketball

___Women's Basketball

___ Men's Soccer

___Women's Soccer

___Volleyball

___Men's Ice Hockey

___Women's Ice Hockey

___Men's Lacrosse

___Women's Lacrosse

___Football

___ Field Hockey

___Tennis

___Baseball

___ Softball

___ Skiing

___ Wrestling

___ Swimming and Diving

Indicate any other athletic participation during the sport collegiate season apart from your participation in the Plymouth University Teams and write the average number of days per week and the average number of hours per day in which you participated or participate.

Athletic Activity	Days per week	Hours per week

Indicate below any of the following that may apply to your previous or current history of injury. Indicate the current condition based on the next scale.

0. not injured
1. no restrictions
2. occasional flare up; symptomatic treatment
3. active but requires support treatment
4. restriction of activity but remains active
5. not active

Previous history of surgical interventions.

___ Yes. If yes, Body part and side ___________________________

___ No. Surgery date ________________________________

Reason for surgery ___________________________

Current condition _____________________________

Previous history of injury in the lower back or lower extremities within the last three months, requiring absence from practice or play or alternative conditioning for more than three days

___ Yes. If yes, Body part ___________________________________

___ No. Injury ______________________________________

Injury date _________________________________

Current condition _____________________________

Current injury on the lower back or lower extremities that will require medical attention

___ Yes. If yes, Body part ___________________________________

___ No. Injury ______________________________________

Injury Date _________________________________

Current condition _____________________________

Indicate below any current or past history of orthotics use

___ Yes ___ No

APPENDIX E

INFORMED CONSENT

PLYMOUTH STATE UNIVERSITY
INSTITUTIONAL REVIEW BOARD
INSTRUCTIONS FOR THE PREPARATION OF INFORMED CONSENT

SECTION I

AGREEMENT TO PARTICIPATE IN

An Examination of Lower Extremity Sex Differences in Continuous Relative Phase and Ground Reaction Forces during a Drop Jump and Two Different Unplanned Cutting Maneuvers

Arnau Galobardes i Tuneu
19 Highland Avenue / Suite 2635
Plymouth, NH 03264
(603) 254- 4175
agalobardes@plymouth.edu

SECTION II

1.Purpose:

The purpose of this research is to examine differences between men and women related to the way they move their lower extremities during a Drop Jump and two different unplanned cutting maneuvers. A Drop Jump is defined as dropping from a height and jumping after landing. A cutting maneuver is defined as the changing in running direction that occurs in many sport situations.

2.Description:

Principal Investigator at PSU: Arnau Galobardes i Tuneu.

Description of the Project: Your participation in this study has been requested according to the results obtained from your current history of injury and level of sports participation. These results have been extracted from the Sport, Fitness, and Injury History questionnaire that you completed. You would have been declared ineligible to participate in this study if you had reported either of the following:

1- Previous history of surgical interventions in any part of your lower back or lower extremities
2- Any previous history of injury in the lower back or lower extremities, within the last three months, requiring absence from practice or play or alternative conditioning for more than three days.
3- If you have a current injury on the lower back or lower extremities that will require medical attention.

The practice and testing sessions require that you complete a Drop Jump and two different unplanned cutting maneuvers. During both training and testing sessions you will have to step on a force plate which is a system that measures how hard your hits the ground (Ground Reaction Forces). During the training session you will be instructed on how to perform the tasks. During both the training and testing session you will also be connected by cables to a system that analyzes body motion. In the testing session, two practice trials will be allowed for each task prior to data collection during six trials for the Drop Jump and eighteen trials for the two unplanned cutting maneuvers.

Project Duration and Participant Involvement: The principal investigator of this study, an Athletic Training graduate student at Plymouth State University, asks for your participation in a 90-minute training session and in a 60-minute testing session 24-72 hours after the training session. The entire length of the project including data collection, reduction, statistical analysis, and presentation is expected to last 12 months.

3-Procedures:

At your arrival at the laboratory you will need to wear a comfortable t-shirt, athletic shorts, socks, and athletic shoes. Your height and weight will be measured and recorded by the investigator. A warm-up protocol consisting in five minutes pedaling on a stationary bicycle will be continued by the placement of the motion sensors on your body. During the first 15 minutes of the training session you will be instructed to execute 3-different maneuvers. After this 15-minute instructional-period, you will self select which foot (right or left) you prefer to start the two unplanned cutting maneuvers and land on the landing area for the rest of the training session and for the test session. You will be able to ask questions about any concerns that you have. The total time of the training session will be approximately 90 minutes.

Twenty four to seventy two hours after this training session you will be asked to return to the Human Performance Laboratory wearing similar clothes and the same athletic shoes than the day you came for the training session. Again, you will be able to ask questions about any concerns that you have. Following the same protocol for the warm-up and the sensors set-up, measurements will be taken from your body motion and foot forces (Ground Reaction Forces) during the three maneuvers. Additionally two cameras will record your lower extremities while you perform the tasks. The total time of assessment will be approximately 60 minutes.

<u>Application of equipment:</u> Using Velcro® bands and pre-wrap, seven small sensors will be placed and attached to your feet, lower legs, thighs and lower back. These sensors will transmit to the computer the position of your lower back and lower extremities and this data will be used to obtain a live three-dimensional simulation of your lower extremities and pelvis.

<u>Task A (Drop Jump) assessment:</u>

You will be asked to drop from the step using a two foot take-off, land on the force plate with both feet at the same time and perform a vertical maximum jump to finally land on the force plate with both feet. You will be asked to keep your hands on your waist all along the maneuver. The distance of the step related to the landing area will be based on the length measurements of your arm and hand, trunk and legs (anthropometric measures).

<u>Task B (cut and free upper extremity motion) assessment.</u> You will be placed in the same position as for task A (Drop Jump). You will initiate an approaching maneuver towards the force plate with a one-foot take-off and will target and land the force plate with the same foot that started the approaching maneuver. This will be the same foot that you will have elected during the first part of the training session.

Between the step and the force plate, one photoelectric switch will create a photoelectric field. When you will be approaching the force plate and cut the field, one of the two bulbs placed on your field of vision will be lit. Illumination of the right bulb will indicate the need to perform a right cutting maneuver. Illumination of the left bulb will indicate the need to perform a left cutting maneuver. To perform a correct 45º cutting maneuver you will have to remain in the alleys marked on the floor. You will be allowed to freely move you upper extremities during the whole maneuver.

Task C (cut and grab the ball) assessment. All that was explained in task B is valid for task C excepting the hand placement. In task C you will be asked to catch a ball that will be hanging between the starting point and the force plate. The height and the distance of the ball will be based on the length measurements of your arm and hand, trunk and legs (anthropometric measures) similar to the Drop Jump.

4-Risks:

The risk involved for you during the testing procedure is minimal. All the maneuvers take place on a 320 x 122 cm wooden platform and are typical functional movement patterns for any physically active individual. Additionally, and for the unplanned cutting maneuvers, two 122 x 122 cm. wooden platforms will be placed next to the 320 x 122 cm. wooden platform to offer a secured exiting area. An investigator will be present during the tests to ensure safety during the practice and test sessions.

Overall, there is the possibility of mild muscle soreness, muscle strains, and ligamentous sprains to the lower extremity and lower back. The tasks have been designed to minimize any injury risk. The injury risks that involve the maneuvers tested are the same that you would encounter in your practices and games.

5-Benefits:

There is no direct benefit to the participants. However, the results of this study will provide information about lower extremity sex differences in Continuous Relative Phase and Ground Reaction Forces during unplanned cutting maneuvers. The results will also provide information on how to design functional tests. All these findings may be used to develop injury prevention programs and to identify individuals with a higher predisposition to suffer injuries.

6-*Alternative Procedures:*

It has been determined that the procedures for the research offer the minimal amount of risk to the subject. This investigation is strictly voluntary and you are not required in any way to participate.

7-Confidentiality:

Confidentiality will be maintained by coding each participant with a number that will be used for all the documentation. That number will not be associated with your name in any way throughout data collection or analysis. During the data collection, data reduction and discussion processes, data will be kept in a locked file cabinet. This data will be retained for five years in a locked filing cabinet in the Health and Human Performance Graduate Research Office at Plymouth State University (Draper and Maynard Building Room 405).

Related to the camera recordings, only your lower extremities will be recorded and only the investigators of this research will review these recordings.

Your final decision on whether to participate or not in the study will not be communicated to any of the captains, teammates, coaches, faculty members or anyone other than the researcher.

*8-Right to Withdrawal***:**

Participation in this study is voluntary and you may withdraw your participation at any time during the data collection. Withdrawal of your participation in this study will not have any prejudice, penalty or loss of any care or benefits to which you are otherwise entitled.

9-Costs and Compensation:

The participation in this study will not generate any expenses to you. In the event you sustain a major injury, emergency medical services will be notified. However, no economical compensation or any other form of compensation will be provided as a result of such injury for medical care, hospitalization, and loss of income, pain or any other form of consequence as a result of such injury.

10-Other:

Results of this study will be presented on the Plymouth State University campus during the Graduate School’s Annual Project Presentation. You will be provided with any significant findings at the conclusion of the study.

11-Contact information: **Principal Investigator**

Arnau Galobardes i Tuneu
19 Highland Avenue / Suite 2635
Plymouth, NH 03264
603- 254-4175

Faculty supervisor

Marjorie A. King PhD, ATC, PT.

Plymouth State University
Department of Health and Human Performance
17 High Street, MSC #22
Plymouth, NH 03264
603-535-3108

For questions regarding rights as a research subject, all questions should be directed to the Plymouth State University Institutional Review Board at:

Institutional Review Board Member
John M. Rosene, DPE, ATC
Associate Professor – Health and Human Performance
Plymouth State University
MSC #22
Plymouth, NH 03264
(603) 535-3114
jmrosene@plymouth.edu

SECTION III (Certification)

I CERTIFY THAT I HAVE READ AND FULLY UNDERSTAND THE ABOVE PROJECT. THAT I HAVE BEEN GIVEN SATISIFACTORY ANSWERS TO ALL MY QUESTIONS AND THAT I HAVE BEEN ADVISED THAT I AM FREE TO WITHDRAW MY CONSENT AND TO DISCONTINUE PARTICIPATION IN THE PROJECT OR ACTIVITY AT ANY TIME WITHOUT PREJUDICE. I WILLINGLY CONSENT TO PARTICIPATE.

______________________________ _______________________

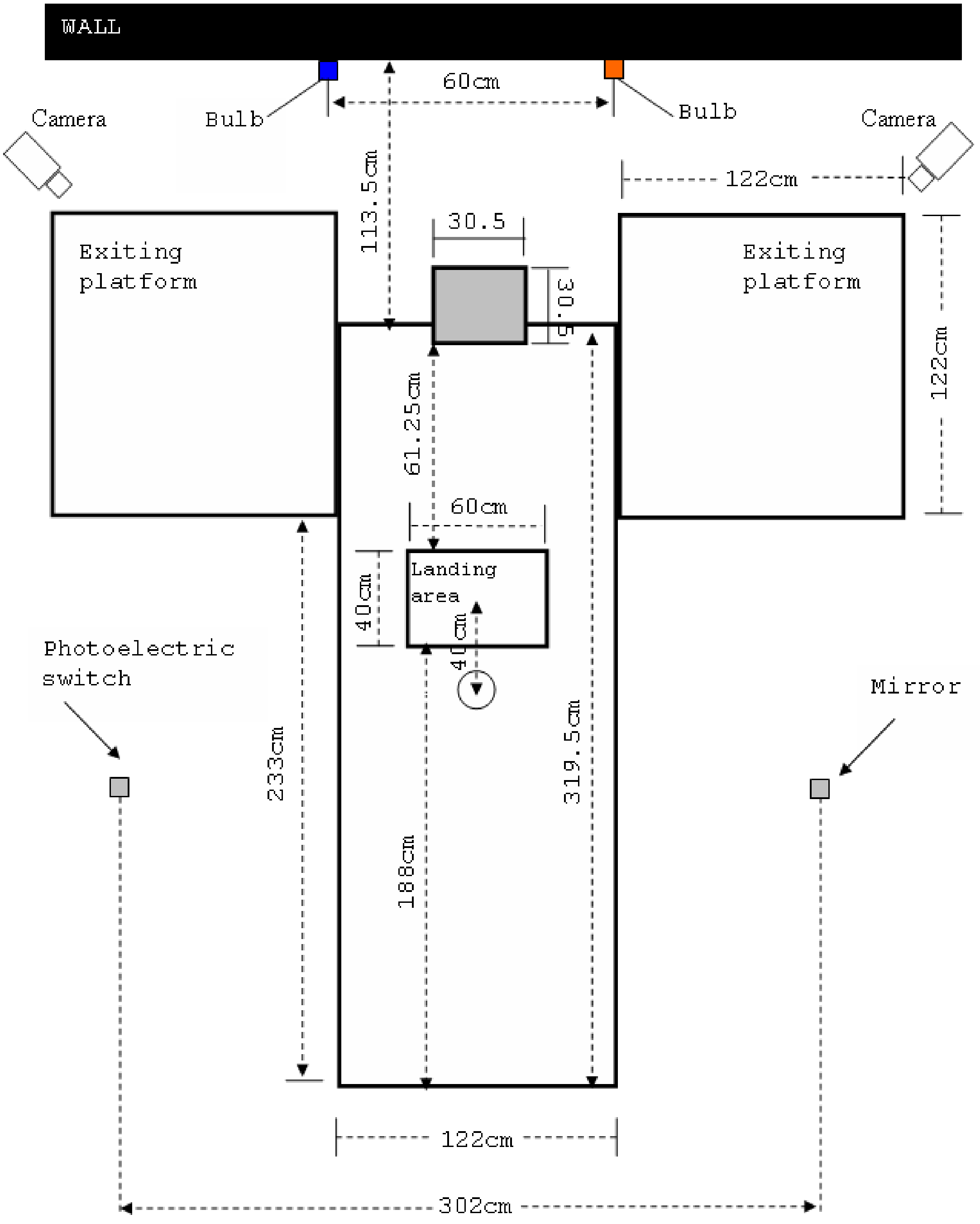
Signature of Subject **Date**

If you cannot obtain satisfactory answers to your questions or have comments or complaints about your treatment in this study, contact:

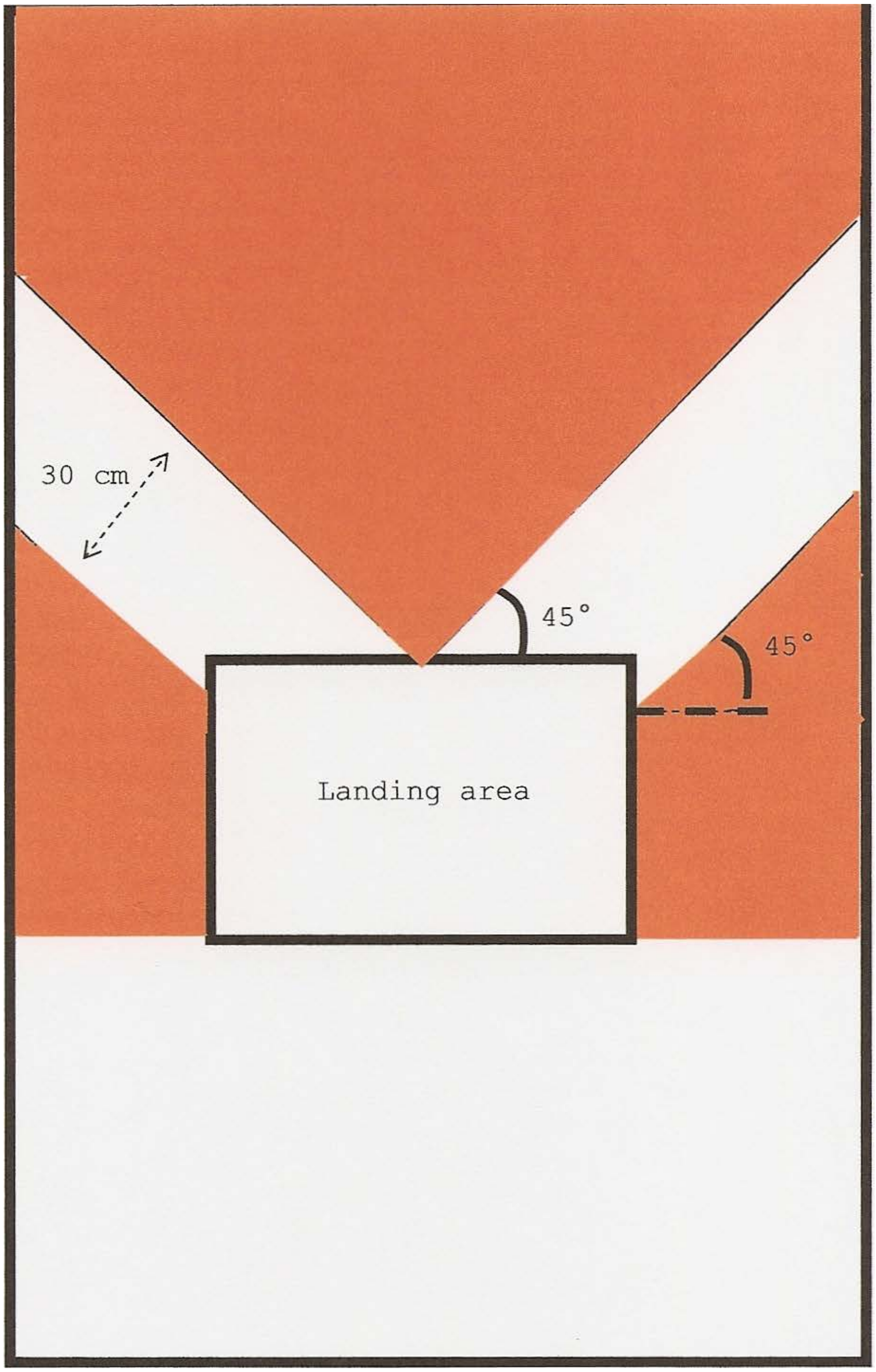
Institutional Review Board, Plymouth State University
John M. Rosene, DPE, ATC
Associate Professor – Health and Human Performance
jmrosene@plymouth.edu

APPENDIX F

TESTING AREA SETUP



1:25 Scale



1:10 Scale

APPENDIX G

DATA COLLECTION FORM

An Examination of Lower Extremity Sex Differences in Continuous Relative Phase during a Drop Jump and Two Different Unplanned Cutting Maneuvers

Arnau Galobardes i Tuneu
Plymouth State University
Masters' Thesis

Data Collection Form

Subject ID:____________________

Gender: ____M ____F Age: ________________ (yr)

Height: _____________ (cm) Weight: _____________ (kg)

Training Session

Date:____________________ Time:_____________

Time after last team practice _________________ (hr)

Shoe brand _____________________________________

Starting position set-up

Height of the volleyball _________________ (cm)

Distance of the step
(From center of landing area) ____________ (cm)

Height of the photoelectric switch ______ (cm)

Order of task practice randomly selected

1st Task practiced ____________

2nd Task practiced ____________

3rd Task practiced ____________

4th Task practiced ____________

Lower limb selection to perform the tasks after the 15-minute instructions period

____ R ____ L

Testing Session

Date: ____________________ Time:_______________

Time after training session ______________________(hr)

Time after last team practice ___________________(hr)

Shoe brand ______________________________________

Order of task test randomly selected

1st Task tested ____________

2nd Task tested ____________

3rd Task tested ____________

4th Task tested ____________

Kinematic assessment

Task A (Drop Jump)	
Trial	Step with both feet in landing area
0	
1	
2	
3	
4	
5	

Task B (cut and free upper extremity motion)				
Trial	Sidestep (S) or Crossover (X)	Direction OK?	Land within limits?	Video analysis
0				
1				
2				

3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				

Task C (cut and grab the ball)				
Trial	Sidestep (S) or Crossover (X)	Direction OK?	Land within Limits?	Video analysis
0				
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				

12				
13				
14				
15				
16				
17				

APPENDIX H

DATA TABLE

TASK C				TASK B				TASK A							
	Krot - Fooin/ev			Habd/add - Fooin/ev	Krot - Fooin/ev			Habd/add - Fooin/ev	Krot - Fooin/ev			Habd/add - Fooin/ev			
DP	MARP	DP	MARP	DP	MARP	DP	MARP	DP	MARP	DP	MARP	Weight (kg)	Height (cm)	Age (yr)	Sex S
53.3	94.06	40.55	112.64	41.07	103.42	37.66	119.91	27.03	146.93	67.32	115.6	72.5	167	19.98	W9
20.92	85.75	28.55	102.01	26.42	76.12	25.76	77.80	11.71	161.54	23.22	147.13	95.5	170.5	18.71	W8
28.96	73.07	22.83	149.59	30.58	82.9	13.94	158.7	15.78	46.46	45.09	107.28	82.5	177.5	18.81	W7
50.76	68.25	31.2	87.36	29.45	39.65	37.96	99.68	54.38	112.3	65.66	107.55	94.5	178.5	18.6	W6
26.11	114.25	47.72	93.89	30.52	100.49	38.72	105.13	11.11	149.81	14.07	27.3	84.5	171.5	19.83	W5
21.55	95.91	45.92	97.86	28.99	81.57	31.85	85.34	11.72	157.91	22.28	31.08	52.9	156	21.82	W1
39.23	45.88	39.92	68.69	19.65	32.24	23.31	75.73	16.87	160.64	21.61	31.47	68	170.5	21.24	M9
46.06	130.63	69.39	99.4	68.11	107.71	39.12	123.23	12.35	125.73	44.31	61.53	83.9	189	19.43	M8
29.55	127.37	50.21	112.64	27.63	134.6	48.78	67.42	9.53	157.31	10.73	39.78	90	188	22.11	M5
55.3	63.87	39.5	141.97	29.56	35.29	11.68	164.16	24.05	90.76	30.13	78.25	70.5	178	20.08	M4
17.25	141.66	25.85	49.73	15.5	145.58	82.1	83.39	11.92	141.37	13.94	33.02	87	181	23.25	M3
41.47	90.73	40.37	137.94	29.79	85.34	16.37	154.03	20.49	144.73	22.5	113.26	75.5	177	20.98	M2
25.05	58.38	24.59	139.49	28.42	61.22	24.24	130.31	58.45	97.55	56.65	101.88	82.5	191	21.5	M1

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