PLAYER PERCEPTIONS AND BIOMECHANICAL RESPONSES TO TENNIS COURT SURFACES: THE IMPLICATIONS TO TECHNIQUE AND INJURY RISK

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

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Abstract

Elite tennis players are required to perform on a variety of tennis court surfaces which differ in mechanical characteristics, such as friction and hardness, influencing their performance and risk of injury. To understand the influence of surfaces on performance and injury risk, three studies were conducted to investigate tennis players' perceptions and biomechanical responses during tennis-specific movements on different court surfaces. In study 1, tennis players perceptions of acrylic and clay courts were identified following a thematic inductive analysis of semi-structured interviews (n = 7) to develop of a series of visual analogue scales (VAS) to quantify perceptions during studies 2 and 3. Perceptions of predictability of the surface and players' ability to slide and change direction emerged, in addition to anticipated perceptions of grip and hardness. Study 2 aimed to examine the influence of court surfaces and prior clay court experience on perceptions and biomechanical characteristics of tennis-specific skills. Perception, kinematic, insole pressure and mechanical data were collected on an acrylic and a clay court. In agreement with findings reported in study 1, lower mechanical friction and hardness on the clay court were perceived and accompanied by less predictability and greater difficulty to change direction whilst being easier to slide. As result of sliding, players' adopted an altered technique on the clay court compared to the acrylic leading to reductions in loading provide evidence to explain lower injury risks previously reported on clay courts. Prior clay court experience did not influence players' perceptions. However, biomechanical response to the clay surface differed, such that players with high clay court experiences contacted the ground with an everted foot, believed to contribute to controlling sliding. Differences in perception-response relationships were reported between experience groups suggesting players with greater clay court experience are better able to choose an appropriate response to improve their performance. Friction properties of the surface may change during play on clay courts due to player movements and sliding on the court. Therefore there may be areas of expected and unexpected changes to friction to which players must

respond to. Study 3 aimed to examine the influence of changes in friction and players awareness of these changes on perceptions and biomechanical response. Compared with study 1 and 2, players found it more difficult to identify differences in perceived grip during study 3, possibly due the smaller mechanical friction differences reported. Unexpected reductions in friction produced greater initial ankle inversion angles compared to the expected decreases in friction, increasing players' risk of injury. Lower horizontal and vertical loading rates were reported on the lower friction conditions where further sliding was reported; suggesting a reduced injury risk by allowing longer time spent applying the forces.

This thesis has identified key perception variables that enabled a holistic understanding of perceptions and their interaction with biomechanical response. Mechanical friction was an important factor influencing players' ability to slide. Sliding on clay resulted in altered loading characteristics, pressure distributions and kinematics potentially reducing players' injury risk. Tennis players' experience of clay courts does not influence their perceptions of the surface but the response that players adopt, which lower their risk of injury and increase performance. It is important when playing on a clay court that friction properties are maintained across the court during a tennis match as much as possible to reduce injury risks, due to the influence of unexpected changes to friction on perceptions and response.

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Symbols and Abbreviations

COM_d	Centre of mass moment arm
COM_{seg}	Segment centre of mass
COP_d	Centre of pressure moment arm
COP_{seg}	Location of force on segment
GRF_{seg}	Ground reaction force applied to the segment
M_{GRF}	Moments applied by the GRF
M_{eff}	Moments applied by the acceleration forces
M_{joint}	Joint moment
M_{weight}	Moments of the weights of the segments
RF_{seg}	Reference frame
T_q	GRF torque
a_{seg}	Segment COM acceleration component
m_{seg}	Mass of the segment
α_{seg}	Segment angular acceleration
AA	Artificial Athlete
AAA	Advanced Artificial Athlete
ACL	Anterior cruciate ligament
ANOVA	Analysis of variance
BW	Body weight
COF	Coefficient of friction
COM	Centre of mass
COP	Centre of pressure
CPR	Court pace rating
DLT	Direct linear transformation
EMG	Electromyography
ES	Effect size
Exp	Experience group
Fshear	Shear force
Fshear	Shear force
Fx	Medio-lateral force
Fy	Anterior-posterior force

Fz	Vertical force
GRF	Ground reaction forces
HR	Heart rate
ICC	Intra-class correlations
ITF	International Tennis Federation
JCS	Joint coordinate system
L.Exp	Low-experience group
LTA	Lawn Tennis Association
LWD	Lightweight Deflectometer
M_a	Ankle moment
M_h	Hip moment
M_k	Knee moment
M_s	Support moment
R1	Reduction in friction 1
R2	Reduction in friction 2
R_{joint}	Resultant forces at the joint
RMSE	Root mean squared error
VAS	Visual analogue scale
Δ	Change in
I	Moment of interia
JC	Joint centre
g	Gravity

Declaration, Communications and Publications

This thesis was conducted in collaboration with the sport-surfaces research group established by the International Tennis Federation (ITF). Therefore mechanical data collected within this thesis was collected by colleagues in the Department of Mechanical Engineering at the University of Sheffield. All other material within this thesis is original work conducted and written by the author. The following communications and publications are a direct consequence of this work.

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Starbuck, C., Stiles, V., & Dixon, S. (Accepted). *The influence of changes in friction during turning on clay court surfaces*. Paper presented at the BASES.

Damm, L., Starbuck, C., Stocker, N., Clarke, J., Carré, M., & Dixon, S. (2014). Shoe-surface friction in tennis: influence on plantar pressure and implications for injury. *Footwear Science, DOI: 10.1080/19424280.2014.891659*.

Dixon, S. J., Damm, L., Starbuck, C., Clarke, J., & Carré, M. (2014). *Understanding player response to changes in shoe-surface friction during tennis-specific movements*. Paper presented at the 7th World Congress of Biomechanics.

Ura, D., Carré, M. J., Starbuck, C., & Dixon, S. J. (2014). Effect of varying the volume infill and on synthetic clay surfaces in terms of the shoe-surface friction. *Procedia Engineering, 72*, 877-882.

Starbuck, C., Damm, L., Stiles, V., Capel-Davies, J., Clarke, J., Carre, M., et al. (2013). *The influence of previous experience on clay on player response to tennis surfaces during a running forehand.* Paper presented at the BASES Biomechanics Interest Group, University of Wolverhampton.

Damm, L., Starbuck, C., Stocker, N., Clarke, J., Carré, M., & Dixon, S. (2012). *Plantar pressure depends on the playing surface in tennis.* Paper presented at the BASES Biomechanics Interest Group, University of Ulster.

Starbuck, C., Stiles, V., Miller, S., & Dixon, S. (2011). *Player perceptions of tennis surfaces.* Paper presented at the BASES Biomechanics Interest Group, University of Chichester.

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unexpected
response
tennis-specific
mechanical
friction
slide
players
differences
perceptions
surface
reported
suggesting
sliding
risk
greater
knee
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acrylic
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influence
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longer
properties
hardness
grip
predictability
ability
tennis

CHAPTER 1: INTRODUCTION

Tennis is a popular sport played worldwide on a variety of surfaces including clay, grass, acrylic, asphalt, and carpet. In particular, on the professional tour, players must adapt their movements and games to the changes in court surface with limited transition time. Players must adapt to these surfaces to achieve the balance and stability required to perform successful tennis shots. Differences in rally length and shot rate have been observed with changes in court surface, for example on clay, rally length averages approximately 7.7 s while on hard courts (acrylic) it is 5.8 s per rally (O'Donoghue & Ingram, 2001). Additionally, clay courts produce higher physiological responses, such as higher mean heart rates and blood lactate accumulation, compared to acrylic courts possibly due to altered movements (Reid et al., 2013). Either as a consequence of changes in performance (i.e. rally length, shot type, shot rate, types of movement) or separate to altered performance aspects, different court surfaces affect injury incidence (Nigg & Segesser, 1988). Clay surfaces are regarded as having the lowest injury frequency represented by 0.20 treatments per match compared to hard courts that are reported to have a frequency of 0.37 treatments per match (Nigg & Segesser, 1988; Bastholt, 2000), with clay courts observed to have lower incidence of knee injuries compared to acrylic courts (Kulund, McCue, Rockwell, & Gieck, 1979).

Changes in surface properties have been reported to alter human movement and loading, which influence injury risks and performance (e.g. movement and game style). Observations of tennis-specific skills have reported changes in ground reaction forces (GRF) on surfaces differing in cushioning (Stiles & Dixon, 2007) and friction (Damm et al., 2013). A longer braking phase and later peak knee flexion were reported during turning on high friction surfaces, suggested to be a strategy to lower joint loads (Durá, Hoyos, Martínez, & Lozano, 1999). Lower insole pressures were reported on clay surfaces compared to acrylic (Girard, Eicher, Fourchet, Micallef, & Millet, 2007; Damm et al., 2012), whilst clay courts resulted in increased horizontal forces, due to less knee flexion at impact, allowing for sliding (Damm et al., 2013). Changes in surface properties have therefore been reported to alter human movement and loading, which have been associated with difference in injury risk and performance (e.g. movement and game style).

Perceptions are a result of a dynamic process that allows us to respond to changes in our environment (Coren, Porac, & Ward, 1979; Sherwood, 1993; Visell, Giordano, Millet, & Cooperstock, 2011). Perceptions are an important contributor to improving understanding of human response to changes in surfaces (Hennig, Valianr, & Liu, 1996; Milani, Hennig, & Lafortune, 1997; Lake & Lafortune, 1998), given that loading rates have previously been associated with perceptions of surface cushioning (Stiles & Dixon, 2007). Mechanical tests are often used to characterise playing surfaces. Previous research has suggested differences in mechanical ranking of surface properties such as hardness (Dixon, Collop, & Batt, 2000) and friction (Durá et al., 1999) compared with biomechanical results on these surfaces. Therefore by examining perceptions, which provide information regarding players' experiences of tennis surfaces, improved understanding of the link between mechanical properties and biomechanical changes can be developed.

The overall aim of this thesis is to increase knowledge of the influence of tennis playing surfaces on player perceptions of these surfaces and their relationship to players' lower limb biomechanics. This information will benefit the characterisation of tennis surface properties and improve understanding of how perceptions of tennis surfaces relate to biomechanical variables which in turn are associated with injury risk and performance.

CHAPTER 2: LITERATURE REVIEW

2.1 Surfaces Properties and Mechanical Tests

Surfaces are complex structures, with multiple layers that contribute to their behaviour (Bartlet, 1999), and can be influential in performance (O'Donoghue & Ingram, 2001; Kerdok, Biewener, McMahon, Weyand, & Herr, 2002; Fernandez-Fernandez, Kinner, & Ferrauti, 2010) and injury risks (Nigg & Segesser, 1988; Bastholt, 2000). Differences in mechanical properties, in particular cushioning and friction, results in different responses or adaptations during running (Dixon, Collop, & Batt, 2005), turning (Durá et al., 1999) and tennis-specific skills (Girard et al., 2007; Stiles & Dixon, 2007; Damm et al., 2013).

Mechanical tests provide characteristics of playing surfaces (Carre, Hohnson, & Haake, 2002; Carre, James, & Haake, 2006; Clarke, Carré, Damm, & Dixon, 2013). Characteristics such as cushioning and surface stiffness have been reported to influence biomechanics of running and tennis strokes (Ferris & Farley, 1997; Dixon et al., 2000, 2005; Stiles & Dixon, 2007). Cushioning is described as the reduction in force and is often compared as ratio to force reduction properties of concrete (Dixon, Batt, & Collop, 1999). Surface stiffness is the ratio between peak force and displacement (Carre et al., 2006). Several mechanical tests have been devised to measure surface cushioning and stiffness these include the SERG impact hammer (Carre et al., 2006), the Lightweight Deflectometer (LWD; Fleming & Young, 2005), the Artificial Athlete (AA) and Advance artificial Athlete (AAA; Fleming, 2011).

The SERG impact hammer has previously been used to indicate mechanical differences between clay and acrylic courts (Damm et al., 2013; Damm et al., 2014). The SERG impact hammer was originally designed to examine ball-surface interactions (Carre et al., 2006) therefore does not replicate human loading during dynamic tennis movements however the device is able to rank surfaces according to the impact properties. The LWD measures load and deflection, the device is flexible in determining drop height, contact area and contact duration, therefore can be adjusted to different loading patterns observed during sporting movements (Fleming & Young, 2005). The Artificial Athlete was first developed to replicate peak impact force of heel-toe running on athletic tracks (Fleming, 2011). The Artificial Athlete measures force reduction when a 20 kg weight is dropped at 55 mm onto a sprung bearing plate (Fleming, 2011). The Artificial Athlete was further developed into the Advanced Artificial Athlete which incorporated an accelerometer which enables peak surface deformation and the energy restitution to be measured (Fleming, 2011). Biomechanical research has highlighted humans ability to adapt to changes in surface cushioning within the first contact with the surface through kinematic and joint stiffness alterations (Ferris, Liang, & Farley, 1999), which mechanical tests are unable to replicate. Mechanical devices provide some indication of which surface has more cushioning however the device are unable to replicate human loading and account for biomechanical measures such as running velocity, foot placement player mass and individual variations which influences loading (Caple, 2011).

The Pendulum test is currently the standard portable test for examining dynamic friction (British Standards, 2002). However, reports have identified that the average normal loading of the pendulum device is 12 N (Lewis, Carré, Kassim, & Goforth, 2011), which is significantly lower than forces applied during running and dynamic tennis movements (Dixon et al., 2000, 2005; Damm et al., 2013). The pendulum device was designed to measure slipping, therefore does not replicate sliding which is often observed on clay courts. Other mechanical friction tests include the English XL which was developed to measure floor slipperiness when evaluating slip and fall incidences (Gravano et al., 2011). With low loading of 136 N, the English XL does not replicate the higher loading produced during tennis specific movements (Stiles & Dixon, 2007; Damm et al., 2013). The location and direction in which the English XL test is administered influences the results produced on non-uniform surfaces (Gravano et al., 2011), such as clay courts. Developing mechanical tests incorporating biomechanical measures provides an appropriate insight into loading on different tennis courts surfaces.

Recently a fixed traction test device was developed using biomechanical data to provide a more in-depth analysis of mechanical friction of playing surfaces (Clarke et al., 2013). Examination of an acrylic surface and a clay surface highlighted two typical friction regimes; the static regime and the dynamic regime (Clarke et al., 2013). Clarke et al. (2013) identified the static regime as the initial increase in traction force with minimal horizontal displacement. The peak traction force indicates the transition into the dynamic region where the force remained relatively constant with larger horizontal displacements. This transition at the peak traction force leads to the onset of a slip, alternatively in tennis peak traction force provides an indication to the onset of sliding (Clarke et al., 2013). Although the device provides peak and average friction measures the device does not reflect the dynamic nature of loading during movement illustrated in Figure 2.1. Mechanical friction devices provide a constant normal load throughout the test; therefore does not account for the varying loading and adaptations humans perform during sporting movements. During sliding on clay courts, an unloading of the normal force has been observed and suggested as a mechanism to grip and un-grip the clay surface during sliding (Damm et al., 2014), which is not replicated by current mechanical tests. However, the fixed traction device can provide a good indication of the frictional properties where the use of biomechanical factors such as foot angle can be adjusted (Clarke et al., 2013).

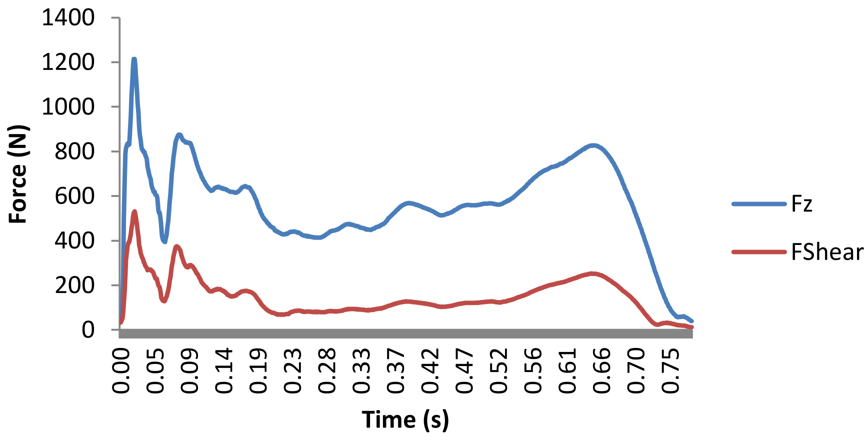

Figure 2.1: Example vertical (Fz) and horizontal (FShear) forces during a turning movement on a synthetic clay surface

Mechanical tests provide detailed profiles characterising surfaces, however there is little evidence of a correlation between mechanical test results from surfaces and biomechanical measures (Durá et al., 1999; Dixon et al., 2000). Existing mechanical measures for cushioning and friction have generally been unable to replicate biomechanical measures. For example peak impact forces during running were maintained on surfaces with mechanically different impact absorbing abilities (Dixon et al., 2000). Mechanical measures of coefficient of friction were greater than those measured during turning, possibly due to kinematic adaptations (Durá et al., 1999). Although mechanical tests provide characteristics of surfaces, they do not reflect tennis players experience on the surfaces, therefore both biomechanical and perceptual measures provides the link between mechanical properties and players experiences, which leads to the development of more appropriate mechanical tests.

2.1.1 The Influence of Cushioning Properties on Biomechanical Response

Cushioning is defined as the reduction in force applied and often results in changes in kinematics (Bartlet, 1999). Cushioned surfaces store and return elastic energy have been associated with reduced metabolic cost during running (Tung, Franz, & Kram, 2014). The varied amounts of cushioning between surfaces was previously regarded to account for the changes in injury risk due to excessive loads during running (James, Bates, & Osternig, 1978; Cavanagh & Lafortune, 1980; Nigg, 1986; Miller, 1990). However, studies have reported no such differences in GRF during running on surfaces with varied cushioning ability, possibly due to individual kinematic adjustments such as reduced ankle dorsi flexion and increased knee flexion (Dixon et al., 2000).

Stiles & Dixon (2006) initially investigated the running forehand foot plant on three tennis surfaces (cushioned acrylic hard court, carpet and sand-filled artificial turf) with respect to a concrete baseline (representing zero cushioning surface). Minimal and inconsistent kinematic changes failed to explain an unexpected reduction in peak vertical impact forces on the harder baseline surface. The small sample of players (6 females) that ranged greatly in experience (world-ranked to recreational) could have used different methods of coping with the changes in surfaces during this task orientated movement causing the variability and lack of significant kinematic changes between the surfaces (Stiles & Dixon, 2006). The authors were unable to ascertain which mechanical properties of the surfaces influenced the differences in GRF, likely due to the variation in both cushioning and friction when comparing existing playing surfaces in this manner.

By using a consistent top cover for all playing surface conditions, a later study was able to maintain frictional properties between surfaces with different cushioning (Stiles & Dixon, 2007). Using this approach, changes in GRF were detected during a running forehand foot plant (Stiles & Dixon, 2007), similar to previous reports (Stiles & Dixon, 2006). Reductions in average and peak loading rates and peak braking force were reported on surfaces with increased cushioning (Stiles & Dixon, 2007). Changes in peak heel pressures and peak heel loading rates coincided with changes in cushioning such that pressure increased with a reduction of cushioning. Increased surface deformation on the more cushioned surface, resulting in increased contact area was suggested to cause the reduction in pressure on the more cushioned surface. Following inconsistent group kinematic differences between surfaces, individual analysis showed some initial kinematic changes to surface cushioning, such as a reduction of heel impact velocity for the less cushioned conditions.

Surface cushioning properties have been reported to influence tennis players loading (Stiles & Dixon, 2007). However, current research have been unable to establish kinematic adjustments to surface cushioning that may account for differences observed in loading characteristics. Examining players' experiences on tennis courts with different cushioning properties will improve understanding of players adaptations to these changes in mechanical properties.

2.1.2 The Influence of Friction Properties on Biomechanical Response

Friction is the force acting in the opposite direction of motion between two contacting surfaces such as a shoe and playing surface (Bartlet, 1999; Dixon et al., 1999). Greater friction often leads to faster player movements; however excessive friction produces overloaded joints and results in injury, this is more apparent in sports with fast turning movements such as tennis (Durá et al., 1999; Nigg, Stefanyshyn, Rozitis, & Mundermann, 2009). Greater sprint performance has been previously associated with greater mechanical friction up until a critical point (coefficient of friction 0.82), where further increases in friction was suggested to increase risk of injury (Luo & Stefanyshyn, 2011). Alternatively low friction can lead to slipping and has been suggested to increase knee joint moments during turning movements (Fong, Mao, Li, & Hong, 2008; Nigg et al., 2009). In tennis, players utilise the lower friction available on clay surfaces by sliding (Miller, 2006; Damm et al., 2013). Tennis players tend to slide into a stroke so that on completion of the stroke they have finished sliding and are able to change direction immediately reducing time to turn on the slippery clay surface (Miller, 2006; Damm et al., 2013; Pavailler & Horvais, 2014). Sliding results in changes in loading and kinematics thus altering the injury profile on these surfaces (Damm et al., 2013).

Nigg et al. (2009) examined a side-shuffle and a v-cut movement on five surfaces ranging in sliding ability. Lower ankle moments and higher knee moments were produced on surfaces with greater sliding ability, suggesting reduced loading in the ankle and increased knee loading, which presents altered injury patterns on surfaces with different sliding properties (Nigg et al., 2009). The high knee adductor moments reported on sliding surfaces (Nigg et al., 2009) have been associated with patellofemoral pain (Stefanyshyn, Stergiou, Lun, Meeuwisse, & Worobets, 2006). However, high friction surfaces are often associated with greater knee injuries (Dowling, Corazza, Chaudhari, & Andriacchi, 2010). High friction has been reported to produce lower knee flexion angles and greater external knee flexion and knee valgus moments during cutting tasks resulting in an increased risk of anterior cruciate ligament (ACL) injuries (Dowling et al., 2010).

A study of in-shoe pressure data for 10 tennis players, reported whole foot pressure to be lower on clay courts compared to acrylic courts, as a results of longer contact times during baseline and serve and volley movements (Girard et al., 2007). Similar findings have been reported during on-court examination of a running forehand between artificial clay and indoor acrylic court and suggested to be due to adaptations in players' strategy for example sliding on clay (Damm et al., 2014). Higher loading on the hallux and lesser toe areas and lower loading on the medial and lateral midfoot regions were found on acrylic court compared to clay, suggesting a possibility of different injury patterns (Girard et al., 2007). The medial and lateral midfoot regions have been suggested to be sensitive to changes in pressure (Nurse & Nigg, 1999), therefore on the clay court greater midfoot pressure aiding in control of movement. On the acrylic court, where play tends to be more aggressive, greater loads whilst pushing off suggests sensitivity to maintaining balance during that phase of the movement (Nurse & Nigg, 1999). However, Damm et al. (2012) reported lower midfoot medial and lateral loads on clay, which was suggested to allow for sliding by preventing 'sticking' during a running forehand. Differences reported between the two studies are due to the number of steps analysed, differences in movements and differences between courts examined, therefore suggesting the influence of movements upon adaptations to surfaces. When performing a running forehand and a side jump COP (centre of pressure) location was reported to shift medially on a clay court compared to an acrylic court (Damm et al., 2014). The authors suggested this medial shift would aid sliding and prevent the lateral region of the foot from ‘ploughing’ into the clay infill top layer, thus reducing risk of inversion injuries by preventing fixation of the foot.

Lower levels of friction and increased risk of slip has been associated with a more ‘cautious’ gait in walking, which includes contacting the ground with a flatter foot and with greater knee flexion (Heiden, Sanderson, Inglis, & Siegmund, 2006). Lower friction was reported to reduce heel strike pressures and increase hallux pressures, possibly due to an increase in plantar flexion, in order to adapt and maintain balance (Fong et al., 2008). It must be noted that these studies examined walking and does not reflect kinematic and loading changes to surface friction during dynamic tennis movements.

Force plate data have revealed greater horizontal forces on clay suggested to facilitate sliding compared to an acrylic court (Damm et al., 2013). Greater knee extension at impact on a clay surface increases the utilised COF, whilst knee flexion at impact was suggested to better dissipate braking forces on the acrylic surface. This is unlike the ‘cautious’ gait previously reported in walking studies (Heiden et al., 2006; Fong et al., 2008), suggesting that when completing complex sporting movements players altering their kinematics in order to successfully perform a skill rather than prevent slip on low friction surfaces.

2.2 Dynamic Stability Control

The majority of sports require a high demand of dynamic stability to dissipate high loading as well as maintaining balance needed to perform dynamic movements such as a tennis strokes (Behm & Anderson, 2006). If dynamic stability cannot be maintained the ability to dissipate loading and maintain balance can result in increased risk of injury and reduced performance (Wuebbenhorst & Zschorlich, 2012). Previous research has suggested several strategies for stability control, these include reactive and anticipatory strategies (Patla, 2003).

When changes to the environment are not predicted or expected a reactive response occurs following sensory detection of these changes (Patla, 2003). Moritz & Farley (2004) examined unexpected changes in hardness during hopping, where an increase in ankle and knee flexion, reducing leg stiffness, occurred prior to any neural control and muscle activity. A reactive response to induced slipping when walking on mechanically controlled steel rollers, which could be locked or unlocked, included a flatter foot, elevated centre of mass, reduced braking impulse and an attenuated muscle response magnitude (Marigold & Patla, 2002).

Anticipatory strategies to surface changes occur from the identification of a potential perturbation from both visual input and past experiences (Patla, 2003). When changes are anticipated a response to these changes often begins prior to ground contact, for example increased knee flexion and muscle activity were observed prior to landing on an anticipated harder surface (Moritz & Farley, 2004). When lower friction surfaces are anticipated a more cautious gait occurred during walking (Cham & Redfern, 2002; Marigold & Patla, 2002;

Heiden et al., 2006). Responses included a reduction in the peak utilised coefficient of friction (COF), reducing slip potential, through reductions in shear forces (Cham & Redfern, 2002; Marigold & Patla, 2002). Further adaptions to the anticipated slippery trials were reduced hip, knee and ankle joint moments and shorter stance duration and stride length (Cham & Redfern, 2002). A flatter foot, greater initial knee flexion, reduced braking impulse, lower loading rate and increased anticipatory muscle activity have also been reported to occurred during anticipated changes to friction (Marigold & Patla, 2002; Heiden et al., 2006). Early knee flexor moments have been associated with walking on slippery surfaces (Cham & Redfern, 2002), which corresponds to the early activation of the tibialis anterior and bicep femoris (Marigold & Patla, 2002). Flexion at the knee and ankle were suggested to increase stability through lowering the centre of mass (COM) closer to the base of support (Cham & Redfern, 2002; Marigold & Patla, 2002). Following the actions of tibalis anterior and bicep femoris, the gastrocnemius and rectus femoris were then employed to control the lower limb and contribute to the large extensor moments to achieve support of the lower limb (Winter, 1980; Cham & Redfern, 2002; Marigold & Patla, 2002).

Friction properties of the surface may change during play on clay courts due to player movements and sliding on the court. Therefore there may be areas of expected and unexpected changes to friction level to which players must respond and attempt to maintain balance in order to successfully coordinate a tennis stroke. Previous literature examples that have examined expected and unexpected changes to surface friction focus on walking, where the aim is to reduce slipping. However, in tennis sliding is often used to aid performance during rapid decelerations, therefore it is more appropriate to examine response to surface changes through a more dynamic movement for a surface, such as clay, that encourages sliding.

2.3 Tennis Injury Risks

Injury incidence in tennis can vary between 0.04 to 3.0 injuries per 1000 hours as reported in a systematic review of 28 descriptive epidemiological tennis studies between 1966–2005 (Pluim, Staal, Windler, & Jayanthi, 2006). The varied incidence reported is most likely due to different methodologies and definitions used (Pluim et al., 2006; Abrams, Renstrom, & Safran, 2012). Lower extremity injuries are reported to be more prevalent in comparison to other body locations (Chard & Lachmann, 1987; Hutchinson, Laprade, Burnett, Moss, & Terpstra, 1995; Bylak & Hutchinson, 1998; Sallis, 2001; Pluim et al., 2006). Upper extremity injuries were often chronic overuse injuries, such as lateral epicondylitis (more commonly known as tennis elbow), whilst acute injuries, for instance ankle sprains, are more prevalent in the lower extremities (Pluim et al., 2006; Abrams et al., 2012).

2.3.1 Biomechanical Risk Factors of Lower Limb Tennis Injuries

Ankle inversion injuries are most commonly reported in tennis (Pluim, 2006; Abrams et al., 2012). Ankle inversion injuries typically occur when the foot is inverted and plantar flexed, its least stable position, producing stress to the taut talofibular ligament resulting in damage to the ligament (Beynnon, Murphy, & Alosa, 2002; Willems, Witvrouw, Delbaere, De Cock, & De Clercq, 2005; Brukner & Khan, 2010). Characteristically sudden ankle inversion sprains are a result of fixation of the foot, particularly on high friction surfaces (Newton et al., 2002), with high levels of ankle inversion angles during early stance

(Kristianslund, Bahr, & Krosshaug, 2011). Greater inversion angle reduces effectiveness of the everter moments to control the subtalar joint (Konradsen, Peura, Beynnon, & Renström, 2005). Greater everter moments are reported during high inversion angles (Konradsen et al., 2005) therefore weak everter muscles, observed in those with previous ankle injuries, reduced the everter moments required to prevent sudden inversion, thus increasing injury risk (Konradsen et al., 2005). A greater impulse in the lateral heel and a more lateral COP at push off have been associated with an increased risk of ankle inversion injuries due to less force needed to invert the ankle which reduces their ability to accommodate to changes in the surface (Willems et al., 2005; Girard et al., 2007).

Following injuries at the ankle in frequency of occurrence, knee injuries such as ACL and medial meniscal injuries and patellofemoral pain have been associated with the high demands in tennis (Bylak & Hutchinson, 1998; Abrams et al., 2012; Hjelm, Werner, & Renstrom, 2012). Patellofemoral pain is classified as a dull, aching pain in and around the patella (Perkins & Davis, 2006; Brukner & Khan, 2010). Onset of pain occurs during weight-bearing activities that involve a high volume of knee flexions such as tennis or running (Brukner & Khan, 2010). Loading of the patellofemoral joint has been calculated to be 0.5 body weights during walking and up to 7-8 bodyweights during stair climbing with the increased loading a result of greater knee flexion (Matthews, Sonstegard, & Henke, 1977). Repetitive weight bearing movements can lead to overloading the structures around the patella resulting in pain (Brukner & Khan, 2010). Knee extensor moments reported to support the knee during walking and running suggests the quadriceps to be working eccentrically during the support phase (Winter, 1980). It is suggested that longer time spent flexing at the knee, will lead to increased time the quadriceps are contracting eccentrically, thus potentially increasing risk of developing patellofemoral pain (Gecha & Torg, 1988; Stefanyshyn et al., 2006). High knee abduction moments, observed on sliding surfaces (Nigg et al., 2009), used to counteract the external adductor moments have also been associated with increased risk of patellofemoral pain (Stefanyshyn et al., 2006).

The ACL provides stability in the knee by preventing forward movement of the tibia in relation to the femur and controlling rotational movement, and is therefore important in the control of pivoting movements (Brukner & Khan, 2010). ACL injuries tend to occur during landing, pivoting and cutting movements when deceleration or acceleration occurs (Yu & Garrett, 2007). Risk factors included lower knee flexion, which increased shear forces, and valgus positioning during rotation of the tibia and femur (Yu & Garrett, 2007; Brukner & Khan, 2010). In tennis the degree in which the knee flexes during dynamic movements are influenced by mechanical surface properties (Dowling et al., 2010; Damm et al., 2013), thus altering ACL injury risks.

The menisci provides cushioning to absorb force during impact (Brukner & Khan, 2010). Injuries to the menisci are often a result of shear and compressive stresses during knee flexion and femoral rotation which exceed its ability to resist force during twisting movements (McDermott, 2006; Brukner & Khan, 2010). During a cross sectional study of 20 females, greater and earlier knee abductor moments, due to the medial orientation of GRF (Figure 2.2), as well as a higher degree of internal foot rotation during walking were associated with greater severity of reported medial menisci tears (Davies-Tuck et al., 2008).

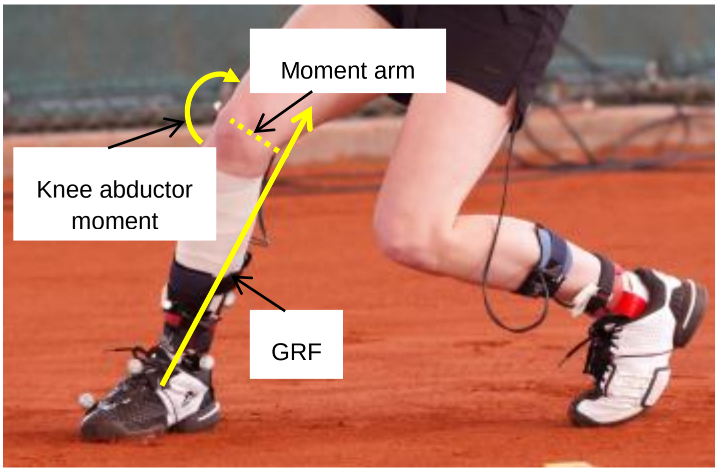

Figure 2.2: A schematic diagram illustrating the medial shift in GRF resulting in greater knee abductor moments

2.3.2 Tennis Surfaces and Injury

Differing injury frequencies have been associated with different tennis surfaces (Nigg & Segesser, 1988; Bastholt, 2000). Nigg & Segesser (1988) sent out questionnaires (25% response rate) to tennis players and reported differences in injury frequency of six tennis surface types (clay, synthetic sand, synthetic surface, asphalt, felt carpet and synthetic grill; Figure 2.3). Clay and synthetic sand resulted in the lowest incidence of injuries, whilst felt carpet and synthetic grill were reported to have up to 6 to 8 times greater injury frequency then clay. Due to the varied injury incidence between surfaces of assumed similar compliance, the authors proposed that friction contributed most to differences in injury frequencies in tennis.

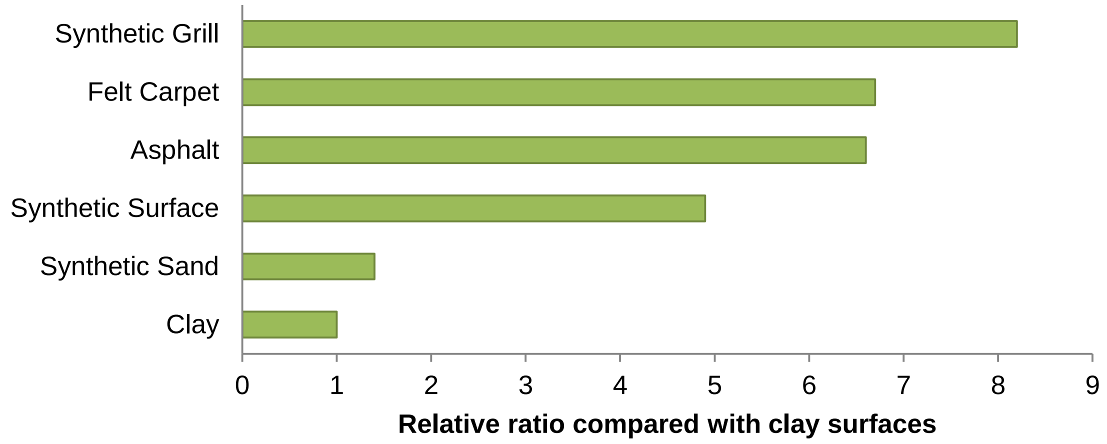

Figure 2.3: Relative ratios for injury risk of different tennis surfaces compared with clay (adapted from Nigg & Segesser (1988)

However, when adjusting for percentage playing time over the year there were no differences in injury risks between the hard courts and clay courts, providing an index of sustaining an injury 1.0 and 0.8 respectively (Hjelm et al., 2012). Lower extremity injuries were more prevalent on hard courts (56%) compared to clay (38%), yet no significant differences were reported (Hjelm et al., 2012). Observational evidence suggests that senior male tennis players who predominantly played on clay courts had fewer knee injuries compared to those who predominantly played on hard courts (Kulund et al., 1979). Greater injury frequency observed on hard courts are due to the higher loads and faster movements reported on these courts (Lynch & Renström, 2002; Dowling et al., 2010). Whilst clay courts, which are associated with lower injury rates, permit sliding, suggested to reduce stress on the lower extremities due to increased contact time (Durá et al., 1999).

It is apparent that lower limb injuries, in particular injuries at the knee and ankle are highly common in tennis (Pluim, 2006; Abrams et al., 2012). Studies have identifed surface properties in particular friction as a risk factor of lower limb injuries (Nigg & Segesser, 1988; Bastholt, 2000). Currently, there are no epidiomiological studies that have examined the incidence of specific injuries such as patellofemoral pain, on different court surfaces. Therefore it is difficult to identify which surface properties influence ankle and knee injuries. However, previous research has examined the relationship between surface properties and the risk of a particular injury risk during tennis and cutting movements (Stiles & Dixon, 2007; Nigg et al., 2009; Dowling et al., 2010; Damm et al., 2014).

2.4 Tennis Performance

Tennis is an intermittent sport where players experience short bouts (4 – 10 s) of high intensities, followed by short bouts (10 – 20 s) of rests during a match that can last from one to five hours (Christmass, Richmond, Cable, Arthur, & Hartmann, 1998; Fernandez, Mendez-Villanueva, & Pluim, 2006). Tennis players cover an average distance of 3 m per shot, totalling 8 – 12 m per point (Fernandez et al., 2006). The majority of tennis strokes (80%) are made within 2.5 m of the players' ready position, whilst 10% of strokes occur with 2.5 – 4 m and are suggested to primarily involve sliding (Verstegen & Marcello, 2002; Ferrauti, Weber, & Wright, 2003; Fernandez et al., 2006). Only 5% of strokes are over 4.5 m in distance, requiring player to run in order to return the ball (Fernandez et al., 2006). Tennis requires agility, coordination and balance to successfully perform movements such as baseline to net, close range, wide ball recovery and sprinting (Verstegen & Marcello, 2002; Ferrauti et al., 2003).

Greater physiological responses, such as higher mean heart rate and lactic acid accumulation have been reported on clay courts in comparison to acrylic courts (Murias, Lanatta, Arcuri, & Laino, 2007; Martin et al., 2011). However, these studies did not account for the influence of distance covered and duration of rallies, thus longer rallies associated with clay courts accounted for the greater physiological response (O'Donoghue & Ingram, 2001; Murias et al., 2007; Martin et al., 2011). When considering duration and distance covered, physiological (mean heart rate) and perceptual (rate of perceived exertion) responses were significantly greater on clay compared to an acrylic court, during two identical training sessions (Reid et al., 2013). Interestingly stroke production was not reported to alter physiological responses on clay and acrylic courts, rather stroke velocity was a better indicator of response (Fernandez-Fernandez et al., 2010). Altered movement patterns such as change in direction, or even sliding on clay provides an explanation to the greater physiological response observed when duration and distance are comparable.

Following examination of female players on an indoor acrylic court, increased physiological response was associated with longer rally duration, more strokes per rally and more changes of direction per rally (Fernandez-Fernandez, Mendez-Villanueva, Fernandez-Garcia, & Terrados, 2007). Therefore external factors such as surfaces, which influences style of play; types of movements (e.g. sliding), shot type, shot rate and rally length, as shown in Table 2.1, influences physiological response (O'Donoghue & Ingram, 2001; Johnson & McHugh, 2006). Rally length on clay was considerably longer than other tennis surfaces, a greater proportion of baseline points (52.8 ± 12.4%) were utilised, whilst at Wimbledon, where the playing surface is natural grass, the server approached the net more, reducing rally length (O'Donoghue & Ingram, 2001). A greater proportion of serves and volleys were reported during Wimbledon (grass) and US open (acrylic) compared to the French Open (clay), which had more ground strokes such as forehand topspins (Johnson & McHugh, 2006).

Table 2.1: Rally lengths and percentage baseline points of the four Grand Slams adapted from O'Donoghue & Ingram (2001)

Grand Slam	Rally Length (s)	% Baseline Points
Australian Open (Hard)	6.3 ± 1.8	46.6 ± 14.2
US Open (Hard)	5.8 ± 1.9	35.4 ± 19.5
Wimbledon (Grass)	4.3 ± 1.6*	19.7 ± 19.4*
French Open (Clay)	7.7 ± 1.7*	51.9 ± 14.2*

***Significantly (p<0.05) different from all other surfaces**

More aerobic fitness is required on the clay court compared to acrylic court due to the greater distances that are covered by players on clay (9.8 ± 2.5 m) compared to acrylic (7.7 ± 1.7 m) courts (Girard & Millet, 2004) and the greater proportion of baseline play on clay court compared to acrylic (Fernandez et al., 2006). Fast courts, such as grass and acrylic, result in players attempting to take advantage of the lack of time to produce winners, whereas clay courts (slow) result in tennis players building up a point and attempting to move their opponent around the court more.

From the literature, greater physiological responses (mean heart rate and lactic acid accumulation) were observed on clay courts when compared to acrylic courts (Murias et al., 2007; Martin et al., 2011). The greater response observed on clay courts was attributed to the different styles of play and longer rally length (O'Donoghue & Ingram, 2001). Additionally altered movements such as sliding on clay alters muscle activity and biomechanical measures which provides further understanding of increased physiological response such as greater heart rate (HR) and lactate accumulation on clay courts when rally length and distance covered are maintained.

2.5 Perception

2.5.1 Why Examine Perceptions?

Mechanical data, for both cushioning and friction, have been unable to replicate biomechanical responses (Durá et al., 1999; Dixon et al., 2000). Perceptions are an important link between mechanical properties and biomechanical changes, by providing further information of how the stimulus of surface properties influence human response (Fleming, Young, Roberts, Jones, & Dixon, 2005). Therefore, by further examining perceptions of surfaces will distinguish what variables are important and can be perceived by tennis players, but also provide understanding on how their perceptions inform their movement and therefore loads experienced on different tennis surfaces.

2.5.2 What are Perceptions?

Perceptions are subjectively formed, conscious awareness that an individual uses to interpret their environment (Carrterette & Friedman, 1973; Coren et al., 1979; Sherwood, 1993). Without this constant interpretation and awareness, we could not successfully interact with the environment (Sherwood, 1993; Visell et al., 2011). Figure 2.4, adapted from Goldstein (1999), represents the perceptual process highlighting the continuous and dynamic changing of perceptions. Changes in stimulus (e.g. touch) are detected by receptors such as mechanoreceptors in the skin, where sensory information is converted to electrical signals (Sherwood, 1993; Goldstein, 1999). These signals are transported to the brain (Sherwood, 1993; Goldstein, 1999). The brain continuously integrates and processes the information received and refers to previous experiences to respond appropriately to the situation (Coren et al., 1979; Gescheider & Bolanowski, 1991; Sherwood, 1993; Goldstein, 1999; Roberts, Jones, Harwood, Mitchell, & Rothberg, 2001). Five perceptual systems (auditory, visual, haptic, smell and taste and orientation of the body) identified by Coren et al. (1979) overlap and interact to provide a complete picture of our environment (Gibson & Carmichael, 1968; Coren et al., 1979; Holliins, Faldowski, Rao, & Young, 1993).

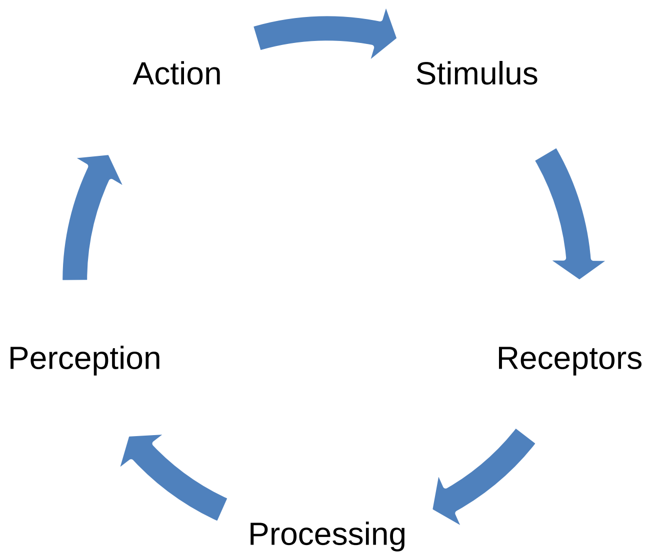

Figure 2.4: The perceptual process adapted from Goldstein (1999)

2.5.3 <u>Measuring Perceptions</u>

Both quantitative and qualitative approaches have been used to understand perceptions in sport. A qualitative approach provides a method of collecting explorative and in-depth data (Patton, 1990). Semi-structured interviews have been used previously to identify and construct relationships between player perceptions and artificial hockey surfaces (Fleming et al., 2005) and perceptions of sports equipment (Roberts et al., 2001). Fleming et al. (2010) used information gathered from interview data to inform and develop questionnaires, which then allowed for the collection of further perception information on a larger population and provide comparisons between different groups of runners.

Mathematical scales are used to quantify perceptions (Stevens, 1951). The use of ordinal, interval or ratio scales, to assign numbers to perceptions (Stevens, 1951; Saris, 1988) rely upon the ability to perceive a stimulus and make judgements on the intensity of the stimulus (Han, Song, & Kwahk, 1999). The reliability of different scales (ordinal, Likert and visual analogue scale) have been examined for perceived comfort of footwear during locomotion following a mixed linear model analysis of five repeated sessions (Mills, Blanch, & Vicenzino, 2010). Ordinal scales were the most reliable measure of comfort perception (Mills et al., 2010). However, the nature of ordinal scales only reveals the order of perceptions and does not report magnitude differences of perceptions (Stevens, 1951). A visual analogue scale (VAS) was able to provide magnitudes of perceptions and was found to be more reliable than a Likert scale.

VAS provide simple measures of subjective experience and have been suggested to have both interval and ratio properties (Aitken, 1969; Price, McGrath, Rafii, & Buckingham, 1983; McCormack, de L Horne, & Sheather, 1988). VAS are both versatile and easily constructed (Aitken, 1969; McCormack et al., 1988). Intra-class correlations of 10 consecutive sessions rating perceived comfort, revealed coefficients of 0.799 suggesting the VAS to be a reliable measure (Mündermann, Nigg, Stefanyshyn, & Humble, 2002).

Discriminative validity has been established for perception of pain where VAS was used to discriminate different intensities of experimentally induced pain (Price et al., 1983).

A VAS consists of a horizontal line, often 100 mm, with descriptive words for maximal and minimal extremes, known as anchor words (Aitken, 1969). Anchor words and line length are important considerations for reliability and sensitivity when constructing a VAS (Aitken, 1969; McCormack et al., 1988). Anchor words may be interpreted differently by different people (Aitken, 1969), therefore work and clarity of these words are needed before data collection. Line lengths of 100 mm to 150 mm have been recommended to have the greatest sensitivity (Stevens & Marks, 1980; Chaput, Gilbert, Gregersen, Pedersen, & Sjödin, 2010).

2.5.4 Perceptions of Surfaces

An inductive analysis of 22 semi-structured interviews conducted by Fleming et al. (2005) revealed that players were able to highlight differences between hockey pitches such as a ‘hard’ pitch or a ‘low’ ball bounce, which formed the basis for identifying key themes. These themes included pitch properties (e.g. pitch type), ball-surface interaction (e.g. ball bounce), player-surface interaction (e.g. surface grip), player performance (e.g. previous experience) and playing environment (e.g. irrigation). Relationships between these themes were established based on the overlap provided by quotes which allowed player perceptions of artificial surfaces and factors that influence perceptions to be identified, for example surface hardness was related to injury risk.

The perception of surfaces are important for the control of human locomotion enabling succinct and successful movements (Visell et al., 2011). Humans are able to perceive differences in surface cushioning and friction during tasks using both haptic and visual perceptions (Lockhart, Woldstad, Smith, & Ramsey, 2002; Joh, Adolph, Campbell, & Eppler, 2006). Studies have examined perceived friction or slip during walking studies, to establish safety considerations for working environments (Chiou, Bhattacharya, & Succop, 2000) and to understand the influence of previous experience and awareness (Heiden et al., 2006) and age (Lockhart et al., 2002) upon perception and response. Lockhart et al. (2002) identified possible adaptations to perceived slipperiness in 15 young and 15 elderly participants. They suggested that young participants were able to adapt to an increase in floor slipperiness by altering their peak utilised COF and slip distance. However, a degradation in perception of slipperiness and therefore lack of adaptations were observed in the elderly group (65 years or older).

Perceived cushioning has been examined in running studies (Hennig et al., 1996; Milani et al., 1997) and tennis-specific studies (Stiles & Dixon, 2007), to understand humans ability to identify differences in cushioning and the relationship with biomechanical variables. Correlations of GRF with perceptions of cushioning of shoes and surfaces have been observed (Hennig et al., 1996; Milani et al., 1997; Stiles & Dixon, 2007). High correlations between perceived cushioning and GRF variables such as loading rate, mean peak frequency and peak braking force have been reported (Hennig et al., 1996; Milani et al., 1997; Stiles & Dixon, 2007), where a reduction in perceived cushioning relates to an increase in loading rate and mean peak frequency and a reduction in braking force. Alterations in locomotion accounts for these changes in GRF to reduce injury risk (Hennig et al., 1996).

Plantar pressure provides sensory information to formulate perceptions of cushioning (Hennig et al., 1996; Nurse & Nigg, 1999). Plantar foot receptors and sensory information gained from these receptors are important in postural and movement control (Kennedy & Inglis, 2002; Visell et al., 2011). Peak heel pressures have been reported to correlate with perception of cushioning, such that as perceived cushioning increases, peak heel pressures are reduced (Hennig et al., 1996; Milani et al., 1997; Stiles & Dixon, 2007). Nurse & Nigg (1999) examined sensitivity to pressure stimuli in five locations (the heel, the lateral and medial arches, the first metatarsal head and the hallux) of the plantar foot. Their findings suggested that the heel was the least sensitive in response to pressure stimuli whilst greatest sensitivity occurred at the medial and lateral arches. Subjects who had greater plantar foot sensitivity were reported to have greater peak pressures at the hallux suggesting that the hallux was more functional in stability as centre of pressure moves forwards during push-off. During walking participants were able to perceive changes in midfoot cushioning (Witana, Goonetilleke, Xiong, & Au, 2009), suggesting sensory information gathered at midfoot region to be essential in establishing surface perceptions.

Previous experiences have been highlighted to be a key factor that influences perceptions (Coren et al., 1979; Gescheider & Bolanowski, 1991; Chiou et al., 2000; Roberts et al., 2001; Heiden et al., 2006). Chiou et al., (2000) suggested that those who were more cautious during their assessment of slipperiness of surfaces were then later more stable during workplace like tasks. While awareness of potential slip alters approach to surfaces, prior slip experience results in a more cautious gait for example greater knee flexion and flatter foot at ground contact and increase in anticipatory muscle activation (Heiden et al., 2006). The influence of previous experience of tennis surfaces has not been previously examined. Therefore investigating the influence of previous experience on tennis courts would reveal differences in perceptions and response to a specific surface type.

2.6 Summary

Tennis is one of the few sports which requires players to perform on a wide variety of court surface types throughout a season. These surfaces differ in mechanical properties such as cushioning or friction (Bartlet, 1999), and have been suggested to influence both performance and injury risk (Nigg & Segesser, 1988; O'Donoghue & Ingram, 2001). In tennis, lower extremity injuries (50-70%) are most prevalent, with acute ankle sprains and knee injuries commonly reported (Pluim et al., 2006; Abrams et al., 2012). Surfaces with lower frictional properties have been reported to reduce injury risk, particularly at the ankle (Nigg & Segesser, 1988; Bastholt, 2000).

Frictional properties have been reported to influence players movement (Damm et al., 2013) such as allowing for sliding on lower friction clay surfaces, reported to be beneficial when changing direction (Miller, 2006; Pavailler & Horvais, 2014). Differences in match play have been reported between the surface types, with longer rallies, greater distances run and slower shot rates on clay courts (O'Donoghue & Ingram, 2001). Changes in surfaces can result in changes in response such as changes to kinematics and loading, thus influencing injury risk and performance (Durá et al., 1999; Dixon et al., 2000;

Stiles & Dixon, 2006, 2007; Fong et al., 2008; Nigg et al., 2009; Girard, Micallef, & Millet, 2010).

The formation of perceptions allows humans to interact with their environment (Coren et al., 1979; Sherwood, 1993). Research has suggested that we are able to identify changes in surface differences such as friction and cushioning (Lockhart et al., 2002; Stiles & Dixon, 2007). The development of perceptions enable humans to choose appropriate responses to surfaces, therefore relationships between perceptions and biomechanical response provides an insight to different responses observed on tennis surfaces with different mechanical properties. Previously perceptions of friction was associated with altered utilised COF (Lockhart et al., 2002), whilst reduced cushioning perceptions were associated with increased loading rates (Hennig et al., 1996; Milani et al., 1997; Stiles & Dixon, 2007) thus providing some evidence for a perception response relationship.

2.7 Rationale

Examining perceptions of surfaces provides an insight into how players perceive tennis surfaces and how this influences their response to these surfaces (Hennig et al., 1996; Milani et al., 1997). Studies have examined the influence of cushioning and friction on perceptions. However, as reported by Fleming et al. (2005), there could be other variables unaccounted for which influence perceptions. To the author's knowledge perceptions of tennis surfaces have not previously been reported. In order to understand the perception response relationship with tennis surfaces, tennis player's perceptions of tennis courts must first be identified. The use of qualitative interview provides the explorative method (Patton, 1990) required to identify tennis players' perceptions.

Surfaces have been reported to influence performance (i.e. strategies and movements) and injury risk through changes in biomechanical variables during running (Dixon et al., 2005), turning (Durá et al., 1999; Nigg et al., 2009) and tennis-specific skills (Girard et al., 2007; Stiles & Dixon, 2007; Damm et al., 2013). The majority of these studies collected data in laboratory situations. Although this approach is more controlled compared to on-court analysis, an applied setting would provide a more realistic representation of human interaction with tennis surfaces, improving external validity. Pressure insoles provide a tool to examine loading during on-court scenarios. Studies have reported changes in pressures between tennis surfaces, where greater pressures were reported on higher friction surfaces (Girard et al., 2007) and on surfaces with least cushioning (Stiles & Dixon, 2007). Kinematic analysis provides information of how changes in loads are accounted for, for example changes in knee flexion at impact have been associated with alterations in horizontal forces during a tennis forehand foot plant (Damm et al., 2013) or ankle dorsi flexion adaptations have maintained GRF on cushioned surfaces during running (Dixon et al., 2005). Both pressure and kinematic data informs our understanding of injury risks and performance on different tennis surfaces.

Previous experience has been reported to influence both perceptions and response to surfaces (Coren et al., 1979; Heiden et al., 2006). Tennis players often spend the majority of their playing time on acrylic courts compared to clay courts (Hjelm et al., 2012); therefore experience on clay can differ between players influencing players' perceptions of the surface as well as their response to clay courts. Therefore the examination of prior clay court experience on perceptions and response is required to provide further insights into tennis players' response on tennis courts.

Friction has been suggested to be an influential factor to biomechanical response and have often been associated with injury incidences (Nigg & Segesser, 1988; Bastholt, 2000). To the author's knowledge no studies have examined different levels of friction on clay courts with minimal changes to other mechanical properties. Furthermore, changes in friction properties during a rally on clay may alter due to a player's movements, therefore resulting in expected and unexpected changes in friction which the player must adapt to. Previously expected and unexpected changes to surface properties have influenced the onset time of muscle activation and other biomechanical responses (Cham & Redfern, 2002; Marigold & Patla, 2002). However, recent studies have focussed on walking or hopping therefore further research examining tennis specific movements aiding in understanding of players response to changes in clay court properties.

2.8 Thesis Aims

This thesis aims to examine the influence of tennis court surface properties on players' perceptions and biomechanical responses. By understanding tennis perceptions and players' response to surfaces the current thesis will provide the information required by the International Tennis Federation (ITF) in the development of appropriate mechanical tests. Additionally the thesis aims to examine the relationship between perceptions and player response to provide an insight into injury risks and altered techniques.

2.8.1 Specific Aims

To achieve the overall aim several specific aims were identified and developed throughout the research project in accordance with findings in the literature and each study. The specific aims are as follows:

1. Identify tennis players' perceptions of different tennis court surfaces and investigate which perceptual themes were deemed influential to their performance and risk of injury (Study 1).
2. Quantify tennis players' movements on different types of tennis court surfaces. Identify whether changes in mechanical properties elicit changes in biomechanical response during tennis-specific movements (Study 1, 2 and 3)
3. Examine the relationship between perceptions of tennis courts and player biomechanical response to the surfaces (Study 2).
4. Examine the influence of previous clay court experience upon players' perceptions and biomechanical response and perception response relationship, with respect to injury risks and performance of the tennis-specific skills (Study 2).
5. Increase understanding of different strategies employed to gain stability during dynamic tennis movements during expected and unexpected changes in friction (Study 3).

CHAPTER 3: STUDY 1: IDENTIFYING TENNIS PLAYERS' PERCEPTIONS

3.1 Introduction

The requirement for tennis to be played on a multitude of surfaces which can differ in mechanical properties such as friction and cushioning (Miller, 2006; Damm et al., 2013), has been found to lead to adaptations, such as modified movements and techniques (Miller, 2006; Girard et al., 2007; Damm et al., 2013). Modified movements and techniques on different surfaces have been reported to alter loading and kinematic characteristics during dynamic movements such as turning (Durá et al., 1999; Dowling et al., 2010) and running forehand foot plants (Stiles & Dixon, 2007; Damm et al., 2013).

Mechanical data used to define surface properties, do not always reflect biomechanical data collected on different surfaces. For example during running, peak impact forces were maintained for surfaces with differing mechanical cushioning (Dixon et al., 2000). Thus current mechanical tests used to characterise playing surfaces are not appropriate in providing understanding of players' experience of tennis courts. Different biomechanical responses to different surface properties have been suggested to be a result of our perceptions of these properties which have allowed us to respond appropriately to these changes (Hennig et al., 1996; Milani et al., 1997; Stiles & Dixon, 2007). Perceptions have been suggested to provide an insight to humans' experiences of surfaces (Fleming et al., 2005), and are therefore likely to influence response, as well and mechanical surface properties. Therefore understanding tennis players' perceptions could aid in the development of appropriate mechanical measures.

Perceptions allow us to interact with our environment and are formed from the integration of sensory information sent to the brain from the sensory receptors (Coren et al., 1979; Sherwood, 1993; Goldstein, 1999). Quantitative studies have provided evidence to suggest that humans are able to identify mechanical differences such as cushioning and friction between surfaces (Lockhart et al., 2002; Stiles & Dixon, 2007). Perceptions of friction have been associated with altered utilised COF (Lockhart et al., 2002) and increased loading rates have been associated with reduced cushioning perception (Hennig et al., 1996; Milani et al., 1997; Stiles & Dixon, 2007), suggesting a relationship between perceptions and human response.

The majority of surface perception studies have focused on either perception of cushioning or friction, yet it is likely that there are other unaccounted perceptual measures. Due to their explorative and in-depth nature (Patton, 1990), interviews have been used to examine perceptions of sport surfaces and equipment (Roberts et al., 2001; Fleming et al., 2005). Fleming et al. (2005) conducted interviews from 22 hockey players following play on a hockey pitch. Themes, suggested to influence perceptions, were constructed using inductive analysis and included pitch properties, ball-surface interaction, player-surface interaction, player performance and playing environment. The authors identified interactions between themes for example surface hardness and injury risks. Although there may be similarities in perceptions between hockey and tennis, it is suggested that perceptions identified by Fleming and colleagues (2005) may not reflect the perceptions of a tennis player due to the differing nature of the games.

The purpose of the current study was to identify factors that influence tennis players' perceptions of tennis surfaces, using interviews to explore the ways in which players either instinctively or deliberately interact with changes in surfaces (see Specific aim 1, p. 56). The study aimed to examine how perceptions identified compare with current mechanical tests results i.e. do mechanical friction values correspond to differences in perceptions of these surfaces? Greater understanding of perceptions of tennis court surfaces gathered in this study will be used to inform further research. Kinematic data were collected to provide an explorative examination of potential tennis court surface differences for tennis-specific skills and to develop kinematic data collection methods for future research.

3.2 Methods

3.2.1 Participants

Seven university tennis players, with a LTA rating between 4.1 and 7.2 and who were free from injury, participated in the present study. Five males (age 20.5 ± 0.71 years, height 1.84 ± 0.01 m, and weight 83.15 ± 6.01 kg) and two females (age 21.0 ± 0.00 years, height 1.67 ± 0.03 m, and weight 59.00 ± 4.24 kg) volunteered. The study was approved by the Institutional Ethics Committee and informed consents were obtained prior to data collection.

3.2.2 General Overview

Kinematic data for a running forehand and an open stance forehand were collected during two tennis drills. On completion of the drills participants then competed in a short match to provide them with further observations of the tennis courts. Immediately following the short tennis match participants were then interviewed to gain an insight to their perceptions of the tennis courts. The procedures (Figure 3.1) were completed on two courts; an indoor acrylic court and an outdoor artificial clay court (Appendix 3), for which the order of testing was randomly assigned prior to data collection.

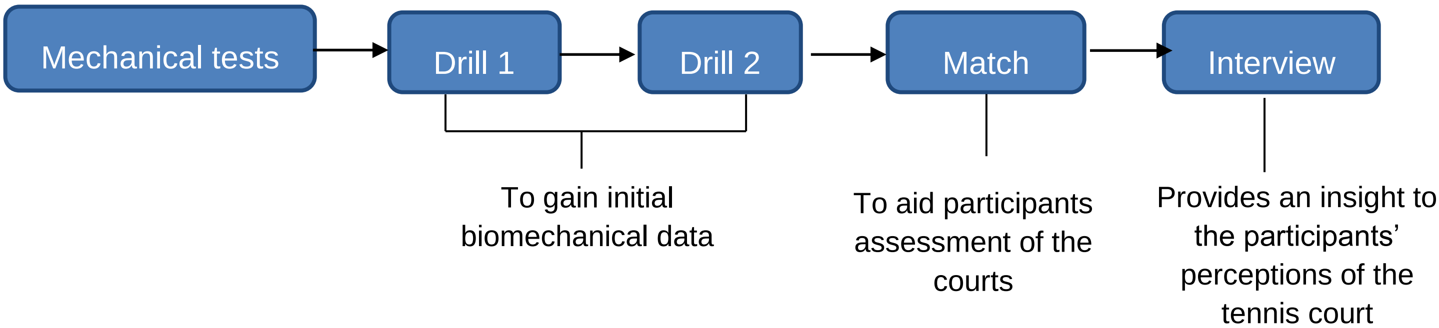

Figure 3.1: A schematic diagram representing the outline of the protocol for each court

3.2.3 Mechanical Data

Mechanical data were collected to provide dynamic and static friction, rotational traction and impact characteristics, for both tennis courts. Mechanical data were collected by colleagues from the University of Sheffield, Sports Engineering Research Group. Mechanical tests included the SERG impact hammer (Carré et al., (2006), the Pendulum test (British Standards, 2002), the Crab III test and the Rotational traction test (using a smooth foot).

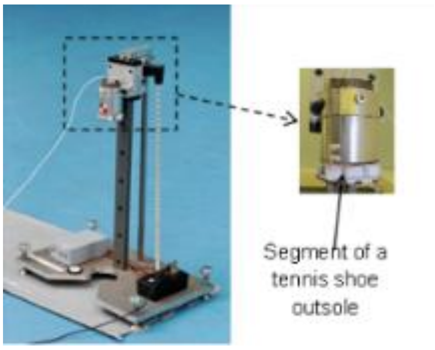

Figure 3.2: The SERG impact test device with hammer profile (detailing the use of a tennis shoe outsole)

Mechanical hardness and stiffness were measured using the SERG impact hammer (Figure 3.2) first described by Carré et al. (2006). To prevent damage to the tennis courts and simulate actual conditions, an outsole of a tennis shoe was attached onto the rigid steel hammer (Figure 3.2), which has previously been successful in comparing impact characteristics of tennis surfaces (Yang, 2010). The voltage signals of an accelerometer within the hammer when dropped provided an output trace during the loading and unloading phases. The raw data were then converted to force and displacement required to measure stiffness and hardness. Hardness was measured using peak force which was identified as the maximum deceleration during impact with the surface. A harder surface was represented with higher impact accelerations. Average stiffness was reported as the ratio of the peak force and the related displacement.

Figure 3.3: The pendulum test device

The Pendulum test (British Standards, 2002), designed to simulate footwear-surface interactions during contact was used to examine dynamic friction of the court surfaces. As described by Miller & Capel-Davis (2006), the Pendulum test consists of a pendulum arm with a spring loaded rubber slider at the end (shown in Figure 3.3). The arm was released allowing the arm to swing and the rubber slider to contact the surface. The swing height provided an indication measure of dynamic coefficient of friction. For the clay courts it was difficult to maintain consistency of the top layer clay infill as the surface particles were substantially disturbed during repeated tests preventing consistent measurements, therefore a 'fresh' area was examined for each repetition.

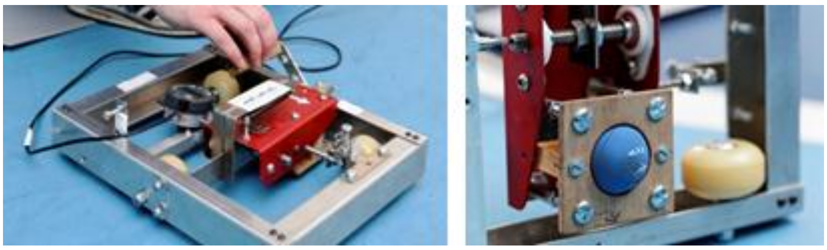

Figure 3.4: The Crab III device and base of device presenting the deformable rubber sphere

The Crab III device (Figure 3.4) measured the friction force between a surface and the deformable rubber sphere. The device was pushed (by hand) along the court surface, where the rubber sphere interacted with the surface causing the cantilever beam to deflect horizontally. The peak deflection was related to the static coefficient of friction between the surface and sphere.

Figure 3.5: The rotational traction test device

The rotational traction device (Figure 3.5) consists of a loaded circular smooth rubber test foot mounted onto the end of a shaft. The test rig was positioned on the surface and free weights were placed onto the shaft to provide the normal load. A torque wrench was connected to the shaft; and the peak rotational torque measured as the foot was rotated by hand.

3.2.4 Tennis Shoes

Figure 3.6: The Adidas Barricade 6.0 clay court shoes including the outsole pattern

The shoes worn by the participants during data collection were the Adidas Barricade 6.0 clay court shoes with a v-shaped tread pattern (Figure 3.6). These shoes, in comparison to the acrylic version (Adidas Barricade 6.0 acrylic shoes) produced similar pressure distribution, loading and kinematic data when examining different tennis courts in the lab (Damm et al., 2013) and during on court scenarios (Damm et al., 2014).

3.2.5 Tennis Drills

Two dynamic tennis movements were assessed within two separate drills (Figure 3.7) as described by Damm et al. (2014). A feeder was used to deliver the ball into the specific areas. For both drills, the participants began on the centre of the baseline in a ready position. Both drills then required participants to perform a backhand stroke followed by a forehand stroke before ending with a backhand return. The performance of a final backhand was to encourage a realistic as possible forehand stroke, by placing some urgency upon the participants. It was intended that the drills reflected a competitive rally whilst compromising for the collection of kinematic data. The players were asked to target their strokes down the line into the target (T) areas.

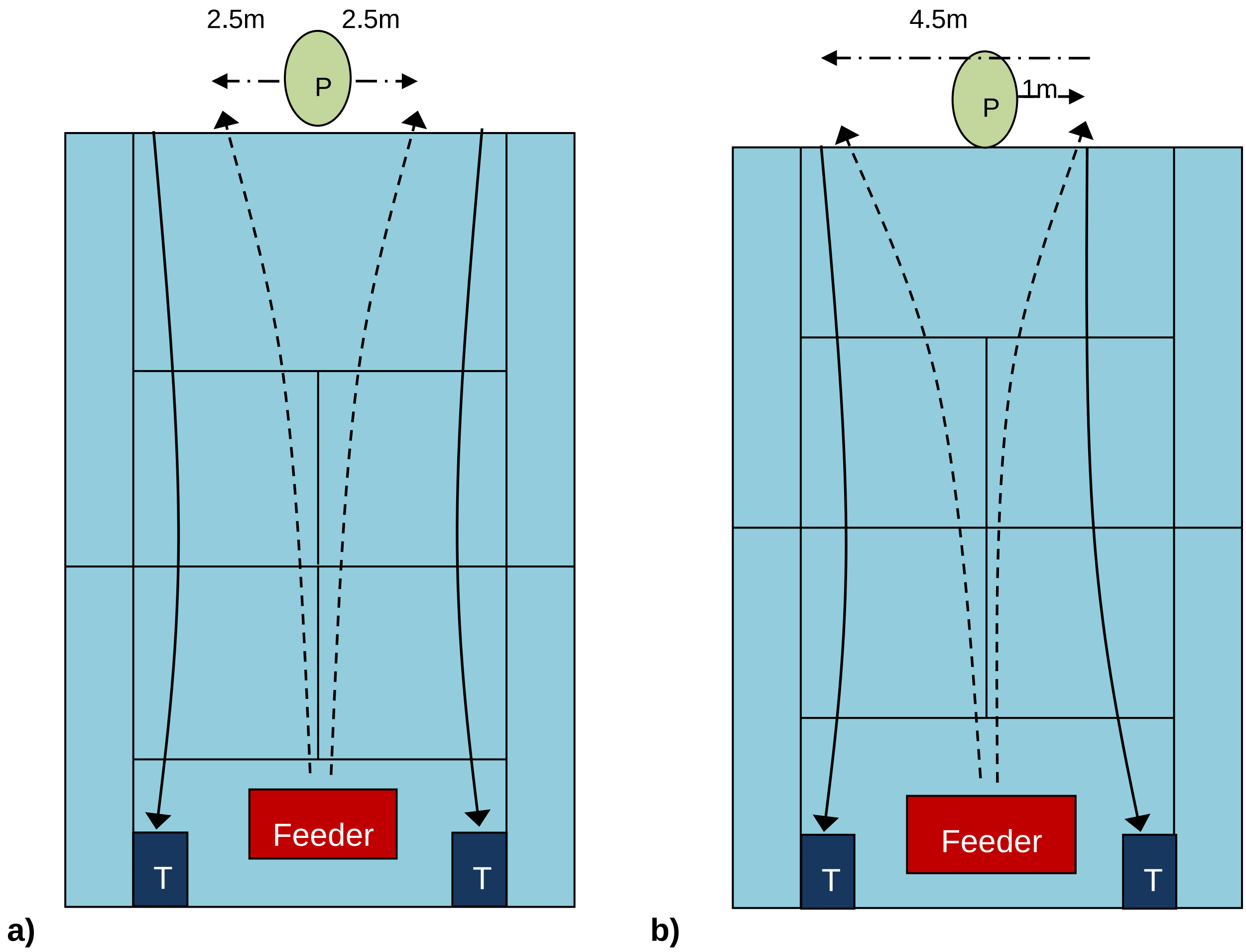

Figure 3.7: A schematic diagram of the drills used a) drill A the participants (P) performed a forehand open stance b) represents drill B where the participant performed a running forehand. T represents the target areas

In drill A (Figure 3.7a), the participants were asked to perform an open stance forehand where the second ball was sent by the feeder once the participants returned to the centre of the baseline following the initial backhand shot. In drill B (Figure 3.7b) the participants performed a running forehand where the second ball was fed immediately after the completion of the initial backhand stroke, requiring the participants to run at speed from the opposite side of the court to perform this forehand stroke. The running forehand included the players reaching for the ball, and planting their dominant foot whilst hitting the ball simultaneously with the racket in their dominant hand. Ten successful trials of each drill were required. Prior to testing the participants were fully instructed on the drill and given time to familiarise themselves with the drills and court surfaces. Following the drills the participants competed in a short match, providing the participants with opportunity for further observations of the tennis courts. Due to time constraints the match was restricted to the best of 10 points.

3.2.6 Kinematic Data

Kinematic data were collected using three 50 Hz cameras (Sony HDV 1080i mini DV), synchronised through event synchronisation of ground contact and ball strike. Cameras were placed around the court so that at any one time a minimum of two cameras were able to capture each lower limb marker. Cameras were placed to capture data within the area of interest at the baseline of the court (Figure 3.9). Data were collected on the dominant leg for all right handed participants (two males and two females) for both forehand strokes. Due to time constraints and the lengthy time to set up and calibrate the cameras, left handed players were omitted from the kinematic data collection.

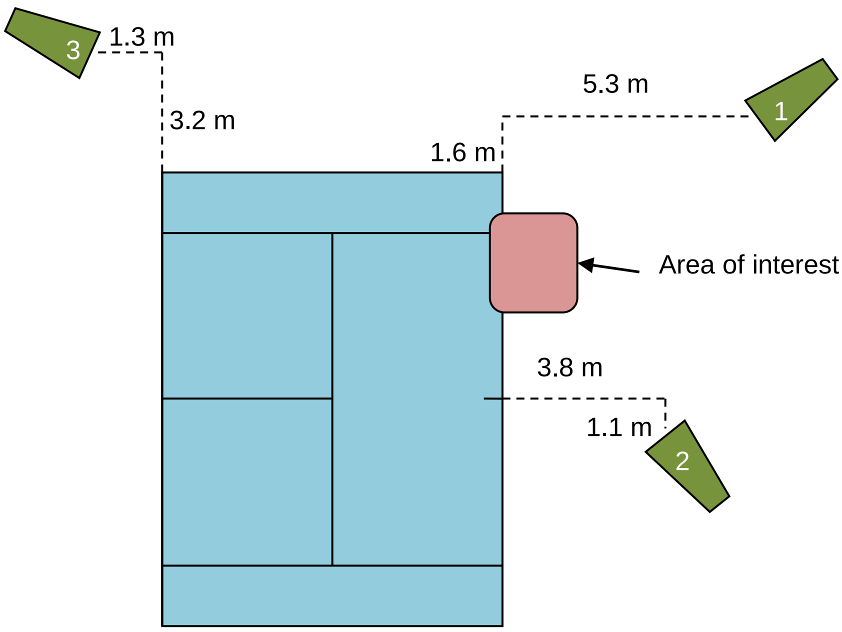

Figure 3.8: Camera set up of three 50 Hz cameras (Sony HDV 1080i mini DV) used for a right handed player for half a tennis court

Figure 3.10 presents the calibration frame used during calibration prior to data collection on either court surface. Direct linear transformation (DLT) was used to determine 3-dimensional spatial coordinates from several sets of 2-dimensional information provided by the three cameras (Abel-Aziz & Karara, 1971). A calibration frame (Figure 3.10) of known coordinates were captured for each camera placement allowing for the construction of a 3-dimensional coordinate system through the least squared method of an over determined system using Vicon Motus (v9.2) software.

Figure 3.9: Calibration frame used, which was placed within the area of interest to ensure accurate three-dimensional calibration of the area

In order to construct a three-dimensional space using DLT, at least six points (corresponding to 12 equations) were needed to determine 11 coefficients (a_{kj}). Eight points (1a, 1c, 2a, 2c, 3a, 3c, 4a and 4c) were used in the current study. From the calibration 3-dimensional coordinates for each of the 11 lower limb markers used were determined from the multiple two-dimensional information using Vicon Motus (v9.2) software using Equation 3.1 and 3.2 explained further by Nigg & Herzog (1999).

$$x_{ij} = \frac{a_{1j}x_i + a_{2j}y_i + a_{3j}z_i + a_{4j}}{a_{9j}x_i + a_{10j}y_i + a_{11j}z_i + 1}$$ Equation 3.1

$$y_{ij} = \frac{a_{5j}x_i + a_{6j}y_i + a_{7j}z_i + a_{8j}}{a_{9j}x_i + a_{10j}y_i + a_{11j}z_i + 1}$$ Equation 3.2

Where for marker *i*:

x_{ij} = *x* coordinate of marker *i* on the film measured with camera *j*
y_{ij} = *y* coordinate of marker *i* on the film measured with camera *j*
x_i = *x* coordinate of marker *i* in the three dimensional space
y_i = *y* coordinate of marker *i* in the three dimensional space
z_i = *z* coordinate of marker *i* in the three dimensional space
a_{kj} = coefficient *k* in the transformation formulas for marker *i*

Root mean squared error (RMSE) provides the error between estimated measures and actual measures and was determined using Equation 3.3. RMSE were calculated using four points (1b, 2b, 3b, 4b) from the calibration frame which were not used during calibration. For the current study RMSE was no larger than 0.06 m in the x, y and z direction.

Equation 3.3

$$RMSE = \sqrt{\frac{sum\ of\ squares\ (actual - estimated)}{number\ of\ data}}$$

Eleven lower limb reflective spherical markers (shown in Figure 3.11) were placed on the dominant leg to establish joint coordinate systems (JCS) adapted from Grood & Suntay (1983) and Soutas-Little et al. (1987) using a custom written MATLAB code (2011b, The MathsWorks). The markers were manually digitised (digitising repeatability, ICC=0.997), using using Vicon Motus (v9.2) software. The 3-dimensional lower limb coordinates were filtered using a 2nd order Butterworth filter with a cut off frequency of 6 Hz prior to the construction of the JCS.

Figure 3.10: Joint coordinate system marker locations: 1) hip (greater trochanter) , 2) medial knee (medial femoral epicondyle), 3) lateral knee (lateral femoral epicondyle), 4) shin (anterior aspect of shank), 5) Achilles 1 (proximal bisection of posterior shank), 6) Achilles 2 (distal bisection of the posterior shank), 7) calcaneus 1 (proximal bisection of the calcaneus), 8) calcaneus 2 (distal bisection of the calcaneus), 9) lateral malleolus, 10) toe (base of 2nd metatarsal), 11) 5th metatarsal phalange

The markers placed on the lower limb allowed for the construction three rotations around each segment (thigh, shank and foot) as shown in Figure 3.12. Unit vectors were constructed for all segments in the *i, j, k* directions. In order to identify the rotations around a joint for example the knee joint flexion, the longitudinal axis of the distal segment (k_{distal}), medio-lateral axis of the proximal segment (*i* $_{proximal}$) and a floating axis were constructed from the cross product of the *k* $_{distal}$ and *i* $_{proximal}$ segments.

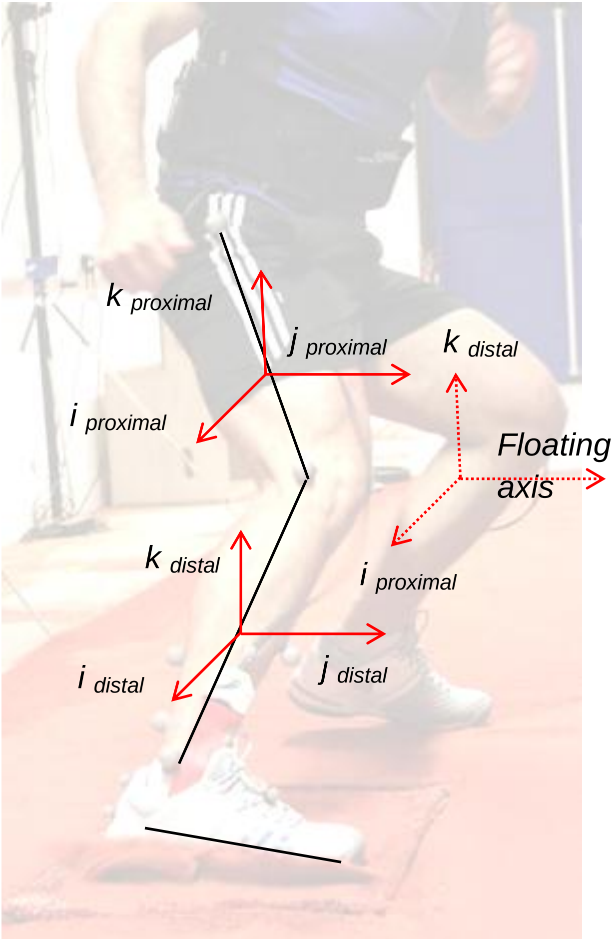

Figure 3.11: A schematic diagram presenting the rotations around the thigh and shank needed to calculate angles around the knee (adapted from Robertson, Caldwell, Hamill, Kamen & Whittlesey (2013))

Equation 3.4 was used to calculate angles at the knee and ankle, with a and b being unit vectors established in the JCS. For example to calculate knee flexion angle (Equation 3.5) the longitudinal axis for the proximal thigh segment (k_{thigh}) and a floating axis (cross product k_{shank} and i_{thigh}) was used. Table 3.1 provides unit vectors for each rotation around the knee and ankle joints, which were inserted into Equation 3.4.

$$\theta = \tan^{-1}\left(\frac{|a \times b|}{a \cdot b}\right)$$ *Equation 3.4*

$$\theta = \tan^{-1}\left(\frac{|k_{thigh} \times floating\ axis\ (knee)|}{k_{thigh} \cdot floating\ axis\ (knee)}\right) \qquad \textit{Equation 3.5}$$

Table 3.1: Unit vectors used to calculate the rotations around the knee and ankle

Variable	*a*	*b*
Knee movements		
Flexion/extension	k_{thigh}	*Floating axis* (cross – k_{shank} & i_{thigh})
Abduction/adduction	K_{shank}	i_{thigh}
Internal/ external rotation	*Floating axis* (cross – k_{shank} & i_{thigh})	i_{shank}
Ankle movements		
Dorsi/ plantar flexion	k_{shank}	*Floating axis* (cross – i_{shank} & k_{foot})
Inversion/eversion	k_{foot}	i_{shank}
Internal/external rotation of the tibia	*Floating axis* (cross – i_{shank} & k_{foot})	i_{shank}

The joint coordinate system allowed the following variables to be calculated relative to a relaxed standing position: initial and peak ankle, knee and rearfoot angle. The hip z-coordinate was used identify initial and peak hip height for each skill on both tennis courts. Occurrence time of peak angles were reported relative to heel contact.

3.2.7 Interviews

Semi-structured interviews were conducted immediately following the procedures on each tennis court to obtain participants' perceptions. An interview guide (Appendix 4) provided a framework of predetermined questions to ensure consistency between interviews of all participants, whilst allowing some flexibility to explore further questions (Patton, 1990). Participants were asked about their observations and perceptions about the court and to identify any differences between the two courts. Interviews were conducted face to face and recorded using digital recording equipment. Interviews lasted approximately 10-15 minutes on each court for each participant resulting in 16 pages of transcribed data (Appendix 5).

3.2.8 Thematic Inductive Analysis

Analysis began during data collection and was recursive in nature. A thematic analysis with an inductive approach was conducted to allow the researcher to actively identify themes that were strongly linked to the data (Braun & Clarke, 2006). Braun & Clarke (2006) six step guide (Figure 3.8) was used to provide a framework for the analysis. Following each interview, data were transcribed verbatim as soon as possible, allowing analysis to begin and refine interview techniques. The process of transcribing, reading and re-reading aided in the familiarisation of the interview data and allowed for initial notes and interpretations. Once the data were transcribed the data were then organised and coded to highlight any patterns within the data. Codes were then collated into broader themes which were reviewed and refined along with the coded extracts to identify any missing themes or codes. Themes were then defined to determine what aspects of the data each theme captured to allow for interpretation.

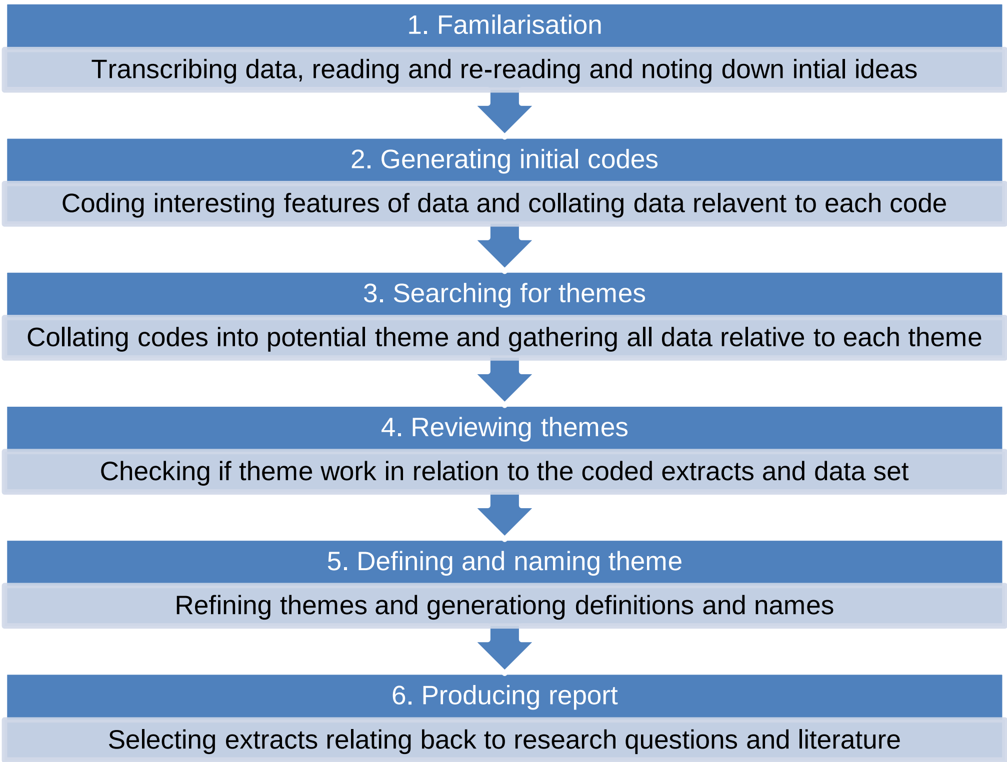

Figure 3.12: A schematic diagram outlining the procedure for the thematic inductive analysis

3.2.9 <u>Statistical Analysis</u>

Significant differences between courts were determined using a paired sample t-test, with an alpha level less than 0.05. Cohen's *d* values were used to calculate effect sizes (ES) for all significant comparisons (Cohen, 1977).

3.3 Results

3.3.1 <u>Mechanical Data</u>

Table 3.2 provides the means and standard deviations for the mechanical data collected on both tennis courts. The clay court produced lower coefficients of friction in comparison to the acrylic court. Rotational traction was lower on the clay court compared to the acrylic court. No differences were observed in peak forces with the SERG impact hammer. However peak loading rate was significantly higher on the acrylic court compared to the clay court. Greater variation in impact characteristics was highlighted on the clay court.

Table 3.2: Means and standard deviations for the mechanical data collected on the clay and acrylic courts

Mechanical test	Clay	Acrylic
Frictional measures		
Pendulum	0.52 ± 0.04	0.63 ± 0.01*
Crab III	0.64 ± 0.04	1.16 ± 0.01*
Rotational Traction (N/m)	13.15 ± 1.53	17.10 ± 1.29*
Hardness measures		
SERG Impact hammer (N)		
Peak impact force (N)	1641.62 ±80.61	1641.30 ± 8.28
Peak loading rate ($kN.s^{-1}$)	1033.50 ± 28.10	1055.20 ± 16.80*

*** denotes significant differences between tennis courts**

3.3.2 Kinematic Data

3.3.2.1 Forehand Open Stance

Table 3.3 provides the kinematic data collected for the forehand open stance stroke on both the clay and acrylic courts. The study revealed a significant (ES = .236, *p* =.022) difference between surfaces for initial hip height, where lower height was observed on the clay compared to the acrylic court. At ground contact the ankle was in a more neutral position on clay (-0.89 ± 9.13^{o}) compared to the acrylic court (4.32 ± 9.75^{o}) where the ankle was slightly plantar flexed (ES = .390, *p* =.012). No differences were observed in the magnitude of initial and peak knee flexion during the open stance stroke. However, peak knee flexion (as shown in Figure 3.13) occurred significantly later (ES = .975, *p* =.039) on the clay court (0.58 ± 0.08 s) compared to the acrylic court (0.37 ±

0.20 s), which coincided with longer contact times on the clay court (1.22 ± 0.34 s) compared to the acrylic court (0.74 ± 0.24 s).

Table 3.3: Means and standard deviations for kinematic data for the forehand open stance stroke on both tennis courts

Variable	**Acrylic Court**	**Clay Court**	***ES***
Hip height			
At impact (m)	0.16 ± 0.06	0.14 ± 0.06	.236*
Minimum (m)	0.12 ± 0.06	0.09 ± 0.07	
Attack angle			
At impact (^{o})	45.03 ± 4.24	42.12 ± 6.22	
Foot angle respect to the horizontal			
At impact (^{o})	8.22 ± 6.89	5.58 ± 4.10	
Ankle dorsi-flexion angle			
At impact (^{o})	4.32 ± 9.75	-0.89 ± 9.13	.390*
Peak (^{o})	-0.77 ± 9.71	0.70 ± 6.89	
Time of peak (s)	0.53 ± 0.11	0.51 ± 0.03	
Ankle inversion angle			
At impact (^{o})	1.12 ± 3.67	8.48 ± 5.31	
Peak (^{o})	14.35 ± 2.77	20.71 ± 7.14	
Time of peak (s)	0.22 ± 0.06	0.24 ± 0.05	
Knee flexion angle			
At impact (^{o})	8.02 ± 12.03	8.60 ± 3.71	
Peak (^{o})	37.23 ± 7.84	39.34 ± 3.18	
Time of peak (s)	0.37 ± 0.20	0.58 ± 0.08	.975*

***denotes a significant difference between the two tennis court, positive ankle flexion angles indicates dorsi flexion, positive ankle inversion angles indicates eversion at the ankle**

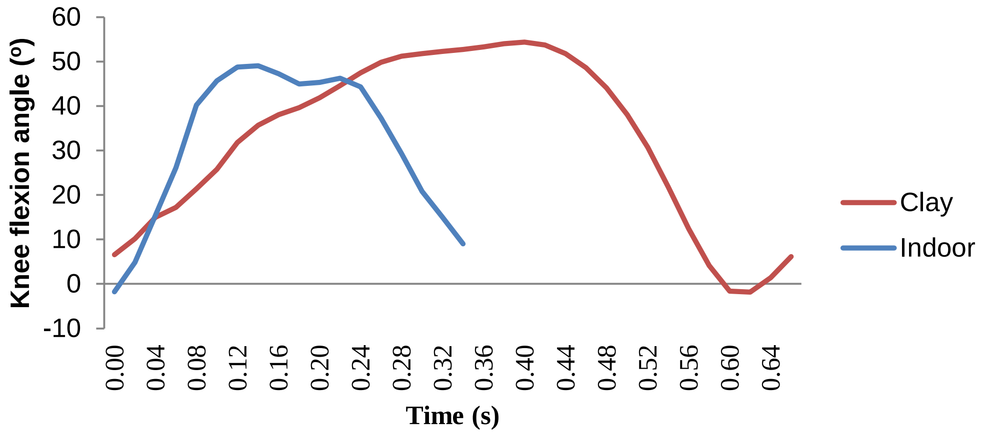

Figure 3.13: Example knee flexion angle time histories for one participant on both the indoor acrylic and clay court

3.3.2.2 Running Forehand

Table 3.4: Means and standard deviations for the kinematic data collected during the running forehand on both tennis courts

Variable	Acrylic Court	Clay Court	*ES*
Hip height			
At impact (m)	0.12 ± 0.05	0.11 ± 0.07	
Attack Angle			
At impact (°)	52.17 ± 5.73	33.32 ± 15.53	
Foot Angle respect to horizontal			
At impact (°)	11.13 ± 2.50	-1.62 ± 6.45	1.87*
Ankle Dorsi-flexion			
At impact (°)	-3.05 ± 8.86	4.62 ± 3.93	
Peak (°)	-7.21 ± 8.39	3.36 ± 8.01	
Time of peak (s)	0.40 ± 0.05	0.53 ± 0.16	
Ankle Inversion Angle			
At impact (°)	12.01 ± 17.64	10.03 ± 5.20	
Peak (°)	28.40 ± 10.90	20.08 ± 9.78	
Time of peak (s)	0.13 ± 0.03	0.26 ± 0.06	1.94*
Knee Flexion Angle			
At impact (°)	2.98 ± 7.94	24.06 ± 7.16	1.97*
Peak (°)	27.53 ± 9.58	44.24 ± 11.25	
Time of peak (s)	0.41 ± 0.06	0.51 ± 0.06	1.18*

***Denotes a significant difference between courts, positive ankle flexion angles indicates dorsi flexion, positive ankle inversion angles indicates eversion at the ankle**

Table 3.4 provides means and standard deviations for ankle and knee movement during the running forehand on the acrylic and clay courts. Unlike the open stance forehand no differences were observed in hip height between the courts. Table 3.4 highlights the significant difference in foot angle relative to the horizontal axis (ES = 1.870, p =.023). Figure 3.14 provides examples of typical foot placement during the running forehand on both courts. On the clay (-1.62 ± 6.45^{o}) participants occasionally contacted the ground with their toes, whilst on the acrylic (11.13 ± 2.50^{o}) the participants typically contacted the ground with their heel.

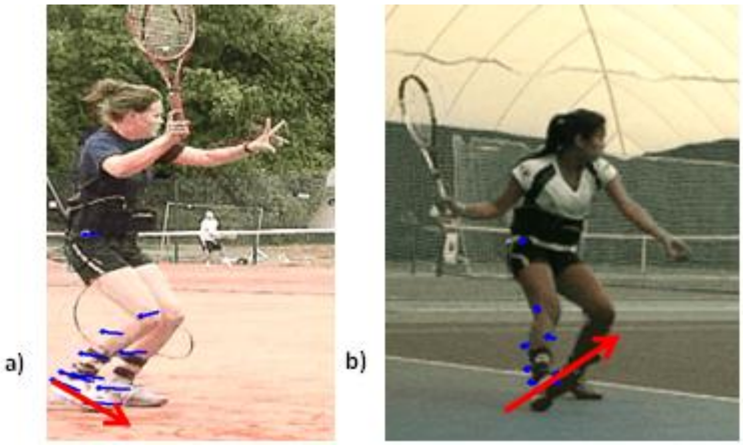

Figure 3.14: Example foot placements for a) clay court compare to and b) acrylic court indicating different approaches to the tennis stroke

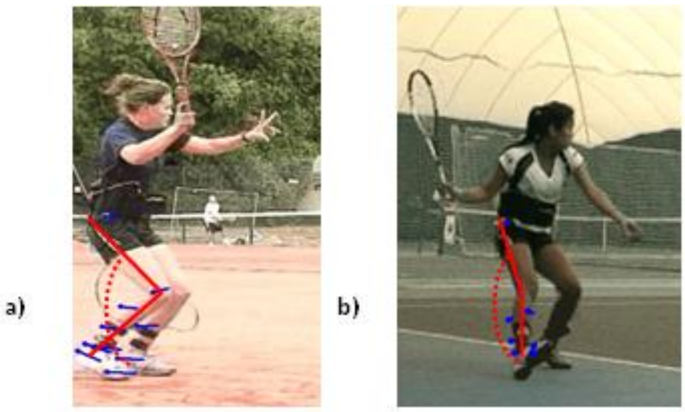

Figure 3.15: Example initial knee flexion angles for a) clay and b) acrylic, highlighting the differences in players approaches to the two tennis courts

Figure 3.15 provides examples of knee flexion at ground contact for both surfaces, which was (ES = 1.97, p =.001) greater on the clay court compared to the acrylic. Figure 3.16presents typical knee angle time-histories for the acrylic and clay court which highlights differences between courts. For instance, on the acrylic court the participants' knee were slightly flexed at ground contact then flexed during the braking phase. Whilst on the clay court participants contacted the ground with a flexed knee then extended their knee into the slide before flexing their knee a second time to brake. Two peak knee flexions resulted in longer contact times on the clay court (0.88 ± 0.17 s) compared to the acrylic court (0.74 ± 0.25 s). In addition to altered techniques, differences in peak knee flexion time (ES = 1.179, p =.003) and peak ankle inversion time (ES = 1.937, p =.021) were observed, where later peak knee flexion occurred on the clay court (.51 ± .06 s) compared to the acrylic court (.41 ± .06 s) and maximum inversion angle occurred 0.13 s later on the clay compared to the acrylic court.

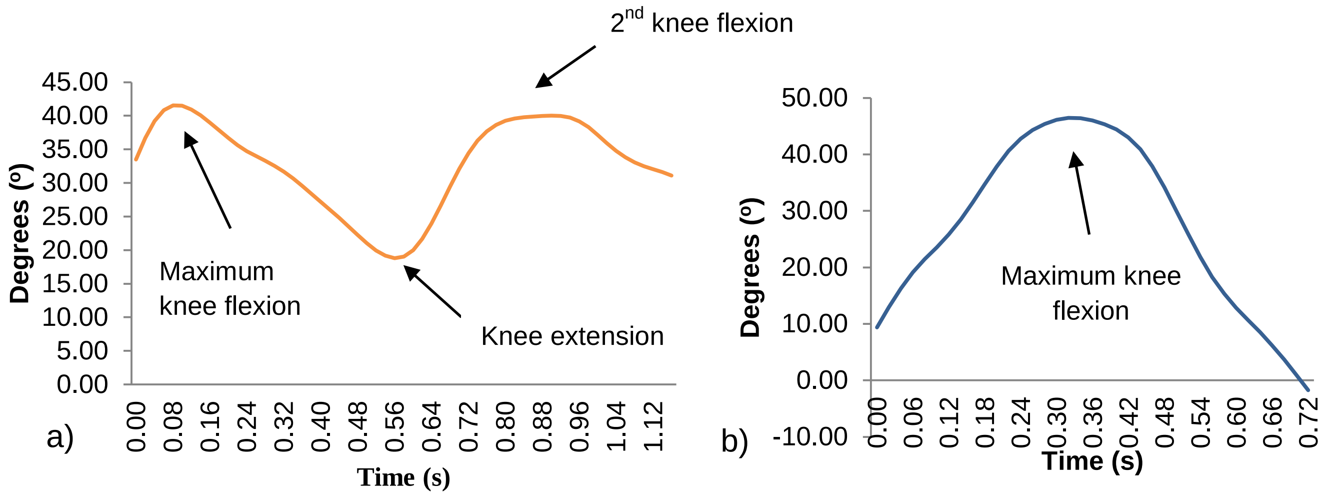

Figure 3.16: Example knee flexion angle time histories for a) the clay court and b) the acrylic court

3.3.3 Perception Data

A thematic inductive analysis was used to highlight emerging themes regarding players' observations, perceptions and the constructs which influence these perceptions. Following the process of examining the interview data sub-themes and base themes were established. Tree structures were formulated to represent the process in which quotes were used to construct base themes, sub-themes and in turn the general themes. The five general themes that emerged from the analysis were:

- Player-surface interactions
- Ball-surface interactions
- Performance
- Injury
- Playing environment

3.3.3.1 Player-surface Interactions

Player-surface interactions included the participants' observations regarding the court properties that influenced their perceptions. Three sub-themes 'predictability', 'hardness' and 'grip', which are represented in Figure 3.18, were developed from the base themes and quotes to create the overall general theme. The predictability of the surface arose from the interview data, where participants were in agreement that the clay court was uneven and unpredictable, whilst the acrylic court was observed to be more predictable and secure.

> Just I don't know you put your foot down you feel secure and on clay it almost feels a bit messy. (Acrylic)
>
> Because it my surface I always play on and everything feels

> a bit more like I know what I am doing. (Acrylic)

Two surface properties that were continuously stated by the participants were hardness and grip. The clay court was described as ‘slippy’ and ‘loose’ and had less grip compared to the acrylic court. Participants identified that the clay court which they observed to have less grip allowed for sliding, without the risk of tripping or fixation of the foot. Alternatively participants perceived the acrylic to have more grip, thus they perceived the surface to be easier to change direction.

> Pushing off side to side is a lot easier here. (Acrylic)
>
> They were good courts, you can move pretty well on them, slide on them without thinking you’re going to fall over. It didn’t grip too much so you didn’t fall over. (Clay)

The participants were able to identify differences between hardness of the courts; they often described the clay as ‘padded’ or ‘soft’ compared to the acrylic where participants were in agreement that the surface was ‘hard’. Participants often discussed their injury risks with their observations of surface hardness. Participants perceived the acrylic court to ‘impact quite badly’, with one participant reporting altering their movement on the acrylic court in an effort to prevent injury.

> But it’s quite like; it’s a hard surface that impacts quite badly sometimes. I’ve had quite bad knee from, pretty certain, from playing on tennis courts like this. (Acrylic)
>
> Otherwise I think it would be too much hard too much energy to my legs so in order to avoid any injuries I try to do little steps. (Acrylic)

Theme	Sub-themes	Base themes	Example quotes
Player-surface interaction	Predictability	Evenness	It's quite, uneven. It was quite uneven sometimes on the courts. (Clay)
		Unpredictable	Yeah I couldn't really tell what was going on. Slide loads or kind of stop. (Clay) Because it my surface I always play on and everything feels a bit more like I know what I am doing. (Acrylic)
		Security	Just I don't know you put your foot down you feel secure and on clay it almost feels a bit messy. (Acrylic) Just felt more grippy more secure. (Acrylic)
	Grip	Movements	I don't know with the loose stuff it was quite good to be able to get that extra slide. (Clay) Pushing off side to side is a lot easier here. (Acrylic)
		Slippery	It was quite hard to move forward, like pushing off it was practically no grip. (Clay) It was quite slippy. (Clay)
		Grip	It's not loose. (Acrylic) Just felt more grippy more secure. (Acrylic)
	Hardness	Injury	It's quite soft under the ground so I know I can jump and it not to hurt. (Clay) But it's quite like, it's a hard surface that impacts quite badly sometimes. I've had quite bad knee from, pretty certain, from playing on tennis courts like this. (Acrylic)
		Altered movement	Otherwise I think it would be too much hard too much energy to my legs so in order to avoid any injuries I try to do little steps. (Acrylic)
		Soft	A bit more kind of padded then a normal hard court. (Clay) It's quite soft under the ground. (Clay)
		Hard	Otherwise I think it would be too much hard too much energy to my legs. (Acrylic) But it's quite like, it's a hard surface that impacts quite badly sometimes. (Acrylic)

Figure 3.17: Player-surface interaction tree structure, representing the process in which general themes developed from quotes

3.3.3.2 Ball-surface Interactions

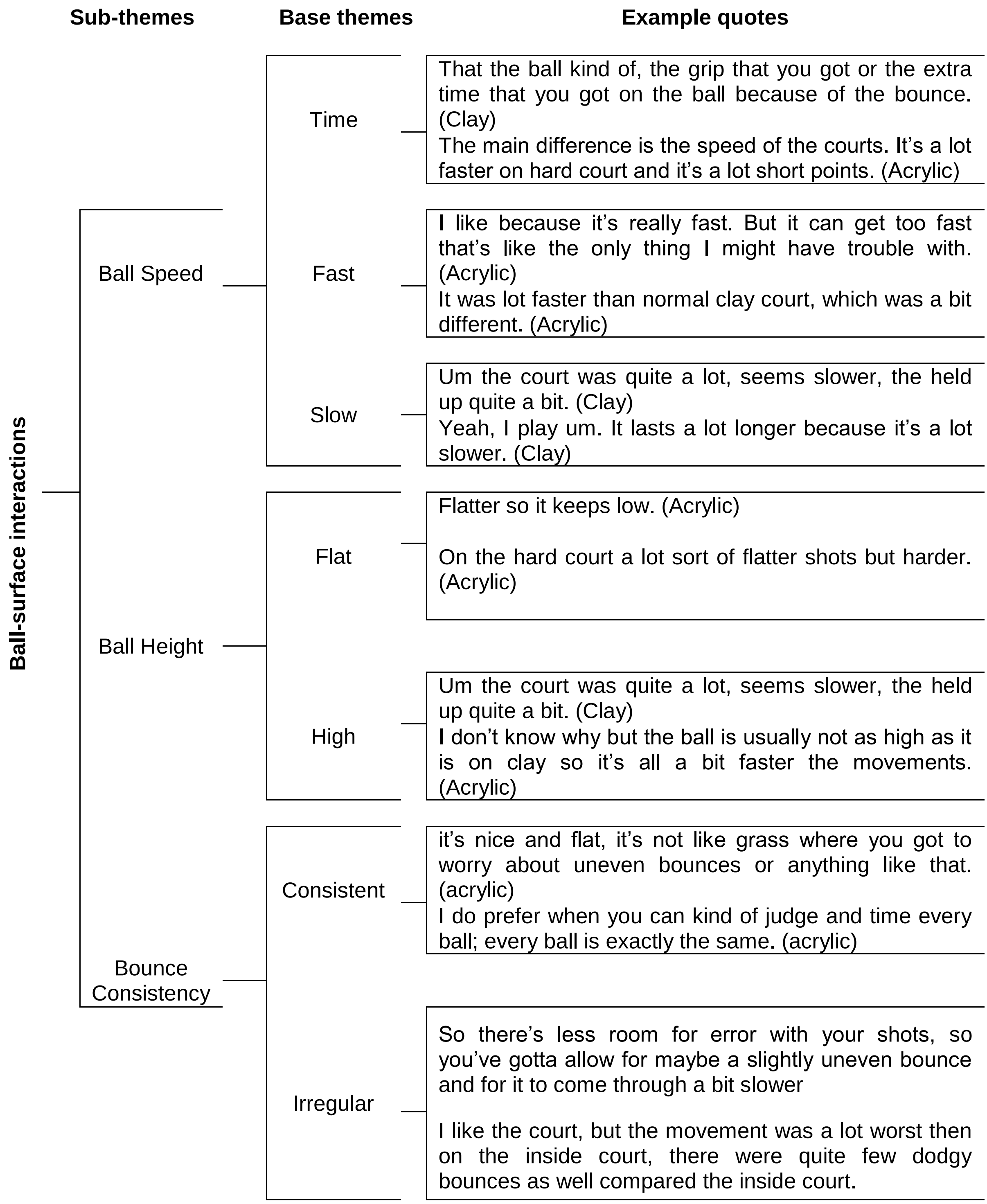

Figure 3.18: Ball-surface tree structure, highlighting the development from interview data to general theme

Ball-surface interactions were integral to the participants' perceptions of the tennis courts, with sub-themes: 'ball speed', 'ball height' and 'bounce consistency'. The tree structure that highlights the development of the theme is presented in Figure 3.19. The acrylic court was perceived to have a faster ball speed compared to the clay court where participants perceived the ball speed to be slow. Participants were in agreement, stating that the clay court resulted in a higher ball bounce compared to the acrylic. Additionally participants considered the consistency of the bounce, where they observed irregular bounce of the ball on the clay court whilst the acrylic court was perceived to have considerably more consistency in the ball bounce. The three sub-themes were often suggested with the use of alternative tactics employed on each court.

> The main difference is the speed of the courts. It's a lot faster on hard court and it's a lot short points. (Acrylic)
> I don't know why but the ball is usually not as high as it is on clay so it's all a bit faster the movements. (Acrylic)
> I'd hit the ball harder; maybe flatter so it keeps low. (Acrylic)

3.3.3.3 Performance

The participants' response to the player-surface interactions and ball-surface interactions were often related to performance or injury. Figure 3.20 shows the tree structure for performance which was formed from three sub-themes 'movement', 'fitness' and 'tactics'. Surface properties such as 'grip' influenced the types of movements performed, where 'pushing off' was deemed easier on the 'grippy' acrylic court, whilst the 'slippery' clay court allowed for sliding.

> You could slide well on it. Some clay courts are really hard to slide on. It was quite good. (Clay)

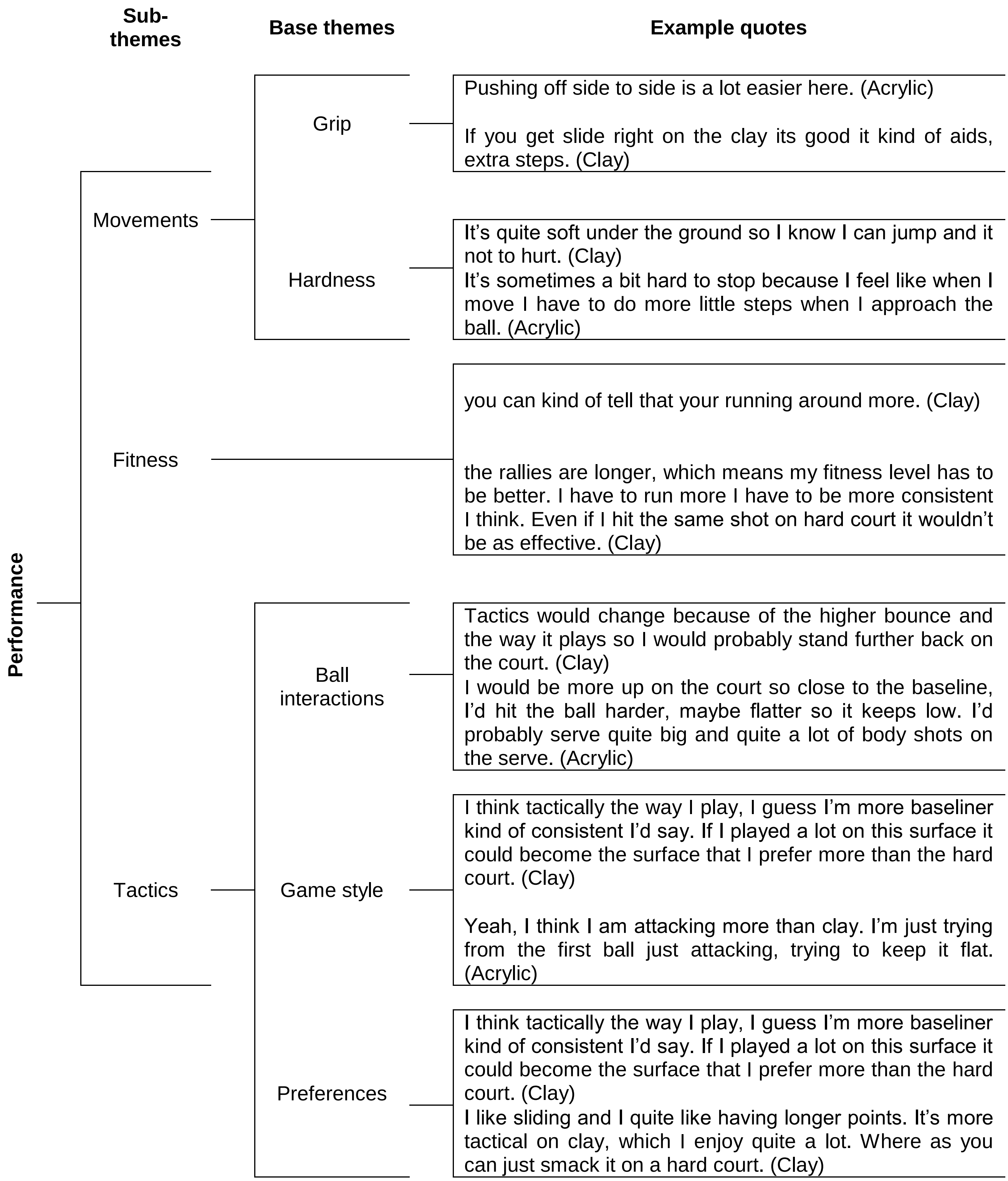

Figure 3.19: Performance tree structure, highlighting the development from interview data to general theme

Tactics were influenced by the players' game style, preferences and ball-surface interactions. Such that when players perceived a higher ball bounce they suggested positioning further back on the court, whilst on the acrylic their tactics would change such that they would hit harder and flatter to take advantage of the surface properties. With the longer and slower rallies suggested on the clay court, the participants highlighted the importance of fitness on this surface.

> The rallies are longer, which means my fitness level has to be better. I have to run more I have to be more consistent I think. Even if I hit the same shot on hard court it wouldn't be as effective. (Clay)
>
> As the ball gripped a lot more I would use a lot more spin, try and get variation probably. (Clay)

3.3.3.4 Injury Risks

The participants identified some possible injury risks influenced through three sub-themes, 'previous experience', 'hardness' and 'grip' (Figure 3.21). Several participants recalled previous injuries sustained on acrylic courts, which they suggested resulted in them being more cautious by having more steps during the testing tennis strokes on the acrylic court. Surface hardness and grip were related when injury risks were discussed. The participants noted that the 'softer' clay surface produced a lower injury risk compared to the harder acrylic court which was suggested to 'impact quite badly'. The participants suggested their low perceived injury risk on the clay court surface was due to lower perceived grip on the surface:

> Like for the movement it's easier because it doesn't hurt as much. Well because I can slide. (Clay)
>
> It's a bit softer on clay because you can slide on the clay. (Clay)
>
> But it's quite like; it's a hard surface that impacts quite badly

sometimes. I've had quite bad knee from, pretty certain, from playing on tennis courts like this. Otherwise I think it would be too much hard too much energy to my legs so in order to avoid any injuries I try to do little steps. (Acrylic)

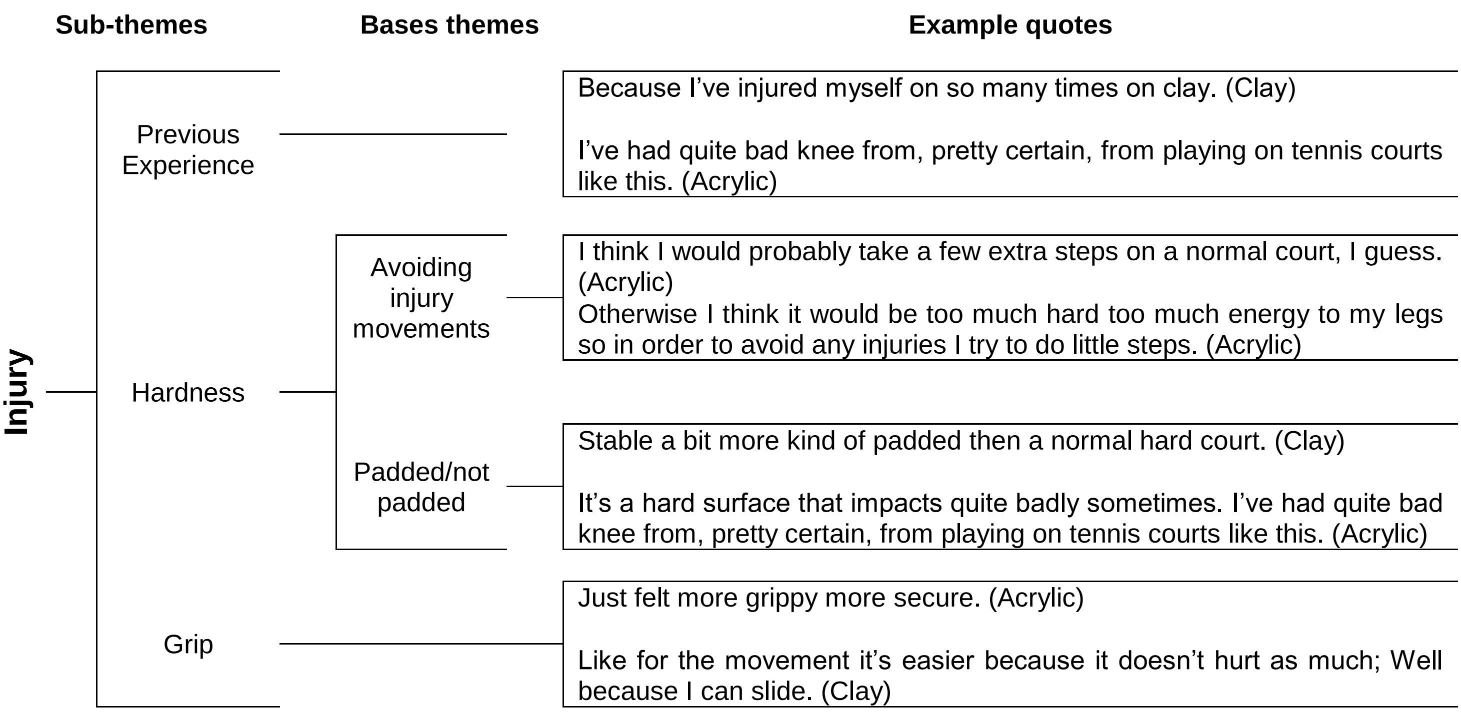

Figure 3.20: Injury tree structure, highlighting the development from interview data to general theme

3.3.3.5 Playing Environment

The playing environment (Figure 3.22) differed between each court for instance an indoor environment for the acrylic court and an outdoor clay court environment, the participants were aware of these differences. With the acrylic court being indoors the participants perceived this to be a more stable and consistent environment, particularly the weather conditions. However, one participant reported the added heat and humidity of the indoor court could affect the ball speed. It was deemed that the outdoor clay court conditions could often change due to the weather. With the clay, the participants understood the changes that occurred to the court if it was not maintained; this was suggested as the cause for irregular bounces on the court.

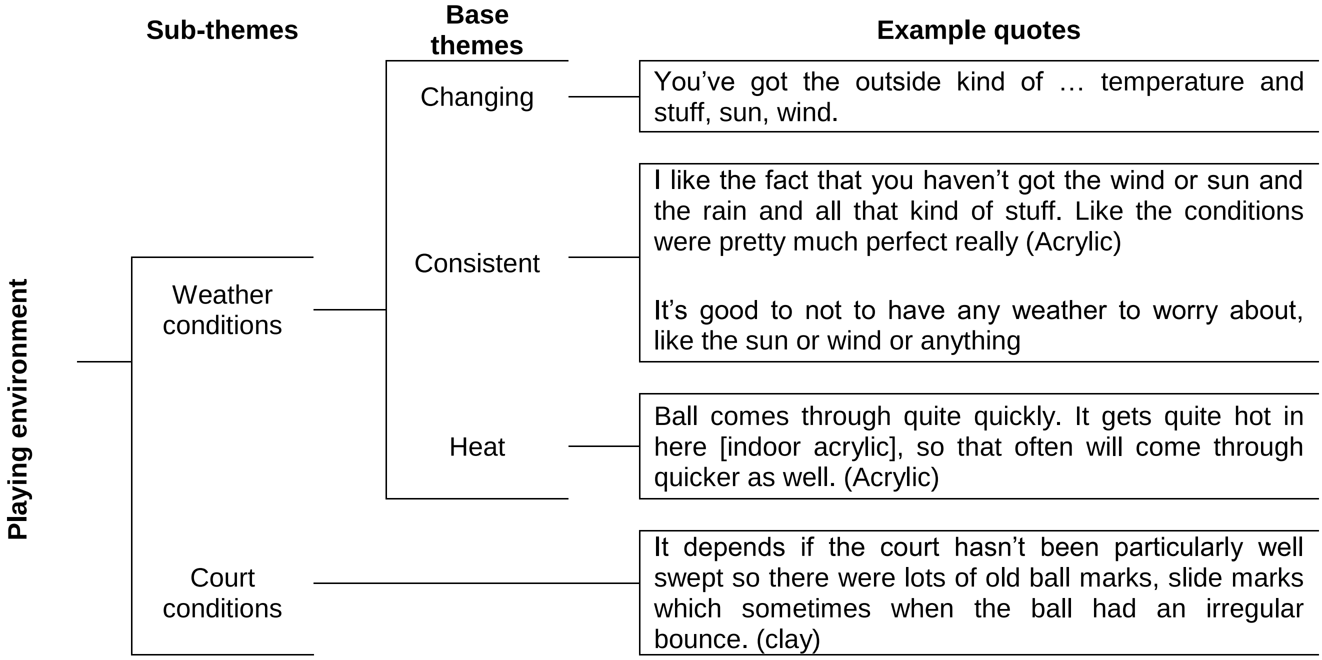

Figure 3.21: Playing environment tree structure, highlighting the development from interview data to general theme

3.3.3.6 Structural Relationship Model

The duality of quotes allowed links between themes and sub-themes to emerge, therefore developing a structural relationship model (Figure 3.23). From the interview data several relationships were identified between the themes, where quotes were placed into more than one theme, for example:

> It's quite soft under the ground so I know I can jump and it not to hurt.

This quote was coded to both the hardness sub-theme and the injury general theme. The participants perceived the hardness of the court and identified that they would have a lower risk of injury on the clay. Similar relationships occurred for other themes, such as grip between the player and the surface was observed to allow for certain movements. For example the participants perceived less grip on the clay court, suggesting that sliding movements were easier but changes of direction were harder compared to the acrylic court.

> Nice crisp movements, quick change of direction, a lot easier to move around I think then the clay. Because you've got better grip on the court. On clay its, a balls hit behind you um, and you've been running one direction, it's a lot more difficult to turn around. Whereas on the hard court you can turn a lot more quicker and get round to the ball. (Acrylic)

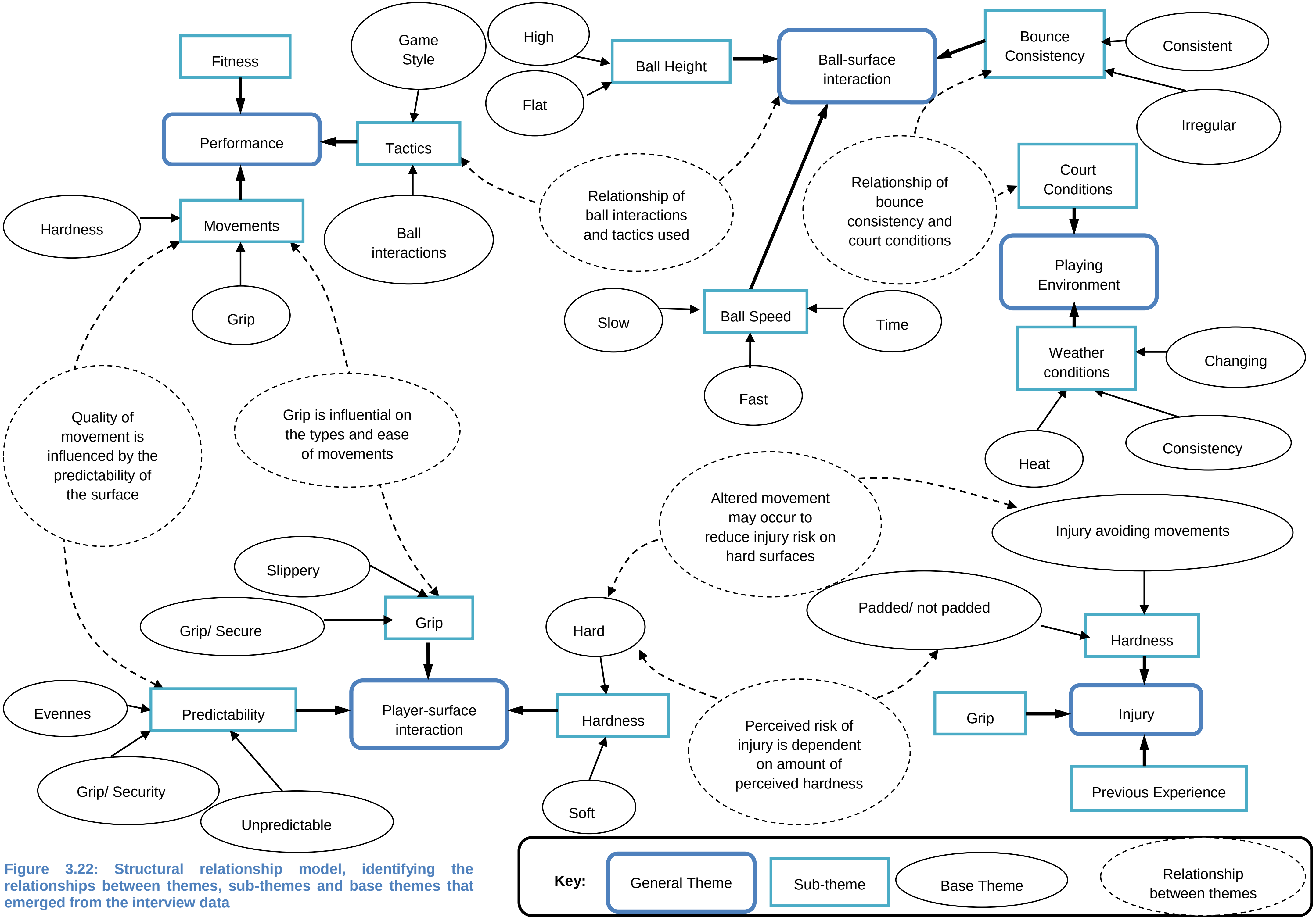

Figure 3.22: Structural relationship model, identifying the relationships between themes, sub-themes and base themes that emerged from the interview data

3.4 Discussion

The present study aimed to identify and examine tennis player's perceptions and responses on two tennis court surfaces. From the interview data several perceptions were identified through general themes, sub-themes and base themes, which have led to the development of a perception questionnaire. The present study identified kinematic differences between courts and has allowed for the development of data collection procedures and highlighted different techniques between the acrylic and clay courts, particularly for the more demanding running forehand stroke.

3.4.1 Mechanical data

The current study reported differences in static and dynamic measures of friction between the surfaces. The mechanical friction reported was similar to that previously reported for clay and acrylic courts (Nigg, 2003; Damm et al., 2014). No significant differences in peak impact force was reported however peak loading rate was significantly lower (2%) on the clay court compared to the acrylic suggesting a later occurrence of peak impact force on the clay court. Greater differences reported mechanical friction compared to stiffness measures of the surfaces in addition to the greater sliding observed on the clay court suggests friction to the important factor influencing players technique reported in the current study.

3.4.2 Biomechanical Data

Although there is low statistical power in the present study owing to the low participant numbers, initial findings highlight some potential differences between surfaces that will be examined further through developed data collection procedures in future studies.

3.4.2.1 Forehand Open Stance

The present study revealed differences between surfaces for hip height, initial ankle flexion and occurrence time of peak knee flexion during the forehand open stance. Hip height, often used as an indicator of centre of mass (COM) height (Ferris, Louie, & Farley, 1998), was revealed to be 12.5% higher at impact on acrylic compared to clay which disagrees with running studies that suggest COM to be maintained throughout stance on different surfaces by altering leg stiffness (Ferris et al., 1998). Results from the present study suggest participants were attempting to improve their stability through lowering their hip height on the lower friction clay court during the forehand open stance (Cham & Redfern, 2002).

The lower mechanical friction clay court reported later knee flexion and the longer contact times observed on the clay court contributing to the reduced loading often observed on clay courts (Durá et al., 1999; Girard et al., 2007). Participants perceptions, previously associated with biomechanical response, influenced their technique and response to the acrylic and clay court. However the present study is unable to identify how these perceptions influenced players' response. Therefore future work exploring the relationship between perceptions and response are required to provide further understanding of player-surface interactions.

3.4.2.2 Running Forehand

Sliding, to allow more efficient change of direction (Miller, 2006; Pavailler & Horvais, 2014), was permitted on the clay court unlike the acrylic court where no sliding was observed. When sliding on the clay court, participants adopted a different strategy in the performance of the running forehand compared to the acrylic court. Participants contacted the ground with a flexed knee and flatter foot on the clay, which has previously been reported to improve stability during walking on slippery surfaces (Heiden et al., 2006). A recent study examining a running forehand foot plant reported an extended knee at impact on a clay surface, suggested to facilitate sliding by increasing traction demand, whilst a flexed knee on the acrylic was suggested to dissipate loads (Damm et al., 2013). These conflicting findings may be due to differences in procedures and skills performed. For instance, Damm et al. (2013) collected data in the laboratory and imitated the tennis stroke which produced a different response, whilst the present study data were collected on court where participants completed several drills involving changes of direction in order to return the next shot.

3.4.3 Perception Data

Five themes emerged from the analysis highlighting participants' ability to perceive differences between the courts such as player-surface interactions and ball-surface interactions. Unlike previous quantitative studies where perceived cushioning and friction were the focus (Hennig et al., 1996; Milani et al., 1997; Lockhart et al., 2002; Stiles & Dixon, 2007), the present study revealed further perceptions such as perceived predictability and perceived ability to change direction. Relationships between themes and sub-themes were developed from further examination of the interview data, where quotes were considered to be coded within more than one theme, illustrated by the structural relationship model. Player-surface interactions and ball-surface interactions were often discussed with the other themes. For example player-surface interactions were often related with injury risks and performance (movements), whereas ball-surface interactions were often related to performance (tactics) and playing environment (court conditions). The themes identified in the present study were similar to those reported from hockey players perceptions of pitches, where differences in surface grip, surface hardness and additionally surface abrasiveness were identified (Fleming et al., 2005).

Participants reported the clay court to be less predictable compared to the acrylic court which was reported to be secure. These perceptions were associated with the greater mechanical friction on the acrylic court, whilst lower mechanical friction on the clay resulted in participants becoming more cautious, potentially to prevent slipping on the low friction surface (Damm et al., 2014). Previous experience, known to contribute to perceptions (Coren et al., 1979; Gescheider & Bolanowski, 1991), may have influenced participants' perceived predictability of the courts. Participants were unfamiliar with clay courts compared to acrylic courts; therefore they had less knowledge of how to interact with the clay court describing it as 'unpredictable,' whilst their greater previous experience on acrylic courts allowed for more predictable circumstances. Fleming et al. (2005) reported previous experience to influence player performance. They suggested that those with greater skill level have experienced a greater range of surfaces and were therefore more able to adapt to changes in surfaces. The participants in the present study were university level players (LTA rating 4.1 – 7.2), therefore it is likely that more elite players are better able to accommodate to changes in surfaces and therefore identify higher predictability values compared to lower level players. Similar LTA ratings between players during research studies must be considered in addition to players' previous clay court experience.

Harder or high friction surfaces, such as acrylic courts, have been associated with increased injury risk due to greater loading and altered kinematics (Durá et al., 1999; Girard et al., 2007; Dowling et al., 2010). Participants identified that the acrylic surfaces results in greater injury risks suggesting greater hardness as a factor. Whilst mechanical tests for hardness reported no differences in peak impact force, mechanical peak loading rates were lower on the clay, providing an explanation for the differences in perceived hardness between the two courts. The higher mechanical translational and rotational friction on the acrylic court also contributed to the higher perceived hardness on the acrylic compared to the clay court. For instance an interrelationship between perception of hardness and friction was observed, where participants noted that the clay was 'soft' because they could slide; therefore lower grip may be associated with lower perceived hardness. Previously perceived hardness and smoothness from finger touch of different surface textures were suggested to be orthogonal dimensions where hardness perceptions were related to increases in smoothness perceptions (Holliins et al., 1993). Therefore the integration of different sensory information overlaps to form perceptions like hardness and grip (Gibson & Carmichael, 1968; Coren et al., 1979; Holliins et al., 1993).

Previous reports suggest that although participants were aware of injury risks from surface properties they were more concerned with the influence upon performance (Fleming et al., 2005). Participants in the present study often discussed differences in the movements that they used on the two courts, for example on the clay court they suggested less grip allowed for sliding and was important in getting to the ball in time by allowing a change in direction after a shot was played. This association between movements such as sliding and change of direction highlight the relationship between player movement on court and their experiences of the surface properties, thus examination of court properties and player ability to change direction or slide provides an insight to their perceptions of the tennis court.

Longer rallies and greater baseline points have been demonstrated on clay courts compared to acrylic courts (O'Donoghue & Ingram, 2001). In the present study participants suggested that on acrylic courts shorter rallies and more aggressive play were due to ball-surface interactions, consistent with previous findings (Fleming et al., 2005). Participants reported inconsistent and higher ball bounce with slower speed on clay provided more time to return the ball, therefore resulting in longer rallies and more baseline shots. Ball speed and height, both of which are influenced by coefficients of friction and restitution between the ball and surface provide the court pace rating (CPR) of the surface (Miller, 2006; International Tennis Federation, 2014). Higher friction with the ball on the clay court will give a CPR of *slow* as opposed to *fast* on the acrylic court which results in lower ball height (Miller, 2006). Players perceptions of ball-surface interactions are consistent with the CPR system employed by the ITF (International Tennis Federation, 2014), however the consistency of the ball bounce is not considered in CPR, yet from the interview data participants are aware of this and suggested altered tactics as result of ball bounce consistency.

3.5 Limitations

The interview data collected in the present study highlighted several perceptions important for tennis players. However, it must be noted that the strength of interview data is dependent on the skills of the researcher (Patton, 1990; Braun & Clarke, 2006). The researcher (interviewer) is the tool for collecting data (Patton, 1990), during the current study the researcher had little prior experience in conducting interviews, which may have inhibited the data collected. To minimise error, practise interviews were conducted along with the construction of an interview guide. Participants were invited to review the transcriptions as well as the interpretation (Patton, 1990), along with similarities with previous studies (Fleming et al., 2005), the data collected was deemed credible.

The present study developed and implemented tennis specific drills. The tennis drills were employed to provide realistic conditions which are often difficult to obtain within the confines of a laboratory. Although the repeatability of the movement when collecting data on court may be questioned, the variability of the data is similar to that reported during studies performed in laboratories. However, on court analysis provides more realistic conditions for the development of perceptions, therefore providing more holistic understanding of tennis players perceptions, which may otherwise be limited during a lab based approach.

3.6 Conclusions

Initial biomechanical data suggest different coping methods on clay (sliding) compared to acrylic when performing fast movements. The present study identified perceptions, such as predictability, ball movement and types of movements in addition to previously reported perceptions of grip and hardness. Participants were able to identify differences in player-surface interactions and ball-surface interactions which related to other themes (performance, injury and playing environment) to provide a more complete picture of their perceptions on both courts. Perceptions of surface grip reflected the mechanical data for friction. However, both tennis courts were similar in mechanical hardness but were perceived to be different; this suggests multiple perceptions may interact to provide a complex interpretation of perceived surface properties.

3.7 Implications

The present study has provided an insight into the factors that influence tennis players' perceptions of clay and acrylic courts. Initial biomechanical results have suggested an altered technique when sliding is permitted. Low mechanical friction on clay is likely to allow for the sliding that was observed on the clay court, suggesting that a comparison of surfaces with different mechanical friction characteristics may provide further insight into the implications of sliding for injury risk and performance. Current knowledge suggests previous experiences influences both perceptions and response (Coren et al., 1979; Heiden et al., 2006). Participants in the current study had little previous experience of clay courts, which may have influenced how they perceived the surface and performed the tennis strokes. Yet it is not known the influence of previous clay court experience on perceptions and response. Therefore future work examining players with different clay court experiences will provide further insight to the development of perceptions and biomechanical adaptations to tennis surfaces.

3.8 Development of perception questionnaire

Using thematic inductive analysis, Study 1 identified tennis players' perceptions of clay and acrylic courts. These perceptual themes were deemed to influence both player performance and risk of injury. The perceptions reported in the present study led to the development of perception questionnaires (Appendix 7), which will allow perceptions to be quantified and examined in relation to biomechanical responses to surfaces. The questionnaire was developed to allow for perceptions of player experiences on tennis courts to be examined. Therefore when developing the questionnaire, perceptions were extracted from sub-themes to ensure the aims of the thesis could be achieved. The language used by participants with the semi-structured interviews as highlighted in the themes, sub-themes and base themes were incorporated into the questionnaire to reduce ambiguity.

CHAPTER 4: STUDY 2: TENNIS PLAYERS' PERCEPTIONS AND BIOMECHANICAL RESPONSES AND THE INFLUENCE OF PRIOR CLAY COURT EXPERIENCE

4.1 Introduction

Over the length of a year elite junior tennis players were reported to spend a greater proportion of their playing time on acrylic courts (70%) compared to the 30% of time spent on clay courts (Hjelm et al., 2012), providing players with different levels of experience on each tennis court surface. These surfaces can differ greatly in mechanical properties such as friction and cushioning, which are often related to changes in performance as a result of altered movement and styles of play (O'Donoghue & Ingram, 2001; Reid et al., 2013). Compared with low friction surfaces, high friction surfaces leads to kinematic adjustments (Farley, Glasheen, & McMahon, 1993), such as greater attack angles, in addition to faster running speeds and movements (Brechue, Mayhew, & Piper, 2005). Whilst as demonstrated in the previous chapter, players accommodate to low friction surfaces such as clay through sliding (Miller, 2006).

As previously highlighted, the surface properties that influence players' performance are also likely to result in changes in injury risk, through altered kinematics and loads (Durá et al., 1999; Girard et al., 2007). Lower injury rates have been reported on clay courts, suggested to be a result of lower friction (Nigg & Segesser, 1988; Bastholt, 2000). Higher friction surfaces have been associated with higher loading particularly on the lateral regions of the foot (Damm et al., 2014). If the foot became fixed to the ground due to the high friction, the higher loads in the lateral region of the foot could overload the ankle resulting in an ankle inversion injury (Damm et al., 2014; Tung et al., 2014). Reports have suggested patellofemoral pain to be a common knee injury in tennis (Abrams et al., 2012). Kinematic adjustments to high friction surfaces include longer braking phases and greater knee flexion (Durá et al., 1999), which have been suggested to contribute to the occurrence of patellofemoral pain (Chard & Lachmann, 1987; Gecha & Torg, 1988; Damm et al., 2013).

Research from walking has provided some insight into human responses to low shoe-surface friction. A flatter foot and flexed knee during initial stance (Heiden et al., 2006), along with greater toe grip and lower heel pressures (Fong et al., 2008), have been suggested to help maintain balance and reduce the risk of slipping during walking on low friction surfaces. However, during a tennis running forehand, greater knee extension was observed at ground contact suggested to facilitate sliding on a low friction surface (clay court) compared with a high friction surface (acrylic court), (Damm et al., 2013). Lower loads have been reported for clay courts compared with acrylic, where pressure distribution patterns have altered between these court surface types (Girard et al., 2007; Damm et al., 2012). A recent study reported the COP to medially shift during tennis-specific movements on a clay compared to an acrylic court, which was suggested to allow for sliding by preventing the foot ‘ploughing’ into the clay infill (Damm et al., 2014). Previous research has highlighted little agreement in mechanical and biomechanical measures (Dixon et al., 2000), suggesting different biomechanical responses to surface properties are influenced by perceptions of these properties (Hennig et al., 1996; Milani et al., 1997; Stiles & Dixon, 2007).

Previous experience and sensory information are combined to formulate perceptions and enable humans to interact successfully within their environment (Coren et al., 1979; Sherwood, 1993; Milani et al., 1997; Lockhart et al., 2002; Stiles & Dixon, 2007). Studies have identified associations between perceived cushioning and friction and biomechanical response to surface and shoe changes. For example, reduced peak loading rates have been associated with increased perceived cushioning (Hennig et al., 1996; Milani et al., 1997; Stiles & Dixon, 2007). These relationships between perceptions and biomechanical response provide understanding of how players experience changing in surface properties which enable them to respond appropriately to these properties. Perceptions and the relationships with biomechanics responses provide understanding of tennis players' experiences of tennis courts and response to different surface properties. Inform how players respond to different tennis courts. Studies have mainly focused on perceptions of cushioning and friction, whilst Fleming et al. (2005) interviewed hockey players and identified other perceptions such as surface abrasiveness to be important. Therefore further research is required to examine other perception variables such as those identified in study 1 and the relationship with biomechanical responses to increase understanding of how tennis surface properties alter player movement and loading.

In addition to influencing perceptions, previous experience can alter our response to surface conditions (Coren et al., 1979; Chiou et al., 2000; Heiden et al., 2006). Previously prior experience and awareness of slippery surfaces resulted in adopting a cautious gait (greater initial knee flexion) which led to reduced GRF and increased muscle activity during walking (Heiden et al., 2006). These studies have examined walking or work-specific tasks, whilst there has been no research examining the influence of previous experience of surface conditions during sport-specific movements such as turning.

The aim of the present study was to examine the influence of changes in tennis surface upon perceptions and biomechanical variables (see Specific aim 2, p. 56), and investigate the relationship between perceptions and biomechanical variables to better understand the influence of perceptions upon factors associated with increased injury risk (see Specific aim 3, p. 56). Based on literature evidence, it was anticipated that player perceptions of hardness and grip would be associated with player loading and kinematic changes. Specifically, it was hypothesised (H_{1a}) that an increase in perceived hardness will be related to greater peak heel pressures and (H_{1b}) lower perceived grip will be associated with greater initial knee flexion. The study also aimed to evaluate the influence of previous experience of clay courts upon perceptions, biomechanics and their relationship (see Specific aim 4, p. 56). It was hypothesised (H_2) that those with prior experience of clay courts will adapt to increase stability through reduced GRF.

4.2 Methods

4.2.1 Participants

Two groups of tennis players volunteered to participate in the present study. Players were grouped according to their experience of playing on clay courts. These groupings were determined by questionnaire (Appendix 6) where those who rated their experience on clay as high or above (i.e. once a month or more) were selected for the experienced group (n = 5, age 28 ± 5.1 years, height 1.78

± 0.1 m, mass 75.00 ± 14.3 kg and LTA rating 2.9 ± 1.6), whereas those who rated no to moderate experience (once a year or less) formed the low-experience group (n = 5, age 26 ±1.3 years, height 1.74 ± 0.1 m, mass 65.75 ± 12.8 kg and LTA rating 3.8 ±1.1). The study was approved by the Institutional Ethics Committee and informed consent was obtained before testing.

4.2.2 General Overview

Kinematic, pressure, and perception data were collected on two randomly assigned tennis courts (acrylic and clay, Appendix 3) at the National Tennis Centre (NTC), London. Kinematic and pressure data were collected for a tennis-specific skill (running forehand) and a turning movement. A questionnaire containing a series of VAS was then completed to obtain perception data.

4.2.3 The Turning Movement

Participants were required to run 5.5 m along the baseline, through a set of timing gates placed 3 m apart at a speed of 3.90 ± 0.20 m.s^{-1} then perform a 180^{o} turn (with their dominant leg) at the tram line before returning to the start (Figure 4.1). During all testing participants wore the same tennis shoes (Adidas Barricade 6.0 clay shoes) as described in Section 3.2.4.

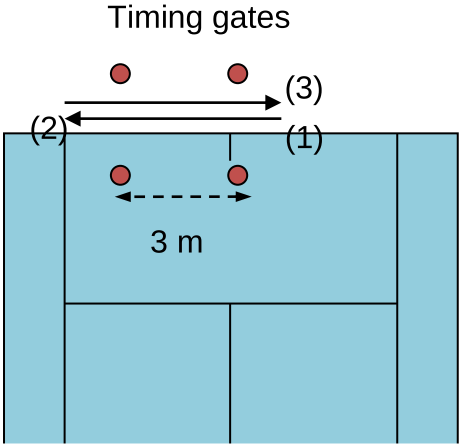

Figure 4.1: A schematic diagram for the turning drill, where (1) represents the participants starting position, where participants ran at speed to point (2) performing an 180^{o} turn at the tram before returning to the starting position (3)

4.2.4 The Running Forehand

The running forehand movement was completed through the dynamic drill, previously explained in study 1 (Section 3.2.4). The only exception to study 1 was the inclusion of a ball machine which fed the ball consistently all trials. Ten successful trials were collected for both movements; any unsuccessful trials were omitted and repeated. Participants were given adequate time to familiarise themselves with the court, the movement and warm up before testing.

4.2.5 Mechanical Data

Mechanical tests were conducted on each tennis court by colleagues from the University of Sheffield, Sports Engineering Research Group. The tests included the Pendulum test (British Standards, 2002), Crab III test, Rotational traction test and the SERG impact hammer (Carré et al., (2006) previously described in Section 3.2.3. Additionally the English Xl and the Lightweight Deflectometer (Fleming & Young, 2005) were also conducted on each tennis court.

Figure 4.2: English XL test device

The English XL, is an inclined-strut tribometer (Figure 4.2). The device includes a circular test foot, which impacts the surface at an inclined angle. Pressure was compressed in a pneumatic cylinder, so that when released the cylinder 'kicked out' and extended, which indicated a slip. The inclined angle was adjusted from a high incline angle to a low incline angle, the angle that a slip (cylinder extends) was recorded following trials without a slip allowed for the calculation of the static coefficient of friction.

The Lightweight Deflectometer (LWD) was used during the mechanical measurement of the court surfaces to examine stiffness of the surfaces by loading a deflection sensor and geophone foot (Figure 4.3). For further information regarding the setup see Fleming & Young (2005). Three drop heights were examined, which equated to contact stress of 225 kPa, 146.25 kPa and 90 kPa.

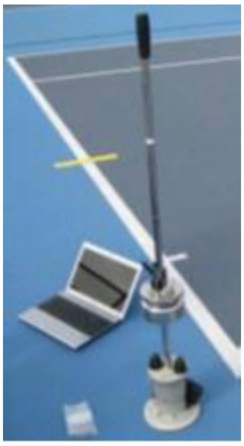

Figure 4.3: The Lightweight Deflectometer device

4.2.6 Perception Data

A short questionnaire comprising a series of visual analogue scales (VAS) was used to collect perception data following play on each court (Appendix 7). These scales were 100 mm in length with two descriptive end phrases, formulated from variables and language identified in previous qualitative work. Perception variables included perceived predictability, grip, hardness, ability to change direction, ability to slide.

4.2.7 Kinematic Data

Kinematic data were collected using three 50 Hz cameras (Sony HDV 1080i mini DV). Kinematic data were synchronised using event synchronisation of LED lights triggered by the pressure system, providing a maximum error of 10 ms. DLT, using Vicon Motus (v9.2) software, was used to reconstruct three-dimensional coordinates from the two-dimensional digitised coordinates of each camera (Abel-Aziz & Karara, 1971) as explained in Section 3.2.8. Reconstruction errors, calculated using RMSE, were no larger than 0.01 m in the x, y and z direction. In order to establish a joint coordinate system (Section 3.2.8) adapted from Grood & Suntay (1983) and Soutas-Little et al. (1987), eleven markers, as reported in Section 3.2.8, were placed upon the lower limb of the dominant leg. The 3-dimensional lower limb coordinates were filtered using a recursive 2nd order Butterworth filter, with an optimum cut off frequency (range of 4-8 Hz) for each coordinate determined using residual analysis (Winter, 1990).

A custom written Matlab code (2011b, MathsWorks.) was used to determine rotations about the ankle and knee joint centres (Section 3.2.8). Kinematic variables included initial and peak ankle, knee and rearfoot angle. Occurrence time of peak angles were reported relative to heel contact. Hip height was measured using the hip z-coordinate. Attack angle at impact was defined as the angle between the y axis and the calcaneus to hip vector.

Sliding was determined using the velocity of centre location of the foot (using the calcaneus 2 marker and toe marker). A sliding phase was determined when the velocity was greater than a threshold of 1 mm.s^{-1} and maintained for more than 10 ms. During this sliding phase, sliding distance was determined by the resultant distance covered by the 5th metatarsal.

4.2.8 Pressure Data

Pressure insoles (100 Hz; Pedar, Novel) were used to obtain data during the deceleration step for each movement. The pressure insoles contained 99 individual sensors to gain distribution patterns for the plantar surface of the foot. The insoles were placed flat within the tennis shoes and were attached to a data acquisition box by a double insulated cable. The data acquisition box transmitted the data to a laptop wirelessly via Bluetooth where data were recorded. The data acquisition box was attached to a synchronisation box using a double fibre optic cable. The data acquisition box, synchronisation box and battery were placed with a belt which was worn around the participant's waist (Figure 4.4) and placed on the lower back to minimise obstruction to the participants when performing dynamic movements.

Figure 4.4: Placement of the belt, worn by participant, containing the data acquisition box, synchronisation box and battery

Prior to any data collection period, the pressure insoles were calibrated using a Trublu calibration device (Novel, GmbH, Munich). The device consisted of rubber membrane within a secured unit. To calibrate, the insoles were placed within the device and were connected to the data acquisition box. A series of known pressures were fed into the system using compressed air, formulating calibration curves for each sensor. The insoles were calibrated to 6 bar (60 $N.cm^{-2}$).

A custom written Matlab (2011b) code was used to identify the start and end point of each step. The code plotted the left and right foot forces throughout the time the data were collected (Figure 4.5) and allowed the researcher to manually click on the graph to give an approximation of the start and end of the step. To further refine the location of the start and end of the step, the code examined the loading within the time frame to identify when the loading rate reached a threshold of 5 $N.s^{-1}$ or above.

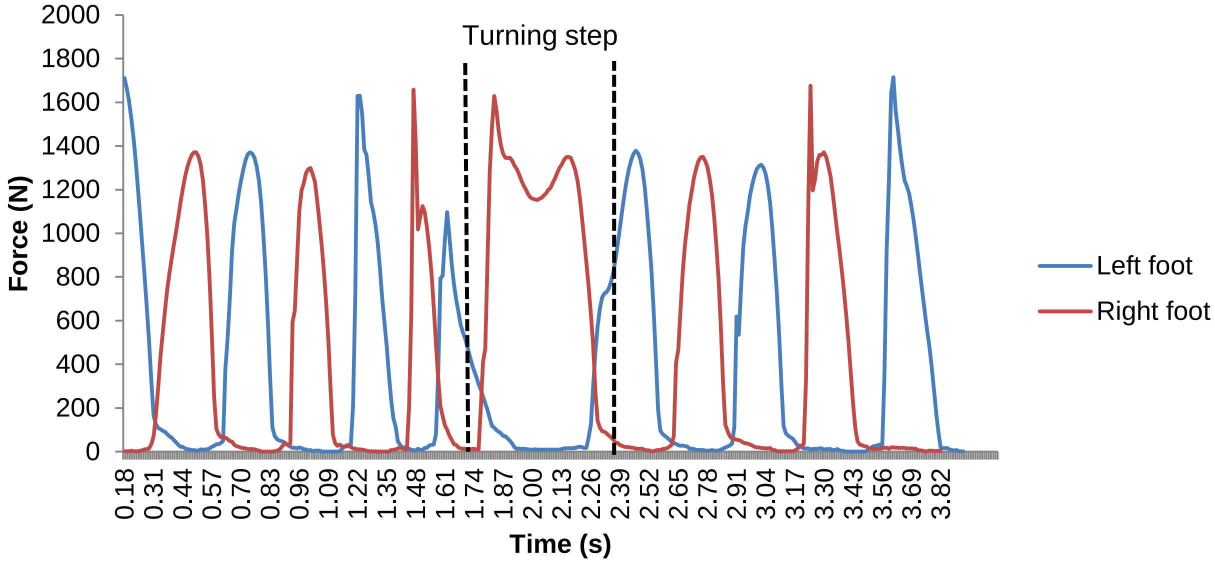

Figure 4.5: Example pressure data collected during a turning movement highlighting the identification of the turning step

Eight masks (Figure 4.6), as previously used by Damm et al. (2012), allowed for a detailed analysis of plantar foot sections. Regional masks included lateral and medial heel, midfoot and forefoot and the hallux and lesser toes.

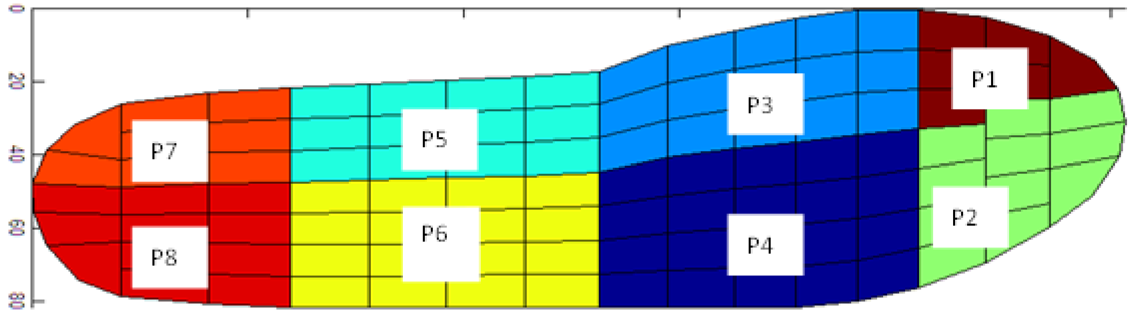

Figure 4.6: A representation of the eight masks (right foot) used; P1: hallux, P2: lesser toes, P3: medial forefoot, P4: lateral forefoot P5: Medial mid foot, P6: lateral midfoot, P7: medial heel, P8: lateral heel

Variables for both whole foot and foot regions included mean and maximum pressures, peak impact and active forces, peak and average loading rates and impulse. The pressure insoles provided an indication of the vertical force parameters during the deceleration step. Peak impact force was established as the peak force during the first 50% of ground contact (Figure 4.7). Peak active force was identified as the peak vertical force value during the final 50% of ground contact. Average loading rate and peak loading rate, reported to be sensitive to changes in surface cushioning during a running forehand foot plant (Stiles & Dixon, 2007), were calculated using the vertical force data. Average loading rate was defined as the ratio between the peak impact force and the occurrence time of peak impact force (Equation 4.1). Peak loading rate was defined as the maximum value of the instantaneous loading rate prior to the peak impact force. Instantaneous loading was calculated using the first central difference method (Equation 4.2).

$$Average\ loading\ rate = \frac{Peak\ impact\ force}{Occurrence\ time\ of\ peak\ impact\ force} \quad \text{Equation 4.1}$$

$$Instantaneous\ loading\ rate = \frac{(force_3 - force_1)}{(time_3 - time_1)} \quad \text{Equation 4.2}$$

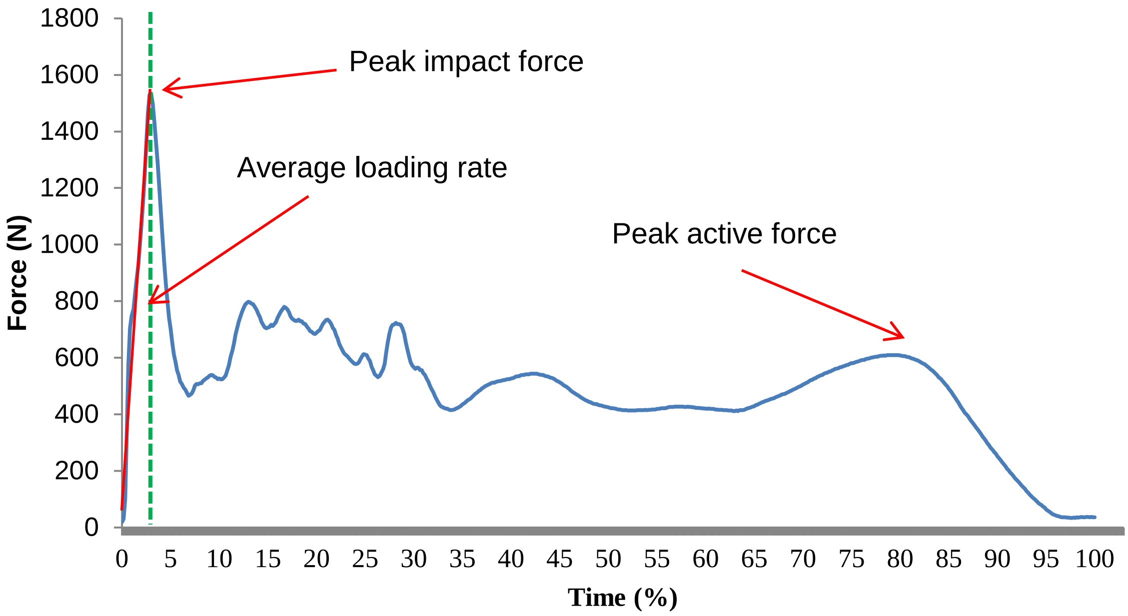

Figure 4.7: An example vertical force time history, illustrating the vertical loading characteristics identified

4.2.9 Statistical Analysis

Comparisons between the groups and surfaces were examined for pressure, kinematic and perception data using a two-way ANOVA with repeated measures, with Bonferonni's corrected alpha post hoc analysis. Effect sizes (ES) were calculated using partial Eta^2 to provide the degree to which the differences were present (Cohen, 1977). Some trials from the pressure data were omitted due to a failed wireless transmission, resulting in data for only four participants in the low-experience group and three participants in the experienced group, meaning group comparisons could not be made. Therefore a paired t-test was conducted to examine differences for the whole cohort of players between the two courts. Pearson's *r* correlations were conducted to examine associations between biomechanical and perception data. Statistical analysis was conduct using SPSS (v.19) software. An alpha level of less than 0.05 determined significance.

$$z(r) = 0.5Log\left(\frac{1+r}{1-r}\right)$$ *Equation 4.3*

$$z = \frac{z(r_1) - z(r_2)}{\sqrt{\left(\frac{1}{n_1-3}\right)+\left(\frac{1}{n_2-3}\right)}}$$ *Equation 4.4*

Fisher Z-transformations were used to examine the differences between group correlation coefficients using Equation 4.3 and 4.4 to transform Pearson's *r* coefficients to normal (z) distributions and to calculate the critical value to determine significance. An alpha level of $p<.05$ was used to identify significance.

4.3 Results

4.3.1 Mechanical Data

Table 4.1: Means and standard deviations for mechanical data collected on the acrylic and clay court

Mechanical test	Acrylic	Clay
Frictional measures		
Pendulum (COF)	0.710 ± 0.027	0.578 ± 0.034*
Crab III (COF)	1.29 ± 0.05	0.85 ± 0.15*
Rotational Traction (N/m)	20.77 ± 4.89	12.24 ± 1.57*
English XL (COF)	1.50 ± 0.07	0.50 ± 0.03*
Hardness measures		
SERG Impact hammer		
Peak force (N)	1751.55 ± 5.87	1723.9 ± 22.15*
Stiffness (kN/m)	302.75 ± 20.44	279.46 ± 12.96*
Lightweight Deflectometer (LWD, MPa)		
High drop height (contact stress = 225 kPa)	444.90 ±31.97	356.80 ± 66.80
Medium drop height (contact stress = 146.25 kPa)	514.90 ± 35.64	273.89 ± 34.51*
Low drop height (contact stress = 90 kPa)	510.80 ± 35.78	329.80 ± 84.01*

*** denotes a significant difference between tennis courts, *P* <0.05**

Table 4.1 provides the means and standard deviations from the mechanical data collected on both tennis courts. The clay court had significantly lower static and dynamic coefficients of friction compared to the acrylic court. Peak force measured by the SERG impact hammer was significantly greater on the acrylic court compared to the clay court, indicating greater hardness on the acrylic court (Clarke et al., 2013). Stiffness also measured by the SERG impact hammer and the LWD was significantly greater on the acrylic court compared to the clay court.

4.3.2 Tennis Court Differences

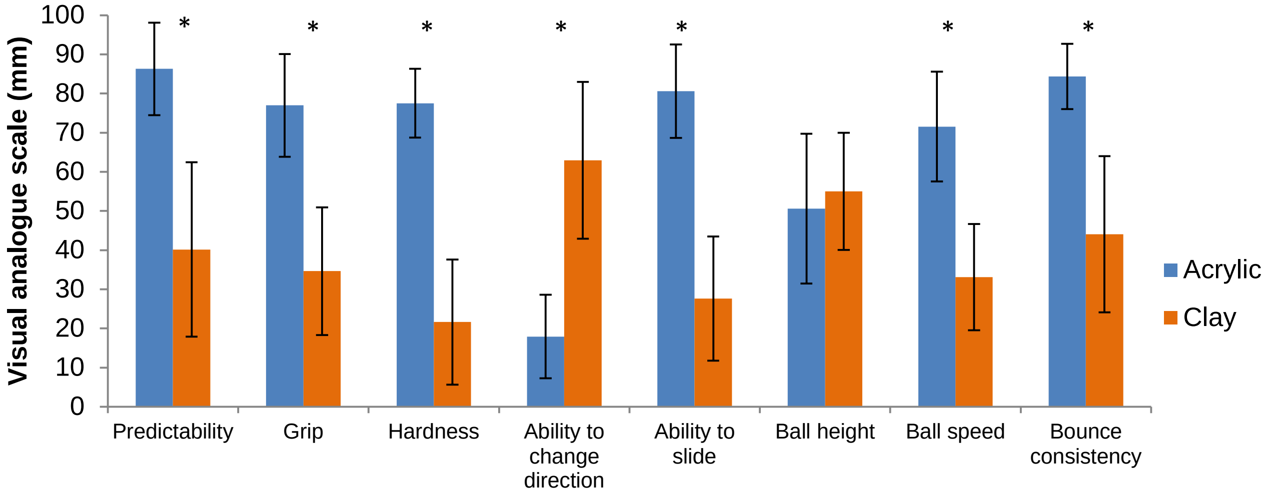

Figure 4.8: Means and standard deviations for the perception variables and comparison between the clay court and hard court, *denote a significant difference between tennis courts, *P* <0.05

The analysis revealed significant differences between tennis courts for all perception variables except perceived ball height (Figure 4.8). The acrylic court was rated to be significantly more predictable, have more grip, greater hardness and was harder to slide on when compared with the clay court. However, the clay court was perceived to be harder to change direction compared to the acrylic court.

Figure 4.9 represents the sliding distances for both the turning movement and the running forehand movement. As highlighted in Figure 4.9 it is noticeable that the participants achieved further sliding distance on the clay court (turn = 0.66 ± 0.40 m and running forehand = 0.65 ± 0.39 m) compared to the acrylic court (turn = 0.35 ± 0.04 m and running forehand = 0.28 ± 0.12 m) during both the turn (ES = .598, *p* =.009) and the running forehand (ES = .445, *p* =.035). Contact time for both the turn (ES = .838, *p* =.000) and running forehand (ES = .502, *p* =.022) were on the clay court (turn = 0.54 ± 0.11 s and running forehand

0.33 ± 0.15 s) compared to the acrylic court (turn = 0.35 ± 0.04 s and running forehand 0.019 ± 0.03 s).

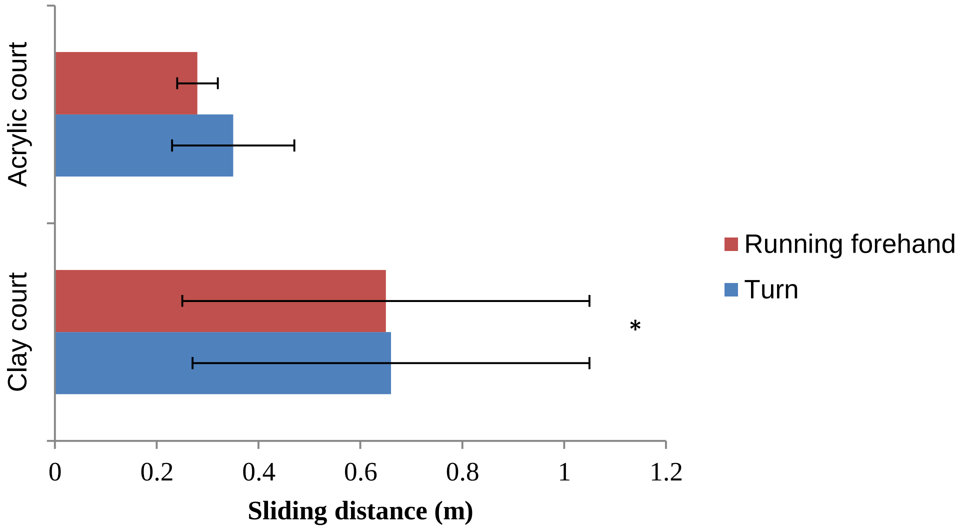

Figure 4.9: Means and standard deviations for sliding distances achieved on the clay and acrylic courts, * denotes significantly different to the acrylic court for both movements, *P* <0.05

No differences in hip height were identified between the courts for the running forehand. However, during the turn, the hip height was 8 cm higher on the clay court (-0.12 ± 0.06 m) compared to the acrylic court (-0.20 ± 0.04 m, ES = .723, *p* =.002). Represented schematically (Figure 4.10), initial attack angle was significantly higher on the clay court (74.35 ± 6.10^{o}) compared to the acrylic court (64.76 ± 5.33^{o}, ES = .572, *p* =.011) during the turning movement.

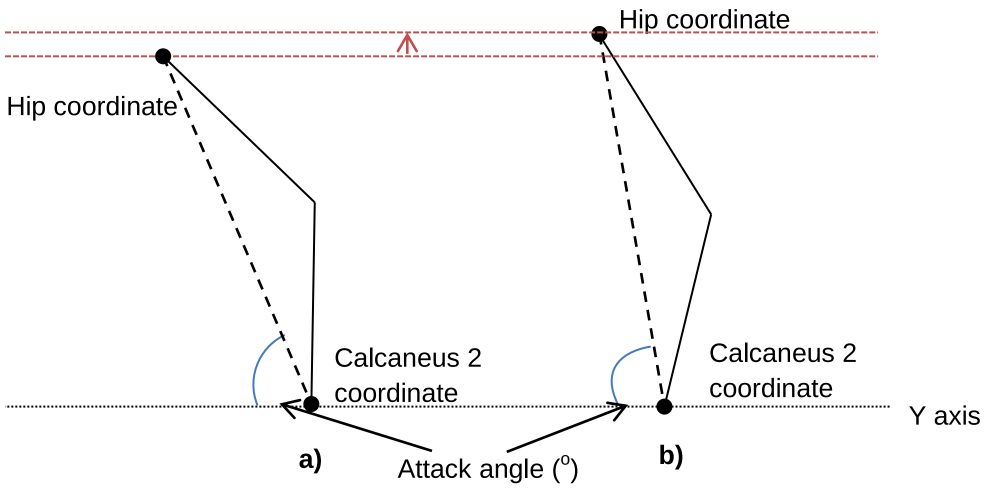

Figure 4.10: A schematic diagram representing attack angle, where a) represents a lower attack angle observed for the acrylic court, b) presents a more upright position observed on the clay court

Table 4.2 and 4.3 provides the means and standard deviations for the kinematic data collected on each tennis court for the turn and running forehand. Court differences in initial knee flexion angle were revealed from the analysis for both movements. Greater initial knee flexion angles, indicating greater flexion, on the clay court (turn = 32.51 ± 9.43^{o} and running forehand = 17.87 ± 10.51^{o}) compared to the acrylic court (turn = 20.78 ± 11.20^{o} and running forehand = 9.20 ± 5.81^{o}) for both movements were revealed.

Table 4.2: Means and standard deviations for kinematic data during the turning movement on each tennis court for both experience groups

Variable	**Acrylic court**			**Clay court**			***ES***
	Experience group	Low-experience group	Total	Experience group	Low-experience group	Total	
Ankle dorsi flexion							
At impact (°)	-2.49 ± 7.65	3.33 ± 8.33	0.42 ± 8.14	7.66 ± 9.44	3.33 ± 8.33	2.46 ± 10.15	.562 [i]
Peak (°)	-20.39 ± 12.84	-27.63 ± 12.84	-24.01 ± 11.90	-14.40 ± 4.98	-22.26 ± 9.23	-18.33 ± 8.12	
Time of peak (s)	0.11 ± 0.09	0.20 ± 0.054	0.16 ± .1	0.29 ± 0.13	0.27 ± 0.09	0.28 ± 0.1	.694*
Ankle inversion							
At impact (°)	-0.28 ± 6.63	-1.74 ± 6.96	-1.01 ± 6.45	3.47 ± 6.69	-4.87 ± 6.05	-0.70 ± 7.45	
Peak (°)	-14.29 ± 10.12	-10.28 ± 4.12	-12.29 ± 7.58	-8.59 ± 4.39	-11.43 ± 3.34	-10.01 ± 3.97	
Time of peak (s)	0.08 ± .01	0.12 ± 0.01	0.08 ± 0.03	0.11 ± 09	0.11 ±0.03	.11 ± 0.02	
Knee Flexion Angle							
At impact (°)	17.28 ± 9.53	24.28 ± 12.68	20.78 ± 11.20	28.05 ± 9.11	36.97 ± 8.22	32.51 ± 9.43	.476*
Peak (°)	31.16 ± 18.17	49.60 ± 9.71	40.38 ± 16.83	51.20 ± 17.61	42.70 ± 23.69	46.95 ± 20.18	
Time of peak (s)	0.16 ± 0.12	0.12 ± 0.10	0.14 ± .10	0.36 ± 0.11	0.15 ± 0.12	.26 ± .16	.456 [g]

*** denotes significant difference between courts, [i] represents a significant interaction between court and group, [g] represents a significant difference between groups, *P* <0.05**

Table 4.3: Means and standard deviations for kinematic data during the running forehand on each tennis court for both experience groups

Variable	**Acrylic court**			**Clay court**			***ES***
	Experience group	Low-experience group	Total	Experience group	Low-experience group	Total	
Ankle dorsi flexion							
At impact (°)	-4.68 ± 3.82	-2.39 ± 9.46	-3.54 ± 6.91	5.09 ± 6.54	5.13 ± 5.63	5.11 ± 5.75	.500*
Peak (°)	-20.04 ± 6.72	-6.41 ± 8.05	-13.22 ± 10.03	-4.01 ± 9.71	-3.60 ± 9.34	-3.80 ± 8.98	.503*
Time of peak (s)	0.05 ± 0.03	0.04 ± 0.3	0.04 ± 0.03	0.10 ± 0.05	0.09 ± 0.05	0.10 ± 0.05	.503*
Ankle inversion							
At impact (°)	-7.41 ± 3.73	-6.71 ± 3.00	-7.06 ± 3.30	6.09 ± 2.30	-4.92 ± 5.76	0.59 ± 8.55	.500*[i]
Peak (°)	-14.93 ± 3.25	-14.99 ± 5.65	-14.96 ± 4.35	-14.54 ± 8.88	-12.53 ± 5.59	-13.53 ± 7.07	
Time of peak (s)	0.09 ± 0.01	0.08 ± 0.01	0.09 ± 0.01	0.22 ± 0.11	0.13 ± 0.05	0.17 ± 0.09	.499*
Knee Flexion Angle							
At impact (°)	13.39 ± 2.48	5.00 ± 5.09	9.20 ± 5.81	19.36 ± 12.54	16.39 ± 9.26	17.87 ± 10.51	.495*
Peak (°)	30.07 ± 14.10	35.04 ± 13.17	32.55 ± 13.13	37.01 ± 7.08	42.48 ± 13.59	39.74 ± 10.61	
Time of peak (s)	0.12 ± 0.04	0.12 ± 0.02	0.12 ± 0.03	0.18 ± 0.16	0.16 ± 0.05	0.17 ± 0.11	

*** denotes significant difference between courts, [i] represents a significant interaction between court and group, [g] represents a significant difference between groups, *P* <0.05**

Ankle dorsi flexion at ground contact was revealed to be significantly different between the tennis courts for the running forehand (ES = .500, p =.027) only. During the running forehand, participants were more plantar flexed on the clay court (5.11 ± 5.75^{o}) at ground contact, whilst on the acrylic (-3.54 ± 6.91^{o}) participants contacted the ground with slight dorsi flexion. No significant court differences occurred for peak ankle dorsi flexion angle during the turning movement. However, results for the running forehand movement revealed a significant difference in peak ankle dorsi flexion between tennis courts (ES = .503, p =.015) such that participants produced significantly greater peak dorsi flexion on the acrylic (-13.22 ± 10.03^{o}) compared to the clay court (-3.80 ± 9.98^{o}). Occurrence time of peak dorsi flexion differed between courts for both the turning movement (ES = .694, p =.002) and the running forehand (ES = .503, p =.02). The clay court (turn = .28 ± .10 s and running forehand = .10 ± .05 s) resulted in later peak ankle dorsi flexion compared to the acrylic court (turn = .16 ± .10 s and running forehand = .04 ± .03 s).

Table 4.4 provides whole foot pressure variables for both tennis courts and both movements. The acrylic court produced significantly (p<.05) greater peak impact forces, peak active forces, average loading rates and impulse compared to the clay court for both movements (Table 4.4). Peak loading rate was only significantly different between the courts for the turning movement, with greater peak loading rate on the acrylic compared to the clay court. For both the running forehand and turning movements, peak active force occurred later on the clay compared to the acrylic court. No differences between the tennis courts were identified for whole foot mean and maximum pressures during the turning movement. However, for the running forehand mean pressures were significantly greater on the acrylic court compared to the clay court.

Table 4.4: Means and standard deviations for whole foot pressure data during the turning and running forehand movements for each tennis court

Variable	Acrylic court	Clay court	*ES*
Turning Movement			
Peak Impact force (BW)	2.86 ± 0.78	2.14 ± 0.59	1.688*
Occurrence time of peak impact force (s)	0.13 ± 0.06	0.12 ± 0.03	
Peak Active force (BW)	2.92 ± 0.75	2.37 ± 0.46	1.055*
Occurrence time of peak active force (s)	0.17 ± 0.09	0.29 ± 0.12	0.985*
Average loading rate (BW/s)	32.69 ± 11.44	21.43 ± 6.20	1.110*
Peak loading rate (BW/s)	83.62 ± 12.74	65.48 ± 28.50	.767*
Impulse (BW.s)	11.47 ± 3.80	8.11 ± 2.00	1.22*
Maximum pressure ($N.m^{-2}$)	49.31 ± 10.56	49.5 ± 10.74	
Mean pressure ($N.m^{-2}$)	14.29 ± 18.49	13.23 ± 17.29	
Running forehand			
Peak Impact force (BW)	2.89 ± .618	2.17 ± .428	2.67*
Occurrence time of peak impact force (s)	.11 ± .019	.11 ± .030	
Peak Active force (BW)	3.01 ± .642	2.31 ± .429	2.92*
Occurrence time of peak active force (s)	.12 ± .024	.15 ± .047	1.25*
Average loading rate (BW/s)	29.73 ± 8.44	24.07 ± 7.81	3.12*
Peak loading rate (BW/s)	96.23 ± 37.60	79.02 ± 17.31	
Impulse (BW.s)	12.05 ± 2.85	7.85 ± 2.09	.750*
Maximum pressure ($N.m^{-2}$)	49.57 ± 7.64	48.87 ± 8.27	
Mean pressure ($N.m^{-2}$)	4.64 ± 1.05	4.04 ± .79	1.23*

***Denotes a significant difference between the clay and the acrylic court, *P* <0.05**

Pressure distribution altered between the tennis courts as highlighted in Figure 4.11, 4.12, 4.13 and 4.14. The maximum pressures at the hallux region revealed a significant difference between courts for the turn (ES = 1.73, p =.004) and the running forehand (ES = 1.01, p =.025), with significantly greater hallux pressures occurring during both movements on the clay (turn = 36.40 ±

9.64 N.m^{-2} and running forehand = 34.51 ± 9.33 N.m^{-2}) compared to the acrylic court (turn = 24.14 ± 12.13 N.m^{-2} and running forehand = 26.96 ± 6.88 N.m^{-2}). At the lateral midfoot region, the acrylic court (21.78 ± 6.26 N.m^{-2}) produced greater maximum pressures compared to the clay court (17.26 ± 5.25 N.m^{-2}) during the forehand movement (ES = 1.17, p =.013), but no significance was observed for the turning movement. Differences between the courts during the turning movement were only detected for the maximum pressures at the lateral (ES = 1.06, p =.031) and medial heel regions (ES = 1.49, p =.005). Greater maximum heel pressures were produced on the acrylic court (lateral = 26.57 ± 7.45 N.m^{-2} and medial = 24.68 ± 6.88 N.m^{-2}) compared to the clay court (lateral = 18.36 ± 4.77 N.m^{-2} and medial = 16.39 ± 4.77 N.m^{-2}).

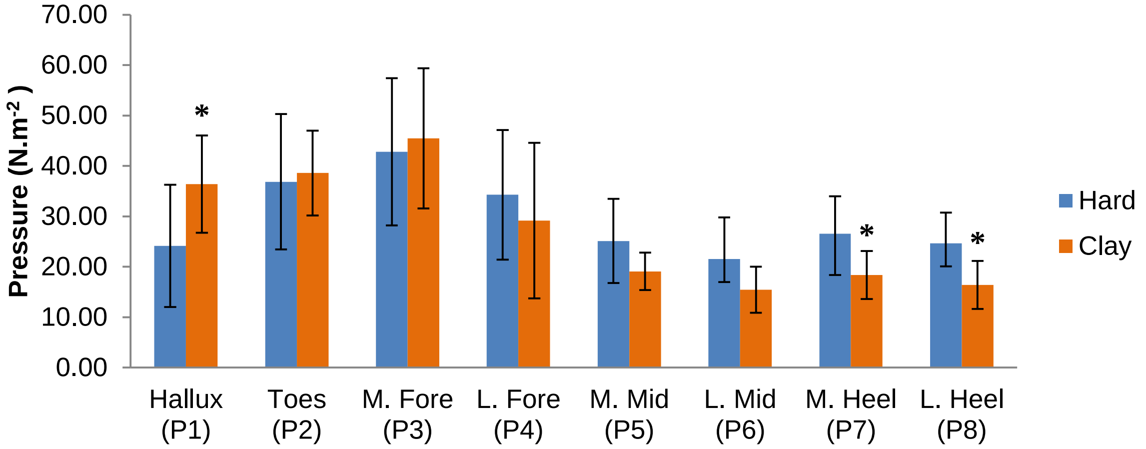

Figure 4.11: Maximum pressures for the eight masks on the acrylic and clay court during the turning movement. * denotes significant difference between courts, *P* <0.05.

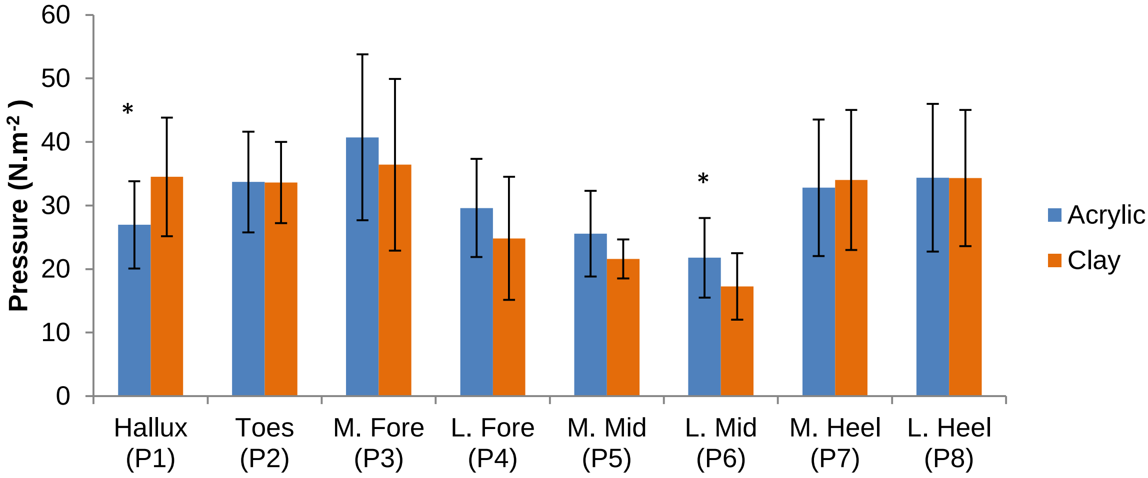

Figure 4.12: Maximum pressures for the eight masks on the acrylic and clay court during the running forehand. * denotes significant difference between courts, *P* <0.05.

Greater mean lateral midfoot pressures were revealed on acrylic court (turn = 4.98 ± 4.92 $N.m^{-2}$ and running forehand = 2.39 ± 0.78 $N.m^{-2}$) compared to the clay court (turn = 3.83 ± 4.41 $N.m^{-2}$ and running forehand = 1.99 ± 0.68 $N.m^{-2}$) for both the turning (ES = .334, p =.013) and the running forehand movements (ES = .820, p =.050). Mean pressures at the medial midfoot region were only significantly different between courts for the running forehand (ES = 1.15, p =.014), with greater mean midfoot pressures produced on the acrylic court (2.93 ± 0.91 $N.m^{-2}$) compared to the clay court (2.36 ± .90 $N.m^{-2}$).

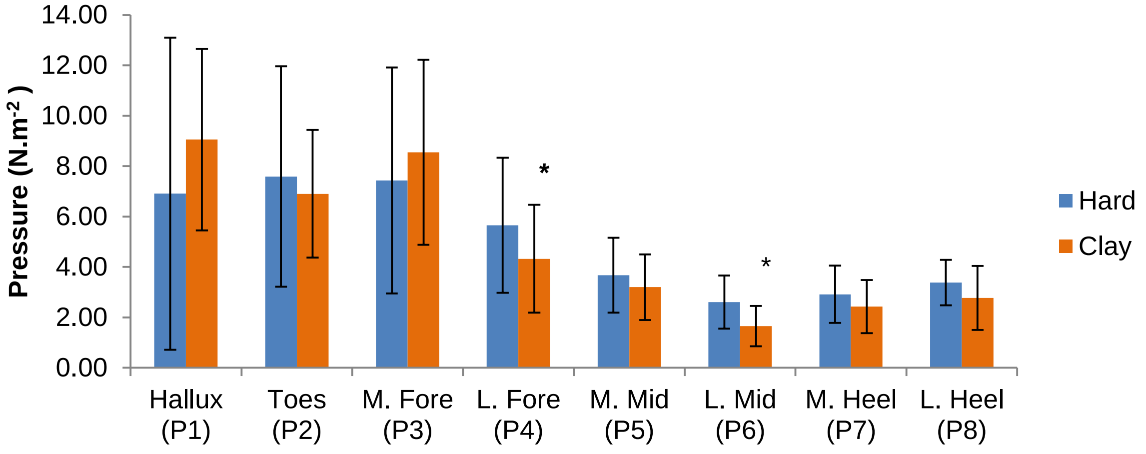

Figure 4.13: Mean pressures for the eight masks on the acrylic and clay court during the turning movement. * denotes significant difference between courts, *P* <0.05.

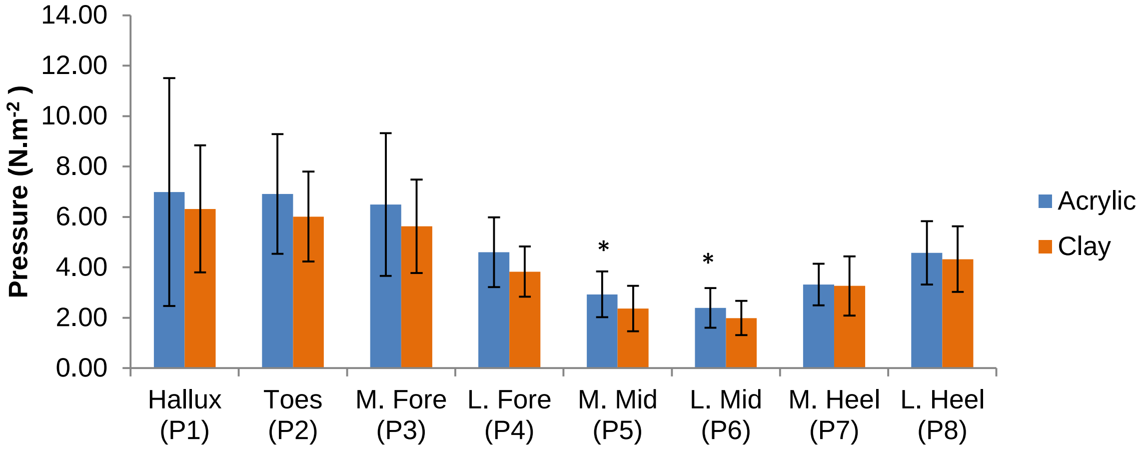

Figure 4.14: Mean pressures for the eight masks on the acrylic and clay court during the running forehand. * denotes significant difference between courts, *P* <0.05.

4.3.3 The Relationship Between Perceptions and Biomechanical Response

Significant Pearson's *r* correlations were revealed between the majority of perception variables (Table 4.5). For instance, perception variables such as perceived grip correlated with perceived predictability (r^2 = .71), whilst perceived hardness was associated with perceived grip (r^2 = .71). Players perceptions of their ability to slide produced a strong correlation with their perceptions of hardness (r^2 = .83).

Table 4.5: Pearson's *r* values for perception variable correlations

	Grip	Hard	Ability to change direction	Ability to slide	Ball Height	Ball Speed	Bounce Consistency
Predictability	0.842*	0.798*	-0.804*	0.676*	0.001	0.508*	0.716*
Grip		0.842*	-0.636*	0.756*	0.220	0.653*	0.734*
Hardness			-0.765*	0.909*	0.0976	0.825*	0.823*
Ability to change direction				-0.613*	0.129	-0.496*	-0.650*
Ability to slide					0.172	0.744*	0.713*
Ball Height						0.191	0.257
Ball Speed							0.720*

*** Denotes a significant correlation, *P* <0.05**

Table 4.6 provides the significant correlation values between the kinematic data and perception data for both the turning movement and the running forehand movement. During the turning movement as perceived hardness increased, attack angle decreased (r^2 = .26) and an earlier time of peak knee flexion (r^2 = .29) was observed. Whilst for the running forehand movement, sliding distance increased as the surface was perceived to have less grip (r^2 = .20), to be softer (r^2 = .28) and less predictable (r^2 = .21) and easier to slide (r^2 = .32). Time of peak ankle inversion was associated with perceived hardness (r^2 = .29) and ability to slide (r^2 = .26) and change direction (r^2 = .20) during the running forehand.

Table 4.6: Pearson's *r* values for significant (*P* <0.05) correlations between kinematic and perception variables for the running forehand and turning movement

Variable	Predictability	Grip	Hardness	Ability to change direction	Ability to slide
Turning movement					
Hip height: at impact	-0.502	-0.521	-0.578	0.458	-0.528
Attack angle	-0.474		-0.512	0.442	
Peak ankle dorsi flexion time	-0.499	-0.569	-0.499	0.474	-0.520
Knee flexion: at impact	-0.447			0.529	
Peak knee flexion time			-0.534	0.478	-0.455
Contact time	-0.634	-0.554	-0.713	0.684	-0.704
Running forehand					
Peak ankle dorsi flexion time			-.514	.582	
Peak ankle inversion time			-.542	.445	-.512
Sliding distance	-.461	-.449	-.528		-.563
Contact time			-.568		-.603

Table 4.7 provides the significant values for Pearson’s *r* correlations between pressure and perception variables for the turning movement. Significant correlations of pressure variables with the perceptions of hardness and grip were most prevalent, particularly during the turning movement. Peak impact forces were associated with perceived grip (r^2= .29) and perceived hardness

(r^2= .26). Average loading rate increased with increased perceived predictability (r^2= .26), grip and hardness (r^2= .37). No significant correlations were identified between pressure variables and perceived ability to change direction.

Table 4.7: Pearson's *r* values for significant correlations between pressure distribution and perception variables for the turning movement

Variable	Predictability	Grip	Hardness	Ability to slide
Peak impact force		0.540	0.510	0.535
Time Peak active force	-0.526	-0.606	-0.520	
Peak loading rate		0.574		
Average loading rate	0.513	0.610	0.558	0.502
Impulse		0.540	0.510	0.535
Maximum hallux (P1)		-0.508		
Maximum medial midfoot (P5)		0.595	0.580	
Maximum lateral midfoot (P6)		0.620	0.649	
Mean lateral midfoot (P6)		0.674	0.633	
Maximum medial heel (P7)		0.659		
Maximum lateral heel (P8)	0.542	0.778	0.618	0.845

Table 4.8 provides the significant values for Pearson's *r* correlations between pressure and perception variables for the running forehand. Perceived grip and ability to slide were the most common perceptions associated with the pressure data during the running forehand. For example as participants perceived grip to increase; peak impact forces (r^2 = .20), impulse (r^2 = .30), maximum pressure at the medial midfoot (r^2 = .25) also increased, whilst peak active force occurred earlier (r^2 = .23) and maximum hallux pressures were reduced (r^2 = .31).

Perceived ability to slide was positively associated with peak impact force (r^2 = .51), peak active force (r^2 = .42), impulse (r^2 = .49) and maximum lateral forefoot (r^2 = .41).

Table 4.8: Pearson's *r* values for significant correlations between pressure distribution and perception variables for the running forehand

Variable	Predictability	Grip	Hardness	Ability to change direction	Ability to slide
Peak impact force		.451			.713
Peak active force					.649
Peak active force time		-.477			
Impulse		.551	.513	-.516	.702
Maximum hallux (P1)	-.579	-.554	-.542		
Maximum lateral forefoot (P4)					.638
Maximum medial midfoot (P5)		.496			

4.3.4 The Influence of Previous Clay Court Experience on Perceptions, Biomechanical Response and their Relationship

When examining the influence of previous experience upon perceptions of the tennis surfaces all perception variables except players' perceived ability to change direction were similar between groups. The experience group perceived it easier (33.7%) to change direction compared to the low-experience group ($p<0.05$).

Previous experience revealed some influence on biomechanical response to the tennis courts. For instance, the occurrence time of peak knee flexion was significantly different between the groups during the turning movement (ES = .456, p =.02), but not for the running forehand. During the turning movement the experience group (0.26 ± 0.03 s) produced significantly later peak knee flexion compared to the low-experience group (0.14 ± 0.03 s).

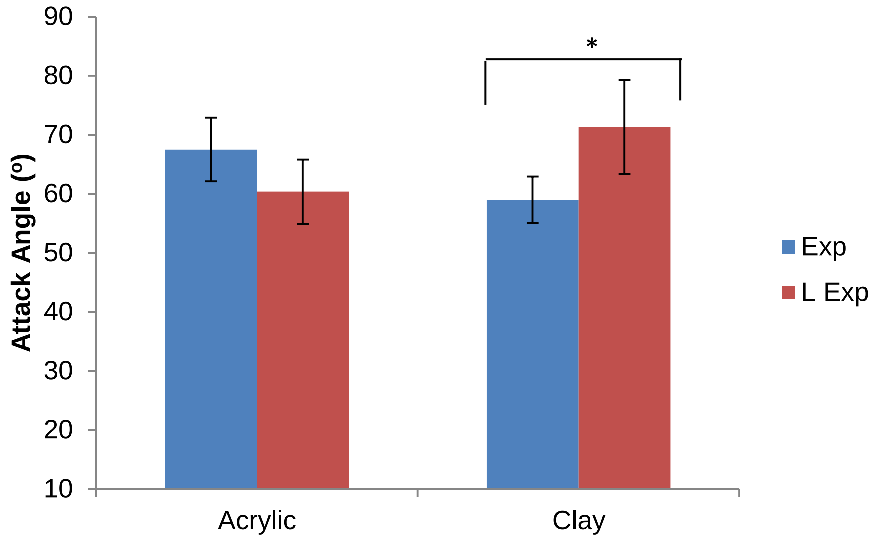

Figure 4.15: Attack angle for the experience group (Exp) and low-experience (L.Exp) group on both tennis courts. * denotes a significant difference between groups on the clay court, *P* <0.05

A significant interaction between court and group were revealed for attack angle during the running forehand (ES = .536, p =.016). Further analysis revealed no differences between experience groups on the acrylic court. However, on the clay court, attack angle was much greater for the experienced group (59.00 ± 3.93^{o}) compared to a more upright position for the low experience group (71.35 ± 7.97^{o}), as shown in Figure 4.15.

During the turning movement a significant interaction between group and court was revealed (ES = .562 p =.013) for initial ankle flexion angle. Post hoc analysis indicated significant differences between courts for the experienced group but no differences for the low-experience group (see Figure 4.16). At impact, the experienced group were plantar flexed on clay (7.66 ± 9.44^{o}), whilst this group were neutral or slightly dorsi-flexed on the acrylic court (-2.49 ± 7.65^{o}).

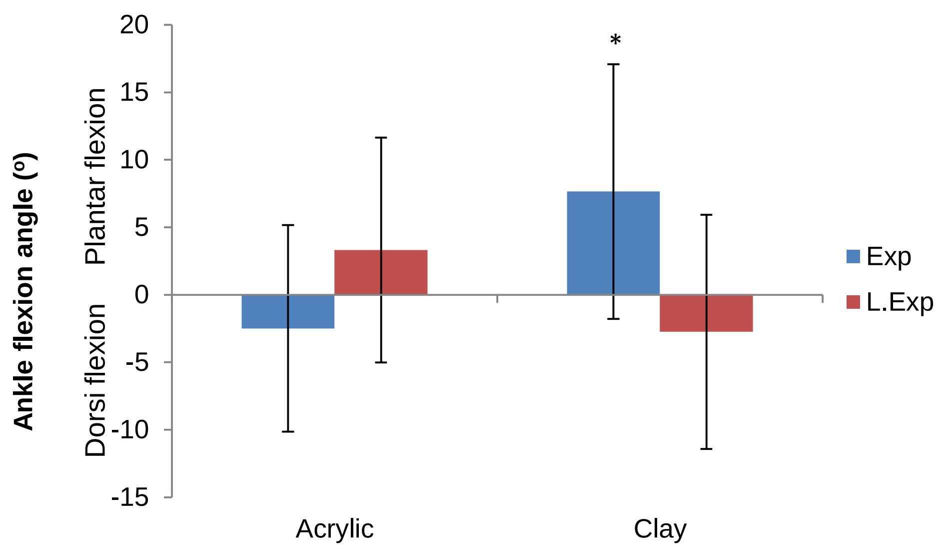

Figure 4.16: Ankle flexion angle at ground contact for both experience groups and both tennis courts during the turning movement. * Denotes a significant difference for the experienced group between tennis courts, *P* <0.05.

Unlike the turning movement, which revealed no differences, a significant interaction between court and group were revealed for initial ankle inversion angle for the running forehand (ES = .500, p =.042). Initial inversion angles were similar between courts for the low experience group (Figure 4.17). However, the experienced group had an inverted ankle (-7.41 ± 3.73^{o}) on the acrylic, whilst on the clay court they were everted at initial ground contact (6.09 ± 3.30^{o}). Peak inversion angles were similar between experience groups and tennis courts for both movements. The occurrence time of peak inversion angle was influenced by the court for the running forehand movement (ES = .499, *p* =.024) with later peak inversion angles during both movements on the clay court (.17 ± .09 s) compared to the acrylic court (.09 ± .01 s).

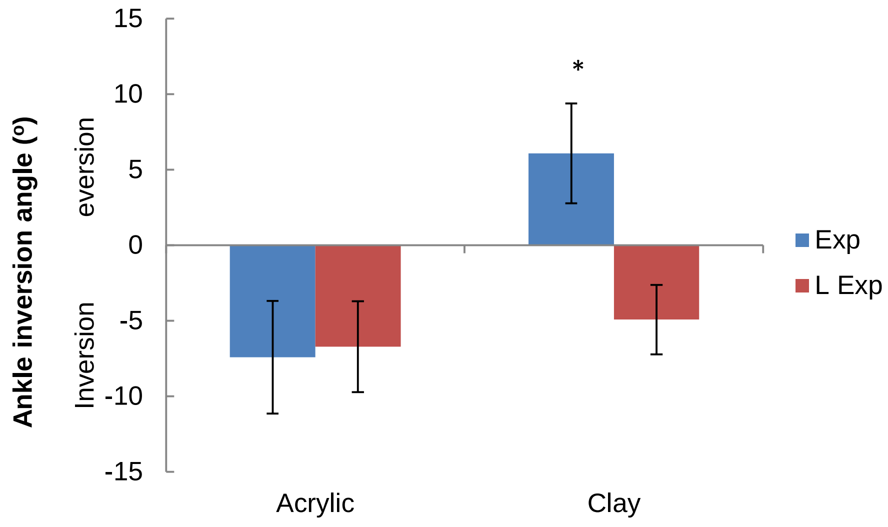

Figure 4.17: Means and standard deviations for ankle inversion angle for both tennis courts and experience groups, * denotes a significantly different to the acrylic court, *P* <0.05

To further understand the influence of previous experiences on perceptions and the relationship with biomechanical data, Fisher's z transformations were used to identify differences in correlation coefficients between groups. No differences were revealed for the turning movement. Yet, for the running forehand the relationship between attack angle and perceived ability to slide were significantly different between groups following analysis using Fisher's z transformations. A positive relationship (r^2 = .56) was formed for the experienced group, whilst a negative relationship (r^2 = .57) occurred for the low-experienced group as shown in Figure 4.18. For the low-experience group as the ability to slide was perceived to become easier a greater attack angle was observed. Whilst for the experienced group, as sliding was perceived easier, attack angle was reduced.

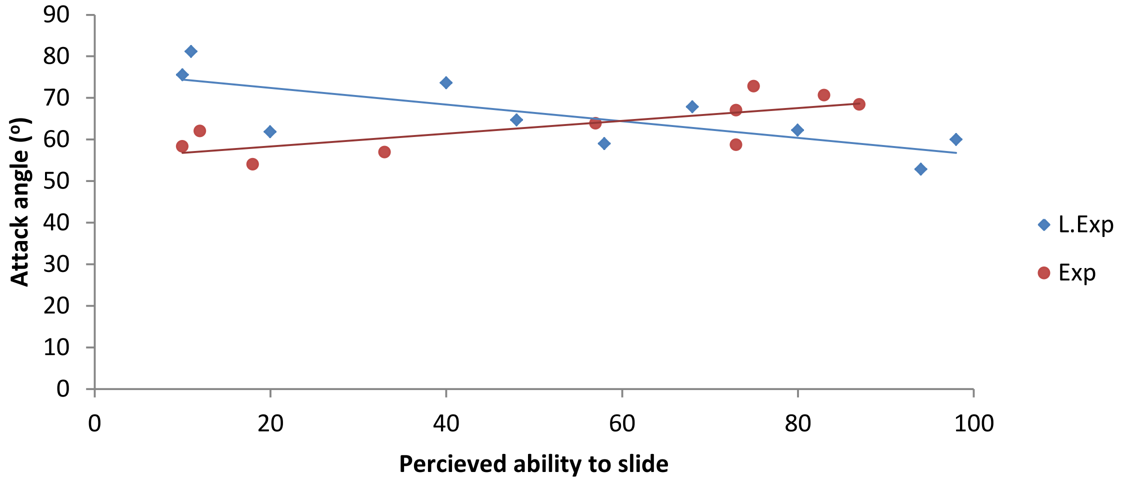

Figure 4.18: Correlations between attack angle and perceived ability to slide, where an increase in number suggests a more difficult ability to slide, for the experience groups, *P* <0.05

Regarding differences in the relationship between perceptions and biomechanical response, it was noticeable that some correlations were significant for one group but not the other. For example during the turning movement attack angle and initial knee flexion were associated with perceived predictability for the experience group, yet this was not observed for the low-experience group (Table 4.9). Initial hip height correlated with perceived grip, hardness predictability and ability to slide for the low-experience group but not the experience group.

Table 4.9: Pearson's *r* values for significant correlations specific to experience groups

Variables	Predictability	Grip	Hardness	Ability to change direction	Ability to slide
Turning movement					
Attack angle	-.724[e]		-.688[e]	.803[e]	
Knee flexion: at impact	-.719[e]			.686[e]	
Contact time	-.723[e]		-.714[e]	.899[e]	
Hip height: at impact	-.669[l]	-.752[l]	-.722[l]		-.698[l]
Time of peak ankle dorsi flexion		-.728[e]			-.614[e]
Time of peak knee flexion			-.644[e]	.661[e]	
Running forehand					
Hip Z impact					.639[e]
Foot angle				.663[l]	
Attack angle			.797[l]		
Ankle DF					-.631[e]
Ankle DF time				.661[l]	
Initial inversion angle			-.635[e]		-.719[e]
Contact time			-.662[e]		-.773[e]
Sliding distance					-.634[e]

[e] indicates a significant correlation for the experienced group, [l] represents significant correlations for the low-experience group, *P* <0.05

4.4 Discussion

The purpose of the present study was to examine tennis players' perceptions and biomechanical response on two tennis court surfaces with distinct cushioning and friction properties – an acrylic court and a clay court. A second aim was to investigate the influence of previous clay court experience on player perceptions and response. The study highlighted court differences in perceptions and player response. Group differences in perception-response relationships and player response suggest experience does not influence player perceptions of a court but the response a tennis player may choose, which has implications on injury risks and performance.

Longer braking has been associated with high friction surfaces in an attempt to reduce the high loading (Durá et al., 1999). In contrast, the current study reported longer braking through later peak active force, ankle dorsi flexion and inversion on the low friction clay court. These differences were attributed to longer contact times as a result of sliding on the court. Lower loading as a result of sliding on the clay court provides some explanation for the lower injury incidences reported on lower friction tennis courts such as clay, in comparison to high friction acrylic courts (Nigg & Segesser, 1988; Bastholt, 2000).

Sliding in tennis can be beneficial by allowing braking to occur during stroke production thus allowing players to prepare for the next stroke immediately after ball strike making for a more efficient movement (Miller, 2006; Pavailler & Horvais, 2014). As a result of sliding on clay it was apparent that an altered technique and approach to the tennis stroke and turning movement occurred compared to the acrylic court where no sliding was observed. Both movements examined in the present study revealed greater knee flexion at ground contact and reduced GRF on clay, both of which have been associated with improved stability on low friction surfaces during walking (Heiden et al., 2006). Flexion at the knee has previously been suggested to improve stability through lowering the COM closer to the base of support (Cham & Redfern, 2002; Marigold & Patla, 2002). High knee flexion during cutting movements has been reported on low friction surfaces and has been suggested to reduce risk of ACL injuries (Dowling et al., 2010).

Unlike previous reports, where greater whole foot mean and maximum pressures on acrylic courts compared to clay courts have been reported (Girard et al., 2007; Damm et al., 2012), few differences were obtained between the acrylic and clay courts. Findings from the present study were similar to those reported during walking where altered pressure distributions between surfaces accounted for a lack of whole foot pressure differences (Fong et al., 2008). The greater pressures in the hallux area were observed on the clay court compared to the acrylic court suggest increased grip needed to turn on the lower friction surface, similar to Fong et al. (2008) who suggested that greater toe grip and lower heel pressures provided balance and grip during walking on slippery surfaces. Greater lateral pressures at the heel, midfoot and forefoot at impact on the acrylic court may suggest an increased risk of ankle inversion injuries due to increased loading on the lateral structures. High loading in the lateral structures of the foot could become detrimental if the foot was to fix as a result of high mechanical friction (Newton et al., 2002).

In contrast to Girard et al. (2007), lower midfoot pressures were reported on the clay court in the current study. This response has been suggested to facilitate sliding on this type of surface by limiting areas of high pressure to prevent ‘sticking’ (Damm et al., 2012). Girard et al. (2007) reported higher midfoot loading on clay compared with hardcourt, suggesting this permitted controlled sliding. Additionally Girard et al. (2007) reported higher hallux pressures on acrylic attributed to a more aggressive play possibly as a result of greater friction. Girard et al. (2007) examined the global effect of playing surface on pressure during two movements, serve and volley and baseline movements, therefore combining pressure distributions from multiple steps which consisted of accelerations, running and cutting which differ in pressure distribution patterns (Orendurff et al., 2008). The findings reported in the current study differ to those reported by Girard et al. (2007) due to the different methods of collecting pressure data. For instance, Girard et al. (2007) collected data during whole tennis strategies (e.g. serve and volley) whilst the present study specifically examined the final step of for each movement.

Participants’ perceptions of the courts inform their response to mechanical differences between surfaces, therefore measuring perceptions can provide an insight into how tennis players differentiate between court surfaces. Similar to previous reports (Lockhart et al., 2002; Stiles & Dixon, 2007), the present study revealed significant differences in perception of the two tennis courts, which corresponded to differences in mechanical data. For instance, the acrylic court, which was mechanically harder and had greater friction, was perceived to be harder and resulted in greater perceptions of grip compared to the clay court.

Unlike previous reports, the present study examined additional perceptions such as perceived predictability and perceived ability to change direction and slide. Perceived predictability was lower on the low friction surface which was also perceived to be easier to slide on yet difficult to change direction. These additional perception measures provide further information regarding player perception of tennis courts which could alter players' response to the surface, thus influencing injury risks and style of play. Results in the present study suggest that the mechanical tests of hardness and friction that were used provided information regarding player perceptions of friction and hardness, yet other perceptions of the surface, such as predictability, were identified and should be considered during the future development of mechanical tests.

Understanding the relationship between perceptions and biomechanical response provides information regarding how humans interact with their environment. It is suggested that this should be used to inform the development of mechanical tests, which currently tend to focus on the measures of cushioning and friction. Perceptions of cushioning and slipperiness have previously been associated with altered response to changes in surface or shoe properties (Hennig et al., 1996; Milani et al., 1997; Lockhart et al., 2002; Stiles & Dixon, 2007). Consistent with results for walking (Heiden et al., 2006), the current study found stability was improved on the low friction clay surface through greater initial knee flexion. In the current study, initial knee flexion was associated with perceived predictability ($p<0.05$), such that initial knee flexion increased as perceived predictability reduced, rather than being related to perceptions of surface grip. This further supports the suggestion that a mechanical measure of surface predictability would enhance the current mechanical characterisation of surfaces for tennis.

From previous research (Durá et al., 1999), it was anticipated that perceptions of surface grip would be associated with longer braking through later peak knee flexion, later peak ankle dorsi flexion and later occurrence of ankle inversion as well as longer contact times. However, in the present study perceptions of grip were not associated with these variables. Rather, perceived hardness and perceived ability to change direction or slide were significantly associated with time of peak knee flexion, contact time, ankle dorsi flexion and inversion time. These relationships suggest that perceived ability to perform a task provides further information to tennis players to inform their response to surface changes. Alternatively, due to the nature of correlational analysis (i.e. unable to suggest causation), shorter braking leading to greater loading experienced by the participants could result in greater perceptions of hardness and harder ability to slide.

In the present study, pressure variables were associated with perceptions of hardness and grip. Consistent with the findings of Stiles and Dixon (2007), as perceived hardness increased heel pressures increased, as hypothesised. Midfoot pressures were also associated with perceived grip and hardness. The pressures at the midfoot, reported to be an area sensitive to changes in pressure (Nurse & Nigg, 1999), provides sensory information regarding surface differences. Hallux pressures were greater on the low friction surface in agreement to previous reports (Fong et al., 2008) and were also associated with reduced grip perception. Greater hallux pressures on the low friction clay court have been associated with increased risk of tendinopathy of the flexor halluces longus, which develops during repetitive loading in the big toe area (Trepman, Mizel, & Newberg, 1995; Lynch & Renström, 2002). Therefore perceptions of hardness and grip were correlated with plantar foot pressure distribution parameters, providing players with information to enable them to slide and maintain balance and grip.

Despite evidence that previous experiences combined with sensory information are used to formulate perceptions (Coren et al., 1979; Gescheider & Bolanowski, 1991; Goldstein, 1999), when examining the influence of prior clay court experience on perceptions of tennis courts few differences were reported between experience groups. This lack of difference in surface perceptions was likely influenced by the familiarisation given to the participants prior to data collection, allowing them time to observe and gain some experience of the court. This was felt necessary for safety reasons, but may have limited the ability to detect differences between experience groups.

Despite few differences detected in perception of the surfaces between experience groups, differences were observed in some of the correlations between perception measures and biomechanical response. For example, for the experienced group initial knee flexion was associated with perceived hardness and ability to change direction, which was not reported for the low-experience group. During the running forehand, movement attack angle was reported to be influenced by both court and experience group. In addition, differences between experience groups were reported in the relationship between attack angle and perceived ability to slide. On the acrylic court, when players perceived the surface to be difficult to slide on the attack angle was similar between experience groups. On the clay court, for which it was perceived to be easier to slide, the experience group approached the court with greater attack angle compared to the low-experience group.

Previously greater attack angles have been associated with faster animal running speeds (Farley et al., 1993). These greater speeds often associated aggressive player on acrylic courts (Girard et al., 2007) suggest that when on clay experienced players were more aggressive in their approach during the running forehand shot compared to the low-experience group. In contrast to the experienced group, the low-experienced group approached the clay court with more caution, consistent with results previously reported from walking studies (Heiden et al., 2006). The low-experienced group increased their stability by shifting their COM anteriorly through a more upright attack angle (Clark & Higham, 2011). These differences suggest that although perceptions were similar, how tennis players respond to perceptions are influenced by their prior experience on a particular type of court. When examining perceptions and response, prior experience of a surface should be considered.

Prior experience on clay produced further adaptions such as altered initial ankle flexion and occurrence time of peak knee flexion which were not observed in the low-experience group. In particular, the experience group were in a plantar flexed position on the clay yet slightly dorsi flexed on the acrylic; however, the low-experience group did not differ in initial ankle flexion angle between courts. Those with prior experience on clay had later peak knee flexion and peak ankle inversion times, suggesting that regular play on clay results in adaptations to reduce loading through longer braking phases (Durá et al., 1999), potentially reducing injury risk on certain tennis courts. These changes in response, along with differences in perception-response relationships between the groups, suggest that although participants perceived similarly, experience leads to additional responses to surface manipulation.

The ankle inversion angle at ground contact during the running forehand movement was revealed to be influenced by the level of clay court experience. On the clay court, participants contacted the ground with the ankle in an everted position, whilst on the acrylic court participants were inverted. In addition to high frictional properties on the acrylic court, increased risk of foot fixation (Newton et al., 2002) along with high levels of ankle inversion angle during early stance have been associated with ankle inversion sprains (Kristianslund et al., 2011). In contrast, an everted ankle to control sliding on the clay, shifts the pressure medially, thus preventing the lateral edge of the shoe digging into the surface, potentially reducing risk of over inversion of the ankle (Damm et al., 2014).

4.5 Limitations

The use of on court analysis in study 2 was a limitation regarding reproducibility of the tennis-specific movements. Yet, the benefits of an on court analysis using the tennis specific drills provided realistic conditions which are often difficult to obtain in confined laboratory conditions improving the ecological validity.

Additionally a turning movement was considered a more controlled movement compared to the running forehand tennis stroke which are influenced by ball movement, yet provided similar variation to the running forehand tennis stroke.

Low sampling frequency of kinematic (50 Hz) and pressure (100 Hz) was a limiting factor which increases synchronisation error within the data and reduces accuracy of temporal data, however the data collected were similar to that reported in the literature. Pressure data were collected using a Pedar system (Pedar, Novel) which has been suggested to be acceptably accurate and reliable (Quesada, Rash, & Jarboe, 1997). For instance, Ramanathan et al. (2010) reported the Pedar pressure system to be repeatable, where out of 160 parameter 93.1% had a coefficient of variation lower then 25, including mean and maximum pressures, with the heel and metatarsal regions being the most repeatable regions. To ensure an accurate assessment, a drift correction, recommended by Hurkmans et al (2006), was implemented for the pressure data.

The anchor words employed in the visual analogue scale, previously deemed a reliable measure of perception (Mündermann et al., 2002; Mills et al., 2010), may be interpreted differently by different people (Aitken, 1969). However as highlighted in Appendix 6 face validity of the questionnaire was achieved, thus minimising the ambiguity of the questionnaire.

4.6 Conclusions

Participants in the present study were able to perceive differences between tennis courts. Biomechanical differences between courts included players sliding on the clay court compared to the acrylic resulting changes in pressure distribution and altered kinematics. The current study reported relationships between perceptions and biomechanical responses. As hypothesised (H_{1a}) perceived hardness was associated with changes in heel pressures, however (H_{1b}) perceived grip was not associated with initial knee flexion rather perceived predictability was. Further relationships that were reported include perceived predictability, which has not been measured previously, to be associated with variables that improve stability; this variable should therefore be considered during the future development of mechanical tests. All participants in the current study demonstrated adaptations consistent with providing improved stability on the clay court during sliding, whilst those with greater experience on clay had additional adaptations such as later knee flexion, reducing loading and potentially reduced injury risk. It was anticipated that prior clay court experienced would influence players' perceptions. However, previous experience does not appear to influence players' perceptions of tennis courts but provides information regarding an appropriate response. Although not directly measured due to a failed wireless transmission later occurrence of peak knee flexion for the experienced group suggests lower GRF when compared to the low-experienced group as hypothesised (H_2). This evidence suggests that when on clay, players with high previous experience are better able to accommodate to the court, highlighting the importance of court familiarisation.

4.7 Implications

The current study examined the player perceptions and responses of tennis surfaces and the influence of prior clay court experience on their perceptions and responses. It was identified that sliding on the low friction clay court resulted in altered technique compared to the high friction acrylic court. These distinct mechanical differences between the acrylic and clay were also perceived by the participants. The acrylic and the clay court used within the current study have distinct differences in mechanical friction, yet it is not known what influence minimal changes in friction during tennis-specific movements on clay court surfaces have on players' perceptions and response. The level of familiarisation that both experience groups received may have influenced the lack of differences in perceptions between the groups. Further investigation is required to understand how the level of familiarisation may influence player perceptions as well as players response. Players were aware throughout the testing procedures of the surface conditions they were being examined on which allowed players to elicit appropriate responses. On clay courts, perceived to be less predictable, there may occasion when players are unaware to changes in surface properties due to their interaction with surface infill, which may lead to altered responses and perceptions, compared to when they expect changes in friction to occur.

CHAPTER 5: STUDY 3: EXPECTED AND UNEXPECTED CHANGES TO FRICTION ON A SYNTHETIC CLAY COURT SURFACE

5.1 Introduction

As previously highlighted, tennis surfaces differ greatly in frictional properties, where acrylic courts have been reported to have coefficients of friction (COF) between 0.8 and 1.2, whilst clay can vary between 0.5 and 0.7 COF (Nigg, 2003). Tennis players must adapt to this varied friction throughout a season, which can influence the style of play (O'Donoghue, 2002) and alter players movements and loading (Durá et al., 1999; Girard et al., 2007; Nigg et al., 2009; Dowling et al., 2010; Damm et al., 2013). Strategies highlighted from study 2 (Chapter 3) and previous literature (Durá et al., 1999) to reduce potentially high loading on high friction surface have included longer braking and later peak knee flexion have been used as strategies to reduce loading on high friction surfaces during turning. Study 2 identified different techniques when turning and performing a running forehand on distinctly different acrylic and clay court surface. For instance, on the low friction clay court players were sliding during both movements reducing loading unlike the acrylic court where higher loading was reported. This lower loading has previously been linked to lower injury risks (Nigg & Segesser, 1988; Damm et al., 2013).

On low friction surfaces, such as clay, it is not unusual to observe players sliding during rapid decelerations such as during changes in direction (Miller, 2006). Tennis players have been reported to utilise greater shear forces and horizontal loading rates in order to increase utilised COF, allowing for sliding to occur on clay surfaces (Damm et al., 2013). In addition, changes in pressure distributions have been reported to facilitate sliding on clay courts compared with high friction acrylic courts (Girard et al., 2007; Damm et al., 2012). Furthermore, ankle and knee moments have been found to differ for lateral movements on sliding compared with non-sliding surfaces (Nigg et al., 2009), with increased knee moments and lower ankle moment suggesting a greater risk of knee injuries such as patellofemoral pain on sliding surfaces (Nigg et al., 2009).

As well as friction differing between courts, friction properties of the surface may change during play on clay courts due to player movements and sliding on the court. Therefore there may be areas of expected and unexpected friction levels to which players must respond and attempt to maintain balance in order to successfully coordinate a tennis stroke. Altered strategies to accommodate for these expected and unexpected changes to a clay court surface include anticipatory and reactive (Patla, 2003). Reactive strategies occur when changes to surface properties are unexpected thus sensory information is used to respond to the changes (Patla, 2003). Often reactive responses include increases in ankle and knee flexion, reducing leg stiffness, occurring prior to any active neural control and muscle activity using passive tissue properties to provide instantaneous response (Moritz & Farley, 2004).

Anticipatory strategies in response to surface changes occur from the identification of a potential perturbation from both visual input and past experiences (Patla, 2003). When changes are anticipated a response often begins prior to ground contact, for example increased knee flexion and muscle activity were observed prior to landing on an anticipated harder surface (Moritz & Farley, 2004). Reported responses to expected reductions in friction during walking included a reduction in the peak utilised friction demand, reducing slip potential, through reductions in shear forces and joint moments (Cham & Redfern, 2002). Further adaptations that have been reported in response to reduced friction during walking studies include a flatter foot, greater initial knee flexion, reduced braking impulse and loading rate and increased anticipatory muscle activity (Marigold & Patla, 2002; Heiden et al., 2006).

During both anticipatory and reactive strategies perceptions are continuously developed to enable humans to interact with the changes in their environment (Coren et al., 1979; Sherwood, 1993). Unexpected changes in surface conditions result in reactive strategies which rely solely on sensory information to produce perceptions to respond to (Patla, 2003). Both prior knowledge and sensory information are used as part of anticipatory strategies when surface changes are expected (Patla, 2003). Thus differences in perceptions occur between expected and unexpected reductions to frictional properties, which alter tennis players' responses. Study 2 highlighted previous experiences to be important in the responses players' choose when performing on clay courts. For instance those with low-experience made adaptations appearing to increase their risk of injury through greater initial ankle inversion angles, previously associated with inversion injuries (Kristianslund et al., 2011).

Previous literature examples that have examined expected and unexpected changes to surface friction focus on walking, where the aim has been to reduce slipping. However, in tennis sliding is often used to aid performance during rapid decelerations. Therefore it is more appropriate to examine response to surface changes through a more dynamic movement on a surface, such as clay, that encourages sliding. From the results of previous studies in this thesis, prior experience is influential in our response, particularly when changes to surfaces are anticipated.

The current study had the following aims:

- To examine the influence of different frictional changes of a clay surface upon player response and perceptions during a turning movement.
- To investigate the influence of the level of familiarisation on players' perceptions and response.
- To examine the influence of expected and unexpected frictional changes of a clay surface upon player response and perceptions during a turning movement.

From the literature and previous work in this thesis, it is hypothesised that:

- The level of friction will influence the tennis players' response such that as friction is reduced, greater shear forces (H_{1a}) and loading rates (H_{1b}) along with later peak knee flexion will occur (H_{1c}).
- Those with lower familiarisation will have greater initial ankle inversion angles (H_2).

- The onset of muscle activation will occur earlier during the expected conditions compared to the unexpected conditions (H_3).
- Expected changes in friction will result in reduced shear loading (H_{4a}) and reduced joint moments (H_{4b}) compared with when friction changes are unexpected.
- During unexpected trials greater peak knee flexion and ankle dorsi flexion will occur (H_5).

5.2 Methods

5.2.1 Participants

Sixteen participants volunteered for the present study and were randomly assigned to one of two groups. These groups included a familiarisation group (n = 8, mass 67.4 ± 7.9 kg, height 1.75 ± 0.08 m, age 19.9 ± 1.2 years and LTA rating 7.27 ± 2.4) who were given extensive familiarisation trials (10) of each friction condition, and a low-familiarisation group (n = 8, mass 66.2 ± 12.6 kg, height 1.72 ± 0.14 m, age 20.0 ± 0.8 years and LTA rating 7.76 ± 2.05), who received one familiarisation trial of each friction level. The study was approved by the Institutional Ethics Committee. Informed consent and physical activity readiness questionnaire results were obtained before any testing occurred.

5.2.2 Testing Conditions

A synthetic clay surface (Appendix 3), consisting of a carpet base layer and a top layer with sand infill, was used during the present study. In the area where players were turning (above the force plate), the frictional conditions were altered through the use of different volumes of sand (Table 5.1), as identified in

Appendix 8. The three levels of friction formulated a baseline condition (12 kg.m^{-2}; as recommended by the manufacturers), a reduction in friction (R1, 16 kg.m^{-2}) and a further reduction in friction (R2, 20 kg.m^{-2}).

Table 5.1: Range of static coefficient of friction (COF) during a range of normal forces (1000N – 1600N) for three volumes of sand infill identified in Appendix 8

	COF	**Volume of Sand (kg.m^{-2})**
Baseline	0.61 - 0.64	12
Reduction in friction 1 (R1)	0.59 - 0.65	16
Reduction in friction 2 (R2)	0.54 – 0.59	20

The three friction levels allowed for five testing conditions to be examined. These testing conditions consisted of a baseline condition (12 kg/m^2), two expected conditions ER1 (16 kg/m^2) and ER2 (20 kg/m^2) and two unexpected conditions UR1 (16 kg/m^2) and UR2 (20 kg/m^2). For each of the expected trials, participants were told which condition they were going to experience. For the unexpected trials, participants were told they would experience the baseline condition. Prior to each testing condition a baseline condition was conducted in order to allow for comparisons to be made (Figure 5.1). The order of the five testing conditions was randomly assigned. Ten trials of each condition were collected with any unsuccessful trials omitted and repeated.

B	ER1	B	ER1	B	UR2	B	UR1	B	B	B	UR2	B	UR1	B	ER1	B	ER2

Figure 5.1: An example of the random order of testing which continued until 10 trials of each condition were completed. The shaded area represents the trials in which data were collected. The unshaded areas represent a baseline condition. B = Baseline, ER1 = Expected R1, ER2 = Expected R2, UR1 = unexpected R1, UR2 = Unexpected R2

Prior to each trial the infill sand on the area of interest (force plate) was removed, the sand for the next condition was then weighed and placed on the area of interest and spread evenly. To enable ease of preparing the infill a removable square of the synthetic clay surface was placed over the force plate and was secured using Velcro® to enable quick removal of the sand and to ensure no movement of the synthetic clay surface during data collection. During all testing participants wore the same tennis shoes (Adidas Barricade 6.0 clay shoes) as described in Section 3.2.4.

5.2.3 The Turning Movement

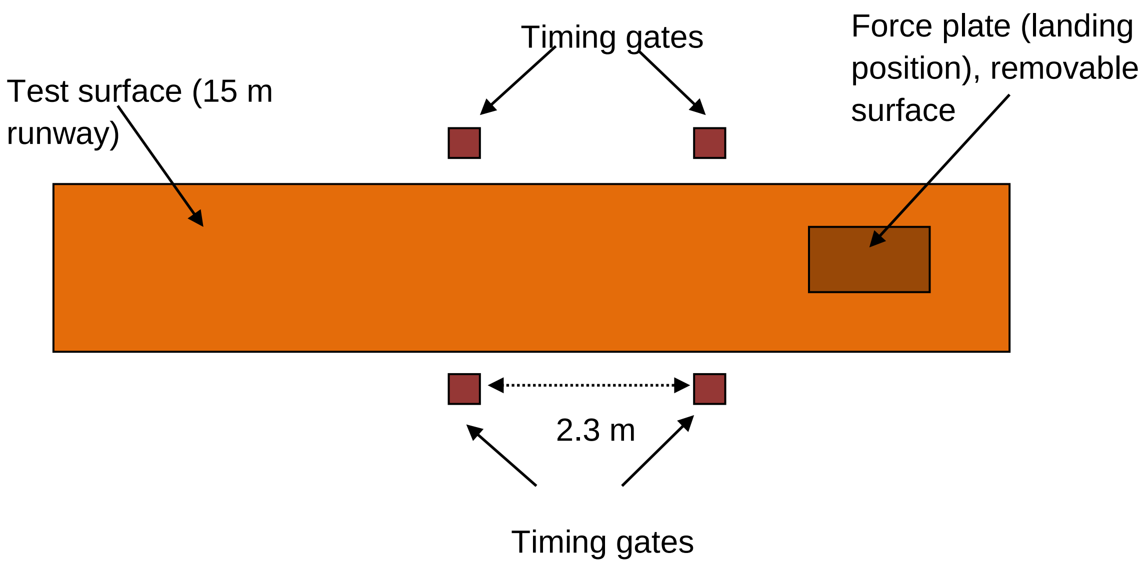

Figure 5.2: A schematic diagram illustrating the run way and position of the force plate where participants were asked to turn on different levels of friction

During each trial participants performed a 180^{o} turning movement. Participants were asked to run at speed (3.9 ± 0.20 m.s^{-1}) down the run way (Figure 5.2) and turn on the force plate (with the required friction condition) before returning to the start at speed, maintaining a dynamic scenario.

5.2.4 Data Collection

5.2.4.1 Kinematic Data

Three-dimensional lower limb kinematic data (120 Hz) were collected to examine ankle and knee movement. Data were collected in the Biomechanics Research Lab at the University of Exeter, using a passive marker motion capture system consisting of eight cameras (opto-electronic system; Peak Performance Technologies, Inc., Englewood, CO), placed in an oval shape around the force plate. Eleven lower limb markers (see Section 3.2.8) on the dominant leg were used to construct a joint coordinate system with a custom written Matlab code (2011b, MathsWorks). A quintic spline filter was applied to the raw data (Peak Performance default optimal smoothing technique using 5th degree quintic polynomials). All kinematic data were presented relative to a relaxed standing trial. Kinematic variables included initial and peak angles for the ankle and knee. Attack angle at impact was defined as the angle between the running direction (y axis) and the calcaneus to hip vector. Initial foot y angle was taken immediately prior to ground contact and was determined as the angle (Figure 5.3) between the anterior-posterior axis of the foot and the yz plane.

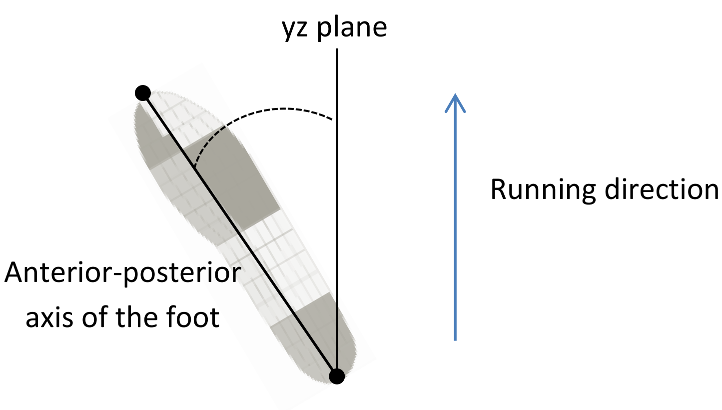

Figure 5.3: A schematic diagram illustrating the foot angle, defined as the angle between the anterior-posterior axis of the foot and the y axis of the lab

Sliding was determined, through a similar method used in study 2 (Section 4.2.6), using the velocity of centre of the foot (determined from the calcaneus 2 marker and toe marker). A sliding phase was determined when the velocity was greater than a threshold of 1 $mm.s^{-1}$ and maintained for more than 10 ms. During this sliding phase, sliding distance was determined by the resultant distance covered by the 5th metatarsal marker. Sliding rotation was determined as the difference between the maximum and minimum foot y angle during the sliding phase.

5.2.4.2 Force Plate Data

Ground reaction forces (GRF) were measured at a 960 Hz sampling rate using an AMTI force plate (Advanced Mechanical Technology, Inc, Newton, MA). Vertical force parameters included peak impact force, peak active force, average loading rate and peak loading rate. These variables were obtained as described in Section 4.2.8. Shear forces (Fshear) were established using Equation 5.1 where the resultant force of the anterior-posterior (Fy) and medio-lateral forces (Fx) was calculated.

$$Fshear = \sqrt{Fx^2 + Fy^2} \qquad \text{Equation 5.1}$$

Peak shear force was determined as the maximum value within the first 50% of ground contact. The first central difference method (Equation 4.2) was applied to the shear force to identify the maximum horizontal loading rate. The utilised coefficient of friction (COF) was determined as the ratio between the shear force (Fshear) and the vertical force (Fz) as shown in Equation 5.2. Peak utilised COF, suggested to indicate the transition between the static and dynamic regimes (Clarke et al., 2013), was determined as the maximum COF value.

$$COF = \frac{Fshear}{Fz}$$ *Equation 5.2*

5.2.4.3 Joint Moments

The use of synchronised three-dimensional force and kinematic data allowed for the estimation of joint moments in the frontal and sagittal planes using inverse dynamics (Robertson et al., 2013). To examine knee and ankle moments the thigh, shank and foot segments were considered as well as the forces and inertial parameters from the respective segments and those of the dital segments (Nigg et al., 2009). Local coordinate systems of each segment for all parameters; GRF, COP, force segments resulting from gravity, segment centre of mass accelerations proximal and distal moment arms and proximal and distal joint centre locations, were required and determined from the transformation of the global coordinate system. The transformation to the local coordinate system provided the reference frame (RF_{seg}) for each segment and included the medio-lateral (x_{seg}), anterior-posterior (y_{seg}) and vertical (z_{seg}) vectors shown in Equation 5.3 (Robertson et al., 2013). Where *i* was the frame number and x, y and z were the separate component vectors.

$$RF_{seg} = \begin{bmatrix} x_{seg}(i,x) & x_{seg}(i,y) & x_{seg}(i,z) \\ y_{seg}(i,x) & y_{seg}(i,y) & y_{seg}(i,z) \\ z_{seg}(i,x) & z_{seg}(i,y) & z_{seg}(i,z) \end{bmatrix}$$ *Equation 5.3*

Moments acting on a joint were determined by multiplying the magnitude of the force by the perpendicular distance to the centre of mass, known as the moment arm (Robertson et al., 2013). Therefore the centres of mass of each segment were required prior to the estimation of joint moments using Equation 5.4 and 5.5.

$$COM_d = COM_{seg} - JC \qquad \text{Equation 5.4}$$

$$COP_d = COP_{seg} - JC \qquad \text{Equation 5.5}$$

Where COM_{seg} represented the segment centre of mass, COP_{seg} corresponded to the point where the force acted upon the segment; *JC* was the joint centre coordinates (e.g. ankle joint centre). The moment arms used within the calculation of joint moments corresponded to COM_d and COP_d. To obtain the segment centre of mass, in addition to other segment parameters (mass, length and inertia components), regression equations, deemed more accurate then use of cadaver data, were conducted (Shan & Bohn, 2003), whilst density values were taken from cadaver data (Dempster, 1955), accounting for participant gender, height and body mass.

$$M_{GRF} = COM_d \times GRF_{seg} \qquad \text{Equation 5.6}$$

$$M_{weight} = COM_d \times m_{seg}g \qquad \text{Equation 5.7}$$

$$M_{eff} = COM_d \times m_{seg}a_{seg} \qquad \text{Equation 5.8}$$

$$M_{joint} = -T_q - M_{GRF} - M_{weight} + M_{eff} + I\alpha_{seg} \qquad \text{Equation 5.9}$$

In order to estimate joint moments (M_{joint}; Figure 5.4), as shown in Equation 5.9, all the forces acting at the joint were considered (Hof, 1992; Zatsiorsky, 2002). These included the moments applied by the GRF (M_{GRF}), the moments of the weights of the segments (M_{weight}), the moments applied by the acceleration forces (M_{eff}) and the moments due to rotational accelerations ($I\alpha_{seg}$). These were determined through Equation 5.6, 5.7 and 5.8. GRF_{seg} indicated the GRF exerted upon the segment, $m_{seg}g$ represented the mass of the segment multiplied by gravity, a_{seg} indicated the acceleration components at the segment COM and the GRF torque (T_q) vectors. The moments due to rotational accelerations ($I\alpha_{seg}$) were determined by the moment of inertia of the segment (I) and the segment angular acceleration matrix (α_{seg}). The use of inverse dynamics to calculate joint moments was determined firstly distally (ankle moments) then proximally (knee moments) so that the influence of the distal moments were considered when determining the proximal moment (Hof, 1992; Nigg et al., 2009). Positive moments were indicated by anticlockwise moments. Peak knee and ankle moments and their occurrence times were identified in the sagittal and frontal planes.

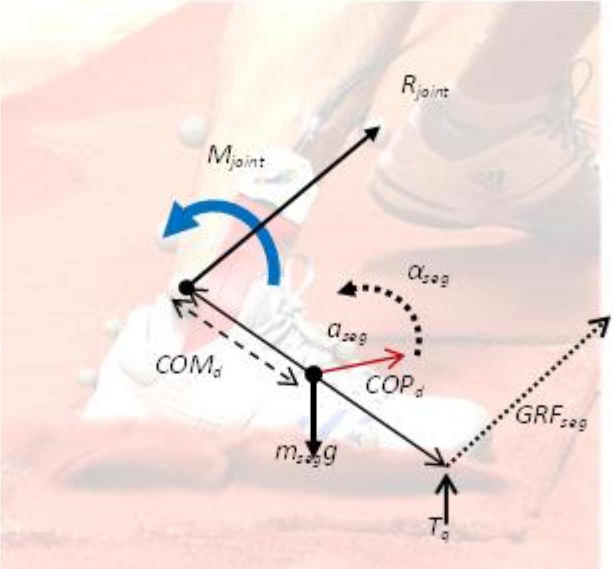

Figure 5.4: A free body diagram (adapted from Robertson et al. (Robertson et al., 2013) representing moment arms, forces and accelerations of the segment, R_{joint} represents for resultant forces at the joint.

5.2.4.4 Pressure Data

Pressure insoles provided data at 100 Hz for the turning step as described in Section 4.2.8. Eight masks (4.2.8) were used for the analysis of plantar foot sections, which included both lateral and medial masks for the heel, midfoot and forefoot, hallux and lesser toes. Variables for both whole foot and foot regions included mean and maximum pressures and occurrence time of peak pressures. The sum of the medial and lateral heel masks was used to represent heel loading rate.

5.2.4.5 Electromyography (EMG)

Table 5.2: Recommended electrode placement and orientation adapted from the SENIAM project (1999)

Muscle	Location of Electrodes	Orientations of electrodes
Rectus femoris	50% between the anterior spina iliaca superior and superior part of the patella	In the direction of the line from the anterior spina iliaca superior to the superior part of the patella.
Bicep femoris	50% between the ischial tuberosity and lateral epicondyle of the tibia	In the direction of the line between the ischial tuberosity and the lateral epicondyle of the tibia.
Gastrocnemius (medial head)	Most prominent bulge	In direction of the leg
Tibialis anterior	1/3 tip of fibula to tip of medial malleolus	In the direction of the line between the tip of the fibula and the tip of the medial malleolus.

Muscle activity was measured for the bicep femoris, rectus femoris, tibialis anterior and medial head of the gastrocnemius muscles. Electrode placement and orientation were placed with regards to the SENIAM project guidelines (1999) as shown in Table 5.2. Prior to placement of the surface electrodes hair was removed and abrasive gel and alcohol wipes were applied to abrade and cleanse the skin.

EMG data were collected using a Trigo wireless system (Delsy, Boston, MA, USA) which was synchronised with kinematic and force data. The electrodes used were wireless, 37 x 26 x15 mm with parallel bar configuration, contact material 99.9% Ag and inter electrode spacing 10 mm. A sampling rate of 4000 Hz with a common-mode rejection ratio of 80 dB was applied to the data using EMG Works (4.0) software.

Raw data were processed using custom written Matlab code (2011b). Processing of the data included filtering the raw data using a 5^{th} order band pass (15 – 500 Hz) Butterworth filter. The filtered data were then full-wave rectified and then smoothed using RMS with a 20 ms window, as advised for fast movements (Konrad, 2005). For each participant and condition, data were normalised to the mean of the peak RMS, as previously recommended (Albertus-Kajee, Tucker, Derman, Lamberts, & Lambert, 2011).

To allow for the identification of onset of muscle activity the threshold based on the percentage of the peak EMG was established in a similar manner to that described by Steele and Brown (1999). Visual examination of a sample of onset times with thresholds between 3 – 25% of the peak EMG value for each participant and condition were used to establish percentage threshold for each muscle. The following thresholds were established; rectus femoris 12%, bicep femoris 18%, tibialis anterior 15% and gastrocnemius 7%. Onset time was computed at the point at which muscle activity was greater than the threshold for a minimum of 30 ms. Data were collected from 50 ms prior to ground contact through to toe-off to ensure collection of both anticipatory and reactive responses to surface changes. An earlier onset time was indicated by a higher value.

5.2.4.6 Perception Data

A short questionnaire (Appendix 7) comprising of VAS was used to collect perception data. These scales were 100 mm in length with two descriptive end phrases, formulated from variables and language identified in study 1.

Perception variables include perceived predictability, grip, hardness, ability to changing direction, ability to slide. Perception data were collected following the familiarisation trials and following trial 2, 5 and 8 of each condition to provide a mean and variation of perceptions during each condition.

5.2.4.7 Statistical Analysis

Three independent variables were determined for the present study, two within-subject variables (friction level and expectation condition) and one between-subject variable (familiarisation group). Therefore a three-way mixed model ANOVA was conducted to examine the influence of each independent variable on the dependent variables and to identify interactions between the independent variables. An example output from SPSS (v.11) is presented in Appendix 9. An alpha level of 0.05 was used to identify any significant main effects or interactions.

5.3 Results

5.3.1 Kinematic data

The analysis revealed that friction condition was not a main effect for kinematic data. Sliding rotation provided the degree to which the foot rotated in the transverse plane when sliding during the turning movement. Friction level and expectation condition were found to have no significant effect upon sliding rotation (Table 5.6). However, familiarisation group was found to significantly influence the amount of foot rotation that occurred during sliding (ES = .465, p =.01). Those with greater familiarisation (28.61 ± 2.11^{o}) produced greater sliding rotation compared to the low-familiarisation group (19.02 ± 2.28^{o}).

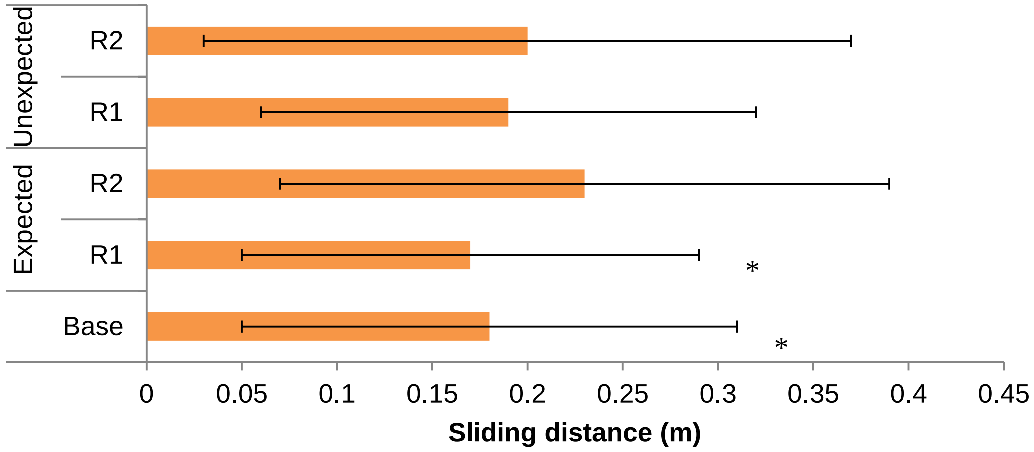

Figure 5.5: Means and standard deviations for sliding distance for each friction level and each expectation condition, * denotes significantly different to the expected R2 condition

Figure 5.8 provides the sliding distances obtained during the turning movement for each friction level and each expectation condition. During the expected trials friction was a contributing factor that influenced the sliding distances achieved (ES = .355, p =.008). For instance, the lowest level of friction (R2; 0.23 ± 0.16 m) produced significantly greater sliding distance compared to the expected R1 (0.17 ± 0.12 m) and baseline (0.18 ± 0.13 m) conditions which had greater friction. However, these differences in sliding distance with friction level were only observed for the expected conditions and no differences were obtained for the unexpected conditions.

During the expected trials, friction level was found to have a significant influence on the occurrence time of peak knee flexion (ES = .270, p =.023), which was not observed for the unexpected condition. Post hoc analysis revealed that when expected, the R2 condition (0.34 ± 0.09 s) resulted in a later peak knee flexion than observed for the baseline condition (0.31 ± 0.07 s; Table 5.7). A significant interaction between friction, expectation and group were identified for the magnitude of peak knee flexion (ES = .401, p =.015). Post hoc analysis revealed that during the unexpected R1 friction condition the familiarisation group exhibited lower peak knee flexion (37.07 ± 6.08°) than the low-familiarisation group (44.77 ± 5.44°). Although not significant (*p* =.057) similar findings occurred during the expected R2 condition, where the familiarisation group (36.52 ± 6.10°) had lower peak knee flexion than the low familiarisation group (42.77 ± 5.45 °).

Table 5.3: Means and standard deviations for kinematic data collected for each friction level and expectation condition

		Expected		Unexpected		
Variable	**Baseline**	**R1**	**R2**	**R1**	**R2**	***ES***
Attack angle (°)	34.31 ± 6.60	32.81 ± 7.45	35.03 ± 7.49	31.18 ± 6.80	34.29 ± 7.05	
Knee flexion angle						
At impact (°)	17.26 ± 13.64	13.63 ± 13.61	16.47 ± 12.04	15.28 ± 16.04	15.28 ± 10.09	
Peak (°)	40.01 ± 5.22	39.46 ± 5.67	39.64 ± 6.23	40.92 ± 6.83	40.18 ± 5.82	.401*
Time of peak (s)	.31 ± .07	.30 ± .07	.34 ± .09	.32 ± .08	.33 ± .13	.270[f]
Ankle flexion angle						
At impact (°)	4.36 ± 12.57	3.01 ± 11.30	4.56 ± 11.98	7.35 ± 13.70	6.71 ± 10.66	
Peak (°)	-12.19 ± 7.27	-10.90 ± 8.87	-12.29 ± 7.41	-13.81 ± 9.32	-10.21 ± 7.67	
Time of peak (s)	.26 ± .12	.19 ± .12	.22 ± .12	.24 ± .11	.23 ± .09	
Ankle inversion angle						
At impact (°)	-4.60 ± 17.16	2.15 ± 13.26	-2.80 ± 17.04	-11.18 ± 17.12	-4.28 ± 12.04	.595[e#]
Peak (°)	-30.40 ± 8.50	-29.29 ± 7.50	-27.85 ± 8.73	-31.72 ± 8.82	-29.91 ± 7.42	.280[e]
Time of peak (s)	.24 ± .09	.23 ± .08	.19 ± .08	.19 ± .12	.26 ± .14	

[f] denotes a significant difference in friction for the expected conditions, [e] denotes a significant main effect for expectation condition, [#] denotes a significant interaction between friction level and expectation condition, * denotes a significant interaction between friction level, familiarisation group and expectation condition

Expectation condition influenced the initial ankle inversion angle (ES = .595, *p* =.001), where unexpected conditions resulted in a more inverted ankle at ground contact (-7.73 ± 3.24^{o}) compared to the expected conditions (-.33 ± 3.82^{o}), where participants were more neutral. Friction level was found to interact with expectation condition for initial ankle inversion angle (ES = .485, *p* =.006). Figure 5.9 highlights the interaction between expectation and friction level for initial ankle inversion angle. The unexpected R1 condition (-11.18 ± 17.12^{o}) produced significantly greater ankle inversion in comparison to both expected conditions which were close to neutral (R2, -2.80 ± 17.04^{o}) or slightly everted at ground contact (R1, 2.15 ± 13.26^{o}; Figure 5.9). Although not significant, peak ankle inversion angle findings were similar to initial ankle inversion angle, where expectation was an influencing factor (ES = .280, *p* =.052). During the unexpected trials greater inversion values (-30.82 ± 2.00 ^{o}) were observed compared to the expected conditions (-28.57 ± 2.00 ^{o}).

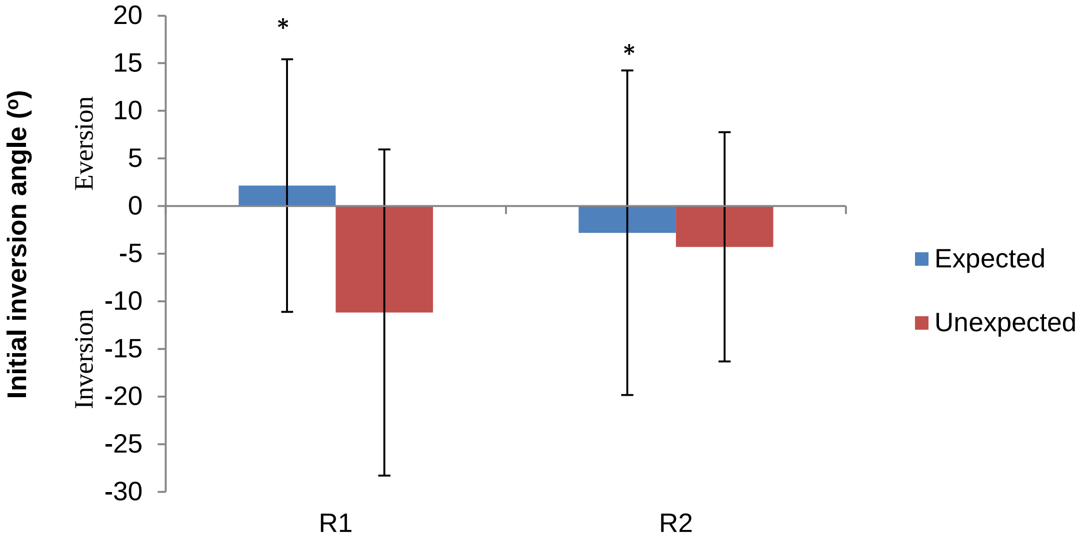

Figure 5.6: Means and standard deviations for initial ankle inversion angle for each expectation condition and each friction level, * denotes significantly different to unexpected R1 condition

5.3.2 Force data

Table 5.4: Average and peak loading rates for the vertical and horizontal forces

Variables	Baseline	Expected		Unexpected		*ES*
		ER1	ER2	UR1	UR2	
Average loading rate (BW/s)	37.75 ± 19.31	42.19 ± 21.18	41.67 ± 19.78	40.78 ± 20.58	40.14 ± 19.12	.224[*]
Peak vertical loading rate (BW/s)	140.22 ± 87.74	153.25 ± 99.97	138.44 ± 91.00	142.08 ± 87.17	132.61 ± 80.62	.345[f]
Horizontal peak loading rate (BW/s)	54.94 ± 26.84	58.97 ± 30.60	54.92 ± 27.29	58.59 ± 28.69	51.57 ± 30.14	.396[f]
Peak utilised COF	.62 ± .13	.55 ± .08	.53 ± .14	.55 ± .10	.51 ± .07	.576[g]
Time of peak utilised COF (s)	.035 ± .02	.039 ± .02	.043 ± .02	.036 ± 0.01	.043 ± .02	.306[f]

[*] denotes a significant interaction between expectation and group, [f] denotes a significant main effect for friction level, [g] denotes a significant main effect for familiarisation groups

Table 5.3 presents the means and standard deviations for the vertical and horizontal loading rates and peak utilised COF measured during the turning movement for each condition. Irrespective of expectation condition and familiarisation group, peak vertical loading rate was significantly lower during the R2 (lowest friction) conditions (135.52 ± 23.16 BW/s; ES = .345, *p* =.027) compared to the R1 conditions (147.67 ± 25.77 BW/s). Friction level significantly influenced peak horizontal loading rate (ES = .396, *p* =.016), with lower horizontal loading rates produced during the R2 conditions (53.25 ± 10.45 BW/s) compared to the R1 conditions (58.78 ± 10.92 BW/s). The occurrence time of peak utilised COF was observed to be significantly later for R2 friction level (.043 ± .004 s; ES = .306, p =.040) compared to the R1 friction level (.037 ± .003 s). Significant differences between familiarisation group was only observed for peak utilised COF where the familiarisation group had significantly lower peak utilised COF (.488 ± 0.02) compared to the low-familiarisation group (.577 ± 0.02, ES = .416, p =.013).

A significant interaction between friction level and expectation condition was observed for average loading rate. The expected R1 condition (42.19 ± 21.18 BW/s) was had significantly (ES = .224, p =.048) greater average loading rate compared to the baseline condition (37.75 ± 19.31 BW/s). Yet the unexpected conditions were similar between friction levels. Expectation was found to be a significant main effect for peak shear force (ES = .299, p =.043), with greater peak shear force occurring during the expected conditions (522.18 ± 41.94 N) compared to the unexpected conditions (506.22 ± 42.55 N). The analysis revealed a significant interaction (ES = .297, p =.044) between group, friction level and expectation condition for the occurrence time for peak impact force. Although a significant interaction was observed post hoc analysis was unable to identify where the interaction occurred. Figure 5.10a highlights means and standard deviations between the experience groups during the expected R1 condition. Figure 5.10b suggests possible differences between groups during both unexpected conditions.

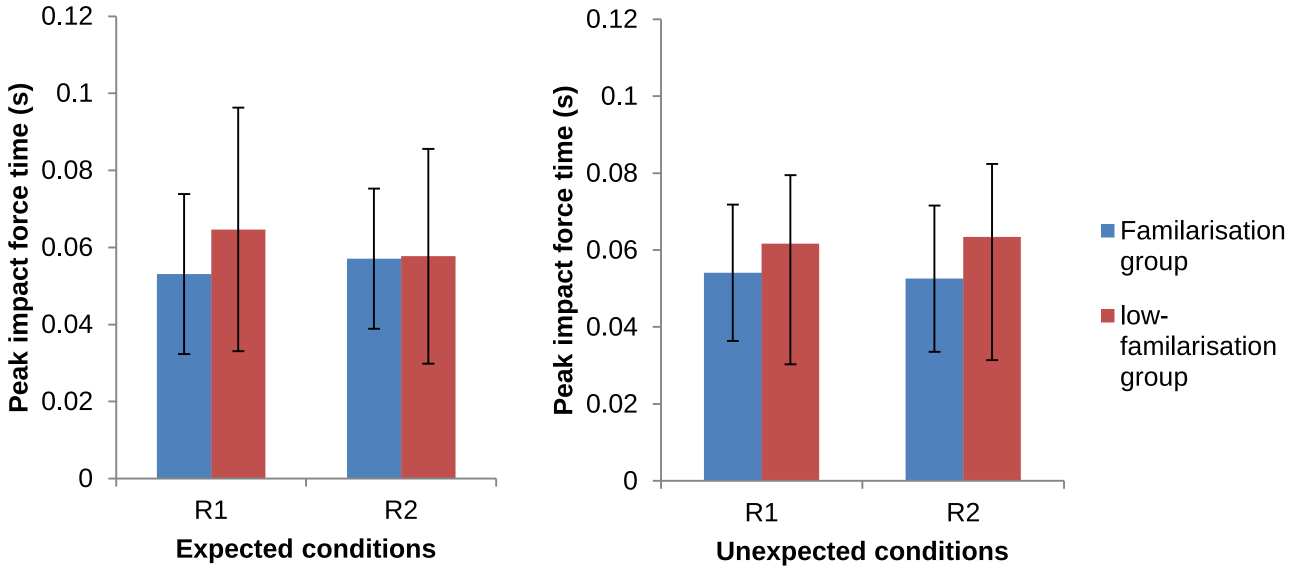

Figure 5.7: Means and standard deviations for both familiarisation groups for each friction level for a) expected conditions, b) unexpected conditions

5.3.3 Pressure data

Table 5.4 presents the whole foot pressure data collected for each condition. Friction significantly influenced whole foot mean pressures (ES = .439, *p* =.014), where lower mean pressures were observed for the lowest friction condition (R2, 30.19 ± 1.42 N.m^2) compared to the R1 condition (31.10 ± 1.52 N.m^2). No effects of friction level were observed for the maximum pressure and occurrence time of maximum whole foot pressures (p>.05). Both familiarisation groups and expectation conditions influenced the whole foot mean pressures (ES = .368, *p* =.028). When conditions were expected the familiarisation group (33.30 ± 5.94 N.m^2) produced greater mean pressures compared to the low-familiarisation group (28.67 ± 4.55 N.m^2). However, this difference between groups was not observed during the unexpected conditions. Expectation condition resulted in differences in maximum whole foot pressures (ES = .435, p

=.014). During the expected conditions (381.91 ± 28.65 $N.m^2$) greater maximum pressure was produced compared to the unexpected conditions (367.80 ± 28.41 $N.m^2$).

Table 5.5: Means and standard deviations for whole foot pressure data

		Expected		Unexpected		
Variable	**Baseline**	**ER1**	**ER2**	**UR1**	**UR2**	***ES***
Mean Pressure ($N.m^{-2}$)	31.68 ± 6.21	31.61 ± 6.00	30.72 ± 5.69	30.87 ± 5.43	29.94 ± 4.92	.439[*f]
Maximum pressure ($N.m^{-2}$)	389.08 ± 84.53	392.70 ± 87.76	391.75 ± 83.41	380.60 ± 72.38	376.68 ± 81.40	.435[e]
Time of maximum pressure (s)	.42 ± .15	.43 ± .14	.45 ± .16	.43 ± .12	.42 ± .10	

[f] denotes a significant difference between friction condition irrespective of expectation and familiarisation group, [e] denotes a significant main effect for expectation conditions, * denotes a significant interaction between familiarisation group and expectation

Expectation condition influenced the medial forefoot, medial and lateral midfoot and heel maximum pressures. Greater maximum pressures were observed during the expected conditions compared to the unexpected condition as presented in Figure 5.11. The analysis revealed significant differences between expectation conditions for maximum loading rate at the heel (ES = .635, p <.001), where greater maximum heel loading rates occurred for the expected conditions (35.38 ± 5.07 N/s) compared to the unexpected conditions (33.20 ± 4.75 N/s). Familiarisation group also influenced the outcome of expectation conditions (ES = .325, p =0.033), during the expected conditions no differences were observed between groups. However, during the unexpected conditions maximum heel loading rate was significantly greater for the familiarisation group (36.81 ± 19.52 N/s) compared to the low-familiarisation group (33.52 ± 17.80 N/s).

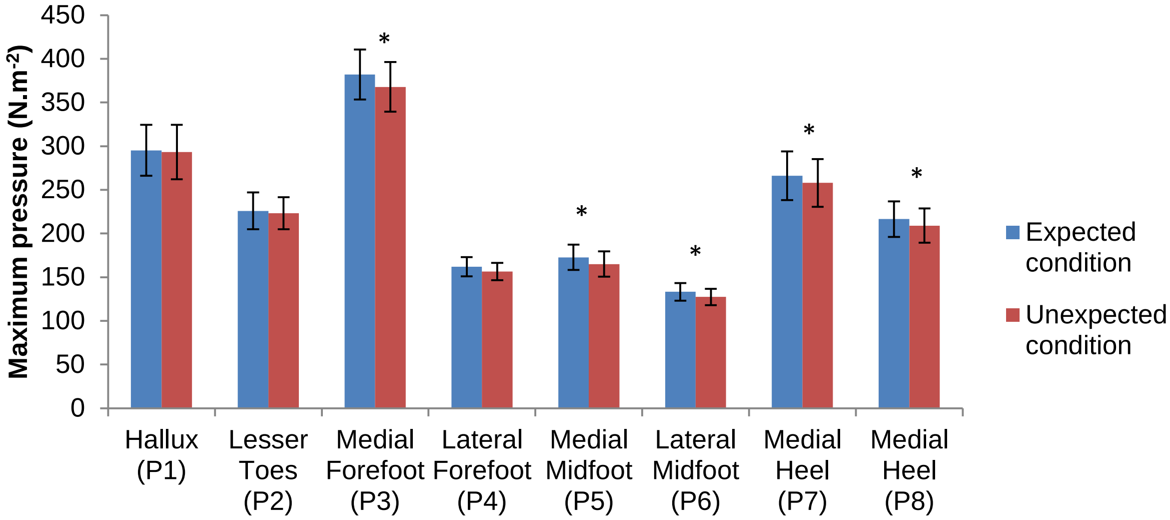

Figure 5.8: Means and standard deviations for maximum pressures for each mask produced during expected and unexpected conditions, * denotes a significant difference between expected and unexpected conditions

5.3.4 Internal Loading

For moment data (Figure 5.5), at the ankle, friction was an influencing factor, particularly in the sagittal plane as presented in Table 5.5. Peak dorsi flexor moment (ES = .357, p =.031) was lower in the lowest friction level (R2, 29.44 ± 7.03 N.m) condition compared to the R1 condition (40.40 ± 7.03 N.m). For peak plantar flexor moments (ES = .295, .055), although not significant, lower magnitudes in plantar flexor moments were observed during the R2 condition (-174.20 ± 14.36 N.m) compared to the R1 conditions (-192.10 ± 15.12 N.m). A later occurrence time of peak knee abductor moments (ES = .441, p =.029) during the R2 (.195 ± .04 s) conditions was observed compared to the R1 (.168 ± .05 s) conditions.

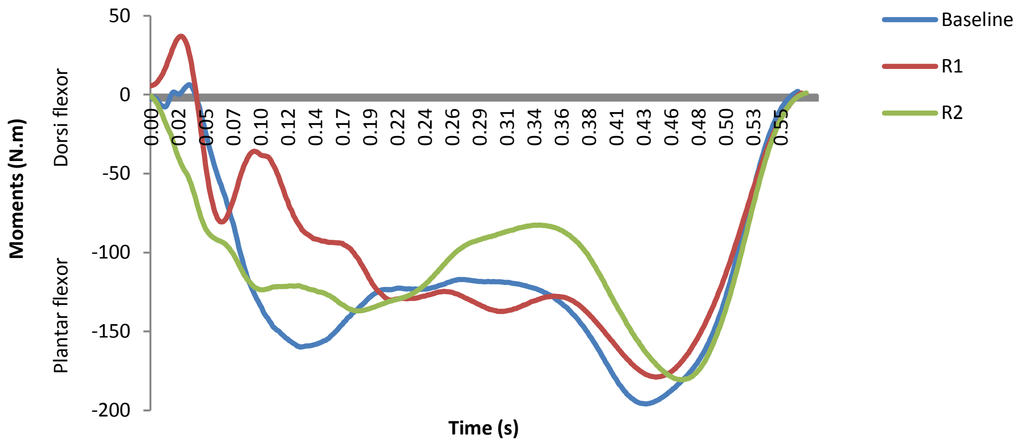

Figure 5.9: Example time history for ankle flexor moments on each friction condition

A significant interaction between familiarisation group and friction level (ES = .287, *p* =.024) was observed for the occurrence time of peak knee abductor moment (Figure 5.7). For the familiarisation group knee abductor moments occurred significantly later on the baseline condition (.35 ± 21 s) compared to the expected R2 condition (.26 ± .17 s). However, for the low-familiarisation group knee abductor moment occurred significantly sooner on the baseline condition (.23 ± .14 s) compared to the expected R1 condition (.32 ± .15 s). This interaction between group and friction was similar to that observed for the occurrence time of peak knee flexor moment (ES = .288, *p* =.024). Peak knee flexor moment occurred significantly later on the baseline condition (.35 ± 21 s) compared to the expected R2 condition (.26 ± .17 s) for the familiarisation group. Yet, for the low-familiarisation group peak knee flexor moment occurs sooner on the baseline condition (.23 ± .14 s) compared to the expected R1 condition (.32 ± .15 s).

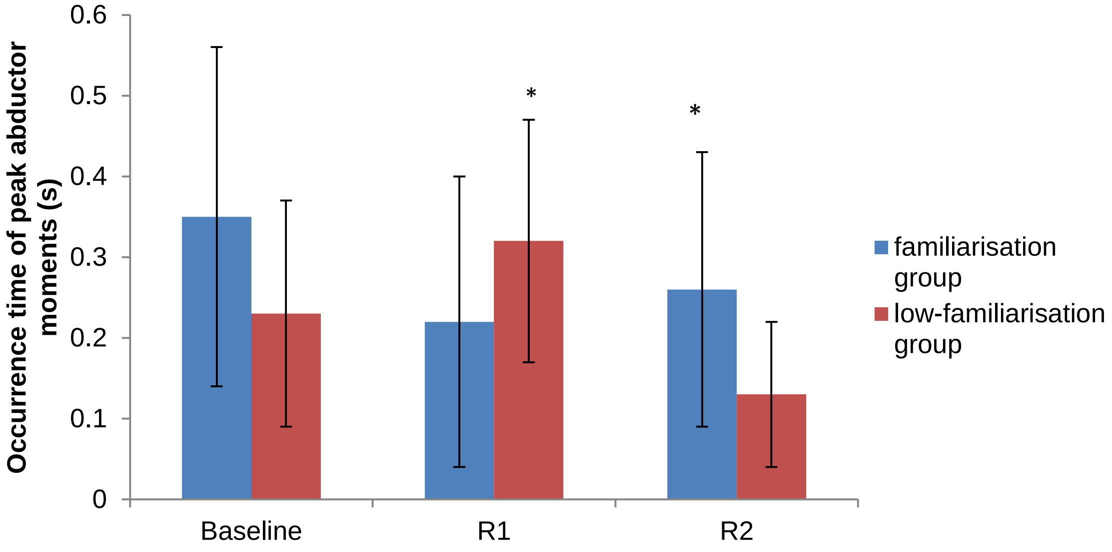

Figure 5.10: Means and standard deviations for each friction level for the expected conditions for occurrence time of peak abductor moments, * denote significantly different to baseline condition

The analysis revealed a significant interaction between group, expectation and friction for peak eversion moment (ES = .330, p =.04, Figure 5.12). Further analysis highlighted that for the familiarisation group there were no differences between expectation and friction level. However, for the low-familiarisation group, at the R1 friction level, the expected condition produced significantly greater peak eversion moments (-158.43 ± 99.39 N.m) compared to the unexpected condition (-150.56 ± 95.04 N.m). When comparing the unexpected conditions for the low-familiarisation group, the lowest friction level produced greater eversion moments (R2, -164.61 ± 97.64 N.m) compared the unexpected R1 condition (-115.56 ± 95.04 N.m).

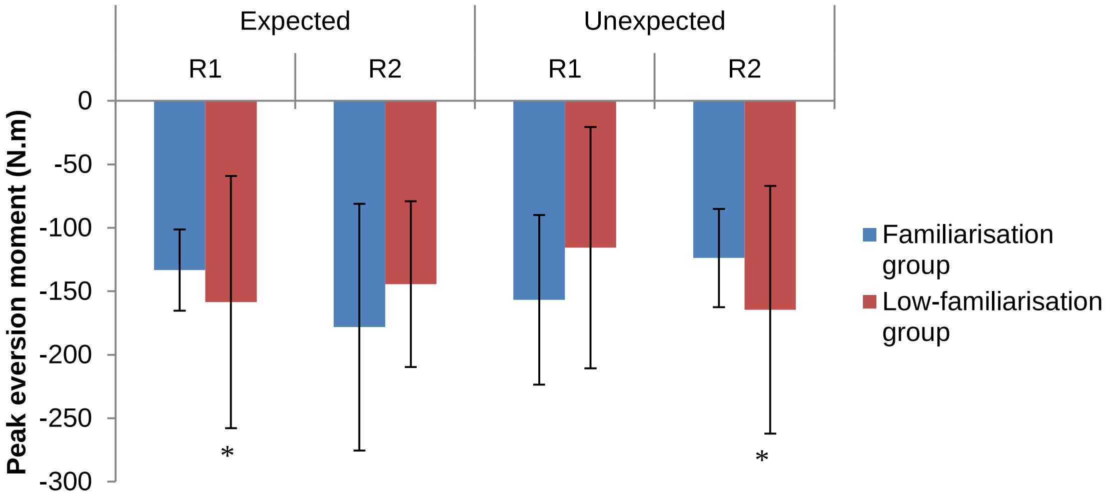

Figure 5.11: Means and standard deviations for peak eversion moment for each expectation condition and each friction level, * denotes significantly different to unexpected R1 condition in the low-familiarisation group

Table 5.8 provides the means and standard deviations for each expectation condition and friction level for the internal loading at the knee joint. Expectation condition influenced the occurrence time of peak knee abductor moment (ES = .364, *p* =.029). During the expected conditions participants produced a significantly later peak knee abductor moment (.21 ± .04 s) compared to the unexpected conditions (.16 ± 0.5 s).

Table 5.6: Mean and standard deviations for internal loading for the knee for each expectation

		Expected		Unexpected		
Variable	**Baseline**	**R1**	**R2**	**R1**	**R2**	**ES**
Peak flexion (N.m)	-51.84 ± 20.60	-41.18 ± 22.39	-46.74 ± 25.62	-36.41 ± 16.54	-41.27 ± 20.40	
Time of peak flexion (s)	.270 ± .105	.290 ± .141	.238 ± .158	.232 ± .096	.213 ± .109	.288*
Peak extension ($N.m^{-1}$)	85.47 ± 35.73	89.02 ± 37.69	94.56 ± 41.91	88.67 ± 36.31	86.66 ± 46.60	
Time of peak extension (s)	.298 ± .187	.320 ± .181	.264 ± .145	.244 ± .158	.265 ± .188	

* denotes a significant interaction between friction and group

5.3.5 EMG

Table 5.9 provides the onset times of muscle activity for each expectation condition and each friction level. Onset of muscle activity prior to ground contact did not differ between groups, friction and expectation for the rectus femoris, bicep femoris and gastrocnemius. However, a significant interaction between group, expectation condition and friction level was observed for the onset time of the tibialis anterior muscle (ES = .343, p =.013). Post hoc analysis revealed no differences in onset time for the low-familiarisation group between conditions. However, for the familiarisation group there was a significant difference during the R2 friction level, where an earlier onset of tibialis anterior occurred during the expected conditions (.031 ± .014 s) compared to the unexpected conditions (.016 ± .021 s). The familiarisation group also produced a later onset of the tibialis anterior activity during the R2 condition (.016 ± .021 s) compared to the R1 (.038 ± .010 s) condition when unexpected.

Table 5.7: Mean and standard deviations for onset of muscle activity prior to ground contact for each expectation condition and friction level

	Expected			Unexpected		
Variable	**Baseline**	**R1**	**R2**	**R1**	**R2**	***ES***
Rectus femoris (s)	.036 ± .015	.033 ± .022	.038 ± .019	.027 ± .022	.032 ± .027	
Bicep femoris (s)	.040 ± .001	.036 ± .012	.034 ± .015	.038 ± .015	.035 ± .016	
Tibialis anterior (s)	.031 ± .013	.035 ± .012	.037 ± .012	.036 ± .013	.027 ± .025	.343*
Medial head of the gastrocnemius (s)	.035 ± .014	.033 ± .016	.034 ± .018	.034 ± .018	.038 ± .012	

*** Denotes a signifciant interaction between friction level, familarisation group and expectation condition**

5.3.6 Perceptions

Perception data were collected for each condition following the 3rd, 6th and 8th trials. Table 5.10 provides the means and standard deviations for the perception variables for each expectation condition and friction level. No significant group differences or interactions between group and condition were revealed (p>.05). Friction influenced players perceptions, for instance, the baseline condition was observed to be significantly greater compared with the expected R2 condition for perceived grip and ability to slide. Irrespective of expectation, R2 had lower values compared to the R1 condition for perceived predictability, grip and ability to slide. R2 was perceived to be less predictable, have greater grip and harder to slide compared to the R1 condition.

Table 5.8: Means and standard deviations for each perception parameter for each expectation and friction condition

Perceptions (VAS, mm)		**Expected**		**Unexpected**		
Variable	**Baseline**	**R1**	**R2**	**R1**	**R2**	***ES***
Predictability	58.13 ± 18.02	52.67 ± 17.15	45.52 ± 22.80	49.18 ± 18.81	44.33 ± 17.25	.356^{f}
Grip	47.49 ± 17.38	43.85 ± 17.17	31.44 ± 24.81	41.29 ± 18.67	37.51 ± 17.68	.352^{f}
Hardness	45.12 ± 18.43	41.18 ± 16.40	22.25 ± 13.69	37.12 ± 12.80	32.10 ± 12.04	.406^{e}*
Ability to change direction	42.43 ± 18.66	46.25 ± 17.50	59.74 ± 17.08	52.73 ± 16.13	52.91 ± 13.76	.394*^{f}
Ability to slide	39.10 ± 17.39	34.53 ± 14.57	21.69 ± 17.41	33.96 ± 14.44	27.51 ± 11.67	.415^{f}

^{f} denotes and significant main effect for friction level, ^{e} denotes a significant main effect for expectation condition, * denotes a significant interaction between friction and expectation

A significant interaction between expectation and friction level was revealed for perceived hardness (ES = .400, p =.015, see Figure 5.13). Further analysis revealed that during expected conditions, greater hardness was perceived for the R1 condition (43.26 ± 14.81 mm) compared to the R2 (23.17 ± 13.72 mm). However, the differences in perceived hardness in friction levels were not observed for the unexpected conditions. At the lowest friction level (R2), when unexpected (33.03 ± 11.92 mm) participants' perceived the surface to be harder compared to when they expected a change in friction (23.17 ± 13.72 mm). However, this difference in expectation was not observed for the R1 condition.

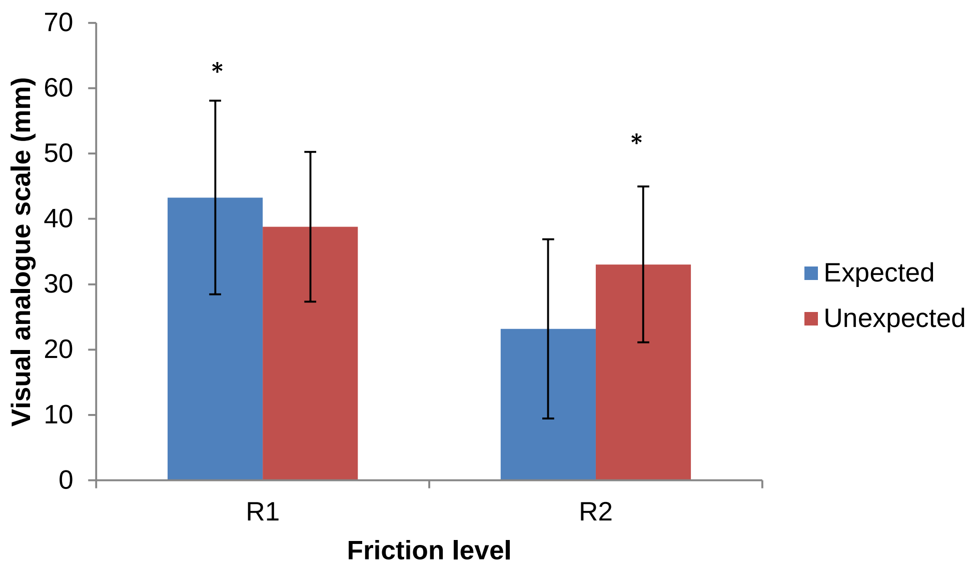

Figure 5.12: Means and standard deviations for perceived hardness for each friction level and expectation condition. * denotes significantly different to expected R2 condition

A significant interaction between expectation and friction level was revealed for the perceived ability to change direction (ES = .394, p =.016). Post hoc analysis revealed no significant differences between expectation conditions and no differences between friction levels during the unexpected conditions. During the expected conditions participants perceived the lowest level of friction (R2; 57.82 ± 15.95 mm) to be harder to change direction compared to R1 (43.96 ± 15.66 mm; as shown in Figure 5.14).

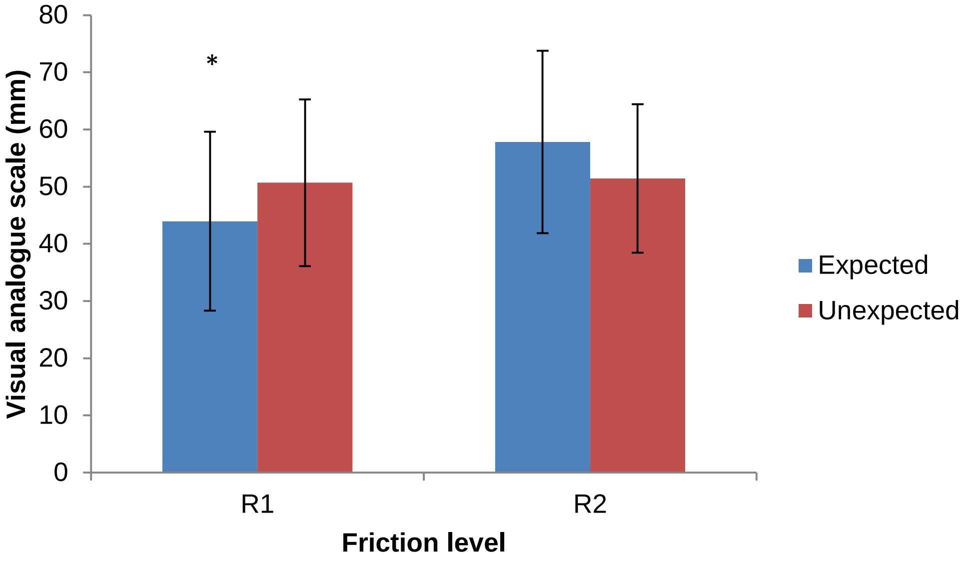

Figure 5.13: Means and standard deviations for perceived ability to change direction for each friction level and expectation condition. * denotes significantly different to the expected R2 condition

5.4 Discussion

The current study had three aims; the first aim was to assess players' biomechanical response to changes in friction level on a synthetic clay surface. Findings from the current study suggested that changes in friction led to alterations in loading characteristics as well as ankle and knee joint moments, with lower loading and joint moments during the lower friction conditions. The second aim was to investigate whether the level of familiarisation, which was found to have minimal differences in biomechanical and perceptual measures. Thirdly, the study aimed to examine the influence of expected and unexpected frictional changes of a clay surface upon player response and perceptions during a turning movement. The data suggest that expectation of surface changes result in changes in frontal ankle joint kinematics and moments as well as changes in pressure distribution patterns.

5.4.1 Sliding Distance

Sliding on clay is a common aspect of tennis (Miller, 2006), where players aim to initiate sliding in a timely manner to enable an efficient change of direction (Pavailler & Horvais, 2014). For instance players will slide into a tennis stroke, whereby on completion of the stroke they will be ready to move for the next shot. Sliding distance in the present study (0.17 – 0.20 m) was lower than that reported in study 2 (Section 4.3.2; 0.66 ± 0.4 m). These differences could be a result of the lower calibre of players in the present study, in addition to the fact that participants in the present study had little or no prior clay court experience. As hypothesised, as friction was reduced, through greater volumes of sand, further sliding distances were achieved when the players were aware of the lower friction. Increases in sliding distances were only apparent for expected reductions in friction. When unexpected, no differences were reported, suggesting players are able to increase sliding when appropriate through prior anticipatory knowledge of the surface. However, when unexpected changes occurred, players depended more on sensory information (Patla, 2003), resulting in lower shear forces when compared to the expected conditions, providing an explanation for the absence of changes in sliding distance during the unexpected reductions in friction.

Sliding occurs when the horizontal force applied is greater than the static friction force (Clarke et al., 2013; Damm et al., 2013). Previous reports have identified higher shear forces on low friction clay surfaces compared to a high friction acrylic surfaces which resulted in increased utilised COF leading to players sliding on the clay court (Damm et al., 2013). Yet, the present study did not report mechanical friction level to influence the shear forces as expected. Damm et al. (2013) examined two distinct levels of friction (acrylic and clay surfaces), where the utilisation of friction differed such that when on the acrylic surface participants reduced their shear loading to reduce friction, possibly reducing injury risks associated with loading on high friction surfaces, whilst on the clay the greater shear force would enable participants to overcome the static friction and initiate sliding (Clarke et al., 2013; Damm et al., 2013). The present study focused on clay surfaces where participants were able to slide during all conditions. With no differences in shear force observed across the three surface friction levels, the lower friction surfaces allowed greater sliding distances owing to a lower resistance to sliding (lower mechanical COF). Further sliding reported during the lowest friction level resulted in reduced horizontal and vertical loading rates. The lower rate of loading on the lower friction surface as a result of further sliding suggests a reduced risk of injury by allowing more time spent applying the horizontal and vertical loads (Nigg & Segesser, 1988; Bastholt, 2000; Stiles & Dixon, 2007).

5.4.2 Knee Flexion and Flexor Moment

Longer braking phases, through later peak knee flexion, have previously been suggested to result in reduced loading to accommodate the potential high loading when turning on high friction surfaces, therefore reducing the risk of injury (Nigg & Segesser, 1988; Durá et al., 1999). However, in accordance with study 2, later peak knee flexion, and thus later braking occurred on the lower friction clay surface instead of the higher friction clay conditions. It is important note that the mechanical friction properties of the surfaces reported in the Durá et al. (1999) study had a greater range of mechanical friction (.93 - .43) which span those previously observed for clay and acrylic courts (Wuebbenhorst & Zschorlich, 2012). However, the present study focused on low friction levels on a clay surface where the coefficient of friction ranged between 0.63 - 0.54, similar to that previously reported for clay court surfaces (Wuebbenhorst & Zschorlich, 2012). As highlighted in study 1 and 2, marked differences in friction (acrylic and clay) resulted in distinct differences in technique to enable sliding on clay. This may explain contrasting results with those of Durá et al (1999). The present study reported players sliding for all conditions, which was not reported by Durá et al. (1999), therefore suggesting the later braking through later peak knee flexion is a result of further sliding.

Although later peak knee flexion is attributed to longer braking and therefore reduced loading (Durá et al., 1999), there is potential increase in fatigue and risk of patellofemoral pain as result of longer time spent dissipating loads during turning (Damm et al., 2013). For instance, time spent in flexion results in longer eccentric contractions of the quadriceps associated with increased risk of patellofemoral pain (Gecha & Torg, 1988; Stefanyshyn et al., 2006). Along with later knee flexion, knee abductor moments, used to counteract the external adduction moment exerted during turning (Luo & Stefanyshyn, 2011), occurred significantly later during the lower friction condition (R2), when longer sliding occurred. Whilst the magnitude of knee abductor moments were maintained between friction conditions. It has been suggested that high knee abductor moments have been associated with increased risk of patellofemoral pain (Stefanyshyn et al., 2006). Stefanyshyn et al. (2006) observed greater impulse of the knee abductor moments, a later occurrence time of the knee abductor moments reported in the current study may lead to greater impulse. Therefore lower friction can lead to further sliding, thus increasing the time spent in flexion and time to peak knee abductor moments which may increase the risk of patellofemoral pain on clay courts.

Unlike previous running and walking studies, where the knee extensor moments are generally predominant (Luo & Stefanyshyn, 2011), the present study reported a high knee flexor moments during turning. The present study contradicts findings recently reported by Shrier et al. (2014) who presented high extensor moments during an 180^{o} turning movement. Shrier and colleagues (2014) examined the turning movement on artificial turf and did not report sliding to be apparent. As observed in study 2, different techniques are employed when sliding is observed compared to when no sliding is reported. It could be hypothesised that differences in technique influences the orientation of the GRF with the knee joint which has implications on the joint moments estimated. Further investigation is necessary to better understand the occurrence of the high knee flexor moment, suggested to lead to collapse at the knee, and minimal knee extensor moments.

Calculation for Winter's (2011) support moment can provide a suggested explanation of the current study results regarding the existence of a large knee flexor moment during stance. Winter's (2011) support moment suggests that there is a collaboration between muscles at the hip, knee and ankle joint preventing the collapse of the knee. Winter's (2011) support moment is described in Equation 5.10, where M_s = support moment, M_k = knee moment, M_a = ankle moment, M_h = hip moment.

$$M_s = M_k - M_a - M_h$$ *Equation 5.10*

The high negative plantar flexor moments reported in the present study, contributed to the positive support moment, using the above equation. Figure 5.15 presents example time-histories for the sagittal plane joint moments for the knee and hip, highlighting the relatively large contribution of the plantar flexor moments to supporting the lower limb during turning. The plantar flexor moments during the turning movements counteracts the forward rotation of the leg thus preventing knee flexion and stabilising the leg (Winter, 1980). However, the present study did not measure hip joint moments; therefore further investigation is required to understand the contribution of the hip joint moment to maintain support during turning on different friction conditions. In the present study greater plantar flexor moments were observed during R1 friction levels compared to the lower R2 friction levels. Larger plantar flexor moments in females have been associated with increased ACL injury risks (Decker, Torry, Wyland, Sterett, & Richard Steadman, 2003). Therefore on the higher friction clay surface, where plantar flexor moments were greater, there may be an increased risk of this injury.

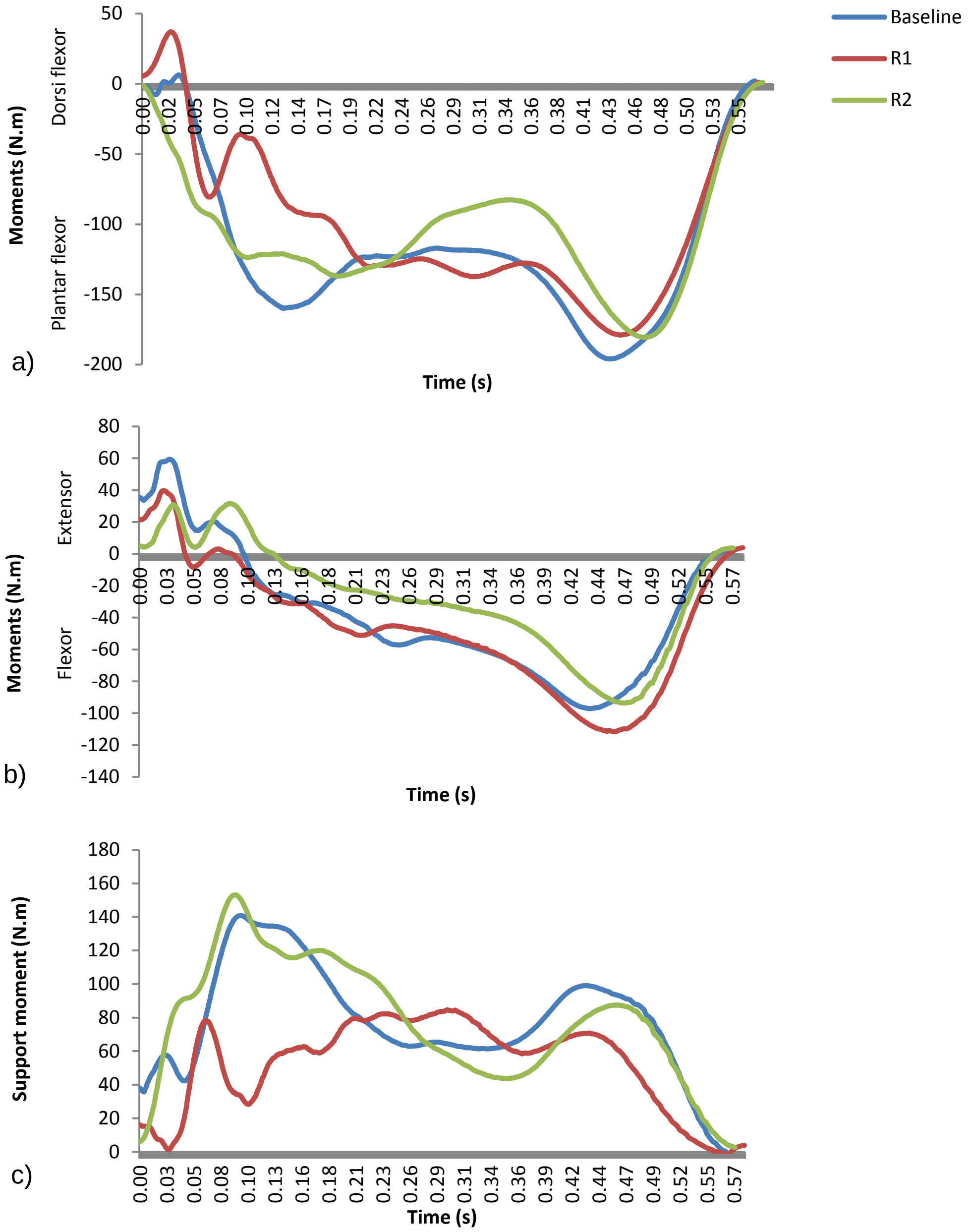

Figure 5.14: Example moment time histories for the expected conditions (baseline, R1, R2) for a) ankle flexor moments, b) knee flexor moments and c) support moments, illustrating the contribution of the plantar flexor moment to the support moment

5.4.3 Ankle Inversion

High ankle inversion, particularly in early stance of a turning movement, have been reported to be a mechanism for sudden ankle inversion sprain (Kristianslund et al., 2011). In the present study ankle inversion angle at ground contact was reported to be greater for the unexpected conditions compared to the expected conditions. The greater inversion angles reported for unexpected conditions will likely increase injury risk due to the lower effectiveness of evertor muscular control for an inverted position (Cham & Redfern, 2002; Konradsen et al., 2005). Participants in the present study produced greater eversion moments to control the ankle during the expected conditions compared to the unexpected conditions, reducing the amount of inversion observed on the expected conditions when compared to the unexpected conditions. Therefore increased risk of inversion injuries when reductions in friction were unexpected are suggested, as a result of greater initial inversion angles and lower eversion moments observed.

5.4.4 Muscle Activity

As proposed anticipatory strategies in response to surface conditions rely on prior knowledge and familiarisation of the surfaces leading to earlier onset of muscle activity prior to ground contact compared to reactive strategies (Marigold & Patla, 2002; Patla, 2003; Moritz, 2004). Previously suggest reactive strategies depend more on sensory information, therefore often resulting in altered kinematics during stance and later onset of muscle activity (Patla, 2003; Moritz, 2004). The present study provides evidence to support these previously proposed strategies. At the lowest level of friction (R2) the onset time of the tibialis anterior occurred earlier when the condition was expected compared to unexpected, suggesting a response to increase control of the ankle dorsi/plantar-flexion. However differences in tibialis anterior onset times were only found to be significant for the low-familiarisation group. Therefore prior knowledge of friction level led to an earlier onset of muscle activity and earlier control of the ankle, appears to be irrespective of extensive familiarisation to these changes.

5.4.5 Pressure Distribution

Lower friction levels were found to reduce whole foot mean pressures, yet unlike previous studies (Girard et al., 2007; Damm et al., 2014), the current study did not identify friction to influence pressure distribution of pressure across the foot plantar surface. It is suggested that a lack of differences in plantar pressure distribution was due to the smaller variation in the level of mechanical friction examined compared to previous studies which included both acrylic and clay surfaces (Girard et al., 2007; Damm et al., 2012). However, expectation of changes in friction influenced the pressure distribution. For example greater pressures were reported in the midfoot and heel regions as well as the medial forefoot region during expected reductions in friction compared with the unexpected reductions. The greater pressures indicate an increase in the normal loading in these foot regions. Using a bespoke traction testing device, Clarke et al. (2013) identified a relationship between normal loading and horizontal displacement velocity, such that velocities were reduced as normal loading increased. Thus the results in the present study suggest that greater pressure during the expected conditions allowed more control when sliding, supported by differences in sliding distance for the expected conditions only. Therefore players' awareness of surface friction will prevent them from slipping through controlled sliding.

5.4.6 Perception

Participants in the present study were able to identify differences in mechanical friction between the surface conditions, where participants perceived the lower friction (R2) level to have less grip, was easier to slide on and was less predictable compared to the R1 condition. The present study is in agreement with previous perception studies where participants were able to identify differences in mechanical properties (Hennig et al., 1996; Milani et al., 1997; Lockhart et al., 2002; Stiles & Dixon, 2007), although the current study is the first to identify this during sliding on clay surface with different levels of friction.

Perceptions are developed as a combination of previous experiences and sensory information (Coren et al., 1979; Sherwood, 1993; Milani et al., 1997). When expected, the R1 condition was perceived to be significantly harder compared to the R2 condition. These findings suggest that during anticipated changes participants were influenced by prior experience (Patla, 2003), for instance greater volume of sand may be perceived to be softer. However, during unexpected conditions participants became reliant on sensory information which is not influenced by previous experiences leading to no perceived differences (Patla, 2003).

Interestingly participants identified the R1 condition to be easier to change direction compared to the R2 condition during the expected conditions, yet participants did not perceive differences in their ability to change direction during the unexpected conditions. During match play, tennis players may not be able to perceive unexpected reductions in friction, which may result in participants being unable to accommodate a reduction in friction. This may lead to reduced accelerations during the propulsive phase or a slip leading to reduced performance or an increase in injury risk (Reinschmidt & Nigg, 2000; Clarke et al., 2013).

5.5 Limitations

Unlike studies 1 and 2, the current study was undertaken within laboratory conditions which limited the movements analysed, therefore reducing the ecological validity of the data. Study 2 reported similar findings between the running forehand and turning movement, therefore the turning movement was employed to accommodate for the lack of space and provide a controlled movement often used in tennis. Data presented in the current study is similar to that reported during the turning movement on the clay court during study 2 suggesting the data is consistent to that reported on court. This laboratory approach used in study 3 allows the manipulation of court surfaces to better understand the influence of surface properties biomechanical response during tennis specific movements. The lower level of players within the current study may limit the application of the findings in the current study, where previous reports have highlighted differences in stroke performance between expert and novice tennis players (Girard, Micallef, & Millet, 2005).

5.6 Conclusions

To conclude, sliding is an influencing factor in players' response when examining clay court surfaces. In particular when reductions in friction were expected longer sliding distances were observed accompanied by reduced horizontal loading rates, as hypothesised (H_{1b}), leading to reduced injury risks. Contrary to the study hypothesis (H_{1a}), the current study did not report changes in shear forces. Later knee flexion (H_{1c}) and later knee abductor moment were observed during lower friction conditions when sliding was also observed. It is suggested that this may lead to greater fatigue and increased risk of patellofemoral pain during prolonged sliding on clay surfaces with low shoe-surface friction. Therefore prior to performing on low friction clay courts players must employ appropriate conditioning training to minimise fatigue. Level of familiarisation resulted in minimal changes in biomechanical responses, with no differences in initial ankle inversion angles, in contrast to the study hypothesis (H_2). As anticipated, earlier onset of tibialis anterior was reported during the expected conditions compared to the unexpected conditions. Earlier onset of muscle activity, greater shear loading (accept H_{4a}), greater eversion moments (reject H_{4b}) and differences in pressure distribution patterns during expected conditions indicated that players exert greater control during sliding through increased normal forces. However, when unexpected reductions in friction occur players may put themselves at risk of slips or reduced performance due to their inability to perceive differences in their ability to change direction and therefore not accommodating for the lower friction through altered pressure distributions and ankle inversion angles. Participants were able to identify differences in mechanical friction however participants found minimal changes to friction harder to differentiate. The level of familiarisation did not influence players' perceptions. Yet, during expected conditions previous experience was found to lead to perceived differences in hardness in the absence of mechanical hardness differences. Therefore players' preconceptions of a surface could lead to inappropriate responses during tennis play on clay court which could lead to greater injury risk or reduced performance.

CHAPTER 6: GENERAL DISCUSSION

6.1 Summary of Findings

The current thesis aimed to examine the influence of tennis court surface properties on players' perceptions and biomechanical responses and the relationship between perceptions and responses. Five specific aims were identified in order to achieve the overall thesis aims. Study 1 utilised the explorative nature of qualitative interviews (Patton, 1990) to identify tennis players' perceptions (Specific aim 1, p. 56). Similar to Fleming et al. (2005), additional perceptions were reported by the participants that have previously not been measured quantitatively, in particular, perceptions of predictability and perceived ability to change direction and slide. The perceptions of hardness and grip collected within this thesis corresponded to those reported in the literature both qualitatively and quantitatively (study 1 and 2), where players were able to identify differences in the mechanical properties of the surfaces, in particular surface friction (Lockhart et al., 2002). When examining smaller changes to friction on a clay court surface (study 3), players had more difficulty in identifying the differences in surface friction. Therefore, in the current thesis, the ability to perceive differences in mechanical friction are dependent on the size of the difference.

The current thesis aimed to examine whether changes in mechanical properties elicited changes in biomechanical response during tennis-specific movements (Specific aim 2, p. 56). From study 1 and 2 it was evident that mechanical friction surface properties influenced players' response to the surface. Lower mechanical friction, facilitating sliding, resulted in an altered technique of the tennis specific movements compared to higher friction conditions where no sliding was observed. Players would alter their technique on the clay court surfaces, making adjustments consistent with an attempt to improve stability through kinematic adaptation (greater initial knee flexion and reduced vertical GRF). This observation of kinematic adjustments supports suggestions made by authors interpreting pressure data (Girard et al., 2007; Damm et al., 2014), where differences in pressure distributions between tennis court surfaces were attributed to kinematic adjustments when these were not directly measured. Additionally, when friction was reduced on a synthetic clay surface, as reported in study 3, players were able to slide further compared to higher friction clay surface conditions, highlighting the importance of the level of mechanical friction on tennis players' ability to slide. Further sliding reported in on lower friction conditions (Study 3) resulted in later knee flexion and lower horizontal and vertical loading rates. Therefore findings with the current thesis suggest mechanical friction and the ability to slide influences both player movement and loading.

To better understand player responses to tennis court surfaces, the current thesis aimed to examine the relationships between perceptions and biomechanical responses (Specific aim 3, p. 56). Study 1 indicated relationships between perceptions and biomechanical response during tennis-specific movements on a clay and an acrylic court. Due to the nature of qualitative methods it was difficult to identify clear correlations between perceptions and biomechanics. Study 2 quantitatively measured perceptions and reported several relationships between these stability variables and perception variables. For instance, improved stability through greater knee flexion was observed as a surface was perceived to have lower predictability. Additionally the grip of a surface was increased through larger hallux pressures as perceived grip was reduced. These findings suggest that participant perceptions of grip and predictability are influential to tennis players' response to maintain stability during tennis-specific movements as illustrated in Figure 6.1. The development of perceptions which humans respond to is a dynamic and cyclic process (Coren et al., 1979), therefore the current thesis provides evidence of this process that tennis use to respond appropriately from their perceptions.

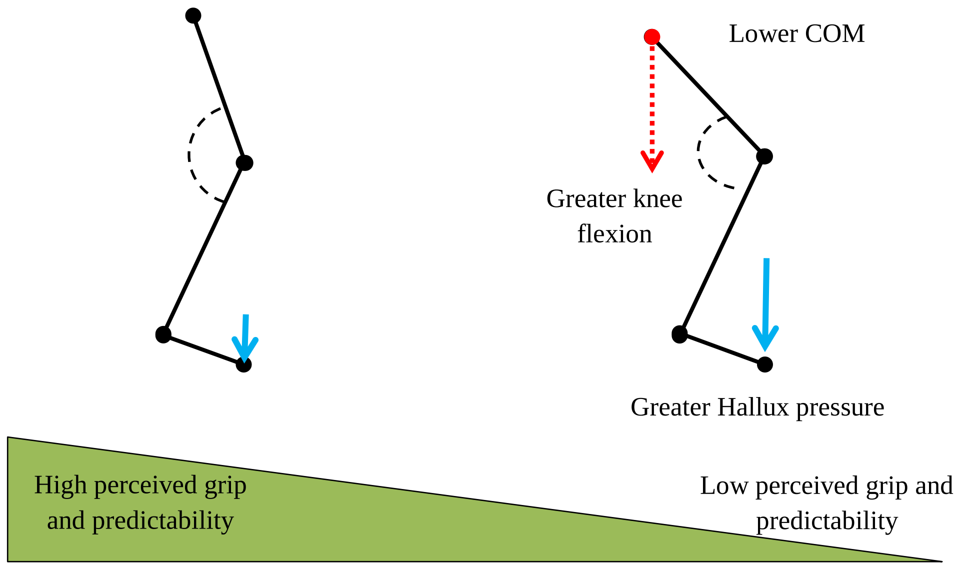

Figure 6.1: An illustration of the relationship between biomechanical response and perceptions, where biomechanical changes to lower perceived predictably suggest players are attempting to improve stability on the lower friction surface

Study 2 also aimed to examine the influence of previous clay court experience upon players' perceptions and biomechanical response and perception response relationship (Specific aim 4, p. 56). Previous experience and familiarisation are important in the development of human perceptions to enable appropriate actions from these perceptions (Coren et al., 1979; Sherwood, 1993). However, findings from the current thesis suggest that humans are able to identify differences in the study surfaces irrespective of the level of familiarisation and prior experience of the surface. Although previous clay court experience did not influence perceptions, biomechanical response was found to differ. Altered biomechanics included changes in time spent braking and position of the lower limb position and ankle joint at ground contact, therefore resulting in changes in technique and risk of injury. The perception-response relationships reported in study 2 were influenced by prior clay court experience. For example, a significant difference in the correlation between attack angle and perceived ability to slide was reported between those with high clay court experience and those with little previous clay court experience. The findings within this thesis suggest that prior clay court experience has little influence on tennis player's perceptions. However, prior clay court experience influences the relationship between perceptions and response, suggesting that those with high clay court experience choose altered response based on similar perceptions.

Study 3 provided an insight into the influence of anticipatory and reactive responses during expected and unexpected changes in friction during turning on a clay court surface (Specific aim 5, p. 56). From study 3 it was apparent that perceptions were influenced by the expected and unexpected conditions. For instance during the expected conditions perceptions were developed using both sensory information and previous experience (Coren, Porac, & Ward, 1979; Patla, 2003), whilst when unexpected changes in friction were unexpected players became more reliant on sensory information (Patla, 2003). Earlier onset of muscle activity, greater shear loading, greater eversion moments and differences in pressure distribution patterns reported during expected conditions suggests that players exert greater control during sliding. Therefore findings from the current study suggests when players expect changes in friction they are able to adjust their response appropriately from their perceptions.

6.2 Implications of the Thesis Findings

6.2.1 Implications on characterising tennis court surfaces

Perceptions are formulated in the brain from sensory information received by sensory receptors, allowing humans to interact successfully with changes in their environment (Coren et al., 1979; Sherwood, 1993). Previously quantitative measures of perceptions of surfaces have focussed on perceptions of surface cushioning (Milani et al., 1997; Stiles & Dixon, 2007) and friction (Lockhart et al., 2002). However, findings from the current thesis and Fleming et al. (2005) suggest there are other perceptions, such as perceptions of predictability and perceived ability to change direction and slide that players suggest influence their performance and injury risks. Perception data collected throughout this thesis improves understanding of tennis players’ experiences on tennis court surfaces. Based on these findings the following recommendations are made:

- The inclusion of multiple perception analysis (e.g. visual analogue scales to measure grip, hardness, predictability and ability to perform tennis specific movements) when characterising court surfaces to improve understanding of players' experience of tennis court surfaces.

- The inclusion of other characteristics such as predictability and players ability to slide or change direction should be considered when developing mechanical devices

In addition to examining player perceptions the current thesis reported differences in biomechanical response between changes in surface properties. Sliding has been suggested to be beneficial to players during match play, in particular during movements that require rapid deceleration (Miller, 2006; Girard et al., 2007; Damm et al., 2013). When comparing an acrylic court, where sliding does not typically occur, with a clay court where sliding is common, the data presented in study 1 and 2 revealed an altered technique to perform the tennis specific skills. Changes in pressure and loading were also observed with changes in technique. When developing mechanical tests biomechanical data such as loading, pressure distribution and foot position would better reflect tennis players' movements and loading, therefore improving characterisation of tennis court surfaces.

Results from the present thesis have provided evidence that differing biomechanical response to different tennis court surfaces are related to tennis players perceptions of the court surface. The relationships between perceptions and biomechanical response provide an indication of the differing injury risks previously reported on tennis surfaces with different mechanical properties (Nigg & Segesser, 1988). Therefore when developing mechanical tests and characterising tennis courts surfaces the collection of perceptions provides an indication of players' response, thus indicating the injury risks of the surface. Measuring perception provides further information regarding players experience of the surface which can supplement mechanical measures but also aid in the development of new mechanical tests. Figure 1 illustrates the relationship between perceptions and biomechanical response to tennis surfaces and how this information can inform the development of mechanical tests. The present thesis identified that player perceptions of their ability to perform tasks such as sliding and changing direction influenced their biomechanical response and were suggested to be related to their performance and injury risks. Therefore recommendations for future development of mechanical tests should attempt to replicate sliding and changing of direction type movements, with the use of biomechanical data such as loading characteristics and foot placements. Additionally these types of movements do not occur in just the vertical or horizontal direction, therefore the development of mechanical tests in two-dimensions (horizontal and vertical) may be more appropriate, as suggested by Yukawa and colleagues (Yukawa, Ueda, & Kawamura, 2014).

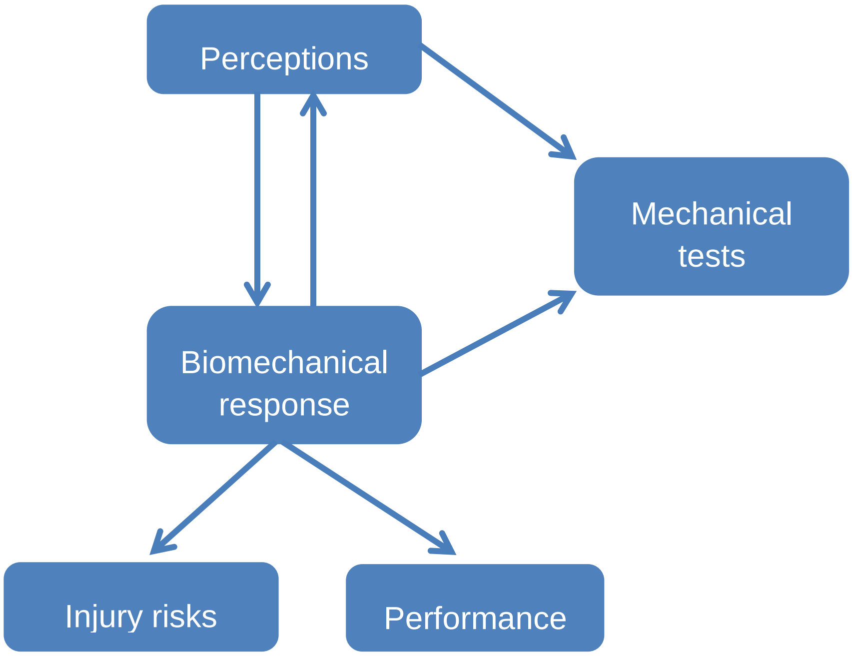

Figure 6.2: A schematic diagram illustrating the link between mechanical test development and biomechanical and perception data

6.2.2 Players' ability to adapt to tennis court surfaces: implications on technique and injury risks

Sliding has been suggested to be beneficial to players during match play, in particular during movements that require rapid deceleration (Miller, 2006; Girard et al., 2007; Damm et al., 2013). From study 1 and 2 it was evident that mechanical friction surface properties influenced players' response to the surface. Such that lower mechanical friction facilitating sliding resulting in an altered technique of the tennis specific movements compared to higher friction conditions where no sliding was observed. Players would alter their technique on the clay court surfaces, making adjustments consistent with an attempt to improve stability through kinematic adaptation (Heiden et al., 2006). On the clay court, players exhibited a more upright approach, greater initial knee flexion and reduced GRF, adjustments consistent with an attempt to gain stability. This observation of kinematic adjustments supports suggestions made by authors interpreting pressure data (Girard et al., 2007; Damm et al., 2014), where differences in pressure distributions between tennis court surfaces were attributed to kinematic adjustments when these were not directly measured.

Although previous experience did not influence perceptions, biomechanical response was found to differ. For instance, those who reported themselves to play regularly on clay and thus have high prior clay court experience had an altered biomechanical response to the clay court compared to those who had little clay court experience. Study 2 highlighted that both groups had similar biomechanical response when performing tennis-specific skills on acrylic courts, possibly as a result of their similar acrylic court experiences. Findings from study 2 suggest that players with clay court experience reduced their risk of injury on the clay court, by increasing the time they spent braking potentially reducing loading (although directly measured), through later knee flexion (Durá et al., 1999). Additionally, previous experience influences players technique on clay resulting in a lower attack angle compared to those with little clay court experience, thus suggesting a with a more aggressive approach compared to those with little experience on clay, who were more cautious in their approach. This faster and more aggressive approach and style of play is likely to be advantageous during match play.

Players with lower clay court experience may put themselves at greater risk of injury as a result of the inverted position in which their foot contacts the court. This inverted foot position focuses the loading laterally which increases the likelihood of the foot digging into the clay infill, increasing the likelihood of in fixation of the foot to the surface and inversion of the ankle (Damm et al., 2014). Those with high clay court experience contacted the ground in an everted position, thus reducing the likelihood of digging into the clay surface, and aiding control of the subtalar joint during sliding.

Lower vertical forces have previously been observed on low friction clay surfaces, in particular when compared to high friction acrylic court surfaces (Damm et al., 2013). Similar findings were reported during study 2, where lower impact and active forces were reported on the clay court compared to the acrylic court. Loading rate, previously linked to injury (Miller, 1990; Stiles & Dixon, 2007), was also reported to be lower on the clay court compared to the acrylic court. Previously during the examination of two distinct tennis surfaces (acrylic and clay), sliding has been suggested to be initiated with greater shear loading and greater horizontal loading rates on clay surfaces (Damm et al., 2013). Unlike Damm et al. (2013), study 3, which examined the synthetic clay court with different levels of friction, identified decreases in the loading rate of the horizontal and vertical forces as a result of further distances covered when sliding. These results suggest that when playing on the distinctly different tennis court surfaces (clay and acrylic) the shear forces required to overcome the mechanical friction are greater on the clay courts to facilitate sliding. However, when players perform on similar clay court surfaces, shear forces are maintained whilst the sliding distance influences the rate at which the shear force is applied. Longer sliding distances reported on the lower friction surfaces resulted in lower vertical and horizontal loading rates due to the increased the time spent applying the force, thus supporting previous suggestions of friction being an important factor in reducing injury risks on tennis court surfaces (Nigg & Segesser, 1988; Bastholt, 2000).

The longer time spent braking has been identified as contributing to lowering the high loads when turning on a high friction surface (Durá et al., 1999). In contrast, in the current thesis provided evidence to suggest extended braking phases on the lower friction surfaces compared to the higher friction surfaces resulting in lower loading reported on these lower friction surfaces. Reduced loading reported on the lower friction surface were likely to be a result of longer braking through kinematic technique changes such as later peak knee flexion and further sliding distances, suggesting reductions in friction to contribute to reduced injury risks as previously reported (Nigg & Segesser, 1988; Bastholt, 2000). Alternatively, the longer contact times during sliding on clay courts are likely to be associated with longer muscle contractions, increasing the physiological response (heart rate and blood lactic acid accumulation) reported on clay courts, resulting in fatigue (Murias et al., 2007; Martin et al., 2011; Reid et al., 2013). Not only does fatigue reduce players performance through reduced accuracy of groundstrokes (69% reductions) and serves (30% reduction; Davey, Thorpe & Williams, 2002), but also increases injury risks (Bylak & Hutchinson, 1998). Although sliding on clay is beneficial for performance and reducing injury risks through lower forces and longer time applying these forces, tennis players must be aware of the impact sliding has on fatigue. Therefore appropriate conditioning is required to minimise fatigue which could increase injury risks and reduce performance.

In addition to differences in loading between the acrylic and clay courts, study 2 also reported differences in pressure distribution, possibly as a result of altered technique. When comparing two courts with distinctly different friction properties, lower midfoot and heel pressures, previously be suggested to allow for sliding by preventing the foot from fixing to the surface (Damm et al., 2012), were observed during sliding on the lower friction clay court when compared to the high friction acrylic court. However, when examining minimal friction differences pressure distribution patterns remained similar, suggesting the altered technique employed on different surface types (acrylic v clay) to allow players to slide accounted for the different pressure distributions.

The distribution and the magnitude of force within foot regions have been suggested as a good indicator of overuse injuries compared to overall force magnitude (Damm et al., 2014; Girard, Eicher, Fourchet, Micallef, & Millet, 2007; Stiles & Dixon, 2007; Willems et al., 2005). Greater hallux pressures on the clay court compared to the acrylic court suggested that players were making adjustments in an attempt to increase grip on the lower friction surface (Fong et al., 2008). Greater hallux pressures have been associated with an increased risk of tendinopathy of the flexor halluces longus, which develops during repetitive loading in the big toe area (Trepman et al., 1995; Lynch & Renström, 2002). Thus greater hallux pressures on the clay court surfaces are likely to lead to greater risk of tendinopathy of the flexor halluces longus. Study 2 identified greater pressures in the lateral regions of the foot during tennis-specific movements on the acrylic courts compared to the clay. The higher pressures in these lateral regions may increase players' risk of injury by overloading the lateral structures, if the foot was to become fixed to the high friction surface an ankle inversion sprain could occur (Damm et al., 2014; Tung et al., 2014).

Anticipatory strategies in response to changes in surface conditions rely on prior knowledge and familiarisation (Patla, 2003), when changes in friction were unexpected players became more reliant on sensory information (Patla, 2003). Findings reported in study 3 suggest that unexpected changes in friction where players must adapt using only sensory information increases players likelihood of an ankle inversion injury. Alternatively, players increased their control of sliding during the expected conditions through greater pressures in the medial regions of the foot, earlier onset of muscle activity of the tibialis anterior, which eccentrically controls ankle inversion during ground contact. Additionally, players had greater everter moments during the expected conditions and therefore were able to control the subtalar joint during sliding. Greater control of sliding and the subtalar joint suggest reduced player risk of ankle inversion injury during the expected condition when compared to the unexpected condition. Unexpected changes in clay court friction may occur during match play as a result of players' interaction with the surface, which could have implications on biomechanical aspects related to injury. Therefore maintenance of the clay court surfaces during match play in addition to appropriate conditioning training of the lower limb musculature controlling the subtalar joint is important in preventing ankle inversion injuries on clay court surfaces.

The current thesis provides evidence of tennis players ability to adapt to different tennis court surface properties through biomechanical response, potentially influencing both injury risks and performance. Sliding is a key component on clay courts which may lower risk of injury through longer braking and lower loading. However the longer time spent braking, through sliding, may lead to the greater physiological response, such as higher heat rate and great accumulation of lactic acid, that is often observed on clay (Reid et al., 2013), which will further increase fatigue associated with longer rallies and greater time spent at the baseline (O'Donoghue & Ingram, 2001). Furthermore, prior experience and ability to anticipate changes in surface properties, reduces injury risk and allows for greater control of sliding.

Biomechanical data collected within this thesis furthers understanding of the influence of tennis court surface properties on players' response and therefore the implications on performance and injury risks. Based on these findings the following recommendations are made:

- Players must adopt appropriate conditioning training prior to clay court matches to minimise fatigue, therefore reduce risk of injury and maintaining performance.
- Findings in the present thesis indicate greater risk of injury on the greater mechanical friction surfaces (acrylic) therefore appropriate pre-habilitation may reduce players risk before the acrylic court season.
- Players must be given sufficient time to adapt to tennis court surfaces and develop appropriate responses to the court surfaces to ensure improved performance and reduced risk of injury.

6.3 Future Research

When collecting perception data of tennis court surfaces both qualitative and quantitative measurements on court allow for a more holistic approach. As identified in study 1, playing environment was a key theme that players identified. Therefore when examining tennis court characteristics the use of on court analysis are more appropriate in providing greater information regarding the playing environment and factors such heat and weather that can influence players' perceptions of the surface, thus improving ecological validity. Additionally, on court analysis that examines tennis-specific skills allows tennis players to perform tennis strokes without the restraints of laboratory situations. Therefore on court analysis of biomechanical data will lead to more ecologically valid data regarding players' performance of tennis strokes which are more appropriate in the development of mechanical tests, such as providing a biomechanical profile of tennis specific movements. To enhance the understand of on court tennis play an imbedded force plate into different tennis courts would allow understanding of horizontal loading and joint loading that has not previously been established on court.

When examining perceptions and biomechanical response future work would benefit from a combination of on court analysis and lab data. On court analysis can provide applicable data required for the development of mechanical tests. Whilst the use laboratory situations enable the manipulation of court surfaces to better understand the influence of surface properties biomechanical response during tennis specific movements. The current thesis was limited to tennis specific movements, aiming to push the boundaries of the surfaces examined.

However, future work should establish biomechanical and perceptual measures during a range of movement such as baseline to net movements to develop a greater profile for development of mechanical tests. Additionally further research is required to understand the development of perceptions and how players produce an appropriate response on different surfaces. This would enable players to develop more appropriate responses in order to reduce injury risks and improve performance.

The current thesis examined the biomechanical response to different court surfaces which were characterised by differing hardness and friction properties. The results of previous literature were used to identify the influence tennis court surface have upon injury risk and performance. Therefore future research examining the implications of surface properties on biomechanical response and injury risks directly is required. Previous epidemiological studies that have examined tennis injuries have not be able to identify specific injuries associated with different tennis courts, therefore future work should investigate specific tennis surface injuries. Along with biomechanical studies, this will provide a better understanding of injury risks on tennis courts, thus allowing for appropriate interventions to be developed.

6.4 Conclusions

This thesis identified multiple perceptions that influence players' response that have previously not been examined, impacting on performance and injury risks. Findings highlight that prior clay court experience has little influence on perceptions, whilst unexpected changes in friction resulted in altered perceptions compared when the frictional changes was expected. Differences in biomechanical response were observed between tennis court surfaces, where the clay court, providing mechanically lower friction, reduced loading through longer braking as a result of sliding. These responses were altered by player's previous clay court experiences, suggesting a reduced risk of injury through longer time braking and altered ankle kinematics. Previous clay court experience led to an altered technique that suggested a more aggressive approach on the clay court compared to those with lower clay court experience enhancing players' performance. The thesis identified relationships between perceptions and biomechanical response, where perceptions not previously examined were associated with players' response (e.g. attack angle was associated with players' perceived ability to slide). These relationships were further influenced by prior clay court experience, leading to differences in response that influence both risk of injuries and performance. For instance, players with greater clay court experience increased their attack angle as they perceived the surface to become easier to slide, whilst the low experience group reduce their attack angle. Finally tennis players' awareness of changes in friction can influence their response, where players were able to perceive differences during expected conditions, which enabled them to accommodate for changes in friction. These changes in biomechanical response in response to changes in friction were not apparent during the unexpected conditions, possibility due to players' inability to perceived differences between conditions, potentially increasing their risk of injury. Tennis players alter their technique following their perceptions of a given tennis court surface to enhance their performance which leading to altered injury risks.

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Appendix 1: Informed Consent

SPORT AND HEALTH SCIENCES

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INFORMED CONSENT

I confirm that I have read the Information Sheet concerning this project and understand what it is about. The purpose of this study has been clearly explained to me and any risks involved in my participation have been made explicitly clear. All my questions about it have been satisfactorily answered I understand that I am free to request further information at any stage.

I understand that:

- My participation in the study is entirely voluntary;
- I am free to withdraw from the project at any time without any disadvantage;
- Information I give will be used for the completion of PhD at the University of Exeter and publications resulting from the PhD. If the results of the study are published, anonymity of the participants will remain. Data will be retained until completion of the PhD, where following this it will be destroyed unless used for publication.
- My identity in this study will remain anonymous; where each trial will be coded (assigned a number to allow identification of each subject).
- The data [*questionnaires*] will be destroyed at the conclusion of the project but any raw data on which the results of the project depend on will be retained in secure storage. Only the supervisor and the researcher will have access to these raw data which is stored securely in the laboratory computer.
- There are minimal risks associated with the study protocol however these have been outlined in the information sheet.
- I agree to take part in this project.

Date:

Signed (participant):

Researcher:

Miss Chelsea Starbuck (PhD student)

cs279@ex.ac.uk,

07917845821

Supervisors:

Dr S. Dixon (s.j.dixon@exeter.ac.uk)
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Appendix 2: Participant Information Sheets

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INFORMATION SHEET

Study 1: Identifying Tennis Players Perceptions

Thank you for showing an interest in this study. Please read this information sheet carefully before deciding whether or not to participate. If you decide to participate, we thank you. If you decide not to participate thank you for your time in considering our request and there will be no disadvantage to you in any kind.

Aims of the study

The purpose of the study is to gain a greater understanding of player perceptions of different tennis courts and to consider how perception relates to player movement on the court. It aims to provide a holistic understanding of player perception and to inform the development of questionnaires to assess player perception of surfaces.

What types of participants are needed?

We are looking for 10 university tennis players (both males and females) who are unfamiliar with the courts played at Torquay Tennis Club. We are interested in those who have not played on clay or indoor court at this particular tennis club, if you have played on these type of courts but at different clubs then you are eligible to participate. The focus will be on players with a LTA rating of 5.2 or better. Participants must be free from injury (including any continuous or recurring bouts of hip, knee or ankle pain), or disease that would restrict their ability to perform tennis specific movements and complete a short game. Participants are required to fill out a physical activity readiness questionnaire and CVD risk factor assessment form before participating in the study.

What is required from the participants?

Should you agree to participate in the study, you will be asked to visit Torquay Tennis Club, in Torquay on one day. A minibus will be provided for transport from both Streatham and St Luke's campus to the venue. You will gain experience of playing on two courts (artificial clay and hard court) at the Torquay Tennis Club, where you will be asked to warm up and then perform several drills that will include tennis specific movements. Movement data will be collected with use of video cameras. Markers will be placed on the participants lower limbs to allow for ease of analysis. Following data collection you will then be asked to play a short match to allow you to get a feel for the court. Following this a short interview will be conducted where you will be asked to relate what you observed and perceived about the court. Following all court assessments one final interview will be conducted to gain any further information, preferences and differences identified for the courts played on.

What is being tested?

Participant's height (m) and weight (kg) will be measured prior to testing. During the tennis drills movement data of the lower extremities will be collected using three 50Hz cameras. Audio recordings of the interviews will be collected to allow for transcription and analysis.

What will participants need to bring?

Participants are required to wear appropriate clothing for tennis play. You will be required to bring your own racquets and wear well-fitting trainers during data collection. You will need to bring enough refreshments for the whole day of travel and testing.

What will happen with the data?

The data collected will be retained and stored securely in a locked cabinet by the researcher. The raw data will only be accessed by the researcher and their supervisor. Data will be retained until completion of the PhD, where following this it will be destroy unless used for publication. All data will be coded (assigned a number to allow the identification of each subject) and stored securely on the laboratory computer. The data collected in the study will be used for the base of further research.

Can participants change their mind and withdraw from the project?

You may withdraw from participating in the study at any time and without any disadvantage to yourself of any kind. You may also request that any information collected about you be destroyed or deleted and not used either now or in the future.

Any questions?

If you have any questions about this project, either now or in the future, please feel free to contact.

Thank you for your time and consideration.

Miss Chelsea Starbuck (PhD student)

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INFORMATION SHEET

Study 2: The Influence of Prior Clay Court Experience Upon Tennis Players Perceptions and Biomechanical Responses

Thank you for showing an interest in this study. Please read this information sheet carefully before deciding whether or not to participate. If you decide to participate, we thank you. If you decide not to participate thank you for your time in considering our request and there will be no disadvantage to you in any kind.

Aims of the study

The purpose of the study is to gain a greater understanding of player perceptions of different tennis courts and to consider how perception relates to tennis player's movement on the court. The study aims to examine the influence of previous experiences of tennis courts on perceptions.

What types of participants are needed?

We are looking for 15-20 tennis players (both males and females) to volunteer for this study. The focus will be on players with a LTA rating of 5.2 or better. Participants must be free from injury (including any continuous or recurring bouts of hip, knee or ankle pain), or disease that would restrict their ability to perform tennis specific movements and complete several short tennis drills. Participants are required to fill out a physical activity readiness questionnaire and CVD risk factor assessment form before participating in the study.

What is required from the participants?

Should you agree to participate in the study, you will be asked to visit the National Tennis Centre (NTC), in London on one occasion. You be given the opportunity to gain experience of playing on three tennis courts (synthetic clay, outdoor clay and outdoor hard court). You will be asked to warm up and then perform several drills that will include tennis specific movements. Movement data will be collected with use of video cameras. Markers will be placed on your lower limbs to allow for ease of analysis. Pressure data will also be collected using pressure insoles. During the data collection you will be asked to complete a short questionnaire which will relate to your observations and perceptions of the tennis court.

What is being tested?

Your height (m) and weight (kg) will be taken prior to testing. During the tennis drills movement data of both legs will be collected using three 50Hz cameras. Pressure data will be collected during the drills using pressure insoles (100Hz) inserted into your shoes and perception data will be collected through a short questionnaire. Purpose of data

What will participants need to bring?

Should you volunteer you will be required to wear appropriate clothing for tennis play as well as warm clothing for the outdoor testing. You will be required to bring your own racquets, however tennis shoes will be provided for you to wear. You will need to bring enough refreshments for the completion of testing.

What will happen with the data?

The data collected will be retained and stored securely in a locked cabinet by the researcher. The raw data will only be accessed by the researcher and their supervisor. Data will be retained until completion of the PhD, where following this it will be destroy unless used for publication. All data will be coded (assigned a number to allow the identification of each subject) and stored securely on the laboratory computer. Therefore if results of this project are published any data included will in no way be linked to any specific participant. You are welcome to request a copy of the results of the project should you wish. The purpose of the data collected will allow the researcher to investigate the relationship between tennis player's movements and their perceptions of tennis courts.

Can participants change their mind and withdraw from the project?

You may withdraw from participating in the study at any time and without any disadvantage to yourself of any kind. You may also request that any information collected about you be destroyed or deleted and not used either now or in the future.

Any questions?

If you have any questions about this project, either now or in the future, please feel free to contact.
Thank you for your time and consideration.

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UNIVERSITY OF EXETER

INFORMATION SHEET

Study 3: The Influence of Expected and Unexpected Changes in Friction on Player Perceptions and Responses

Thank you for showing an interest in this study. Please read this information sheet carefully before deciding whether or not to participate. If you decide to participate, we thank you. If you decide not to participate thank you for your time in considering our request and there will be no disadvantage to you in any kind.

Aims of the study

This study aims to examine player perceptions and response to expected and unexpected changes to friction and to investigate the influence of previous experience upon player perceptions and response to friction changes.

What types of participants are needed?

We are looking for 20 tennis players (both males and females) to volunteer for this study. Participants must be free from injury (including any continuous or recurring bouts of hip, knee or ankle pain), or disease that would restrict their ability to perform tennis specific movements and complete dynamic turning movements. Participants are required to fill out a physical activity readiness questionnaire and CVD risk factor assessment form before participating in the study.

What is required from the participants?

Should you agree to participate in the study, you will be asked to visit the Biomechanics Research Laboratory, St Luke's on one occasion for a maximum of 3 hours. You be asked to perform a turning movement on a synthetic clay surface with three different levels of friction, where expected and unexpected reductions in friction will randomly occur.

Movement data will be collected with use a 3-dimensional passive marker system. Markers will be placed on your lower limbs to allow for ease of analysis. Pressure data will also be collected using pressure insoles. Force plate will collected force data and an electromyography (EMG) system will collect data on muscle activity. During the data collection you will be asked to complete a short questionnaire which will relate to your observations and perceptions of the synthetic clay surface.

What is being tested?

Your height (m) and weight (kg) will be taken prior to testing. During the turning movement movement, loading and muscle activity will be measured on your dominant leg. Perception data will be collected through a short questionnaire.

What will participants need to bring?

Should you volunteer you will be required to wear appropriate clothing for tennis play. Tennis shoes will be provided for you to wear. You will need to bring enough refreshments for the completion of testing.

What will happen with the data?

The data collected will be retained and stored securely in a locked cabinet by the researcher. The raw data will only be accessed by the researcher and their supervisor. Data will be retained until completion of the PhD, where following this it will be destroy unless used for publication. All data will be coded (assigned a number to allow the identification of each subject) and stored securely on the laboratory computer. Therefore if results of this project are published any data included will in no way be linked to any specific participant. You are welcome to request a copy of the results of the project should you wish. The purpose of the data collected will allow the researcher to investigate player perceptions and response to changes in friction.

Can participants change their mind and withdraw from the project?

You may withdraw from participating in the study at any time and without any disadvantage to yourself of any kind. You may also request that any information collected about you be destroyed or deleted and not used either now or in the future.

Any questions?

If you have any questions about this project, either now or in the future, please feel free to contact.

Thank you for your time and consideration.

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Appendix 3: Tennis Court Surface Information

Brand	Name	Type	Where	Website	Description	ITF Classification
Rebound Ace	Rebound Ace	Cushioned acrylic	Exeter University Biomechanics research laboratory	http://www.reboundace.com.au/#home	Composition of recycled SBR rubber, urethane and acrylic with a textured acrylic finish	5 fast
Pavitex	Top Clay	Clay	Exeter University Biomechanics research laboratory	http://www.pavitex.com/	Synthetic fibre bonded membrane in 100% UV stabilised PP fibre, with clay dressing to cover membrane	1 slow
TigerTurf	Rally	Artificial clay	Exeter University Biomechanics research laboratory	http://www.tigerturfworld.com/eu/home/	A dense, red, polypropylene fibrillated surface, designed to be over filled with red granulate, replicating a clay court	5 fast
DOE Sports	n/a	Cushioned acrylic	Torquay Tennis Club	http://www.doesport.co.uk/downloads/74-tennis-club.html	n/a	3 medium
AMB pro limit	Clay Pro	Artificial clay	Torquay Tennis Club	http://www.ambsports.com/index.html	Short-pile, densely tufted carpeted with specially selected silica sand	3 medium
DOE Sports	GreenSet Grand Prix acrylic	Cushioned acrylic	National tennis centre	http://www.doesport.co.uk/downloads/74-tennis-club.html	Sprung timber base overlaid with resin offering 58% shock absorbency	3 medium
n/a	Northern European Clay	Clay	National Tennis Centre	n/a	n/a	n/a
DOE Sports	FRENCH COURT	Artificial clay	National Tennis Centre	http://www.doesport.co.uk/downloads/74-tennis-club.html	Sand and clay over filled textile carpet on pervious asphalt and stone foundation	Slow

Appendix 4: Study 1 Interview Guide

Interview Guide

Aims

- The purpose of the study is to gain a greater understanding and identify player perceptions of different tennis courts.
    - Gain a holistic understanding of player perception, in order to generate suitable questionnaires to gain greater understanding of player perceptions on a larger scale.

Questions

After play on each court

- Considering your movement, what do you think about the court you just played on?
    - How did it feel? (Hard/ soft? Sliding/ did it grip?)
    - How did you move around it? (Was it slippery? Hard/ easy?)
    - Did you feel that you did anything differently?
    - How well do you feel you adapted to the court?
- How did the court affect the way you played?
    - Tactics? Positioning around the court?
    - Technically? In terms of the skills you used? How they were executed?
    - Did the ball change? How? How does this affect your game?
- What is your favour type of surface?
- Was there anything you liked/ disliked about the court you just played on?
    - What? Why? How would you prefer it to be?

After the participant has played on all the courts

- What differences did you find between the courts you have played on today?
    - How did feel/ you perceive it different? (Changes in hardness? Grip?)
    - How did the way you play change? (Technical? Mobility? Tactically?)
    - Were changes with the ball? (How did it differ? What affect did this have?)
- Which court would prefer to play on again?
    - Why? Was it the way it felt? Was it the grip?
    - Past experiences? Successes?
    - Easy to adapt to?

Appendix 5: Study 1: Transcriptions

Participant 1[1]

Court 1 = Artificial Clay

Q: Considering your movements, what do you think about the court you have just played on? How did it feel?

P:, I guess the movement there is quite a lot of slide on the courts. At high pass. It was quite uneven sometimes on the courts.

Q: So, you couldn't tell what was going on, it was unpredictable?

P: Yeah I couldn't really tell what was going on. Slide loads or kind of stop, hence why I thought.

Q: So did feel that your movements were slightly different at all considering to your normal court?

P: Yeah, I think normally I'd be, I think I would probably take a few extra steps on a normal court, I guess.

Q: Do you think it would affect the way you played tactics or positioning or anything technically?

P: Um the court was quite a lot, seems slower, the held up quite a bit. So I guess tactics whys I probably um… as the ball gripped a lot more I would use a lot more spin, try and get variation probably. On a hard court I wouldn't, I could a bit but not to the extent you could on this kind of court, the amount that it grips it quite big to an extent.

Q: So, what sort of court would you prefer? What's your favourite sort of surfaces?

P: I'd say probably normal hard acrylic court.

Q: Is that because play on it more?

P: Yeah mostly because I play on it more. I play on it. I think tactically the way I play, I guess I'm more baseliner kind of consistent I'd say. If I played a lot on this surface it could become the surface that I prefer more then the hard court. Because its properties, so it's slow, it gives me a lot more time to get to the ball but I guess at the moment as I play on hard court most that it was I prefer.

---

[1] Due to time constrictions the participants could did not play a match.

Q: Is there any anything you liked or disliked about the court?

P: I can't say there is anything I really didn't like. I don't think I disliked anything. I did like the fact that the ball kind of, the grip that you got or the extra time that you got on the ball because of the bounce. As in they gripped so much more is the main thing I liked about the court.

Q: In terms of the feel of the court was it any different to what you are used to how did feel, like under your feet?

P: Under my feet yeah I was obviously more stable a bit more kind of padded then a normal hard court. Under your feet you can kind of tell that your running around more kind of yeah padded.

Court 2 = Artificial Indoor

Q: When you are moving on this court what do you think about?

P: Comparison or on its own?

Q: Which ever you easiest to describe

P: Comparison whys I think that it's a lot easier to move around the court because of the surface, especially on the second drill that its a lot easier to get around.

Q: Why do you think the surface different so it makes it easier?

P: It's not loose; I don't know with the loose stuff it was quite good to be able to get that extra slide. So if you got the slide you got the forehand in without taking those extra steps, as long as you judge the slide well its actually probably easier in that respect. Pushing off side to side is a lot easier here.

Q: Which court did you prefer?

P: I'd say, I think probably this hard court, just because you can move around easier. If you get slide right on the clay its good it kind of aids, extra steps. It takes extra steps to get in place obviously if your not clay you take those extra steps. So if you get your slide right beneficial but it's really hard to get it right so if I had more practice maybe on the clay then I would prefer that probably.

Participant 2[2]

Court 1 = Artificial Clay

Q: Considering your movement that you have done on the court what do you think about the court you have just played on?

P: I quite liked it; I haven't played on clay for a little while. Yeah it was good

Q: Do you think it made you move differently, how did you move around it?

P: The clay itself, it did a little bit. I never slide but I was sliding a little bit. It's quite soft under the ground so I know I can jump and it not to hurt.

Q: Do you think in terms of your movement again you would do anything differently to what you are use to? How well you adapted to the court? The skills?

P: I don't know, sorry.

Q: So, during a match what tactics would you employ?

P: Tactics would change because of the higher bounce and the way it plays so I would probably stand further back on the court. I would take more topspin and I know I would have to attack differently. So I would get up more on the court. Probably more angles as well.

Q: What is your favourite type of surface?

P: I really like grass just because you hardly get to play on it, but my favourite is probably acrylic. I'm not fit enough really to be on clay.

Q: Was there anything you liked or didn't like about the court?

P: No I thought it was quite a good clay court. Quite a lot of clay courts don't have the right amount of clay. The ones is Spain are always really thin on the ground but some of them are too packed with clay as well.

Court 2 = Artificial Indoor

Q: On this court considering your movement, what do you think about the way you played?

[2] Due to time constrictions the participants could did not play a match.

P: I was more happy when I played on this one, just because it my surface I always play on and everything feels a bit more like I know what I am doing. Like you put your foot down and you know it's still going to be there rather then clay like.

Q: How do you think it felt differently?

P: Just I don't know you put your foot down you feel secure and on clay it almost feels a bit messy.

Q: Ok, so thinking tactic whys on here how do you think you would play on this court?

P: I would be more up on the court so close to the baseline, I'd hit the ball harder, maybe flatter so it keeps low. I'd probably serve quite big and quite a lot of body shots on the serve.

Q: If we look at the difference of the courts you've played on, is there any differences you noticed?

P: Ball kept a lot lower, it felt a bit like I was hitting the ball harder (indoor).

Q: What about difference in feel between the courts?

P: Just felt more grippy more secure.

Q: Why do you think this was your favourite court?

P: I suppose most of my success has been on this surface, I will always just prefer it. I always play better.

Participant 3

Court 1 = Artificial Clay

Q: So considering your movements of the court you just played on what do you think about it?

P: I like it. Because you can kind of slide, so it's not to hard to stop and change direction.

Q: How do you think you moved around on the court?

P: No, I think I was a bit too cautious, because I was afraid of falling over.

Q: Why do you think you were afraid of falling over?

P: Because I've injured myself on so many times on clay and also because the shoes are quite new. So usually when I've got new shoe I don't move as quick as I possibly could.

Q: So if you had your normal shoes how do you think you would move on this court?

P: Better, faster and like I would be feeling more secure.

Q: Do you tactics wise clay made you do anything different to normal?

P: Yeah because the rallies are longer usually on clay, so I know I can't a winner as easy as I could on hard court for example.

Q: Ok so how would play?

P: Like playing loads of topspin because on clay they bounce higher, so that's what I usually try to do. Then just move better.

Q: What is your favourite surface?

P: I quite like hard court.

Q: Was there anything you liked or disliked about this court?

P: I don't like it personally because, as I said, the rallies are longer, which means my fitness level has to be better. I have to run more I have to be more consistent I think. Even if I hit the same shot on hard court it wouldn't be as effective.

Q: Ok, anything you liked about the court?

P: Like for the movement it's easier because it doesn't hurt as much.

Q: Why doesn't it hurt as much?

P: Well because I can slide.

Court 2 = Artificial Indoor

Q: So considering your movement, what did you think about this court?

P: Good. I like it. I don't know why but the ball is usually not as high as it is on clay so it's all a bit faster the movements.

Q: So how did the court feel to play on?

P: I like it, probably because I train on hard court. The movement was good. It's sometimes a bit hard to stop because I feel like when I move I have to do more little steps when I approach the ball. Just so I can get into the right position, because I can't slide. Otherwise I think it would be too much hard too much energy to my legs so in order to avoid any injuries I try to do little steps.

Q: Tactics wise in the game did you do anything differently?

P: Yeah, I think I am attacking more then clay. I'm just trying from the first ball just attacking, trying to keep it flat.

Q: Any likes or dislikes about the court?

P: I like because its really fast. But it can get too fast that's like the only thing I might have trouble with.

Q: any differences between the two courts?

P: the speed, like the ball. The length of the rallies and just how it bounces like the ball. It's flat. I know if I stand on the baseline and she hits a ball I don't have to move as much as on the clay because of the topspin on the clay.

Participant 4

Court 1 = Artificial Clay

Q: Considering your movements, what did you think about the court you have just played on?

P: I like it. They were good courts, you can move pretty well on them, slide on them without thinking you're going to fall over. It didn't grip too much so you didn't fall over.

Q: How did it feel?

P: It was quite slippy

Q: What type of court do you normally play on?

P: Acrylic hard court.

Q: How do you think it differed from what you are used to?

P: Pretty different. Obviously you can't slide on a hard court really, unless your shoes are pretty worn. That's the main difference.

Q: What about tactics wise, do you think you would do anything different to normal?

P: Yeah, I play um. It lasts a lot longer because it's a lot slower. When I play on clay I generally use more drop shots maybe, moving people about and a bit more topspin.

Q: I'm guessing acrylic is your favourite court, or is therea nother you prefer?

P: Yeah I do like playing on acrylic. I like playing on clay, because I like moving on it.

Q: Why do you like moving on it?

P: I like sliding.

Q: Anything you disliked or liked about the court?

P: It was lot faster than normal clay court, which was a bit different. It was quite hard to move forward, like pushing off it was practically no grip.

Q: Anything you liked?

P: You could slide well on it. Some clay courts are really hard to slide on. It was quite good.

Court 2 = Artificial Indoor

Q: Just thinking about your movements, what did you think about the court?

P: It was probably the best surface to move on because you get the most grip, so you can sort of run more efficiently.

Q: So how do you think it felt?

P: It's better in term like grip and stuff. But it's quite like, it's a hard surface that impacts quite badly sometimes. I've had quite bad knee from, pretty certain, from playing on tennis courts like this.

Q: How do you think you differed between the two games?

P: One the hard court a lot sort of flatter shots but harder, definitely shorter points, less sort of, when a player came into the net was really happening.

Q: Why do you think it was different?

P: On clay you just got a lot more time and because it's longer points, so you need to set up the point a bit more. Because its n clay its slow, its easier for the person to get a shot back, so like a volley one of the easiest ways to hit a shot. You got more opportunity of winners on hard.

Q: Any likes or dislikes for this court?

P: I quite like hard courts, you don't have to hit as hard because you can use your opponents pace a lot more.

Q: Any dislikes?

P: Yeah I don't like because of the speed.

Q: Any differences you noticed about the courts?

P: The main difference is the speed of the courts. It's a lot faster on hard court and it's a lot short points.

Q: Does it feel any different at all?

P: It's a bit softer on clay because you can slide on the clay.

Q: Which one would you prefer to play on again?

P: Probably clay

Q: Why?

P: I don't know I just enjoy playing on it more. I like sliding and I quite like having longer points. It's more tactical on clay, which I enjoy quite a lot. Where as you can just smack it on a hard court.

Participant 5

Court 1 = Indoor Acrylic

Q: Considering your movement on the court, what do you think about the surface you just played on?

P: Yeah, well I'm used to playing on it so.

Q: So how did it feel?

P: Yeah no it’s fine, standard hard court really.

Q: Why do you think that then?

P: Well, I wasn’t slipping and you can’t, it’s not surface you slide on too easily. So once you set off you, you sort of plant you’re not having to worry about skidding or injuring yourself.

Q: What would you do on this court in terms of tactics?

P: Um, more aggressive, maybe hit flatter shots.

Q: why do you think you would so that?

P: Cause it’s quite fast, so I want the ball to come through as quick as possible.

Q: So what’s your favourite type of surface?

P: Yeah, I quite like this surface. I like grass as well.

Q: Why do you like this surface?

P: Well it lets me get into the net and not get picked off too easily, so whereas like on the clay the fact that coming into the net, pretty much whenever I play outdoors, it’s trying to get into the net. On a slow court he [opponent in game] can pick me off really easily, whereas on this I’ve got more of a chance.

Q: Was there anything you liked or disliked about this court?

P: Well, I mean it’s nice and flat, it’s not like grass where you got to worry about uneven bounces or anything like that. Ball comes through quite quickly. It gets quite hot in here [indoor acrylic], so that often will come through quicker as well.

Q: Any dislikes?

P: It’s good to not to have any weather to worry about, like the sun or wind or anything but I slightly prefer, it depends really being outside has its advantages over being inside. It gets quite humid in here especially in the summer. I don’t know if that’s a disadvantage, but in terms of the playing surface it’s, you can’t really complain about anything.

Court 2 = Clay

Q: so considering your movement on this court, what did you think about it?

P: well, er… you've got to think about your movement a lot differently to the hard court?

Q: Why?

P: because you know er, your sliding a lot more there's a few more uneven bounces. So there's less room for error wuith your shots, so you've gotta allow for maybe a slightly uneven bounce and for it to come through a bit slower and yeah obviously you got to, you can slide, it does sort of help you gain a bit more on your footwork.

Q: Did it feel any different?

P: yeah.

Q: How did it feel different?

P: it's slower and I would really want to be sliding on that, the acrylic, but um. Yeah that's pretty much it, slower and less slidy on the acrylic.

Q: Tactics, what would you do on this court?

P: I mean, I probably would stay back a bit more, be a bit more cautious. Um, maybe try and hit with a bit more topspin. But I still would go into the net but you would have to pick your shots a lot more carefully in what you came in on. Because it doesn't come through as fast and if your hit with more topspin then it's going to sit up more.

Q: Anything you liked about the court?

P: well, I like sliding that's good fun. I probably prefer the faster conditions but I think I actually play better on this. I liked, yeah I liked playing on any court really, um, I guess I liked the fact that maybe you get longer rallies that can be quite a good thing.

Q: Any dislikes?

P: uneven bounces.

Q: so you've played on two courts today, any major differences?

P: um, well pretty much said that I think. This is [clay] more uneven bounces, slow um, lets itself to a bit of a cautious game less aggressive, less sort of net play. I think maybe the drop shot would be quite affective on this court, whilst not so affective on that court [indoor acrylic].

Q: Why?

P: because, It's kind of, cause it slices, especially if you have an uneven bounce for a start you stop dead a bit more on the, this surface, I think. But I've not really tried it out, I'd assume that.

Q: Which court would you prefer to play on again?

P: it depends on who I was playing, if I was playing a serve vollyer, I'd probably play them on the clay because it wouldn't suit them. But if I was playing like a baseliner I would probably prefer to play them on that [indoor acrylic] and mix it up a bit more and go into the net try and get them off rhythm a bit more.

Participant 6

Court 1 = Indoor Acrylic

Q: Considering your movement on the court what did you think about this surface?

P: I thought the movement was very easy. It was easy to move around the court, like forehand, backhand it was fine. The shoes kind of helped that as well compared to my normal shoes. With the indoor court as well the movement is pretty good compared to like outdoor courts and stuff.

Q: why do you think that?

P: it's because you grip better, your shoes grip better to the surface.

Q: what about tactics then?

P: well the ball skids through quite fast, I probably get a good approach, come to the net try and put the point away. Get in a good serve as well, I think that's key. Um, and yeah probably just serve and volley I say.

Q: any reason why?

P: because the courts quicker it gives them less time to prepare for the passing shot and to return the serve.

Q: what's your favourite court you normally play on?

P: I normally play on hard court. Which is nice and slow, so I'm use to that. I also like the fast courts as well, because if you get in those good shots then you can finish it off quickly.

Q: so any differences between this court and other courts you have played on?

P: this is just a lot faster. Much faster then the one I play on at home. So yeah it does encourage me to come to the net more. Whereas I tend to play at the back of the court the whole time, you have ages to play your shots.

Q: Is there anything you liked about this court?

P: I like the fact that you haven't got the wind or sun and the rain and all that kind of stuff. Like the conditions were pretty much perfect really. It gripped really well.

Q: Any dislikes?

P: um. I didn't dislike, I liked it.

Court 2 = Clay

Q: Considering your movement on this court what did you think of the surface?

P: I like the court, but the movement was a lot worst then on the inside court, there were quite few dodgy bounces as well compared the inside court.

Q: Why do you think your movement was a lot worst?

P: the shoes were the same but the grip wasn't as good, just because the sand on the surface, the grips not as good. But it's still nice to play on.

Q: How did it feel?

P: I'd say the bounces weren't as good, they are not as consistent. You've got the outside kind of … temperature and stuff, sun, wind. Um, apart from that it was reasonable, it's just not as easy as the inside court.

Q; what about your tactics?

P: um, probably stay back, I would on this one anyway, that's what I was doing in the little tie break game. Just because you got longer on the ball and stuff, you can do something that they've gone longer to pass you. Um, so yeah generally stay back and play ground strokes.

P: what did you like about the court?

Q: I haven't really play on clay properly before, so I quite liked that. The fact that it's a new surface. Generally I do prefer when you can kind of judge and time every ball; every ball is exactly the same. So I liked it but not as much as inside court.

Q: What about dislikes?

P: the bounces. That's my general dislike.

Q: Any major differences between the two courts you played on today?

P: that's slow [clay]; the clays slow, the bounces aren't as good. Inside as well everything is kind of perfect really. But I like the fact that that's [clay] slow and you've got longer to time your shots and judge your shots.

Participant 7

Court 1 = Artificial Clay

Q: Considering your movement on the court, what did you think of the surface?

P: well, it's obviously a clay court, so there's a lot more … there's less coefficient of friction between you and the court so you slide around a lot. Obviously the ball moves a lot slower on clay holds up and slows down but can slide through with a slice but can check up. Um it depends if the court hasn't been particularly well swept so there were lots of old ball marks, slide marks which sometimes when the ball had a irregular bounce.

Q: what tactics would you use on this court?

P: on a clay court, um really what I would be trying to do is stay in the point, try and keep the ball deep and maneuver my player from side to side until an opening to make a winning shot.

Q: Any reasons why?

P: any reasons why, because it's a little bit harder to hit winners because the ball moves a bit slower, it's a little bit harder to generate pace. The surface is a lot easier for the opponent to hit the ball back so rather then hit clean winners, I say it's better to move the player around until you can get a good position on the court to open it up.

Q: Anything you liked about the court?

P: anything I liked about it? Um … well if you're use to playing on clay then it, you can have a good game, the rallies last a long time, it can be quite satisfying to get to a ball which might be quite difficult to get to on another court.

Q: Anything you didn't like?

P: I don't know, I think, it's a bit more difficult to play on clay if you don't regularly play on clay which I don't regularly play on clay. Although I have played on clay. It's a different technique to the way you move, you balance yourself to get to the ball, which takes some skill to get use to. So I guess that's what I didn't like, that I'm not used to playing on clay.

Court 2 = Indoor Acrylic

Q: considering your movement on this court, what did you think about the surface?

P: um, nice crisp movements, quick change of direction, a lot easier to move around I think then the clay.

Q: why is it easier to move around?

P: um, well because you've got better grip on the court. On clay its, a balls hit behind you um, and you've been running one direction, it's a lot more difficult to turn around. Whereas on the hard court you can turn a lot more quicker and get round to the ball.

Q: any other thing? Did it feel any different?

P: well obviously the ball is a lot quicker, it bounces through quicker on the acrylic courts.

Q: what would you do on this court in terms of tactics?

P: tactic, well again trying to keep the ball deep, but I suppose differently on this court is the ball does bounce a bit higher so hitting with a lot of topspin does um, deepen the court a lot that much, so it's a little bit more difficult for your opponent, with ball bouncing up at their shoulder level and it is a lot easier to hit a winner you can hit winners a lot easier from the back of the court. If I was any good at volleys I probably come into the net, but I'm not so I tend to stay at the baseline.

Q: Any likes of this court?

P: I like the way the ball moves quickly, it suits my type of game, I like the bounce the high bounce of the ball and I like to be able to move quickly on the court to get to the ball.

Q: Any dislikes?

P: no, I don't think so.

Q: Any major differences between the courts?

P: well obviously the major difference is the slide, you can't slide on the acrylic court and it's almost impossible to slide on the acrylic court whereas it's very easy to slide on the clay court, depending on what type of shoes you're wearing. Yeah I mean the ball comes a lot quicker on the acrylic, slower on the clay. A ball holds up on the clay, whereas it tends to come through on the acrylic.

Q: which court would you prefer to play on again and why?

P: I prefer the acrylic court because that's what I am use to playing on. I like the faster ball, compared to clay, that's what I'm use to I suppose.

Appendix 6: Reliability and Validity of the Perception Questionnaire

Introduction

Sensory information is processed in the brain to formulate perceptions, allowing humans to interact successfully within their environment (Coren et al., 1979; Sherwood, 1993). To better understand human responses and perceptions, perceptions must be measured, either quantitatively or qualitatively. Qualitative research has provided an in-depth exploration of perceptions (Patton, 1990; Fleming et al., 2005), whilst quantitative methods, through the use of scales, allow perceptions to be quantified.

Mills et al. (2010) examined the reliability of perceptions of cushioning for three scales (ordinal, Likert, VAS) using a mixed linear model analysis of five repeated sessions. The ordinal scale was reported to be the most reliable of the three scales measured. However, ordinal scales are unable to provide magnitude differences and can only rank data (Stevens, 1951). Both VAS and Likert scales are able to provide magnitudes of perceptions, the VAS was revealed to be more reliable than the Likert scale (Mills et al., 2010). Mündermann et al. examined reliability of a VAS of perceived comfort over 10 consecutive sessions reporting an ICC of 0.799.

VAS are normally a 100 to 150 mm horizontal line with extreme words anchoring each end (Aitken, 1969). Line length and anchoring words are important in the reliability and construction of VAS, as a different anchor word may mean different things to different people, therefore when developing scales prior investigation is required to ensure minimal ambiguity within the questions (Aitken, 1969; McCormack et al., 1988).

This study allowed the examination of a series of VAS which measure participant perceptions upon different tennis surfaces. The VAS scales were developed following the completion of Study 1 to enable further insight into tennis players' perceptions during future studies. Reliability of the questionnaire was investigated in order to identify whether the scales were consistent between and within subjects. Face validity of the questionnaire was examined to ensure tennis players understood each variable within the questionnaire. The current study has scope to provide some initial results to compare perceptions of different tennis surfaces.

Methods

Participants

The study was conducted as part of another research project where twelve university tennis and squash players consented and provided their perceptions of the tennis surfaces measured. Anthropometric data for males (age 19.60 ± 1.95 years, height 1.79 ± 0.05 m and weight 71.65 ± 5.66 kg) and females (age 19.6 ± 1.95 years, height 1.70 ± 0.04 m and weight 59.38 ± 3.04 kg) were taken. The study was approved by the Institutional Ethics Committee and informed consents were obtained before testing.

Mechanical data

Mechanical data were collected to provide dynamic and static friction and rotational traction for all surfaces (data collected by colleagues from the University of Sheffield, Sports Engineering Research Group). Mechanical tests included the Pendulum test (British Standards, 2002), the Crab III test and the Rotational Traction test (using a smooth foot) further described in Section 3.2.3.

Protocol

All procedures were completed on three tennis surfaces (synthetic clay, outdoor clay and acrylic, Appendix 3) in the Biomechanics Research Laboratory at the University of Exeter. Figure A1 provides a schematic diagram of the data collection set up. Participants performed three movements which included a running forehand, turning and stopping movement, where order was randomly assigned. The running forehand involved participants running down the run way placing their dominant foot on the force plate whilst performing an imitated forehand stroke before running back to their starting position. For the turning movement, the participants were asked to place the foot perpendicular to their running direction before returning to their starting position. The final movement was a stop, the participants were required to stop with their dominant leg on the force plate and were discouraged from performing a second step. For each movement the participants were required to run at a speed of 4.00 ± 0.20 m.s^{-1}, which was checked using timing gates placed 2.3 m apart and performed the movement on the force plate.

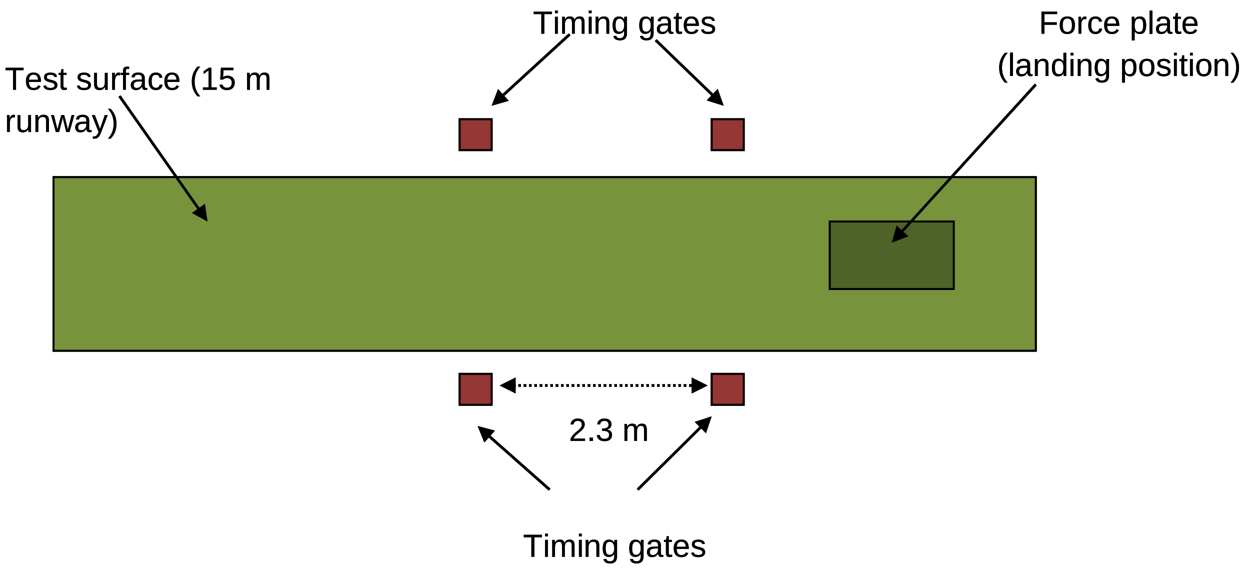

Figure A1: A schematic diagram of the set-up of testing procedures

Visual Analogue Scale (VAS)

Following completion of the three movements on each surface the participants were required to complete a series of VAS (Appendix 7) to assess their perceptions of the surfaces. The VAS consisted of a 100 mm line with two descriptive end-phrases for each perception variable. Questions were based on the themes and sub-themes reported from the interview data. The participants were asked to put a cross on the line to indicate their answer to the question.

Reliability and validity

Inter-rater reliability, through Cronbach's alpha, was conducted to examine the reliability between participants' perception ratings for the three surfaces. Test-retest reliability was conducted for one participant who was asked to complete the protocol on five consecutive sessions. Intra-class correlation coefficient (ICC) analysis was used to compute the consistency of the VAS scores over the five sessions. Participants were verbally asked about each component of the VAS to ensure that face validity was achieved, such that the variables appeared to measure the target variables.

Surface differences

A one-way ANOVA with repeated measures was conducted for each perception variable to examine differences between the three surfaces. An alpha level of 0.05 was used to determine significance.

Results and Discussion

Mechanical data

Table A1 provides the mechanical data collected on each tennis surface, from the data it can be concluded that the acrylic surface had greater frictional properties compared to both clay surfaces. The Crab III and rotational traction device produced significantly greater friction values on the outdoor clay compared the synthetic clay surface. However, lower coefficient of friction was reported on the outdoor clay court compared to the synthetic clay court for the pendulum test device.

Table A1: Means and SD for mechanical data collected on each surface

Mechanical test	Outdoor Clay	Synthetic Clay	Acrylic
Frictional measures			
Pendulum	0.57 ± 0.01*#	0.61 ± 0.03*	0.68 ± 0.02#
Crab III	0.88 ± 0.10*#	0.72 ±0.06*	1.25 ± 0.04#
Rotational Traction (N/m)	16.05 ± 0.96*#	11.60 ± 1.78*	21.10 ± 2.42#

***Denotes significantly different to the acrylic surface, # denotes significantly different to the synthetic clay surface**

Reliability and validity

The study was conducted to examine reliability of a series of VAS and to ensure any ambiguity in questions was corrected. The analysis revealed that the questionnaire was reliable between participants and sessions. The study provided an opportunity to examine perceptions across three different surfaces (acrylic, outdoor clay and synthetic clay). Participants were able to perceive differences between the surfaces, in particular the acrylic surface was perceived to be considerably different compared to the two clay courts which were perceived to be similar.

Inter-rater reliability measures consistency between different raters. The study revealed a Cronbach's alpha of 0.973 suggesting the questionnaire was reliable between raters. Participants' perceptions across surfaces were similar and therefore participants interpreted the questionnaire in similar ways, suggesting that the questions were well worded and anchored to minimise ambiguity which is important when constructing a VAS (McCormack et al., 1988).

Following the analysis it can be concluded that the VAS was consistent between sessions, with an ICC of 0.986. This is higher than previously reported by Mündermann et al. (2002), who reported an ICC of 0.799. The study only examined one participant to gain an insight into consistency over time whilst Mündermann et al. (2002) examined nine participants. The participant used in the test-retest analysis was consistent in VAS scores with the other participants.

Face validity was determined for each perception variable measured using the VAS. Participants reported little difficulty in identifying the definition of each variable and when questioned, it appeared the participants understood the target variables, thus no changes in the perception questionnaire were needed.

Surface differences

A one-way ANOVA with repeated measures highlighted significant differences between the three tennis surfaces for each perception variable (Figure A2). Post hoc analysis revealed the acrylic surface to be significantly greater than both clay surfaces for the perceptions of predictability, grip, hardness and ability to change direction. Participants perceived the synthetic clay surface to be 26.5% softer and 39% easier to slide on compared to the outdoor clay surface. The lack of differences between the clay surfaces suggests difficulty in identifying differences between mechanically similar surfaces. Lake & Lafortune (1998) reported similar difficulties for participants identifying differences in perceptions between impact severities, from which they suggested increased stimulus towards a level considered to be damaging increased the number and types of receptors utilised to contribute to perceptions.

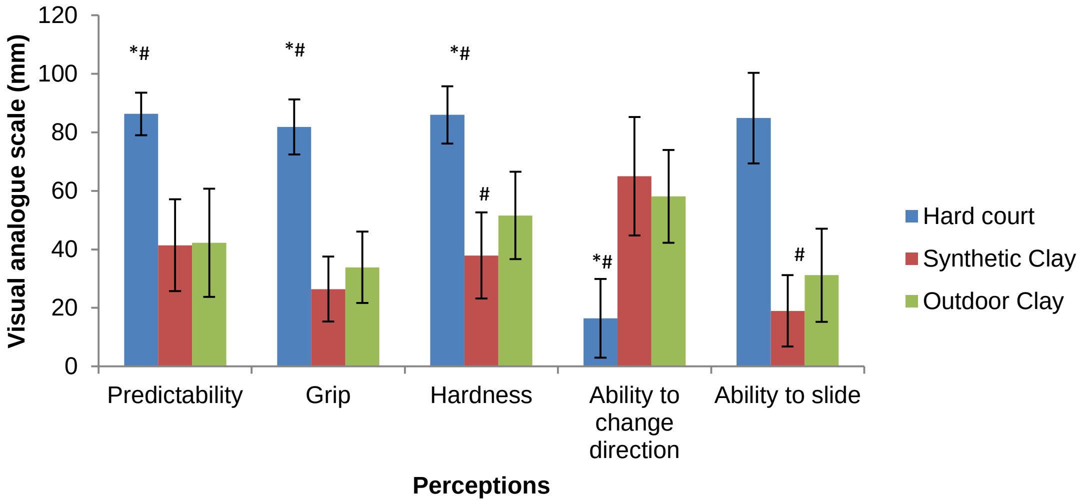

Figure A2: Means and SD of perception parameters for acrylic, clay and synthetic clay surfaces, where Qual 1 indicates Quality of movement 1 (ability to change direction), Qual 2 represents Quality of movement 2 (ability to slide). * denotes significantly different to the synthetic clay surface, # denotes significantly different to the outdoor clay surface

Conclusions

The study identified the perception VAS developed to be reliable between participants and sessions. Face validity was established for the questionnaire. The data suggest that participants were able to perceive differences between the acrylic surface and the clay surfaces. However for surfaces that are similar, i.e. both clay surfaces, differences became difficult to identify.

Appendix 7: Perception Questionnaire

SPORT AND HEALTH SCIENCES

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PARTICIPANT DATA SHEET

Name: ....

Age: ....

Height: ....m **Weight:** ....kg

LTA Rating (if applicable): ....

Please answer the questions below to the best of your ability.

Previous Experience

1. How many times a week do you train?

   ______days a week

2. How many hours do you normally train for?

   ________hrs per session

3. How often do you compete in a year?

4. What types of courts do you normally train and/or compete on?

5. How much experience do you have playing on **synthetic clay** courts? *(Please circle)*

1	**2**	**3**	**4**	**5**
NO EXPERIENCE	LITTLE EXPERIENCE (Played once/twice)	MODERATE EXPERIENCE (Compete/ train a few times a year)	HIGH EXPERIENCE (Compete/ train at least once a month)	VERY HIGH EXPERIENCE (Compete /train once a week)

6. How much experience do you have playing on **outdoor clay** courts? *(Please circle)*

1	**2**	**3**	**4**	**5**
NO EXPERIENCE	LITTLE EXPERIENCE (Played once/twice)	MODERATE EXPERIENCE (Compete/ train a few times a year)	HIGH EXPERIENCE (Compete/ train at least once a month)	VERY HIGH EXPERIENCE (Compete /train once a week)

7. How much experience do you have playing on **hard courts**? *(Please circle)*

1	2	3	4	5
NO EXPERIENCE	LITTLE EXPERIENCE (Played once/twice)	MODERATE EXPERIENCE (Compete/ train a few times a year)	HIGH EXPERIENCE (Compete/ train at least once a month)	VERY HIGH EXPERIENCE (Compete /train once a week)

8. When did you last train or compete on a **synthetic clay** court?

9. When did you last train or compete on an **outdoor clay** court?

10. When did you last train or compete on a **hard court**?

11. Have you experienced any injuries during training?
(If so please specify the location, type of injury, time out of training, how long ago the injury was and whether you have made a full recovery)

12. Have you experienced any injuries during competition?
(If so please specify the location, type of injury, time out of training, how long ago the injury was and whether you have made a full recovery)

13. Are you currently injury-free or do you use an intervention to allow you to perform?

Game style

1. Which court do you prefer to train on and why?

2. Which court do you prefer to compete on and why?

3. During a match what percentage of your time would you spend at the baseline? *(please place a cross (x) on the line below to indicate a percentage of your time)*

0% No time spent at baseline

100% All the time spend at baseline

4. During a match what percentage of your time would you spend at the net? *(please place a cross (x) on the line below to indicate a percentage of your time)*

0% No time spent at net

100% All the time spend at net

PERCEPTION OF SURFACES – QUESTIONNAIRE

Name: **Surface:**

For each question please place a cross (x) on the line to represent your perceptions, feelings or thoughts with regard to the question

Predictability, stability or security

When you were moving around the court how predictable (stable, even, secure) do you think the surface was, terms of your movement?

COMPLETELY UNPREDICTABLE Unstable, uneven, Messy, unexpected	●————————————●	**COMPLETELY PREDICTABLE** Stable, even, secure, expected

Grip

How much grip did the surface provide you?

NO GRIP Slippery & loose	●————————————●	**TOO MUCH GRIP** Secure & grippy

Hardness

How hard did the surface feel to you?

SOFTEST SURFACE Padded, cushioned, compliant	●————————————●	**HARDEST SURFACE** High energy, impacts hard, stiff

Quality of movement 1

How difficult was it to push off or change direction on this surface?

VERY EASY TO PUSH OFF/ CHANGE DIRECTION

No difficulties,

No problems

VERY HARD TO PUSH OFF/ CHANGE DIRECTION

Very difficult, impossible

Quality of movement 2

How difficult was it to slide on this surface?

VERY EASY TO SLIDE

No difficulties, no problems

VERY HARD TO SLIDE

Very difficult, impossible

Ball height

On this court how high do you think the ball bounced?

LOW

Flat

HIGH

Held up

Ball speed

On this court how fast do you think the ball moved?

SLOW Lots of time, longer points	**FAST** Shorter points, less time

Bounce consistency

How consistently do you think the ball bounced on this court?

ALWAYS IRREGULAR Uneven, dodgy	**ALWAYS CONSISTENT** Constant, predictable

Appendix 8: Determination of Infill Volume Using Mechanical and Perception Data

Introduction

A previous study has systematically examined changes in cushioning during tennis-specific movements (Stiles & Dixon, 2007). However, to our knowledge, no studies have examined systematic changes in friction during tennis-specific movements on clay. Changes in friction have been reported to influence tennis players' biomechanical response such as lower knee flexion and altered pressure distribution (Girard et al., 2007; Damm et al., 2013; Damm et al., 2014). These differences have been attributed to players' ability to slide on clay courts (Girard et al., 2007; Damm et al., 2013; Damm et al., 2014).

Clay courts consist of a base layer, either compact stone or carpet, with a top dressing of loosely bound clay or sand infill. Previous reports have demonstrated that particle size and moisture of clay court infills influence mechanical friction levels (Clarke et al., 2013). However, if wanting to examine players' response to changes in surface friction manipulation of these factors would be logistically challenging, since moisture and particle size is difficult to measure and control. Therefore an alternative suggested approach is to vary the volume of sand infill of a synthetic clay court, providing a more accurate and reliable method to ensure changes in friction. Therefore the aim of this study was to examine the mechanical friction of different volumes of sand. In addition the study aimed to examine perceptions of different volumes of sand in order to identify three volumes of sand that are mechanically and perceptually different for the future studies.

Methods

Surface conditions

A synthetic clay surface (Appendix 3), was used. The surface consisted of a carpet base layer and a top layer with sand infill. During the mechanical test three volumes of sand (12 $kg.m^{-2}$, 16 $kg.m^{-2}$ and 20 $kg.m^{-2}$) were examined to provide three levels of friction.

Mechanical data

Mechanical data were collected using a traction test device (Figure A3), further described by Clarke et al. (2013). Mechanical data were collected by colleagues at the University of Sheffield. In order to replicate sliding, often observed on clay (Miller & Capel-Davies, 2006; Damm et al., 2013), the device was adjusted so that the forefoot of a clay court shoe was set at 7^o against the surface and at 90^o of the direction of movement. Damm et al. (2013), reported players exceeded 1000 N during tennis-specific skills, therefore a range of normal force (1000 – 1600 N) was used. Following a secured placement of the synthetic clay carpet, the infill of clay was applied and evenly distributed. The rig consists of a pneumatic ram which produces the required normal load. Once the required normal load is reached, a pneumatic ram provides the horizontal force which increases until sliding is initiated. Three volumes of infill were 12 $kg.m^{-2}$, 16 $kg.m^{-2}$ and 20 $kg.m^{-2}$. Mechanical data collected included static and dynamic coefficient of friction, further details are explained by Clarke et al. (2013). Peak static COF was defined as the peak COF which suggests the transition between the static and dynamic regimes. The average dynamic COF was taken following the peak COF measured between 0.05 m and 0.20 m.

Figure A3: The Traction rig device

Perception data

Perceptions were collected using a series of VAS (Appendix 7) examining perceived predictability, grip, hardness, ability to change direction and ability to slide. Perceptions were measured on one participant to identify further information in addition to the mechanical data. Five volumes of infill (12 $kg.m^{-2}$, 16 $kg.m^{-2}$, 17 $kg.m^{-2}$, 18 $kg.m^{-2}$ and 20 $kg.m^{-2}$) were examined to provide additional information to the mechanical data to determine whether further mechanical measures were required. One participant volunteered to take part in the study, where they were asked to run at speed down a run way (see Section 5.2.3) before turning on the force plate with the required volume of infill before returning at speed to the starting point. The order in which the participant experienced each volume of infill was randomly assigned. Perceptions were taken following each turn, where three repetitions of the five infill volumes were measured.

Results and Discussion

Mechanical data

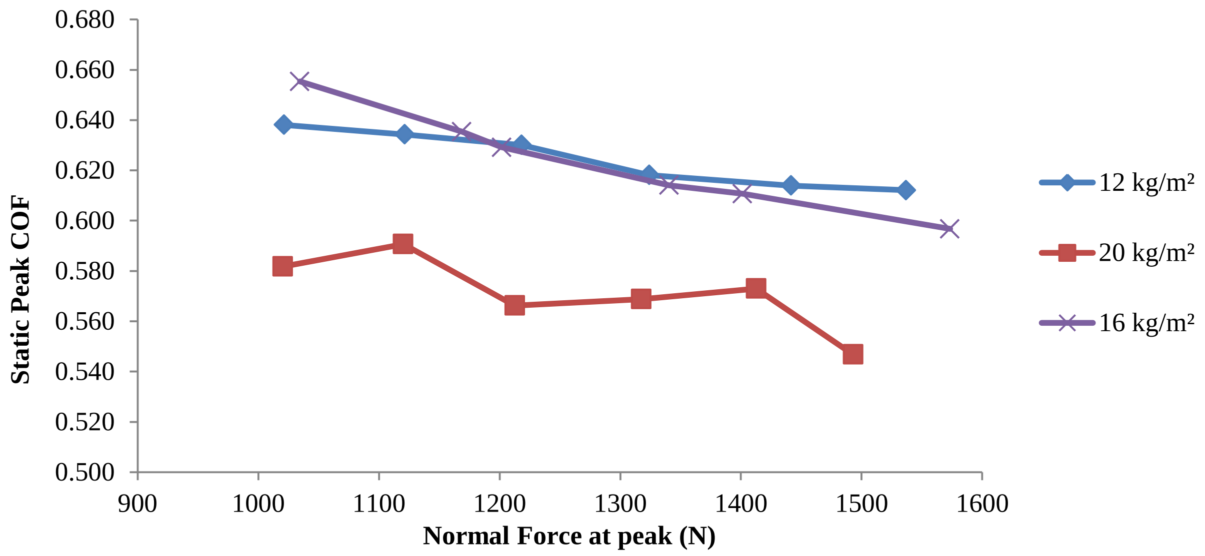

Figure A4: Static peak COF for the three volumes of infill with a range of normal forces

Figure A4 provides the static peak COF for the three volumes of infill, highlighting that as the normal force increased the static COF reduced, suggesting lower static peak COF needed to initiate sliding (Clarke et al., 2013). The 16 kg.m^{-2} infill volume produced the lowest static peak COF compared to the 12 kg.m^{-2} and 20 kg.m^{-2}. Interestingly the 12 kg.m^{-2} and 20kg.m^{-2} conditions produced similar peak COF through the range of normal forces. One possibility for these similarities is a possible build-up of infill ahead of the shoe during the 20 kg.m^{-2} condition which influenced the COF reported (Clarke et al., 2013).

Previously Damm et al. (2014) reported a medial shift in COP to prevent this build-up of clay infill which could lead to overloading the lateral structure if the foot became fixed as a result of this build up. Therefore understanding of pressure distribution will help further develop of mechanical devices to measure friction of clay surfaces.

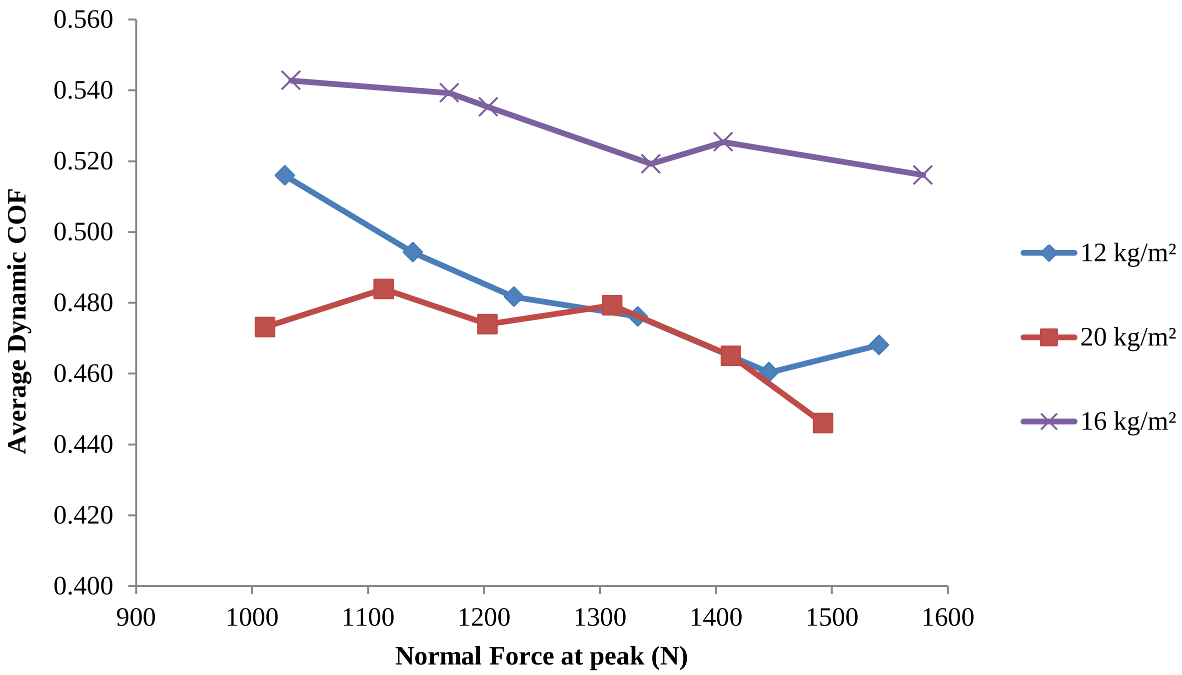

Figure A5: Average dynamic COF for the three volumes of infill

Figure A5 provides the average dynamic COF for the three volumes of infill measured. Similar to the static COF the average dynamic COF was reduced for all conditions as normal force increased. Clarke et al. (2013) established that the majority of horizontal displacement during sliding occurred during the dynamic friction regime. The 20 kg.m^{-2} condition presented higher dynamic coefficient of friction compared to the 12 $kg.m^{-2}$ and 16 $kg.m^{-2}$ conditions which were similar in average dynamic COF.

Perception data

Figure A6 highlights the perception data collected for each volume of infill. Results of the present study reflect those previously reported (in study 2), where the participant was able to identify differences in mechanical friction (Lockhart et al., 2002). The 12 $kg.m^{-2}$ condition was reported to have the greatest level of perceived predictability, grip, hardness and was identified to be easier to change direction, whilst most difficult to slide. The 20 $kg.m^{-2}$ condition which was similar to the 18 $kg.m^{-2}$ condition, was perceived to have lowest predictability, grip and hardness and was perceived to be the most difficult to change direction, whilst easiest to slide.

To identify whether further mechanical data was required perception data was obtain for additional volumes. Both the 16 $kg.m^{-2}$ and 17 $kg.m^{-2}$ conditions were similar in the levels of perceptions for all participants. These conditions were reported to be perceived between the 12 $kg.m^{-2}$ and 20 $kg.m^{-2}$ conditions. It was decided that 12 $kg.m^{-2}$, 16 $kg.m^{-2}$ and 20 $kg.m^{-2}$ would provide sufficient differences in mechanical friction to provide differences in perceptions and no further mechanical measures were taken.

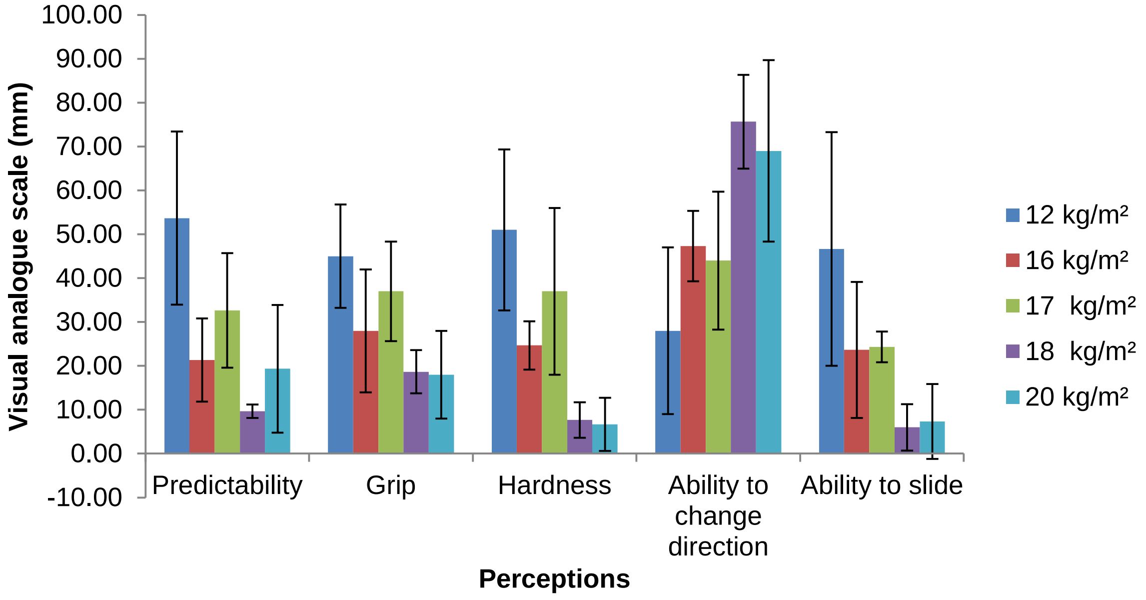

Figure A6: Perception data for the five volumes of infill. Qual 1 represents ability to change direction; Qual 2 represents ability to slide

Conclusions

The study has established three levels of friction, provided by different volumes of sand (12 $kg.m^{-2}$, 16 $kg.m^{-2}$ and 20 $kg.m^{-2}$), which provide mechanical differences in static and dynamic COF, and were perceived to be different for all perception variables.

Appendix 9: Example SPSS output for 3-way ANOVA

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Expectation	Sphericity Assumed	141.974	1	141.974	1.598	.230	.117
	Greenhouse-Geisser	141.974	1.000	141.974	1.598	.230	.117
	Huynh-Feldt	141.974	1.000	141.974	1.598	.230	.117
	Lower-bound	141.974	1.000	141.974	1.598	.230	.117
Expectation * Group	Sphericity Assumed	20.664	1	20.664	.233	.638	.019
	Greenhouse-Geisser	20.664	1.000	20.664	.233	.638	.019
	Huynh-Feldt	20.664	1.000	20.664	.233	.638	.019
	Lower-bound	20.664	1.000	20.664	.233	.638	.019
Error(Expectation)	Sphericity Assumed	1066.319	12	88.860			
	Greenhouse-Geisser	1066.319	12.000	88.860			
	Huynh-Feldt	1066.319	12.000	88.860			
	Lower-bound	1066.319	12.000	88.860			
Friction	Sphericity Assumed	633.178	1	633.178	6.630	.024	.356
	Greenhouse-Geisser	633.178	1.000	633.178	6.630	.024	.356
	Huynh-Feldt	633.178	1.000	633.178	6.630	.024	.356
	Lower-bound	633.178	1.000	633.178	6.630	.024	.356
Friction * Group	Sphericity Assumed	.003	1	.003	.000	.996	.000
	Greenhouse-Geisser	.003	1.000	.003	.000	.996	.000
	Huynh-Feldt	.003	1.000	.003	.000	.996	.000
	Lower-bound	.003	1.000	.003	.000	.996	.000
Error(Friction)	Sphericity Assumed	1146.018	12	95.501			
	Greenhouse-Geisser	1146.018	12.000	95.501			
	Huynh-Feldt	1146.018	12.000	95.501			
	Lower-bound	1146.018	12.000	95.501			
Expectation * Friction	Sphericity Assumed	13.955	1	13.955	.122	.733	.010
	Greenhouse-Geisser	13.955	1.000	13.955	.122	.733	.010
	Huynh-Feldt	13.955	1.000	13.955	.122	.733	.010
	Lower-bound	13.955	1.000	13.955	.122	.733	.010
Expectation * Friction * Group	Sphericity Assumed	23.670	1	23.670	.206	.658	.017
	Greenhouse-Geisser	23.670	1.000	23.670	.206	.658	.017
	Huynh-Feldt	23.670	1.000	23.670	.206	.658	.017
	Lower-bound	23.670	1.000	23.670	.206	.658	.017
Error(Expectation*Friction)	Sphericity Assumed	1376.000	12	114.667			
	Greenhouse-Geisser	1376.000	12.000	114.667			
	Huynh-Feldt	1376.000	12.000	114.667			
	Lower-bound	1376.000	12.000	114.667			