Effects of Different Approach Directions and Sizes of Selected Tennis Forehand Strokes on Knee Biomechanics

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Louise Barbara Beggs

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ABSTRACT

Tennis is a global sport and knee injuries are prevalent, ranging from acute to chronic and minor, to severe. Different directional movements and speeds involved in tennis may lead to a higher chance of injury due to changing loading rates at the knee. This study investigates effects of diagonal and lateral forehand strokes with step or lunge on kinematics and kinetics of the knee on the dominant leg during simulated tennis play. Ten National Tennis Ranking Program (NTRP) players level 4.0 upwards were recruited for the study. A motion analysis system was used to obtain three-dimensional joint kinematics, and force platform to collect ground reaction force (GRF) data. Players performed five trials in four conditions, lateral step, lateral lunge, diagonal step, and diagonal lunge, using a forehand stroke for all four conditions. A two-way repeated measures ANOVA was used, with post-hoc comparisons, with significance set at 0.05 a priori. The results from the study show that there were no significant differences of peak knee extension moment, peak knee abduction moment between the diagonal and lateral forehand shots, either with a step or lunge, or peak abduction moment between approach size in both directions. However, there was a significant difference in knee extension moments depending on approach size in the lateral and diagonal direction, with the lunge approach in each direction being significantly higher than the step. Further study may be required to determine what approach steps and direction movements are more appropriate for players of a standard below NTRP level 4.0, and for a knee OA population.

Keywords: Knee, Tennis, Knee Osteoarthritis, Knee extensor moment, knee abduction moment

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CHAPTER ONE
INTRODUCTION

Tennis is a global sport with tens of millions of people participating worldwide each year, and over 200 nations are a part of the International Tennis Association (www.itftennis.com). Due to the high movement velocities and loads that are part of the game, tennis is a sport with high impacts, primarily on joints in the lower extremity. With the cutting, sprinting, and decelerating movements involved in tennis, it creates repetitive loading on all joints in the lower extremity, leaving the athlete with an increased risk for injury [1]. Overuse injuries have been reported to be as high as 47% in the lower extremity among elite tennis players [2]. Knee injuries are prevalent in tennis, including meniscus damage, ligament damage, and cartilage degeneration [3]. As the knee plays such an important role in movements involved in many sports, including tennis, it is important to understand what leads to acute and overuse injuries.

There are many different movements involved in tennis, but primarily lateral movements to allow movement across the baseline, and diagonal movements to cover more court distance. It is in these movements that loading to the knees may achieve a high value and expose a player to sustaining a knee injury, and subsequent development of knee osteoarthritis (OA). Weight bearing sports, like tennis, have been identified as a risk factor for developing knee OA [4], with up to a 3.6 fold increase risk for knee OA in former elite athletes compared to controls. Osteoarthritis affects over 27 million Americans and is most common in weight bearing joints, namely the knee and hip [5]. It has also been reported that some of the risk factors for OA are overuse [6, 7], excessive musculoskeletal loading, overweight and past injury [8].

It is generally accepted there is an increasing rate of development of knee OA in mid and older aged people [9]. With the prevailing number of knee injuries reported in tennis [3], further investigation into knee loading related biomechanics of the specific movements in tennis is pertinent. This could help to further research in understanding the potential development of knee OA in this population. Following a total knee arthroplasty in elite tennis players, 55% of the patients' surgeons were opposed to patients returning to tennis, 21% permitted it, and 45% advised to return to doubles play only [10]. Therefore, studying the knee loading conditions of high loading movements in tennis could help determine whether tennis is suitable for the knee OA and total knee arthroplasty populations, if certain types of strokes/movements are to be avoided.

Very few studies on lower extremity biomechanics of tennis related movements can be found in literature. However, the biomechanical movements of lunging and stepping, which are seen regularly in tennis, are well documented in literature [11-18]. These movements studied are, for the most part, not sport specific. There is not 100% agreement as to which type of lunge movements causes the greatest loading to the knee. The forward lunge is used regularly by athletes and clinicians to train hip and thigh musculature [14]. Escamilla et al. [14] found that the greatest patelleofemoral joint compressive forces were found between 0° - 50° of knee flexion during a step-in lunge. Another study found that knee flexion angle, peak power, total impulse, and knee work in a frontal step were all lower than a lateral step, but peak knee moments were similar [13]. Conversely, it was found that peak knee power and mechanical energy expenditure were greater during a frontal lunge than a lateral lunge. The peak knee moment and impulse were greater during the lateral lunge [11]. This is interesting as peak power and moment normally do not contradict each other i.e. Flanagan et al. [11] found greater knee range of motion (ROM) during a lateral lunge. In a recent study, it was found that peak knee flexion angles were greater during a frontal lunge compared to a lateral lunge, with lunges performed from a standing position with the dominant leg [12]. Net joint impulses were greater during a lateral lunge compared to a frontal lunge. The net joint impulse was greater in frontal lunges with self-selected step length, compared to a standardized stepping length [12]. Overall there is no consensus in the literature for the ROM, peak moment, and peak flexion angles. A comparison with activities of daily living, such as stair ascent/descent, and sports like badminton and running will provide information on whether tennis is a suitable activity for a knee OA population [19-22].

During a badminton specific study involving three different types of lunges (hop, step-in and kick), the authors found no significant differences between lunge conditions for peak extensor moments at the knee and hip, and that peak extensor moments were greater at the knee compared to the hip and ankle [16]. Importantly, it has been noted that knee kinematics involving flexion are activity (loading) dependent [17]. Another study examined forehand forward and backward lunge tasks in badminton, when comparing a group with knee injuries to a group without, movement at the knee became altered for the knee injury group in certain planes of motion [23].

As sports like badminton and tennis involve varying loads at the knee depending on the type of movement or stroke being hit, this requires further investigation. To our knowledge, there are no studies which investigate the loading to the knee using two different directional movements (diagonal and lateral) in tennis with a step and lunge motion.

STATEMENT OF THE PROBLEM

Although there is literature on the effects at the knee for forward and lateral lunges, and variations in their execution, little is known about tennis specific movements investigated and their effects on the lower extremity, specifically the knee. Most research of the tennis specific lower extremity movements involved different playing surfaces [24, 25]. It would be more pertinent to investigate the biomechanical characteristics of the knee joint during high loading movements, e.g. lateral and diagonal tennis strokes. Furthermore, it unclear what effects of the size of approach (i.e., a step approach or a 3-step approach) may have on knee joint loading during these lunges. Such information would help to provide guidance of game and shot selections for specific groups of players including knee OA and total knee replacement, compared with a less strenuous exercise, i.e., walking. Therefore, the purpose of this study was to investigate effects of diagonal and lateral forehand strokes with step or lunge on kinematics and kinetics of the knee on the dominant leg during tennis play.

HYPOTHESES

It was hypothesised that 1) the diagonal stroke would have greater peak knee extensor moment than lateral forehand stroke due to the fact the player may achieve greater approach speed in the diagonal shot; 2) the peak knee abduction moment would be greater in the lateral forehand stroke than in the diagonal stroke due to the lateral movement; 3) the strokes performed with a lunge would create larger peak knee extensor and abduction moments than those performed with a step in the lateral and diagonal movements, which would in part be due to the increased speed achieved with the 3 steps during the lunge condition.

LIMITATIONS

1. The participants were recruited from a sample that was specifically set at National Tennis Ranking Program (NTRP) level 4.0 and up. All players were of a competitive level of play as per inclusion criteria.
2. Participants may have performed the strokes and movements differently in the lab than they would have during actual competitive play or practice.
3. The manual placement of the retroreflective markers may limit the accuracy of estimation of the joint centers which may affect the accuracy of 3D kinematics.
4. The participants all wore their own tennis specific shoe for testing.

5. All participants had a self selected ball height for each movement which was approximately at hip height.

DELIMITATIONS

1. All subjects were active, healthy, and had no previous history of serious knee injury/surgery. They had no knee injury within the last 6 months that kept them from playing.

2. All subjects were of NTRP Level 4.0 playing standard upwards.

3. The camera system will accurately and reliably collect the reflective marker data and the force plate will accurately and reliably measure ground reaction force data.

4. The anatomical markers would be able to identify joint centers accurately.

5. The movements selected based on survey responses from professional coaches are relevant movements to the variables being investigated and are those that create the largest loading rates at the knee during play.

6. The participants were truthful with the answers to the health questionnaire and do not have any of the injuries used for exclusion criteria.

CHAPTER TWO
LITERATURE REVIEW

The primary the purpose of this study was to investigate effects of diagonal and lateral forehand strokes with step or lunge on kinematics and kinetics of the knee on the dominant leg during tennis play. Also to identify mechanical loading to the knee joint in comparison to walking/running, already referenced in the literature. These differences were investigated in competitive players of level 4.0 or higher, using the National Tennis Ranking Program (NTRP), using males and females and comparing the loading differences at the knee for 2 different tennis movements/strokes. This literature review will discuss the epidemiology of knee injuries related to tennis, gender differences for knee injuries, knee injuries in tennis, biomechanics of the knee during tennis related movements injury risk during high impact activities, and effects of playing surface on biomechanical responses. Finally, this literature review will provide a biomechanical rationale for investigating the variables of interest.

Epidemiology of Knee Injuries in Tennis

Tennis is a global sport with tens of millions of people participating worldwide each year, and over 200 nations are a part of the International Tennis Association. Due to the high velocities of movements and loads that are part of the game, it could be considered a violent sport [26]. With the cutting, sprinting, and decelerating movements involved in tennis, it creates repeated forces (shear, rotational, and compressive loading) on all joints in the lower extremity, leaving the athlete with an increased risk for injury [1]. Overuse injuries are most prevalent representing 67% of all injuries, 47% of all injuries in the lower extremity and 2.3 injuries/1000hours of play time were reported, from a study using 104 randomly selected Danish Elite tennis players using self-registration of injury [2]. More recently in the junior tennis circuit in Brazil, it was reported that overall for males and females aged 10 –

18years,there were 6.9 medical treatments per 1000 games played [27]. It was reported that "Statistics from the United States Tennis Association national teams showed that 19% of all injuries are knee injuries with 70% of the injuries being traumatic and 30% overuse" [26]. It was also reported that 87.5% of injuries were sprain type injuries in the lower extremity [28]. During a tournament, the heavy match schedule can lead to an increasing number of injuries sustained [29].

Knee injuries in tennis are not as widely investigated in the literature as upper extremity injuries, yet lower extremity injuries are twice as common as injuries to the upper extremity [1, 28], with the reported incidence of injury in the literature in the lower extremity ranging from 31% - 67% [30]. This range could be due to differing definitions of injury. Majewski et al noted that despite the complex nature of the knee joint and biomechanics, few studies report frequency and type of knee injury [31]. They conducted a 10-year study on the epidemiology of athletic knee injuries, only including those that occurred during actual play time. Of all injuries reported over a 10-year period in a sports injury clinic, knee injuries represented 39.8% of the total number (19530 reported injuries), of which 68.1% were males and 31.6% females. This figure is supported in the literature [2]. In addition, males have an exposure-response relationship in terms of increased relative risk of knee osteoarthritis (OA) [32]. During a follow-up study of competitors across 4 different sports (tennis, swimming, gymnastics, and football), it was reported that the incidence of injury was significantly different depending on the level the players [33]. The highest level of injury occurrence was at International level (87.5%), regional/county (64%), recreational (47.1%), and national (16.7%) [33]. It should be noted these numbers were based on the number of players still competing at their respective levels, with 8 players at International level, 6 at National level, 25 at regional/county level and the remaining 70 at recreational level.

The knee is an important linkage of the lower extremity and plays a pivotal role in the kinetic chain. It enables an efficient performance and maximizes performance which may also lead to acute and overuse injuries. Due to the demands placed on the knee during tennis, as a result of cutting movements, twisting, sprinting, accelerating/decelerating and jumping, the range of knee injuries reported is extensive, including meniscus damage, degenerative and chondral lesions, osteochondritis dissecans and loose bodies, synovial plica syndrome, fat pad syndrome, ligament injuries, patellofemoral pain syndrome, subluxation of the patella, increased lateral tilt of the patella, cartilage degeneration, dislocation, tendinitis, bursitis, Osgood-schlatters, and stress fractures [3]. According to the results of a more recent study, there were 295 total knee traumas for 433723 active players in regional sports clubs in tennis. The knee structures most at risk for tennis, for 129 recorded injuries, are the medial meniscus (66 injuries), anterior cruciate ligament (ACL) (33 injuries), lateral meniscus (19 injuries), and lateral collateral ligament (LCL) (7injuries) [31]. Perhaps most surprisingly, over 50% of the players were injured between ages of 20 – 29 yrs, a population that would be seen to be 'more healthy' than older individuals. One potential reason for this could be greater playing time for this age group. In competitive players, it is generally accepted that they practice and play a lot more than recreational players. It has been suggested that volume of play may affect injury rates, and that elite players are more at risk for musculoskeletal injuries [30]. Overuse injuries are preventable, as they are a result of repeated trauma.

A study investigating the risk of knee OA during weight-bearing sports, compared runners, tennis players and controls [4]. They found a 1.6 – 3.6-fold increased risk (odds ratio) of knee and hip OA with former elite athletes aged between 40 – 65years for middle and long distance runners, and tennis players compared to a control group. Female ex-elite athletes recorded a higher level of activity i.e. playing more than 4 times per week, than those reported for the control group. These risks were adjusted for weight, height and age differences, and worked out from an odds ratio. As body weight is a risk factor for OA, and the former elite athletes recording lower values for body weight than controls, this shows that the effects of loading on the knee and hip during tennis and running has a detrimental effect on radiologic OA changes. A difference noted was the level of osteophytes found between the runners in patelleofemoral joint (PF) and tennis players in tibiofemoral joint (TF), with double the rate reported in the TF joint for tennis, and double in the PF joint for runners when compared to each other [4]. Due to frequent engagement in cutting related movements, acceleration and deceleration in tennis are thought to be a reason why the tibiofemoral joint is more affected. These results were also supported by findings that reported knee impingement at the medial side during high flexion when the posterior femoral cortex and posterior edge of tibia made contact [17]. These results suggest that players involved in tennis may experience increased risk for knee OA, especially in the medial compartment of the knee. It is well known that mechanical loading of the knee in the frontal plane during walking and cutting movements are internal abduction moments which affects medial knee compartment.

Gender Differences for Knee Injuries

For sport specific injuries, the differences are not widely reported or established. One study looking at reported injuries in a sports clinic over a 14-year period found 556 specific tennis injuries [34]. There were no reported significant gender differences with respect to lower extremity injuries and tennis. During a systematic review of knee injuries during plant and cut manoeuvres, Benjaminese et al. [35] noted that no gender differences were found across the studies for knee flexion, varus/valgus, internal/external rotation, during initial contact, or for knee rotation moments [35]. They questioned the clinical relevance of the findings across the studies, partly due to varying levels of effect size. During a 2-year prospective study of injury profiles for junior players, there were no significant gender differences found for injury distribution, but overall boys had a slightly higher incidence than girls [36].

Several studies have examined junior competitive players and found significant gender differences. Jayanthi et al. reported on the medical withdrawal rate for matches, 16.9 withdrawals per 1000 matches for boys and 14 withdrawals per 1000 matches for girls. These withdrawals increased significantly as age increased and were higher in singles versus doubles, with 17.9 withdrawals/1000 matches and 9.8 withdrawals/1000 matches, respectively [29]. Silva et al. reported 18-year-old males had the largest number of treatments on court at 39% [27]. However, Maffulli et al. noted no significant gender differences in the occurrence of injuries for males and females in 4 sports including tennis [33].

Knee injuries in Tennis

Several studies have performed prospective examinations of tennis players over a series of years to determine incidence, severity, type and injury distribution [10, 36, 37]. It was found that in junior elite players in Sweden, the knee was the 3rd highest injury location with lower extremity injuries accounting for 39% of those reported [36]. The dominant knee was involved in 57% of the injuries, and 72% of knee injuries would be classified as overuse. However, the knee was the most common body part for a severe injury, at 30% of all injuries [36]. Their classification of a severe injury may have skewed the results as a player had to return to 100% pre injury level to be healed and severe level was set at 4 weeks. Overuse injuries can take longer to heal and they were listed as the most common reported overuse injury, which would increase the percentage of severe injuries reported. Hejlm et al (2010) [36] also assessed injury risk factors using a subject pool of 12-18 year old tennis players and found previous injury to be an injury risk factor, along with back injuries with playing more than 6 hours a week identified as a risk factor for back pain. Other literature showed the mere exposure to tennis to be a risk factor for injury [37].

With the high impact forces experienced at the knee during tennis, it is not surprising that a smaller number of people (20%) return to tennis following knee surgery (total knee arthroscopy) [10]. Due to the lack of research into returning to tennis play following a total knee arthroplasty (TKA), Mont et al (2002) [10]conducted a study by means of a survey, with 33 responses totalling 46 TKA. In total, 55% of the patients' surgeons were opposed to patients returning to tennis, 21% permitted it, and 45% advised return to doubles play only. Interestingly a total of 69% of patients who had the surgery was found to be able to play tennis again. The statistics from surgeons suggest that tennis is an activity not recommended for TKA patients after the knee surgery, possibly due to the impact and loading rates recorded at the knee. Returning to doubles play only may reduce some of the adverse effects to the knee due to there being less acceleration/deceleration involved as there are two players covering the court space. This could be beneficial to the knee OA population. The study noted a limitation as their results do not allow them to postulate if returning to playing tennis, a high-impact activity, is contraindicated following TKA. It is unclear if these findings are based on scientific findings in the literature or a surgeon's recommendation for what they think it best for each individual patient.

Biomechanics of Knee during Tennis Related Movements

The biomechanics of the lower extremity is well documented for step-in and lunge movements, and cutting movements. There are many variations of lunge technique. For example, direction of movement, size of the step taken for the lunge movement, whether a step is taken before the lunge, and trunk position all can have a significant effect on the knee. A lunge can be performed as a static movement i.e. the participant stands with 1 foot in front/diagonally/laterally of the other with a large enough space between the feet, so when bending the front knee it doesn't translate beyond the toes of the front foot [14]. The static lunge is a closed chain movement, in that both feet stay stationary throughout the movement, with the front knee bending and lowering the body and back leg towards the floor. A step-in lunge is an open chained movement which involves the participant lifting the front foot and ‘stepping into’ the lunge. The overall aim of the movement is the same as the static lunge with regards to the knee not translating past the toes of the front foot when bending the knee [14]. The main difference to note is that the static lunge does not involve any lifting of the feet while the step-in lunge involves the front foot lifting off the ground and landing in a position in front of where it originated. A step-in, or lunge with a stride is used more in actions that require some kind of movement towards a specific point that would end in having to plant the front foot in a lunge position. A potential reason for needing to investigate these types of movements is due to the fact the movements are prevalent in a number of sports and activities, particularly tennis, and rehabilitation programs. As tennis is played on a court that is of finite size, the area in which a player has to move is restricted by boundaries around the court. In order to prevent running into these boundaries, i.e. player seats, the net, a player is regularly seen to accelerate and decelerate quickly during a match. It is due to these movements and their potential effects on the body, especially the knee that investigating their effects on the lower extremity has gathered attention in the literature. The forward lunge is used regularly by athletes and clinicians to train hip and thigh musculature [14]. It is also important to note that the stride length prior to the lunge has an effect on how fast of the lunge is performed and if the knee is translated past the toes, which could affect knee joint loading. These were supported by their findings in the study that if the knee translates past the toes it may be harmful to the patellofemoral joint, as forces for the short step lunge were 600 – 650N compared to 400 – 450N for a long step lunge. The authors also found the peak knee extensor moment which opposed the knee flexor torque was significantly larger with a stride lunge than without.

Cutting movements have received attention in the research surrounding non-contact ACL injuries. Although this current thesis project will not be looking at ACL injuries specifically, this is an injury that has been noted in the literature [3]. Therefore, information about this type of movement may provide useful information about how knee injuries during this motion may occur during tennis. It was highlighted that documentation on the external loading of the knee during sport specific movements involving a change in direction was somewhat lacking [38]. During side stepping and cutting movements, there are a variety of different loads acting at the knee, including flexion/extension, varus/valgus, and internal/external rotation moments. They noted the technique differences between movements of participants, and as large flexion moments were noted these require a large extension moment to stabilize. Another study examined a variety of different torso and foot positions with a side stepping maneuver [39]. They found that in all tasks the peak knee flexion/extension moment occurred during the knee flexion, and that having a 'foot wide' position (foot planted away from the body) and torso rotation in the opposition direction to the planted foot resulted in higher peak valgus moments, compared to foot close (planted close to the body) and torso facing towards the planted foot. With the differences in body placements during the cutting movement, it would be of value to evaluate the role of the trunk positioning in the movements to be investigated for tennis.

In terms of biomechanical information of tennis in the literature there is much to be found on upper extremity injuries such as tennis elbow, but the results for lower extremity, specifically the knee is somewhat lacking. There have been studies on the effects of different surfaces on the knee [24, 25]. However, literature on effects at the knee during different movements has not received much attention. There is some information on badminton, which is another racket sport involving high impact movements somewhat similar to tennis.

In badminton, the lunge task is common in the execution of all shots going from the base, to striking the shuttlecock, and back to base position [16]. The authors noted that despite the importance of the lunge in sports, there is a lack of literature on the kinetics and kinematics of its execution. The study examined three types of lunge technique (hop, step-in and kick) performed by experienced male players competing at national level for singles play, aged 20 ±2.12 years. All lunges were performed using the dominant leg in an extended position at heel contact. They found no significant differences of peak extensor moments of knee and hip between lunge techniques. However, it is important to note that the peak moments were greater at the knee, than the hip and ankle. The largest vertical ground reaction force was seen during the initial contact phase (heel strike). All 3 lunges used the same fixed distance for performing the skill, this was set at 1.5 times leg length, and approach speeds were not measured.

Common movements in tennis are in the forward, lateral and diagonal directions, to enable players to hit shots from along the baseline (lateral movement), and run towards the net for drop shots (forward movement), and a variety of shots across the court (diagonal). It is therefore important to investigate forward and lateral lunges. The comparison of the forward and lateral lunge has led to some conclusive results [11-13]. However, with regards to the knee, although there were conclusions drawn, the overall loading involved is more complex, with key kinetic and kinematic differences between lateral and frontal movements. Two studies of note had some interesting results when comparing frontal and lateral steps and lunges [11, 13]. In the frontal and lateral step, the subjects stood 21cm below the floor surface with body facing the force plate, with the foot of the dominant leg completely on the force plate, and pushing up onto it by extending the knee and hip [13]. It was a closed chain movement, with subject instructed to shift weight to the dominant leg and not use momentum from the non-dominant leg. The instructions for the lunge were to stand with feet shoulder width apart, stepping forward with the dominant leg, flexing the hip and knee with dorsiflexion of the ankle, to enable lowering the body towards the floor until that the subject could no longer lower further or the trailing knee was approximately 2 inches off the floor. It was found that during the frontal step, knee flexion angle, peak power, total impulse, and knee work were all lower than a lateral step, but peak moments were similar [13]. A step movement does not involve the same flexion of the knee that a lunge does i.e. the movement is not mean to lower the body and trailing knee closer to the floor. Conversely, it was found that during a frontal lunge peak knee power and mechanical energy expenditure were greater than a lateral lunge. The peak knee moment and impulse were greater during the lateral lunge [11]. This was interesting as peak power and moment normally don't conflict i.e. they are both found in the same motion, this would justify further study in lunges for different directions. Flanagan (2004) [11] found the knee range of motion greater during a lateral lunge, in comparison to the finding of a greater range of motion during the frontal step by Wang et al. [13]. In a recent study it was found that for subjects aged 18 – 40 years, peak knee flexion angles were greater during a frontal lunge compared to a lateral lunge, with lunges performed from a standing position, moving forward/laterally with the dominant leg [12]. Net joint impulses were greater during a lateral lunge with a standard step length and self-selected step length compared to frontal lunge with same step lengths. The net joint impulse was greater in frontal lunges with self-selected step length, compared to a standardized stepping length [12]. However, the key differences between the peak knee moment and impulse during a lateral step and lunge should be noted from the previous studies. These results could be age dependent. Wang et al. (2003) [13] and Flanagan et al. (2004) [11], used older adults (> 70 years) in their studies, which may account for the differences found in the results compared to those found in a younger population [12].

The loading to the knee may vary depending on the population and direction of the movement. Another way to look at the comparisons is to take open chain movements (lunge and step) and compare them to closed chain movements (squats). Stuart et al. concluded after comparing two types of squats and a lunge, that the anterior shear force was going in the posterior direction throughout all three movements [40]. Shear force was also highest during flexion, with the lunge having a greater value by 200N, and peak shear force being approximately twice as great, compared to both squats. More notably the lunge had the highest knee extensor moment, and highest for all joint loading at 60° in descent, 90° in the ascent and descent phases. The lunge was also shown to have the highest tibiofemoral compression force which occurred during early stance and remained constant throughout the lunging motion.

At low flexion angles up to 20°, the patellofemoral joint force was greatest during a step in lunge, primarily as the lead foot had a greater ground reaction force at impact to decelerate the body [14]. A step in lunge involves moving the dominant leg forward in a step motion and completing the lunge movement. A lunge without a stride consists of both feet remaining stationary in a closed chain movement, and performing the lunge motion. During each, the researchers ensured the knee of the dominant leg did not translate beyond the toes. A shorter step-in lunge also causes the knee to translate anteriorly past the toes and generates larger forces at the patellofemoral joint than if the knee does not translate past the toes. In comparison between frontal and lateral lunges, the lateral lunge generates larger compressive forces and stress at the patellofemoral joint than a frontal lunge at knee flexion angles between 80° and 90° [14]. Performing a lunge with a stride supported their previous findings, between 0° – 50° the patellofemoral joint compressive forces and stress were greater with a stride than without. Interestingly it has been noted that at higher levels of knee flexion (75° - 110°), the compression forces reached a plateau. So in effect the greatest effects at the knee are recorded prior to the latter stages of flexion, peaking at close to 90° [14]. This is interesting to note as during a tennis match it would be more common to see a lunge with less knee flexion, which may suggest that the forces generated during this motion may have a more detrimental effect than deeper flexion angles. The net joint moment impulse has been found to be greater at the knee during a lateral lunge compared to a frontal lunge for all step length variations. Also for lateral and frontal lunges, the net joint moment impulse was greater with self-selected step length than a standardized pre-set length [12]. Overall in the lower extremity, peak knee extensor moment produced at the knee occurred during a lateral lunge, and peak plantar flexor moment was also greater during the lateral lunge.

Trunk position has been suggested to have an effect on lower limb biomechanics [15]. The authors found that peak knee extensor impulse was greater during a frontal lunge with trunk extension (2.6 ±0.6 Nms/kg) than trunk flexion (2.1± 0.5 Nms/kg), and peak knee flexion angle greater for trunk extension (113.4±7.4°) than trunk flexion (104.3±11.1°). This variable should be monitored when testing the knee during different tennis strokes as it can have an effect on the knee extensor impulse, and could potentially be a 'modifiable' element for movement execution to prevent future injury.

Strength has been postulated as a mitigating factor in movement control of the knee [18]. More specifically, core hip strength, to control the distal segments. Quadriceps forces were approximately 40% greater when lunging with a stride compared to without (static), at 10°-20° descent and 10°-40° ascent [14]. In tennis, fatigue could play a pivotal role in the effects on knee extensor strength, if hip musculature weakness is present. It was, however, found that in a healthy population, the muscular strength at the hip did not affect the movement of the knee during movements such as a forward lunge [18]. If a player has an existing injury, with a muscle weakness at the hip it could be questioned whether this in turn could leave a player more predisposed to sustaining a knee injury. Given the role of the quadriceps forces and their proportional relationship to patellofemoral pain, fatigue coupled with repetitive loading at angles up to 20° of knee flexion could also play a role in knee injury incidence [14]. As knee injuries are prevalent in tennis players, further investigation would be beneficial into which types of movement cause the greatest loading at the knee. The results would provide strength and conditioning specialists vital information to work from when training tennis players. Also any adaptations to training could lead to a lower incidence of developing knee OA, especially medial knee OA, in the future. The information could also be used for the knee OA population to modify their game to avoid certain types of strokes and movements and/or change to double play (to reduce knee joint loading) to enable this population to play and/or compete for longer.

Investigating knee joint loading during generic strength movements is beneficial in gaining knowledge of kinematics and kinetics during motions of movements like a squat, step and lunge. The step and lunge are common movements that can be seen used in racket sports (tennis, badminton, squash).The main shear and compression forces investigated are in the tibiofemoral joint. The lunge has been shown to have a greater magnitude of posterior shear force, 495N ± 72N at a flexion angle of 103° compared with 295N (± 32N at 93°) and 295N (± 33N at 97° flexion) of a front squat and power squat , respectively [40]. In supporting this, the peak tibiofemoral compression force of 716N (± 70N at 76° ± 25°) in the lunge were greater than 500 – 600N in both squat variations. The greatest compression force was noted at footstrike during the stepping forward motion on the right leg. The maximal extension moments were also greater for the lunge with 113N-m ± 23N-m, compared to the front squat of 89 N-m ± 12N-m, and power squat of 86 Nm±13N-m [40]. More specifically the higher net extension moments were observed for the lunge when the knee was flexed to 90° during descent phase compared to both squats, and at 60° flexion during descent compared to the front squat. As a lunging motion is used in tennis for various strokes, it is interesting to note the extensor moment differences at the knee for this open chain movement, over a closed chain squat.

Understanding the loading and kinetics of the knee during weight bearing sports is pivotal. Movement of the tibia has been investigated during lunging and found sharp increases in internal tibial rotation at low and high flexion angles, and that knee kinematics involving flexion is activity (loading) dependent [17]. Muscle strength at the hip may also play a role in the incidence of knee injuries, and during a forward lunge, a stronger external hip musculature may cause the knee to move more laterally. In the case of muscle strength, fatigue at the hip could also play a role in the varus/valgus motion of the knee during tennis [18]. Lunge performance and strength has been highlighted to be pivotal during a variety of weight bearing sports, including badminton, squash and fencing.

Injury Risk and Biomechanics during High Impact Activities

Throughout recent years there has been a push by governments to get societies to become more active, with recommended guidelines for how much activity to do each day. With an increase in physical activity, it is important to understand the injury risks associated with different sports, and recommend their suitability for certain populations, i.e. older adults, especially for those with injuries. Impact force and loading rates have been widely reported for running during recent years. One study compared loading rates and impact forces among different shoe types (distance spikes, racing flats, regular running shoes) [19]. It was reported that running shoes had a loading rate of 148±54BW/s for women 151±47BW/s for men, and a peak vertical impact force of 2.47±0.37BW for women and 2.36±0.55BW for men. However, in another study looking at plantar pressure with training shoes (Nike Air Pegasus) and racing flats (Nike Air Zoom Katana IV) maximum (peak) vertical ground reaction force in training shoes was 2.49 ± 0.62(BW), when compared to racing flats at 2.74 ± 0.58 (BW) [22]. This shows that when running, the impact is greatly increased and can range between 2.3 – 2.8 (BW) [22]. So when running individuals should be aware that the increase in ground reaction force can come close to 3 times their actual body weight.

Osteoarthritis affects over 27 million Americans and is most common in the weight bearing joints, namely the knee and hip [5]. There is an increasing rate of development of knee OA in mid and older aged people [9] It was noted that there are three main risk factors for developing OA, excessive musculoskeletal loading, overweight and past injury [8]. Due to the movements involved in tennis, it is considered a weight bearing sport, due to the accelerating, decelerating, lunging and stepping of the lower extremity. Since the knee is the most affected joint in OA, it would make sense to investigate the effects on peak knee moment (a surrogate measure of knee loading) and ground reaction force during a variety of tennis strokes/movements, to better understand if the sport will predispose players to developing knee OA and if it is suitable for mid and older age people who are at risk of developing knee OA. It has also been reported that a risk factor for OA is overuse [6, 7]. Tennis players who are competing at a higher level, practice and play more tournaments, and therefore may be more susceptible to developing knee OA.

Effects of Playing Surface on Biomechanical Responses

There are a variety of playing surfaces for tennis. The 4 major grand slams are based on clay, hard court and grass courts, and most recreational courts, as they are outdoor, would be hard court surfaces. With the varying surfaces, the biomechanics of movements involved in play could create larger forces in different directions and result in a larger potential for injury. It was reported the evidence was present for an increase in overuse injuries on artificial surfaces compared to when play took place on natural surfaces [25].

In recent years studies have started to look at the difference in injury rates and injuries on different surfaces. A couple of studies investigated the kinetics and kinematics of knee on different court surfaces [24, 25]. The first used different court surfaces over the force plate with a running forehand stroke with foot plant on the non-dominant leg, and yielded results of 2 or more peaks during the first 50ms of stance [25]. They found 0.7 – 1BW for peak posterior GRF during the running forehand stroke with foot plant on the non-dominant leg was almost twice as the peak breaking GRF for running alone. They used 4 different surfaces, baseline, carpet, acrylic and artificial turf. Interestingly their hypothesis regarding loading rates being decreased with a surface with greater mechanical cushioning was rejected. In fact the surface with the least mechanical cushioning (baseline) resulted in the lowest recorded impact forces. They postulated one reason for this was the self-selected landing of the participants to reduce the impact, that players are making their own judgements on what adjustments need to be made to avoid higher impact forces. In a more recent study, it was found the peak impact force occurred early on acrylic and rubber surfaces for a running tennis stroke [24]. Conversely the peak forces (braking) and loading rates were significantly reduced with an increase in shock pad cushioning, with the timing of these peak forces happening sooner on acrylic and rubber surfaces. Therefore, with increased mechanical cushioning the peak loading forces were reduced (22.8% thin foam, 69.9% thick foam). Some variables that had significant differences at impact were initial foot angle, which was lower on acrylic surfaces than rubber (30.9°), and knee flexion angle which was higher on foam surfaces than rubber (-19.8°, -13°). Heel impact velocity was lowest on the acrylic surface (-0.92m/s-^{1}). Supporting the previous study, peak vertical impact force normalized to body weight was recorded to be lowest on the hardest surface. A common element in both studies is the player's ability to select the impact force based on how they view each of the surfaces. It could be argued that a player landing on foam will experience foot strike at a higher rate as they believe it to be a 'softer' landing, than when they play on a harder surface.

Summary

This chapter has reviewed the literature of several aspects relating to knee loading and tennis. It has been established that knee injuries are a prevalent part of the game of tennis, and that playing tennis can have consequences increasing risks of developing knee OA. With such an extensive list of knee injuries associated with tennis, the lack of literature on the loading and related biomechanical responses of the knee during different movements and strokes warrants further investigations. Therefore, more sport specific research on movements in the frontal plane and movements with a cutting motion is warranted for their practical implications in the development of knee injuries and knee OA.

CHAPTER THREE
METHODS

Participants

Ten participants (age: 30±8.52 years, height: 1.70±0.11m, body mass: 67.66±16.14 kg, BMI: 22.99±3.58) (Appendix A) were recruited to participate in the study, from local tennis clubs via flyers (Appendix G), club emails, and word of mouth. The participants were proficient tennis players at National Tennis Ranking Program (NTRP) Level 4.0 or higher (http://www.usta.com/Adult-Tennis/USTA-League/Information/1655_General_Characteristics_of_Various_NTRP_Playing_Levels/). Participants were excluded from the study if they have previous or current major lower extremity injuries (ligament damage, bone fracture, joint dislocation, muscle rupture etc.) and answered 'yes' to any question on the Physical Activity Readiness Questionnaire (PARQ) (Appendix D). They provided written informed consent approved by the Institutional Review Board prior to testing (Appendix C). Each participant attended a single testing session lasting approximately 90 minutes. The number of subjects was determined using G*Power software [41]. The observed power for peak knee extensor moment and the time to this moment was reported at 0.999 for both variables.

Instrumentation

A nine-camera Vicon system (240 Hz, MX and T10, Vicon Motion Analysis Inc, Oxford, UK) was used to collect 3-dimensional (3D) kinematic data. One force platform (1200Hz, Advanced Mechanical Technology Inc, Watertown, MA, USA) was used to capture the ground reaction force (GRF) data. Reflective anatomical markers were placed bilaterally on the acromium processes, trunk, iliac crests, greater trochanters, medial and lateral femoral epicondyles, medial and lateral malleoli, and head of the first and fifth metatarsals.

Reflective tracking markers, in sets of 4 on moulded thermoplastic shells, were placed on the trunk, around the posterolateral pelvis, lateral thigh, and lateral shank. Three individual markers were placed on the superior, inferior and lateral heel. Vicon Nexus and Eclipse programs were used to collect 3D kinematic and GRF data simultaneously.

Professional Coaches Survey

A survey was sent out to professional tennis coaches in clubs around Knoxville asking for specific knee injury information (Appendix F). It asked coaches for their opinion on what injuries they had seen, and what three different strokes/movements they felt caused the largest effects at the knee. The answers were used to determine the movements used for the study. Results showed a trend towards lateral movements, open stance forehands, and the serve. We chose to compare a lateral open stance forehand stroke and diagonal forehand stroke in this study.

Experimental Protocol

Each subject was asked to complete a PARQ, informed consent form, and a demographic information sheet (Appendix E). Each subject was asked to perform a warm-up (self-directed), consisting of running on a treadmill for 5 minutes at a self-selected speed, and stretching of the major muscle groups across major upper and lower extremity joints, and practicing movements for tennis forehand strokes with a step and approach.

In order to simulate realistic tennis strokes during tested movements, a tennis ball was hung with a string from an adjustable overhead bar allowing the ball to swing freely (Appendix I, Fig 1). The height and position of the bar was adjusted for each participant to enable the positioning of the tennis ball for each participant based on his/her self-selected height for a full swing forehand stroke, to mimic 'real play'. Markers were placed on the floor to enable each participant to move from the same starting point each time. Each participant was instructed to bring his/her own tennis racket and wore own tennis shoes for testing, if they failed to bring a racket one was provided for them. The participant was asked to strike the ball with their regular full forehand swing to minimize potential effects different swing speed on the kinematics and kinetics of lower extremity.

Each participant performed five successful trials in each of four movement conditions: lateral lunge, lateral step, diagonal lunge, and diagonal step. The diagonal movements were performed at a 45 deg angle to the force plate. The lunge stroke was performed with a 3-step approach while a step stroke was performed with a single-step approach. The subjects performed at least 3 practice movement trials, for each step and lunge in both directions, to enable them to determine the preferred distance during the 3-step approach for lunge strokes. However, they were allowed more practice steps if needed. They were asked to plant the foot of the leg on the hitting side on the force platform at the end of the step or lunge, and push off the force platform and return to the start position.

Data Processing and Statistical Analysis

C-Motion Visual 3D (C-Motion, Inc. Germantown, MD, USA) was used compute 3D kinematic and kinetic variables. 3D kinematic marker trajectories and ground reaction forces were filtered using a low-pass fourth order Butterworth filter at cut-off frequencies of 8 Hz and 50 Hz, respectively. An x-y-z Cardan rotational sequence was used in joint angle calculations and the right hand rule to determine the conventions for joint kinematics and kinetics. The dependent variables included peak vertical and mediolateral GRFs, time to peak vertical GRF, peak knee flexion angle, knee flexion ROM, peak knee extensor moment, time to peak knee extensor moment, peak knee adduction angle and abduction moment, ankle plantarflexion ROM, inversion ROM, peak plantarfelexion moment, and peak eversion moment. All joint moments were computed as internal moments. Positive values of analyzed variables indicate knee extension angle and extensor moment, knee adduction angle and moment, ankle dorsiflexion angle and dorsiflexor moment, and inversion angle and inversion moment, respectively (Tables 1 and 2). Ground reaction force was normalized to the subjects' body weight resulting in a unit of body weight (BW). Joint moments were normalized to body mass resulting in a unit of Nm/kg. The movement phase was defined as the stance phase measured from the point of impact to toe-off. Loading related variables from the first half of the movement phase were selected for further analyses. A customized computer program (VB_V3D, MS VisualBASIC) was used for additional data processing to generate scripts and models to be used in Visual 3D and determine critical values of variables of interest. Another customized program (VB_Table, MS VisualBASIC) was used to generate statistical files and organize data tables.

A two-way (size of approach × direction of approach) repeated measures analysis of variance (ANOVA) was used to detect differences for approach sizes (step and lunge) and movements (lateral and diagonal strokes) for the selected variables. If a significant interaction was found, a post-hoc comparison using a pair-samples t-test with a Bonforroni adjustment employed to detect exact differences between steps and movements. The alpha level was set at 0.05 a priori.

CHAPTER FOUR
EFFECTS OF DIFFERENT APPROACH DIRECTIONS AND SIZES OF SELECTED TENNIS FOREHAND STROKES ON KNEE BIOMECHANICS

ABSTRACT

Tennis is a global sport and knee injuries are prevalent, ranging from acute to chronic and minor, to severe. Different directional movements and speeds involved in tennis may lead to a higher chance of injury due to changing loading rates at the knee. This study investigates effects of diagonal and lateral forehand strokes with step or lunge on kinematics and kinetics of the knee on the dominant leg during simulated tennis play. Ten National Tennis Ranking Program (NTRP) players level 4.0 upwards were recruited for the study. A motion analysis system was used to obtain three-dimensional joint kinematics, and force platform to collect ground reaction force (GRF) data. Players performed five trials in four conditions, lateral step, lateral lunge, diagonal step, and diagonal lunge, using a forehand stroke for all four conditions. A two-way repeated measures ANOVA was used, with post-hoc comparisons, with significance set at 0.05 a priori. The results from the study show that there were no significant differences of peak knee extension moment, peak knee abduction moment between the diagonal and lateral forehand shots, either with a step or lunge, or peak abduction moment between approach size in both directions. However, there was a significant difference in knee extension moments depending on approach size in the lateral and diagonal direction, with the lunge approach in each direction being significantly higher than the step. Further study may be required to determine what approach steps and direction movements are more appropriate for players of a standard below NTRP level 4.0, and for a knee OA population.

INTRODUCTION

Tennis is a global sport with tens of millions of people participating worldwide each year, with over 200 nations are a part of the International Tennis Association (www.itftennis.com). Due to the high movement velocities and loads placed on the body during the game, it could be considered tennis is a sport with high impacts, primarily on joints in the lower extremity. With the cutting, sprinting, and decelerating movements involved in tennis, it creates high and repetitive loading on all joints in the lower extremity, leaving the athlete with an increased risk for injury [1]. Overuse injuries have been reported to be as high as 47% in the lower extremity among elite tennis players [2]. Knee injuries are prevalent in tennis including meniscus damage, ligament damage, and cartilage degeneration [3]. As the knee plays such an important role in movements involved in many sports, including tennis, it is important to understand what leads to its acute and overuse injuries.

There are many different movements involved in tennis, but primarily lateral movements to allow movement across the baseline, and diagonal movements to cover more court distance. It is in these movements that loading to the knees may achieve a high level and expose a player to a knee injury, or subsequent development of knee osteoarthritis (OA). Weight-bearing sports, like tennis, have been identified as a risk factor for developing knee OA [4], with up to a 3.6 fold increase risk for knee OA in former elite athletes compared to controls. Osteoarthritis affects over 27 million Americans and is most common in weight bearing joints, namely the knee and hip [5]. It has also been reported that some of the risk factors for OA are overuse [6, 7], excessive musculoskeletal loading, overweight and past injury [8]. It is generally accepted there is an increasing rate of development of knee OA in mid and older aged people [9]. With the prevailing number of knee injuries reported in tennis [3], further investigation into knee loading related biomechanics of the specific movements in tennis is pertinent. This could help to further research in understanding the potential development of knee OA in this population. Following a total knee arthroplasty in elite tennis players, 55% of the patients' surgeons were opposed to patients returning to tennis, 21% permitted it, and 45% advised to return to doubles play only [10]. Therefore, studying the knee loading conditions of high loading movements in tennis could help determine whether tennis is suitable for the knee OA and total knee arthroplasty populations, if certain types of strokes/movements are to be avoided.

Very few studies on lower extremity biomechanics of tennis related movements can be found in literature. However, the biomechanical movements of lunging and stepping, which are seen regularly in tennis, are well documented in literature [11-18]. These movements studied are, for the most part, not sport specific. There is not 100% agreement as to which type of lunge movements causes the greatest loading to the knee. The forward lunge is used regularly by athletes and clinicians to train hip and thigh musculature [14]. Escamilla et al. [14] found that the greatest patelleofemoral joint compressive forces were found between 0° - 50° of knee flexion during a step-in lunge. Another study found that knee flexion angle, peak power, total impulse, and knee work in a frontal step were all lower than a lateral step, but peak knee moments were similar [13]. Conversely, it was found that peak knee power and mechanical energy expenditure were greater during a frontal lunge than a lateral lunge. The peak knee moment and impulse were greater during the lateral lunge [11]. This is interesting as peak power and moment normally do not contradict each other i.e. Flanagan et al. [11] found greater knee range of motion (ROM) during a lateral lunge. In a recent study, it was found that peak knee flexion angles were greater during a frontal lunge compared to a lateral lunge, with lunges performed from a standing position with the dominant leg [12]. Net joint impulses were greater during a lateral lunge compared to a frontal lunge. The net joint impulse was greater in frontal lunges with self-selected step length, compared to a standardized stepping length [12]. Overall there is no complete consensus in the literature for the ROM, peak moment, and peak flexion angles. A comparison with activities of daily living, such as stair ascent/descent, and sports like badminton and running will provide information on whether tennis is a suitable activity for a knee OA population [19-22].

During a badminton specific study involving three different types of lunges (hop, step-in and kick), the authors found no significant differences between lunge conditions for peak extensor moments at the knee and hip, and that peak extensor moments were greater at the knee compared to the hip and ankle [16]. Importantly, it has been noted that knee kinematics involving flexion is activity (loading) dependent [17]. Another study examined forehand forward and backward lunge tasks, when comparing a group with knee injuries to a group without, movement at the knee became altered for the knee injury group in certain planes of motion[23].

To our knowledge, no studies have been conducted to investigate loading to the knee of tennis related movements in literature. As sports like badminton and tennis involve varying loads to the knee depending on the type of movements or strokes, investigation is necessary to provide loading related biomechanical information about knee during tennis movements. Additionally, most research of the tennis specific lower extremity movements involved different playing surfaces [24, 25]. It would be more pertinent to investigate the biomechanical characteristics of the knee joint during high loading movements, e.g. lateral and diagonal tennis strokes. Furthermore, it unclear what effects of the size of approach (i.e., a step approach or a 3-step approach) may have on knee joint loading during these lunges. Such information would help to provide guidance on shot selections for specific groups of players including knee OA and total knee replacement. Therefore, the purpose of this study was to investigate effects of diagonal and lateral forehand strokes with step or lunge on kinematics and kinetics of the knee on the dominant leg during tennis play. It was hypothesised that 1) the diagonal stroke would have greater peak knee extensor moment than lateral forehand stroke due to the fact the player may achieve greater approach speed in the diagonal shot; 2) the peak knee abduction moment would be greater in the lateral forehand stroke than in the diagonal stroke due to the lateral movement; 3) the strokes performed with a lunge would create larger peak knee extensor and abduction moments than those performed with a step in the lateral and diagonal movements, which would in part be due to the increased speed achieved with the 3 steps during the lunge condition.

METHODS

Participants

Ten participants (age: 30±8.52 years, height: 1.70±0.11m, body mass: 67.66±16.14 kg, BMI: 22.99±3.58) were recruited to participate in the study, from local tennis clubs via flyers, club emails, and word of mouth. The participants were proficient tennis players at National Tennis Ranking Program (NTRP) Level 4.0 or higher (http://www.usta.com/Adult-Tennis/USTA-League/Information/1655_General_Characteristics_of_Various_NTRP_Playing_Levels/). Participants were excluded from the study if they have previous or current major lower extremity injuries (ligament damage, bone fracture, joint dislocation, muscle rupture etc.) and answered ‘yes’ to any question on the Physical Activity Readiness Questionnaire (PARQ). They provided written informed consent approved by the Institutional Review Board prior to testing. The number of subjects was initially determined as 10 using a β level of 0.80, α level of 0.05, and a effect size of 0.6 using G*Power software [41]. The observed powers for the peak knee extensor moment, and time to this moment were 0.999, and 0.999, respectively.

Instrumentation

A nine-camera Vicon system (240 Hz, MX and T10, Vicon Motion Analysis Inc, Oxford, UK) was used to collect 3-dimensional (3D) kinematic data. One force platform (1200Hz, Advanced Mechanical Technology Inc, Watertown, MA, USA) was used to capture the ground reaction force (GRF) data. Reflective anatomical markers were placed bilaterally on the acromium processes, trunk, iliac crests, greater trochanters, medial and lateral femoral epicondyles, medial and lateral malleoli, and head of the first and fifth metatarsals. Reflective tracking markers, in sets of 4 on moulded thermoplastic shells, were placed on the trunk, around the posterolateral pelvis, lateral thigh, and lateral shank. Three individual markers were placed on the superior, inferior and lateral heel. Vicon Nexus and Eclipse programs were used to collect 3D kinematic and GRF data simultaneously.

A survey was sent out to professional tennis coaches in clubs around Knoxville asking for specific knee injury information. It asked coaches for their opinion on what injuries they had seen, and what three difference strokes/movements they felt caused the largest effects at the knee. The answers were used to determine the movements used for the study. Results showed a trend towards lateral movements, open stance forehands, and the serve. We chose to compare a lateral open stance forehand stroke and diagonal forehand stroke in this study.

Experimental Protocol

Each subject was asked to complete a PARQ, informed consent form, and a demographic information sheet. Each subject was asked to perform a warm-up (self-directed), consisting of running on a treadmill for 5 minutes at a self-selected speed, and stretching of the major muscle groups across major upper and lower extremity joints, and practicing movements for tennis forehand strokes with a step and approach.

In order to simulate realistic tennis strokes during tested movements, a tennis ball was hung with a string from an adjustable overhead bar allowing the ball to swing freely (Appendix I, Fig 1-3). The height and position of the bar was adjusted for each participant to enable the positioning of the tennis ball for each participant based on his/her self-selected height for a full swing forehand stroke, to mimic 'real play'. Markers were placed on the floor to enable each participant to move from the same starting point each time. Each participant was instructed to bring his/her own tennis racket and wore own tennis shoes for testing, if they failed to bring a racket one was provided for them. The participant was asked to strike the ball with their regular full forehand swing to minimize potential effects different swing speed on the kinematics and kinetics of lower extremity.

Each participant performed five successful trials in each of four movement conditions: lateral lunge, lateral step, diagonal lunge, and diagonal step. The diagonal movements were performed at a 45 deg angle to the force plate. The lunge stroke was performed with a 3-step approach while a step stroke was performed with a single-step approach. The subjects performed at least 3 practice movement trials, for each step and lunge in both directions, to enable them to determine the preferred distance during the 3-step approach for lunge strokes. However, they were allowed more practice steps if needed. They were asked to plant the foot of the leg on the hitting side on the force platform at the end of the step or lunge, and push off the force platform and return to the start position.

Data and Statistical Analysis

C-Motion Visual 3D (C-Motion, Inc. Germantown, MD, USA) was used compute 3D kinematic and kinetic variables. 3D kinematic marker trajectories and ground reaction forces were filtered using a low-pass fourth order Butterworth filter at cut-off frequencies of 8 Hz and 50 Hz, respectively. An x-y-z Cardan rotational sequence was used in joint angle calculations and the right hand rule to determine the conventions for joint kinematics and kinetics. All joint moments were computed as internal moments. Positive values of analyzed variables indicate knee extension angle and extensor moment, knee adduction angle and moment, ankle dorsiflexion angle and dorsiflexor moment, and inversion angle and inversion moment, respectively (Tables 1 and 2). Ground reaction force was normalized to the subjects' body weight resulting in a unit of body weight (BW). Joint moments were normalized to body mass resulting in a unit of Nm/kg. The movement phase was defined as the stance phase measured from the point of impact to toe-off. Loading related variables from the first half of the movement phase were selected for further analyses. A customized computer program (VB_V3D, MS VisualBASIC) was used for additional data processing to generate scripts and models to be used in Visual 3D and determine critical values of variables of interest. Another customized program (VB_Table, MS VisualBASIC) was used to generate statistical files and organize data tables.

A two-way (size of approach × direction of approach) repeated measures analysis of variance (ANOVA) was used to detect differences for approach sizes (step and lunge) and movements (lateral and diagonal strokes) for the selected variables. If a significant interaction was found, a post-hoc comparison using a pair-samples t-test with a Bonforroni adjustment employed to detect exact differences between steps and movements. The alpha level was set at 0.05 a priori.

RESULTS

Post hoc comparisons showed that the peak VGRF was greater in lateral lunge ($p = 0.017$) compared to lateral step, but not for the diagonal lunge and step (Table 1). The time for peak VGRF was shorter in lateral lunge ($p = 0.01$) and diagonal lunge ($p = 0.005$) than lateral step and diagonal step. Peak medial GRF was greater in the diagonal lunge ($p<0.001$) than diagonal step, and lateral step than diagonal step ($p=0.043$).

Post hoc comparisons for peak knee flexion angle was greater for the lateral lunge ($p=0.03$) and diagonal lunge ($p=0.035$) compared to the lateral step and diagonal lunge respectively (Table 1). There was a significant direction of approach x size of approach interaction for flexion ROM ($p=0.025$, Figure 2). Post hoc comparisons for flexion ROM were greater for lateral lunge ($p=0.004$) and diagonal lunge ($p=0.047$) compared to lateral step and diagonal step respectively. Post hoc comparisons for peak knee extensor moment were greater for lateral lunge ($p=0.003$) and diagonal lunge ($p=0.002$) compared to the lateral step and diagonal step respectively. The time to peak extensor moment were shorter in the lateral lunge ($p=0.003$) and diagonal lunge ($p<0.001$) than the lateral step and diagonal step.

Post hoc comparisons results showed that plantarflexion ROM was greater in lateral lunge ($p=0.025$) compared to lateral step (Table 2). There was a significant direction x approach interaction for ankle inversion ROM ($p=0.013$, Figure 3). It was greater in lateral lunge ($p=0.023$) compared to lateral step, and also greater during lateral lunge ($p<0.001$) compared to diagonal lunge ($p<0.001$). There was a significant direction of approach x size of approach interaction for peak eversion moment ($p=0.001$, Figure 4). Post hoc comparisons showed that it was greater in lateral lunge ($p=0.01$) compared to lateral step, greater in lateral lunge ($p<0.001$) compared to diagonal lunge, and greater in lateral step ($p=0.008$) compared to diagonal step.

Table 1. Peak GRF and knee kinematic and kinetic variables: Mean ± STD.

Variable	Lateral step	Lateral Lunge	Diagonal step	Diagonal lunge	P value (Approach Direction)	P value (Size of approach)	P value (Interaction)
Peak Vertical GRF (N)	1.42±0.71^	1.99±0.51	1.42±0.50	1.81±0.37	0.362	**0.031**	0.078
Time Peak Vertical GRF (s)	0.11±0.066^	0.07±0.054	0.14±0.076^	0.05±0.029	0.715	**<0.001**	0.257
Loading Rate Peak VGRF (N/s)	31.15±57.98^	63.92±61.36	23.61±28.21^	52.15±46.72	0.419	**0.087**	0.515
Peak Medial GRF (N)	0.49±0.22	0.77±0.67	0.42±0.13^*	0.64±0.13	0.338	**0.028**	0.734
Peak Flexion Angle (deg)	-51.84±13.73^	-63.22±11.39	-56.22±11.27^	-62.98±13.80	0.477	**0.020**	0.229
Flexion ROM (deg)	-26.59±10.09^	-38.47±7.85	-33.08±7.45^	-38.03±10.99	0.215	**0.006**	**0.025**
Peak Adduction Angle (deg)	6.31±5.70	6.17±7.12	3.98±5.81	5.28±6.95	0.058	0.154	0.958
Adduction ROM (deg)	8.43±6.84	8.66±6.93	6.62±4.30	7.01±5.49	0.195	0.691	0.945
Peak Extensor Moment (Nm/kg)	1.27±0.54^	1.95±0.43	1.44±0.39^	2.06±0.44	0.272	**<0.001**	0.786
Time to Peak Extensor Moment (s)	0.206±0.042^	0.149±0.032	0.214±0.061^	0.146±0.042	0.837	**<0.001**	0.466
Peak Abductor Moment (Nm/kg)	-0.29±0.17	-0.41±0.20	-0.35±0.25	-0.45±0.32	0.560	0.104	0.902

[*] = significantly different between lateral step and diagonal step or lateral lunge and diagonal lunge.
[^] = significantly different between lateral step and lunge or diagonal step and lunge

Table 2. Ankle kinematic and kinetic variables: Mean ± STD.

Variable	Lateral step	Lateral Lunge	Diagonal step	Diagonal lunge	P value (Approach Direction)	P value (Size of approach)	P value (Interaction)
Plantarflexion ROM (deg)	-13.28±14.19^	-23.38±10.16	-14.96±13.36	-23.66±8.86	0.869	**0.031**	0.785
Inversion ROM (deg)	7.07±3.86	12.67±6.38	4.05±3.14	5.21±6.31*	**0.001**	0.109	**0.013**
Peak Eversion Moment (Nm/kg)	-0.25±0.11^	-0.38±0.07	-0.20±0.13*	-0.20±0.08*	**<0.001**	0.193	**<0.001**
Peak Plantarflexor Moment (Nm/kg)	-0.99±0.22	-1.01±0.16	-0.94±0.25	-1.01±0.18	0.701	0.429	0.331

* = significantly different between lateral step and diagonal step or lateral lunge and diagonal lunge.
^ = significantly different between lateral step and lunge or diagonal step and lunge

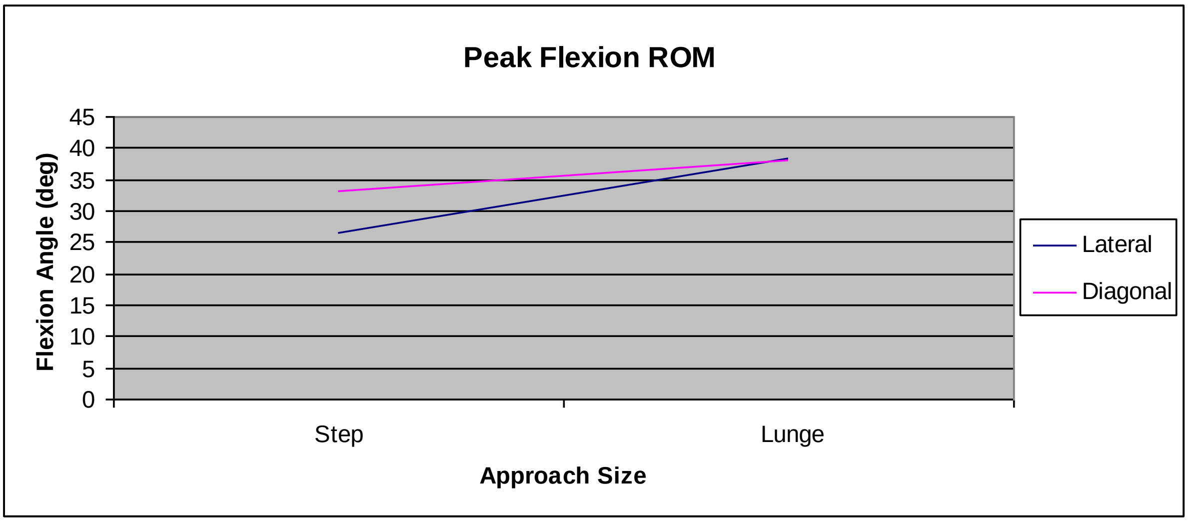

Figure 2. Significant Interactions – Knee Flexion ROM

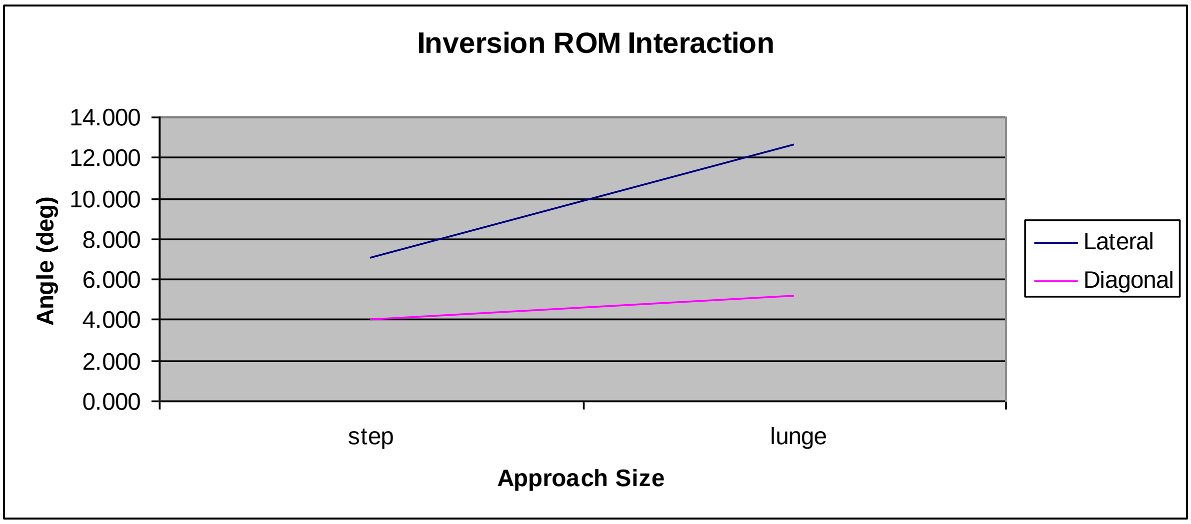

Figure 3. Significant Interactions – Ankle Inversion ROM

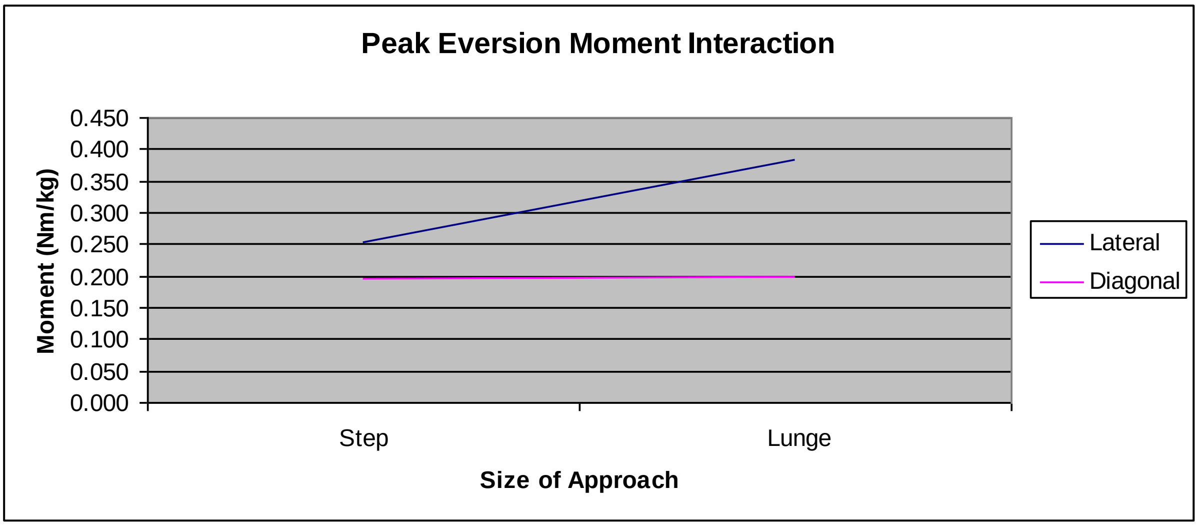

Figure 4. Significant Interactions – Ankle Eversion Moment

DISCUSSION

Effects on Sagittal Plane Knee Biomechanics

The purpose of the study was to investigate effects of diagonal and lateral forehand strokes with a step or lunge on kinematics and kinetics of the knee on the dominant leg during tennis play. It was hypothesised that the diagonal stroke would have greater peak knee extensor moment than lateral forehand stroke. The results showed no significant differences of peak knee extension moment between the diagonal and lateral forehand shots, either with a step or lunge and therefore, the first hypothesis was not supported by our findings. There were no significant differences found for a range of related variables, VGRF and its loading rate, time to VGRF, peak knee flexion, ands knee flexion ROM, when comparing the two directional movements. In addition, no differences were found in plantarflexion ROM and moment.

The literature comparing frontal and lateral lunge and step movements reported significant differences in variables based on the direction of the movement [11, 12]. Two studies examined isolated lunges [11, 12]. One study investigated forward and lateral lunges with short and long step sizes and found a significantly greater knee net joint moment impulse during in the lateral lunge at both step sizes compared to the frontal lunge [12]. The peak knee extensor moment and peak plantar flexor moment were greater during the lateral lunge compared to the frontal lunge [11]. The findings from these studies [11, 12] do not support the results from the current study. Our study reported peak knee flexion angles (deg) of 62.98 - 63.22 for diagonal and lateral lunges, and peak extensor moments (Nm/kg) of 1.95 - 2.06 for lateral and diagonal lunges. Peak knee flexion angles previously reported range from 90-101 deg for frontal lunges, 80-100 deg for lateral lunges whereas peak knee extensor moments were 0.84 Nm/kg for front lunge and 0.93 Nm/kg for lateral lunge [11, 12]. It is clear that the flexion angles of the lunges in the current study are much smaller, but the peak extensor moment was notably larger than previous studies [11, 12].

A key difference which should be noted is that our study investigated the two tennis specific movements with a forehand stroke around the time of impact simulating actual tennis play on court. These movements may not require as much knee flexion and extensor efforts as those lunges performed with maximum efforts in the two previous studies. Our participants were required to push off the dominant leg and back to the baseline following each movement, this was not the case in the previous studies [11, 12]. However, Huang et al. [23] examined a diagonal forward lunge in badminton players with and without knee injuries and found the knee flexion ROM of 61.4 deg for the healthy group, which is similar to the results of the current study.

The VGRF for the lunge conditions in the current study were 1.99 BW for lateral lunge and 1.81BW for diagonal lunge. The results of badminton studies showed VGRF ranged from 2 to 2.21 BW for a forward lunge shot [42], suggesting that tennis lunge shots may place slightly less external loading to the body than those in badminton shots. Our study did not instruct players to carry out the task at maximal effort, nor did it have approach speed requirements. The participants were instructed to carry out movements at maximum effort in one of the badminton studies [16], while the other study required the lunge to be completed within a 3 seconds time frame [23]. Literature reported VGRF in running ranging from 2.36 to 3.06 BW [19, 22] and stair ascent from 1.34 to 1.35 BW for a knee OA population [21], showing the VGRF for tennis lunges to be less than those for running but more than stair ascent. The peak knee extensor moments recorded for badminton for 3 different lunges ranged from 2.5 to 3.3Nm/kg [16] which are greater than those tennis lunges of our study. These differences have important implications in selection of activities for the knee OA population, suggesting that tennis may be a more suitable exercise option than running or badminton for a knee OA population.

Effects on Frontal Plane Knee Biomechanics

There were no significant differences found for peak knee abduction moment between the lateral and diagonal movements. The second hypothesis, that the peak knee abduction moment would be greater during the lateral forehand stroke compared to the diagonal stroke, was also not supported by our findings. In addition, no significant differences were found for peak knee adduction angle and adduction ROM among the lunges. Huang et al. [23] reported an adduction ROM of 13.71deg in the forward badminton lunge condition for the healthy group. The knee adduction ROMs for this study were 8.66 deg for lateral lunge and 7.01 deg for diagonal lunge, which are less than that in a badminton lunge. The peak abduction moments (Nm/kg) for the current study were 0.29 for lateral step, 0.41 for lateral lunge, 0.35 for diagonal step and 0.45 for diagonal lunge, which were also similar between the step conditions and lunge conditions. However, peak medial GRF was greater in lateral lunge (0.77 BW) compared to diagonal lunge (0.64 BW), and lateral step (0.49 BW) compared to diagonal step (0.42 BW). It is interesting that despite these differences in medial GRF, this did not translate to a significant difference in peak abduction moment. This could possibly be explained by the significant differences found in the ankle inversion ROM for the lateral lunge (12.67 deg) and diagonal lunge (5.21 deg) as well as eversion moment for lateral lunge (0.38 Nm/kg) and diagonal lunge (0.20 Nm/kg). The increased inversion ROM and eversion moment of the ankle joint might have been enough to compensate and effectively reduce the loading to the knee in the lateral lunge in the testing requirements in our study. However, the compensations may not be sufficient to prevent increased frontal plane loading to the knee in lateral lunges with maximum effort. It is advisable that tennis participants with medial knee OA should avoid maximum effort lunges, especially the lateral lunge.

When compared to knee OA patients these medial GRF values are much greater than those recorded in stair descent at different step widths (0.11- 0.22 BW), but adduction moments are larger during stair descent (0.71 - 0.77 Nm/kg) compared to the tennis shots [20, 21]. These results again suggest that tennis may be a suitable exercise option for people with medial knee OA due to relatively small knee abduction moments. The results from the badminton study show that players exhibiting knee problems have altered movement patterns when performing the lunge tasks [23]. Our participants were healthy without current knee issues. It is unknown what changes would be seen in both joint kinematic and kinetic patterns for those tennis lunges of participants with knee problems (e.g. knee OA and total knee replacement).

Effects of Approach Sizes on Knee Biomechanics

There was a significant difference found for peak knee extensor moment between the two approach sizes: step and lunge. The hypothesis that the strokes performed with a lunge would create larger peak knee extensor and abduction moments than those performed with a step in both lateral and diagonal directions, was partially accepted. Peak knee extensor moment for lateral lunge was greater (1.95 Nm/kg or 53.5%) than that for lateral step (1.27 Nm/kg) and the peak extensor moment for diagonal lunge (2.06 Nm/kg or 43%) was greater than diagonal step (1.44 Nm/kg). In addition, these peak moments also occurred earlier in the lunges (0.146 and 0.149 s) compared to the steps (0.206 and 0.214s). These results were further supported by the greater peak VGRF (1.81 and 1.99 BW) and loading rates (52.15 and 63.92 BW/s) for lunges compared to steps (1.42 and 1.42 BW; 23.61 and 31.15 BW/s respectively). These kinetic differences were also coupled with greater knee flexion and flexion ROM. Both lunges with a 3-step approach were performed at faster speeds than their step counterparts. These results indicate greater impact and loading rate on the knee joint during the loading phase of the lunge strokes than the step strokes in both directions. The differences between the lunge and step strokes suggest that people with knee problems should modify their game to include less lunge strokes and more step strokes to protect their knees, i.e. playing doubles instead of singles, a suggestion that is supported in previous literature [10].

The abduction moments were not significantly different between lunges and steps, although there seemed to be a trend of greater abduction moment for the lunges ($p = 0.104$). Literature has compared either a lunge or step in two different directions [11-13], our study compares direction and step size differences, and the results from the badminton studies did not report on adduction moments for the knee [16, 23]making direct comparisons with our study for this variable difficult. Lunge performance in badminton players is affected by playing ability [16], so execution could change depending on ability.

One potential reason for our findings being different than the isolated lunge is the diagonal direction is not the same as the frontal direction used in the previous studies [11, 12]. The similar variables reported with badminton are of more significance as tennis and badminton have similar demands and movements. As both approach directions instructed the ball to be hit with an open stance forehand, this motion, regardless of which direction the movement has come from prior to striking the ball, could be argued the footwork and lower extremity kinetics and kinematics when using players of a higher standard, to be almost the same with no significant variability. Investigating this stroke selection technique further with regards to its execution from a variety of directions could strengthen the argument for consistency of play for this level of player.

Some limitations of the study include that the players were tested using their own preferred footwear, but not all players wore a tennis shoe. However, it was decided the movement of the players would be much more consistent with their on-court movements wearing their own tennis shoes. The movement speeds for the steps and lunges prior to foot contact with the force platform were controlled through the requirement of one-step or three-step approaches for the steps or lunges but we did not specify or monitor the actual speeds. This might have increased performance variability of our subjects. The results of this study can be applied to the current NTRP level of player, level 4.0 or higher, but may not represent biomechanical characteristics of tennis players at a lower level. Overhead serves were suggested from the results of the survey as another movement that could expose knee joint to high loading. Future study should also investigate loading characteristics of this tennis stroke.

CONCLUSION

The results from the study show that there were no significant differences of peak knee extension moment, peak knee abduction moment between the diagonal and lateral forehand shots, either with a step or lunge, or peak abduction moment between approach size in both directions. However, there was a significant difference of knee extension moment depending on approach size in the lateral and diagonal direction, with the lunge approach in each direction being significantly higher than the step. The results of this study provided biomechanical guidance for game and shot selections for players who currently have knee problems or are at risk for knee OA. Players with knee OA or other knee problems should elect to play doubles for tennis rather than singles as a step approach is more common than a lunge approach in performing forehand strokes which would reduce loading to the knee.

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APPENDICES

APPENDIX A

INFORMED CONSENT STATEMENT

Effects of Selected Strokes and Movements on Loading of the Knee in Tennis

Principle Investigator –

Louise Beggs
MS Candidate in Biomechanics
Biomechanics/Sports Medicine Lab
1914 Andy Holt Avenue
Knoxville, TN, 37996-2700
Phone: (865) 974-2091
Email: lbeggs@utk.edu

Faculty Advisor

Songning Zhang, Ph.D.
Biomechanics/Sports Medicine Lab
1914 Andy Holt Ave.
Knoxville, TN 37996-2700
Phone: (865) 974-2091
Email: szhang@utk.edu

INTRODUCTION

You are invited to take part in the research study. The purpose of this study is to investigate the effects of diagonal and lateral forehand strokes with step or lunge on the knee on the dominant leg during tennis play. There are parts and words in this consent form that you may not fully understand. Please ask the researchers involved in the study to clarify and explain these elements to you so that you then clearly understand what is being asked/done. Before you agree to take part in the study you must read and understand the following explanation of the study and procedures, risks, benefits etc.

INFORMATION ABOUT SUBJECTS' INVOLVEMENT IN THE STUDY

You should be a Level 3.5 or higher player under National Tennis Rating Program (NTRP) between 18 - 45 years of age, healthy and have not been injured for at least 6 months prior to testing, or have ever sustained serious lower extremity injuries (i.e. ligament damage, bone fracture, joint dislocation, muscle rupture) that affected your ability to play at competition level. The testing session will last approximately 90 minutes. You will be asked to complete a PARQ, this informed consent form, and an information sheet. A 'yes' answer to any question on the PAR-Q will result in further inquiry into the response and a possible cessation of participation. The information sheet asks questions regarding age, gender, number of years playing tennis, level playing tennis at currently, any previous injuries, and if predominantly a singles or doubles player.

You will wear your own tennis footwear, and will wear tight fitting clothing, i.e., spandex. If you do not have tight fitting clothing it will be provided for you. You will be asked to perform a warm-up (self-directed), consisting of running on a treadmill for 3 minutes at a self-selected speed, and stretching of the major muscle groups across major upper and lower extremity joints, and shadow movements for tennis and mimicking forehand strokes.

Before the movement testing trials, several silver balls will be placed on your back, hips, legs, and feet. Reflective markers will be placed on your body which will not hinder your normal movements in tennis. A trial will be collected where we ask you to stand still in your tennis shoes, in the middle of the grey force platform. During the movement trials, you will perform <u>five</u> successful trials in each of the <u>four</u> testing conditions: side lunge, side step, diagonal lunge, and diagonal step. You will be asked to hit a tennis ball hung from a bar placed above you. You will decide the preferred height you want to hit the ball at and the height of the ball will be adjusted for you. You will be given enough time to become familiar with the testing conditions prior to the actual data collection. If you have any further questions, interests, or concerns about any instrumentation, please feel free to ask the investigator.

Potential RISKS

Risks associated with the study are minimal for you as the movements and strokes you will be performing are normal for a tennis player of NTRP Level 3.5 or higher. You will be given sufficient time to warm up and practice for the four movements. You will not be asked to perform any movements that are unfamiliar to you. You are free to withdraw from participation in the study at any point before or during testing without penalty. All testing in the lab is being conducted and equipment will be handled by qualified personnel in the Biomechanics/Sports Medicine Lab. The University of Tennessee does not "automatically" reimburse subjects for medical claims or other compensation. If physical injury is suffered in the course of research, or for more information, please notify Louise Beggs (865) 974-2091. If you have questions about your rights as a subject, contact the Compliance Officer in the Office of Research at the University of Tennessee at (865) 974-3466.

BENEFITS of Participation

There are no direct benefits to you. Potential benefits of the study include furthering research on the effects of loading at the knee during different strokes and movements, and potential injury prevention mechanisms.

CONFIDENTIALITY

Information in the study records will be kept strictly confidential. A coded subject number will be used during data collection, data analysis, and in all references made to the data, during and after collection, and in the reporting of the results. Data will be stored securely and will be made available only to persons conducting the study unless subjects specifically give permission in writing to do otherwise. No reference will be made in oral or written reports which could link you to the study. The results will be disseminated in the form of presentations at conferences, and publications in journals. The consent form containing your identity information will be destroyed three years after the completion of the study before data collection is completed. If you decide to withdraw from the study, your data will be destroyed at the time of withdrawal.

COMPENSATION

Subjects will be provided with free parking in a designated staff parking lot.

Voluntary Participation and Withdrawal

Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at anytime without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study before data collection is completed you data will be destroyed. You may stop participating in this study voluntarily or may be asked to stop if you fail to follow the study procedures or if the investigator feels that it is in your best interest to stop.

CONSENT Statement

The study has been explained fully to my satisfaction and I agree to participate as described. I have been given the opportunity to discuss all aspects of this study and to ask questions. Answers to such questions, if any, were satisfactory. I am qualified for the study and freely give my informed consent to serve as a subject. By signing this consent form, I have not given up any of my legal rights as a subject.

Subject’s name ______________________________   Subject # __________

Subject's signature ___________________________________ Date __________

Investigator's signature _______________________________Date __________

APPENDIX B

PHYSICAL ACTIVITY READINESS QUESTIONNAIRE(PAR-Q)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age and you are not used to being very active, check with your doctor.

No	Yes	
☐	☐	Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?
☐	☐	Do you feel pain in your chest when you do physical activity?
☐	☐	In the past month, have you had chest pain when you were not doing physical activity?
☐	☐	Do you lose your balance because of dizziness or do you ever lose consciousness?
☐	☐	Do you have a bone or joint problem that could be made worse by a change in your physical activity?
☐	☐	Is your doctor currently prescribing drugs (for example water pills) for your blood pressure of heart condition?
☐	☐	Do you know of any other reason why you should not do physical activity?

Please note: If your health changes so that you then answer YES to any of these questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

If you answered YES to one or more questions

Talk to your doctor by phone or in person BEFORE you start becoming much more physically active of BEFORE you have a fitness appraisal. Tell you doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want as long as you start slowly and build up gradually. Or you may need to restrict your activities to those which are safe for you. Talk to your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

If you answered NO to all questions

If you have answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- Start becoming much more physical active – begin slowly and build up gradually. This is the safest and easiest way to go.
- Take part if a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively.

Delay becoming much more active if:

- You are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better, or

  If you are or may be pregnant – talk to your doctor before you start becoming more active.

I understand that my signature signifies that I have read and understand all the information on the questionnaire, that I have truthfully answered all the questions, and that any question/concerns I may have had have been addressed to my complete satisfaction.

____

Name (please print)

____

Signature Date

APPENDIX C
DEMOGRAPHIC QUESTIONNAIRE

ID number _________________________ Date (MM/DD/YY):

_____/_____/_______

Age (in years) ______________ NTRP Level _______________

Height: ___ Feet ___ Inches or ______ cm Weight: _________lbs or ______ kg

Dominant side (circle one): Right Left Years playing Tennis _________________

1. Have you had injury within past six months?

Yes ☐ No ☐

2.Are you currently NTRP Level 3.5 or upwards?

Yes ☐ No ☐

3. Are you predominantly a singles player or a doubles player?

Singles ☐ Doubles ☐

4. Have you ever had Lower Extremity Injury (hip, knee, ankle, foot)?

Yes ☐ (Go to Question 5) No ☐ (Go to Question 9)

5. If you answer yes to question 1, please write the number of lateral ankle sprains you had:

Injury Sustained _____________________ Time since injury (Months) ___________

Injury Sustained _____________________ Time since injury (Months) ___________

6. Have you ever had episodes of your Knee "giving way" or "chronic pain" after initial injury?

Yes ☐ No ☐

7. Have you ever had recurrent lower extremity injuries?

Yes ☐ No ☐

8. If, answering yes in #7, how many times after initial injury?

Left: 1 ☐ 2 ☐ 3 ☐ >3 ☐

Right: 1 ☐ 2 ☐ 3 ☐ >3 ☐

9. After initial injury, did you enrol in any rehabilitation program for it?

Yes ☐ No ☐

10. Have you had major lower extremity surgeries and injuries that may affect the way you walk, run, jump or land (e.g., ACL reconstruction, total/partial knee or hip replacement, bone fractures)?

Left: Yes ☐ No ☐ Right: Yes ☐ No ☐

If yes, please provide more details about these injuries.

____

____

____

APPENDIX D

Knee Forces On the Knee During Tennis Survey

You are invited to participate in this survey related to the forces acting on the dominant knee during tennis play for competitive players. All of your responses are confidential and there are no identifiable markers used that can tie you back to your responses. The survey will take approximately ten minutes to complete. The completion and submission of this survey indicates your informed consent to participate in this study. You must be 18 years of age or older to participate in this research. By completing this form, you indicate your informed consent to participate in the study.

Check one of the followings and fill out the blank:
Coach____________ Years of Coaching Experience ______________
Player_____________ Years of Playing Experience _______________

1. Listed are reported knee injuries for tennis, please circle those you have seen before and indicate the USTA level of player involved if known. Enter "unknown" otherwise.

- Meniscus damage Level of player_______________
- Lateral Collateral Ligament Damage Level of player _________________
- Medical Collateral Ligament Damage Level of player _________________
- Anterior Collateral Ligament Damage Level of player __________________
- Posterior Collateral Ligament Damage Level of player __________________
- Patellar Femoral Syndrome Level of player _________________
- Bursitis Level of player _________________
- Knee Osteoarthritis Level of player _________________
- Other (please specify) Level of player _________________

____

2. In your expert opinion, what 3 types of tennis strokes and/or movements place the largest demands on the dominant knee during play? Dominant Leg is defined as the same side as the racket arm i.e. right handed player, dominant leg is the right.

1) ____
2) ____
3) ____

3. Can you elaborate on the footwork specifics for the types of tennis strokes and/or movements you identified? Please also circle which direction is associated with the identified stroke/movement.

1) A. Lateral (side of body) B. Frontal (front of body) C. Diagonal (Cutting movement)

____
____
____
____
____

2) A. Lateral (side of body) B. Frontal (front of body) C. Diagonal (Cutting movement)

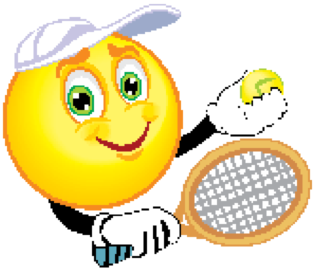
3) A. Lateral (side of body) B. Frontal (front of body) C. Diagonal (Cutting movement)

4. If you have any additional information you feel would be beneficial please write below.

Thanks you for your time and opinion. If you would be prepared to be contacted for additional information please check here □ Email_________________________________

APPENDIX E

THE UNIVERSITY of TENNESSEE UT
KNOXVILLE



SUBJECTS NEEDED FOR TENNIS STUDY

THE UT BIOMECHANICS/SPORTS MEDICINE LAB IS TESTING HOW DIFFERENT TENNIS MOVEMENTS AFFECT THE KNEE

- We will use our lab equipment to test 4 different tennis movements and how each of these affect the knee
- The testing only requires ONE visit to the lab to complete

You will be eligible for testing if you are

- A healthy male or female of USTA Level 4 upwards
- Aged 18 – 45 years of age
- Not currently injured

For more information please contact **Louise Beggs** (865) 974-2091 **or email** LBeggs@utk.edu

Louise Beggs
LBeggs@utk.edu
865 974 2091

Louise Beggs
LBeggs@utk.edu
865 974 2091

Louise Beggs
LBeggs@utk.edu
865 974 2091

Louise Beggs
LBeggs@utk.edu
865 974 2091

Louise Beggs
LBeggs@utk.edu
865 974 2091

Louise Beggs
LBeggs@utk.edu
865 974 2091

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LBeggs@utk.edu
865 974 2091

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865 974 2091

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LBeggs@utk.edu
865 974 2091

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LBeggs@utk.edu
865 974 2091

Louise Beggs
LBeggs@utk.edu
865 974 2091

APPENDIX F

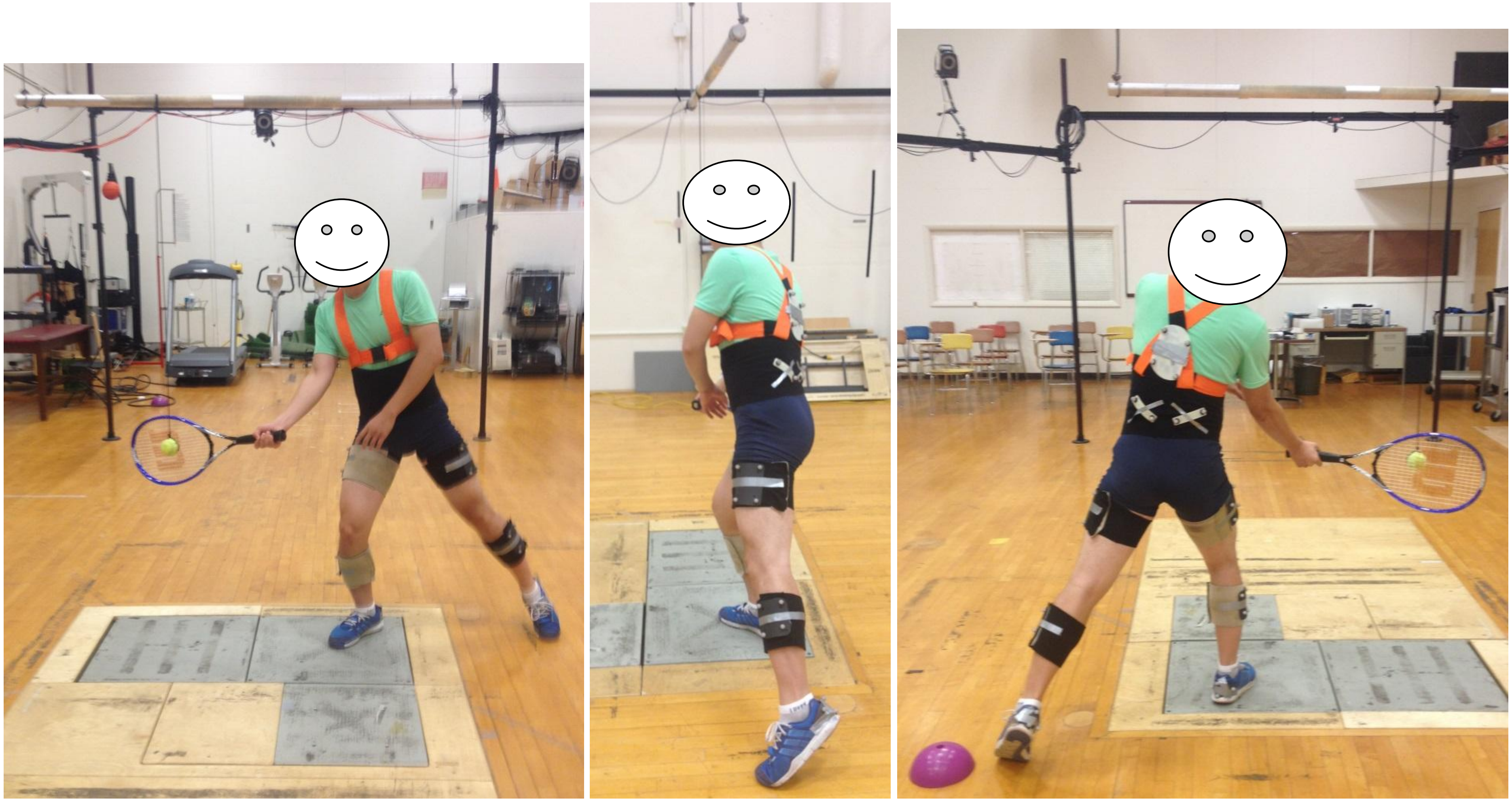

Figure 1. Laboratory set up

Table 3. Individual Subject Characteristics

Subject	Age	NTRP Level	Height	Weight	BMI	Gender	Shoe Brand	Dominant Side
1	20	4.5	1.665	54.5	19.67	F	Nike Tennis	Right
2	23	4	1.69	70.7	24.7	M	Nike Free	Right
3	45	4	1.62	62.3	23.7	F	Adidas Tennis	Right
4	25	5.5	1.99	94.8	23.4	M	Nike Free	Right
5	29	4.5	1.755	92.7	30.1	M	Nike Sneakers	Left
6	42	4.5	1.71	79.5	27	M	Adidas Tennis	Right
7	30	4.5	1.65	53.4	19.6	F	New Balance Tennis	Right
8	24	5	1.665	60.2	21.7	F	Nike Tennis	Right
9	37	4.5	1.665	51.8	18.7	F	Nike Tennis	Left
10	25	5	1.615	56.7	21.3	F	Nike Tennis	Right
Mean	30	4.6	1.7025	67.66	22.987			
Standard Deviation	8.52	0.46	0.109	16.14	3.58			

Table 4. Individual Subject GRF and Ankle Kinetic and Kinematic Variables in Lateral Step: Mean STD

Variables	Peak Vertical GRF (N)	Time Peak Vertical GRF (s)	Loading Rate Peak VGRF (N/s)	Peak Medial GRF (N)	Plantarflexion ROM (deg)	Peak Plantarflexion Moment (Nm/kg)	Inversion ROM (deg)	Peak Eversion Moment (Nm/kg)
Subject								
1	0.912±0.176	0.185±0.066	5.220±1.093	0.338±0.065	-9.389±16.859	-0.936±0.071	1.639±0.882	-0.157±0.034
2	3.287±0.380	0.018±0.005	195.706±60.669	1.061±0.244	-9.745±7.889	-0.822±0.202	12.076±2.968	-0.236±0.059
3	1.390±0.129	0.093±0.048	17.383±6.249	0.510±0.077	.±.[1]	-1.205±0.163	6.000±0.915	-0.283±0.046
4	1.137±0.228	0.069±0.034	18.312±5.585	0.532±0.055	-15.082±8.839	-1.128±0.285	10.212±3.159	-0.369±0.056
5	0.949±0.182	0.072±0.006	13.102±1.759	0.336±0.098	-31.410±2.721	-0.807±0.152	10.250±2.040	-0.515±0.169
6	1.491±0.125	0.233±0.139	9.973±7.792	0.469±0.082	-21.614±1.932	-1.261±0.161	5.212±1.710	-0.238±0.063
7	0.872±0.049	0.047±0.005	18.672±2.587	0.334±0.016	19.933±3.231	-1.195±0.029	1.245±1.109	-0.168±0.008
8	1.478±0.102	0.140±0.022	10.904±2.885	0.501±0.104	-20.789±2.043	-1.112±0.374	6.280±4.302	-0.161±0.064
9	1.631±0.090	0.151±0.010	10.877±1.108	0.533±0.094	-18.013±3.350	-0.750±0.203	6.269±1.445	-0.158±0.100
10	1.039±0.107	0.123±0.088	11.311±5.353	0.315±0.017	-13.386±2.825	-0.640±0.114	11.481±1.091	-0.243±0.033

[1] Not 'available'

Table 5. Individual Subject Knee Kinetic and Kinematic Variables in Lateral Step -: Mean ± STD

Variables	**Peak Flexion Angle (deg)**	**Flexion ROM (deg)**	**Peak Extensor Moment (Nm/kg)**	**Time to Peak Extensor Moment (s)**	**Peak Adduction Angle (deg)**	**Adduction ROM (deg)**	**Peak Abduction Moment (Nm/kg)**
Subject							
1	-67.119±3.676	-42.736±4.858	1.206±0.327	0.239±0.043	7.540±1.830	7.660±1.397	-0.310±0.199
2	-72.477±1.686	-14.140±5.353	1.848±0.275	0.157±0.009	14.744±0.685	2.882±0.673	-0.468±0.283
3	-55.751±6.004	-34.066±4.481	0.994±0.122	0.165±0.028	.±.[2]	.±.[3]	-0.151±0.021
4	-56.843±11.036	-27.607±9.331	2.177±0.401	0.233±0.021	-0.589±2.187	4.764±1.661	0.038±0.112
5	-27.290±5.535	-16.345±5.688	0.364±0.313	0.228±0.061	3.831±0.587	0.486±0.945	-0.265±0.099
6	-60.123±4.515	-37.325±4.934	1.421±0.157	0.179±0.019	1.041±0.617	1.110±1.141	-0.286±0.047
7	-52.433±3.733	-28.470±2.867	0.837±0.077	0.172±0.030	9.821±2.747	17.310±3.001	-0.167±0.071
8	-40.185±2.420	-18.295±2.339	0.801±0.159	0.225±0.060	3.465±2.989	11.530±3.100	-0.435±0.192
9	-47.291±2.814	-31.547±3.221	1.612±0.148	0.179±0.016	2.348±1.122	10.783±0.789	-0.548±0.206
10	-38.873±8.298	-15.376±8.676	1.387±0.191	0.285±0.025	14.627±1.415	19.344±1.586	-0.335±0.083

[2] Not ‘available’
[3] Not ‘available’

Table 6. Individual Subject GRF and Ankle Kinetic and Kinematic Variables in Lateral Lunge : Mean ± STD

Variables	**Peak Vertical GRF (N)**	**Time Peak Vertical GRF (s)**	**Loading Rate Peak VGRF (N/s)**	**Peak Medial GRF (N)**	**Plantarflexion ROM (deg)**	**Peak Plantarflexion Moment (Nm/kg)**	**Inversion ROM (deg)**	**Peak Eversion Moment (Nm/kg)**
Subject								
1	1.678±0.177	0.048±0.007	35.967±8.857	0.737±0.053	-8.155±12.806	-0.925±0.201	6.909±1.626	-0.363±0.087
2	2.763±0.110	0.018±0.003	161.339±37.163	1.549±0.084	-35.254±12.889	-0.923±0.378	22.240±10.351	-0.333±0.081
3	1.782±0.304	0.053±0.016	36.362±12.513	0.757±0.078	-17.252±9.508	-1.246±0.081	10.055±2.891	-0.368±0.051
4	2.869±0.429	0.021±0.015	185.120±94.240	1.514±0.120	-37.679±4.402	-0.975±0.194	16.658±2.812	-0.502±0.034
5	1.855±0.116	0.028±0.018	84.704±35.549	0.856±0.039	-30.730±4.544	-0.730±0.052	3.672±1.161	-0.346±0.069
6	1.511±0.072	0.193±0.020	7.896±0.869	0.637±0.039	-25.116±3.011	-1.017±0.133	4.287±1.387	-0.350±0.038
7	1.635±0.139	0.055±0.042	39.128±15.435	0.825±0.101	-9.262±4.429	-1.211±0.128	19.399±2.658	-0.493±0.079
8	2.441±0.363	0.055±0.002	44.767±8.099	1.182±0.206	-28.993±3.359	-1.060±0.246	13.342±1.603	-0.384±0.080
9	1.790±0.063	0.062±0.003	28.754±1.302	0.777±0.038	-23.052±5.893	-0.858±0.168	12.820±2.555	-0.298±0.044
10	1.550±0.233	0.124±0.048	15.151±9.628	0.574±0.099	-18.289±3.738	-1.114±0.076	17.301±6.304	-0.403±0.151

Table 7. Individual Subject Knee Kinetic and Kinematic Variables in Lateral Lunge : Mean ± STD

Variables	Peak Flexion Angle (deg)	Flexion ROM (deg)	Peak Extensor Moment (Nm/kg)	Time to Peak Extensor Moment (s)	Peak Adduction Angle (deg)	Adduction ROM (deg)	Peak Abduction Moment (Nm/kg)
Subject							
1	-71.037±3.232	-51.463±5.647	1.830±0.078	0.153±0.015	4.130±2.312	5.685±3.983	-0.233±0.105
2	-82.370±2.951	-32.617±5.700	1.952±0.187	0.140±0.031	18.699±5.846	10.147±5.954	-0.429±0.193
3	-55.495±1.479	-41.698±4.866	1.428±0.210	0.125±0.016	-3.566±3.918	.±.[4]	-0.282±0.191
4	-60.709±5.342	-30.158±3.954	2.912±0.364	0.101±0.002	2.172±1.420	3.563±1.870	-0.074±0.166
5	-71.463±2.302	-49.716±2.291	1.688±0.067	0.199±0.016	7.565±2.701	-1.506±3.279	-0.364±0.149
6	-60.094±3.421	-37.489±2.743	1.796±0.182	0.187±0.017	-0.479±0.951	1.873±1.255	-0.428±0.047
7	-75.948±4.887	-42.537±2.458	2.468±0.173	0.133±0.012	4.610±2.294	12.575±1.972	-0.352±0.076
8	-51.080±6.784	-27.960±7.704	1.970±0.162	0.121±0.012	10.935±2.596	17.653±0.657	-0.701±0.125
9	-47.855±3.086	-35.761±3.830	1.727±0.128	0.151±0.002	1.817±0.333	9.207±1.049	-0.452±0.080
10	-56.166±3.420	-35.320±3.702	1.679±0.228	0.185±0.041	15.840±1.303	18.735±0.635	-0.756±0.156

[4] Not 'available'

Table 8. Individual Subject GRF and Ankle Kinetic and Kinematic Variables in Diagonal Step : Mean ± STD

Variables	**Peak Vertical GRF (N)**	**Time Peak Vertical GRF (s)**	**Loading Rate Peak VGRF (N/s)**	**Peak Medial GRF (N)**	**Plantarflexion ROM (deg)**	**Peak Plantarflexion Moment (Nm/kg)**	**Inversion ROM (deg)**	**Peak Eversion Moment (Nm/kg)**
Subject								
1	1.286±0.111	0.037±0.003	35.168±5.631	0.367±0.029	9.951±3.244	-0.630±0.077	-1.480±2.946	-0.103±0.021
2	2.742±0.779	0.031±0.005	95.184±49.044	0.759±0.232	.±.[5]	-1.076±0.261	1.119±1.317	-0.131±0.042
3	1.316±0.076	0.167±0.020	8.020±1.332	0.413±0.037	-20.310±4.185	-0.988±0.177	0.431±0.761	-0.111±0.088
4	1.180±0.111	0.090±0.096	42.055±36.839	0.417±0.089	-14.565±3.440	-1.000±0.176	6.826±3.676	-0.312±0.071
5	0.914±0.311	0.092±0.082	13.453±6.358	0.306±0.054	-31.630±2.835	-0.679±0.333	3.104±2.816	-0.528±0.125
6	1.436±0.062	0.255±0.053	5.846±1.266	0.471±0.126	-27.082±3.231	-1.285±0.124	7.179±2.033	-0.224±0.058
7	1.205±0.032	0.233±0.049	5.401±1.432	0.332±0.021	-4.340±1.479	-1.114±0.115	6.192±1.782	-0.144±0.014
8	1.504±0.059	0.154±0.014	9.824±1.135	0.448±0.042	-28.062±1.058	-1.268±0.229	5.441±1.628	-0.124±0.019
9	1.541±0.105	0.128±0.047	15.271±11.389	0.393±0.025	-11.041±3.294	-0.705±0.184	4.272±0.620	-0.130±0.067
10	1.083±0.042	0.184±0.013	5.907±0.564	0.297±0.015	-7.574±3.074	-0.680±0.152	7.419±1.060	-0.152±0.014

[5] Not 'available'

Table 9. Individual Subject Knee Kinetic and Kinematic Variables in Diagonal Step : Mean ± STD

Variables	**Peak Flexion Angle (deg)**	**Flexion ROM (deg)**	**Peak Extensor Moment (Nm/kg)**	**Time to Peak Extensor Moment (s)**	**Peak Adduction Angle (deg)**	**Adduction ROM (deg)**	**Peak Abduction Moment (Nm/kg)**
Subject							
1	-65.404±3.441	-39.719±2.895	1.213±0.144	0.165±0.021	3.131±1.171	2.310±0.520	-0.383±0.038
2	-63.534±2.024	-21.495±4.622	1.247±0.241	0.155±0.041	11.915±1.334	6.280±2.727	-0.722±0.086
3	-41.269±2.692	-27.690±4.128	0.842±0.128	0.158±0.013	7.089±0.805	8.779±1.246	-0.689±0.131
4	-53.791±1.970	-26.801±3.985	1.857±0.433	0.218±0.074	1.966±0.970	7.888±2.146	-0.221±0.076
5	-54.765±3.777	-41.266±2.865	2.103±0.387	0.274±0.026	4.616±0.966	0.265±0.653	-0.099±0.084
6	-59.837±4.475	-37.314±2.964	1.357±0.152	0.222±0.072	4.323±1.623	3.634±2.103	-0.431±0.071
7	-79.574±6.536	-44.342±3.907	1.881±0.108	0.244±0.071	-1.115±2.979	7.830±3.700	-0.023±0.064
8	-45.092±3.716	-27.121±3.363	1.098±0.194	0.188±0.007	3.496±2.624	11.329±2.627	-0.519±0.112
9	-49.404±3.815	-34.090±2.806	1.516±0.192	0.168±0.019	-7.625±1.096	3.538±1.154	-0.065±0.098
10	-49.534±3.870	-30.932±4.473	1.317±0.106	0.346±0.019	12.015±1.971	14.305±1.544	-0.339±0.032

Table 10. Individual Subject GRF and Ankle Kinetic and Kinematic Variables in Diagonal lunge: Mean ± STD

Variables	Peak Vertical GRF (N)	Time Peak Vertical GRF (s)	Loading Rate Peak VGRF (N/s)	Peak Medial GRF (N)	Plantarflexion ROM (deg)	Peak Plantarflexion Moment (Nm/kg)	Inversion ROM (deg)	Peak Eversion Moment (Nm/kg)
Subject								
1	1.836±0.298	0.059±0.003	31.373±6.027	0.696±0.164	-29.139±12.058	-0.739±0.134	2.099±6.510	-0.131±0.107
2	1.787±0.203	0.045±0.006	40.458±4.495	0.841±0.116	-41.672±7.044	-0.957±0.329	15.389±6.403	-0.120±0.070
3	2.033±0.094	0.058±0.012	36.180±8.077	0.606±0.064	-24.340±10.889	-1.137±0.142	0.008±5.179	.±.[6]
4	2.692±0.123	0.015±0.000	177.678±11.460	0.699±0.139	-24.253±9.851	-0.878±0.234	6.635±1.394	-0.171±0.059
5	1.393±0.129	0.019±0.001	74.655±6.636	0.501±0.029	-24.336±3.912	-0.837±0.078	-3.785±4.110	-0.202±0.033
6	1.552±0.354	0.067±0.006	23.467±6.902	0.748±0.131	-27.242±4.922	-1.127±0.085	4.816±1.135	-0.327±0.088
7	1.625±0.166	0.035±0.003	47.084±7.502	0.548±0.080	-9.308±1.904	-1.032±0.217	15.990±4.410	-0.313±0.111
8	1.904±0.184	0.050±0.007	38.882±8.382	0.748±0.068	-24.281±1.617	-1.394±0.101	1.731±1.336	-0.216±0.006
9	1.820±0.150	0.054±0.006	34.467±5.613	0.555±0.067	-18.605±1.190	-0.987±0.057	2.938±1.480	-0.144±0.051
10	1.468±0.090	0.119±0.062	17.243±12.054	0.409±0.041	-13.378±4.442	-1.027±0.153	6.307±5.350	-0.165±0.057

[6] Not ‘available’

Table 11. Individual Subject Knee Kinetic and Kinematic Variables in Diagonal Lunge : Mean ± STD

Variables	Peak Flexion Angle (deg)	Flexion ROM (deg)	Peak Extensor Moment (Nm/kg)	Time to Peak Extensor Moment (s)	Peak Adduction Angle (deg)	Adduction ROM (deg)	Peak Abduction Moment (Nm/kg)
Subject							
1	-65.671±4.700	-42.893±5.023	2.055±0.140	0.144±0.022	4.937±1.646	0.193±1.533	-0.591±0.066
2	-79.899±9.145	-30.975±9.488	1.649±0.269	0.127±0.028	13.503±1.957	9.295±2.550	-0.246±0.258
3	-52.422±3.005	-38.151±4.500	1.951±0.136	0.105±0.005	10.361±2.954	9.308±2.031	-1.031±0.184
4	-61.636±4.194	-30.755±1.739	2.942±0.405	0.119±0.023	1.047±0.801	7.539±1.713	0.021±0.087
5	-80.411±2.727	-60.711±3.946	1.912±0.089	0.210±0.021	6.750±0.812	1.312±0.530	-0.151±0.039
6	-61.598±3.717	-37.594±4.504	2.033±0.220	0.155±0.017	0.715±0.947	4.275±1.101	-0.655±0.047
7	-82.353±2.963	-50.112±4.073	2.484±0.075	0.116±0.008	6.518±1.852	9.724±3.010	-0.313±0.088
8	-46.883±1.789	-23.974±3.438	2.311±0.278	0.118±0.006	-4.768±0.728	2.678±1.729	-0.472±0.053
9	-49.647±4.925	-37.181±5.019	1.903±0.302	0.134±0.005	-2.916±0.713	6.671±1.214	-0.265±0.125
10	-49.257±3.268	-27.977±5.037	1.386±0.159	0.228±0.045	16.683±4.022	19.147±3.990	-0.824±0.097

VITA

Louise Beggs was born in Belfast, Northern Ireland, to the parents of Robert and Barbara Beggs. She is the youngest of three, Deborah and Graeme. She attended Towerview Primary School and continued to Glenlola Collegiate School in Bangor, Northern Ireland. After graduation, she headed to Northumbria University in Newcastle Upon-Tyne, England, where she was introduced to Sport and Exercise Science and Biomechanics. Louise obtained a Bachelor of Science degree with honours from Northumbria University in 2003 in Sport and Exercise Sciences. Louise then worked in Aberdeen, Scotland, following graduation as an Active Schools Coordinator. She accepted a place at the University of Tennessee in the Kinesiology department with a concentration in Biomechanics, and a Graduate Teaching Associate position in the Physical Education Department in 2012. She graduated with a Master of Science Degree in 2014.