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ABSTRACT

1
2 This study aimed to examine player perceptions and biomechanical responses to tennis
3 surfaces and to evaluate the influence of prior clay court experience. Two groups with
4 different clay experiences (experience group, n=5 and low-experience group, n=5) performed
5 a 180° turning movement. Three-dimensional ankle and knee movements (50Hz), plantar
6 pressure of the turning step (100Hz) and perception data (visual analogue scale questionnaire)
7 were collected for two tennis courts (acrylic and clay). Greater initial knee flexion (acrylic
8 $20.8 \pm 11.2^\circ$ and clay $32.5 \pm 9.4^\circ$) and a more upright position were reported on the clay
9 compared to the acrylic court ($P < 0.05$). This suggests adaptations to increase player stability
10 on clay. Greater hallux pressures and lower midfoot pressures were observed on the clay
11 court, allowing for sliding whilst providing grip at the forefoot. Players with prior clay court
12 experience exhibited later peak knee flexion compared to those with low-experience. All
13 participants perceived the differences in surface properties between courts and thus
14 responded appropriately to these differences. The level of previous clay court experience did
15 not influence players' perceptions of the surfaces; however, those with greater clay court
16 experience may reduce injury risk as a result of reduced loading through later peak knee
17 flexion.

1 **1. Introduction**

2 Tennis surfaces, such as clay and acrylic courts, can differ greatly in mechanical properties
3 such as friction and hardness. These differences have been associated with changes in
4 performance as a result of altered movement patterns and styles of play (O'Donoghue &
5 Ingram, 2001; Reid et al., 2013). Compared with low friction surfaces, high friction surfaces
6 lead to kinematic adjustments (Farley, Glasheen, & McMahon, 1993; Dowling, Corazza,
7 Chaudhari, & Andriacchi, 2010), such as lower attack angles (measured to the horizontal), in
8 addition to faster running speeds and movements (Brechue, Mayhew, & Piper, 2005). Players
9 have been observed to accommodate to low friction surfaces such as clay through sliding
10 (Miller, 2006).

11 Lower injury rates have been reported on clay courts compared to acrylic hardcourts,
12 suggested to be a result of lower friction (Nigg & Segesser, 1988; Bastholt, 2000). Higher
13 friction surfaces, such as acrylic hardcourts, have been associated with high loading,
14 particularly on the lateral regions of the foot (Damm et al., 2014). This suggests the foot to be
15 in an inverted position. High levels of inversion (16°) have previously been linked to ankle
16 inversion injuries (Kristianslund, Bahr, & Krosshaug, 2011). When examining 180° turning
17 movement on a range of test surfaces (including wood, asphalt and synthetic rubber),
18 kinematic adjustments to the high friction surfaces included longer braking phases and
19 greater knee flexion (Durá, Hoyos, Martínez, & Lozano, 1999). These adjustment have been
20 suggested to contribute to the occurrence of patellofemoral pain (Chard & Lachmann, 1987;
21 Gecha & Torg, 1988; Damm et al., 2013), a commonly reported injury in tennis (Abrams,
22 Renstrom, & Safran, 2012). Alternatively, cutting tasks on high friction surfaces have been
23 reported to produce lower knee flexion angles resulting in an increased risk of anterior
24 cruciate ligament (ACL) injuries (Dowling et al., 2010).

1 Pressure insoles provide a tool to examine loading during on-court scenarios. The distribution
2 and the magnitude of force within foot regions have been suggested as good indicators of
3 injury risks compared to overall force magnitude (Willems et al., 2005; Girard, Eicher,
4 Fourchet, Micallef, & Millet, 2007; Stiles & Dixon, 2007; Damm et al., 2014). In tennis,
5 lower whole foot loads have been reported for clay courts compared with acrylic suggesting
6 lower risk of injury on the clay (Girard et al., 2007; Damm et al., 2012). Court surface types
7 have also been associated with different pressure distribution patterns (Girard et al., 2007;
8 Girard, Micallef, & Millet, 2010; Damm et al., 2012, 2014). Girard et al. (2007) reported
9 greater midfoot and hallux pressures on an acrylic court compared to a clay court during
10 tennis specific movements and associated these greater pressures with greater injury risk on
11 the acrylic court.

12 Mechanical tests measure surface properties, yet due to players' ability to adapt to different
13 properties through biomechanical adjustments mechanical tests are unable to replicate players
14 experiences of tennis surfaces (Ferris, Liang, & Farley, 1999; Dixon, Collop, & Batt, 2000;
15 Damm et al., 2013). Perceptions have been suggested to be an important link between
16 mechanical properties and player biomechanics (Fleming, Young, Roberts, Jones, & Dixon,
17 2005). Perceptions can provide information on humans' ability to identify and respond to
18 their environment (Milani, Hennig, & Lafortune, 1997; Stiles & Dixon, 2007). Previous
19 experience and sensory information are combined to formulate perceptions and enable
20 humans to interact successfully within their environment (Coren, Porac, & Ward, 1979;
21 Sherwood, 1993). Studies of sports surfaces have mainly focused on perceptions of hardness
22 and grip, whilst Fleming et al. (2005) identified other perceptions such as surface
23 abrasiveness to be important, following interviews with 22 hockey players. Therefore further
24 research is required to examine additional perception parameters of court surfaces to provide
25 better understanding of how tennis surface properties alter player movement and loading.

1 Greater understanding of tennis players' perceptions and biomechanical response could also
2 enable the development of mechanical tests to better characterise court surface properties.

3 In addition to influencing perceptions, previous experience can alter human response to
4 surface conditions (Coren et al., 1979; Chiou, Bhattacharya, & Succop, 2000; Heiden,
5 Sanderson, Inglis, & Siegmund, 2006). It has previously been observed that prior experience
6 and awareness of slippery surfaces results in the adoption of a cautious gait (greater initial
7 knee flexion), leading to reduced GRF and increased muscle activity during walking (Heiden
8 et al., 2006). Heiden et al. (2006) examined walking, whilst there has been no research
9 examining the influence of previous experience of surface conditions during sport-specific
10 movements such as turning.

11 This study aims to examine the influence of changes in tennis surface upon perceptions and
12 biomechanical variables to better understand the influence of perceptions upon factors
13 associated with increased injury risk and to enable future development of mechanical tests.
14 Based on literature evidence, it was anticipated that tennis court properties would influence
15 tennis players' perceptions and biomechanical response. Specifically, it was hypothesised that
16 players would perceive greater hardness on the acrylic court as a result of greater peak heel
17 pressures. Lower perceptions of grip on the clay court would be observed alongside greater
18 initial knee flexion associated with reduced ACL injury risk. The study also aimed to
19 evaluate the influence of previous experience of clay courts upon perceptions and
20 biomechanics. It was hypothesised that those with prior experience of clay courts would
21 adapt to increase stability through reduced GRF and further increases in knee flexion.

1 2. Methods

2 2.1 Participant Information

3 Ten tennis players (Lawn Tennis Association (LTA) rating 3.6 ± 1.3), volunteered to
4 participate in the current study. Players were grouped into two groups according to their
5 experience with playing on clay courts. These groupings were determined by questionnaire
6 where those who rated their experience on clay as high or above (defined as once a month or
7 more) were selected for the experienced group ($n = 5$, LTA rating 3.0 ± 1.6 , age 28.0 ± 5.1
8 years, height 1.8 ± 0.1 m and weight 75.0 ± 14.3 kg), whereas those who rated no to moderate
9 experience (once a year or less) formed the low-experience group ($n=5$, LTA rating 3.8 ± 1.1 ,
10 age 26.0 ± 1.3 years, height 1.7 ± 0.1 m and 65.8 ± 12.8 kg). No statistical differences (using
11 independent t-tests) in LTA ratings and anthropometric data were observed between groups.
12 The study was approved by the Institutional Ethics Committee and informed consent was
13 obtained before testing.

14 Participants were required to perform $10 \times 180^\circ$ turns on two tennis courts (GreenSet Grand
15 Prix Acrylic laid directly on asphalt and Northern European Clay, order randomly assigned)
16 at the National Tennis Centre (NTC), London. Participants ran 5.5 m along the baseline
17 through timing gates placed 3 m apart at a speed of 3.9 ± 0.20 m.s⁻¹ before performing the
18 turn. Participants wore the same shoes on both tennis courts (adidas Barricade 6.0 clay court
19 shoes with a v-shaped tread pattern) and were given adequate time to habituate themselves
20 with the court and movement before testing.

21 2.2 Mechanical data

22 Mechanical tests were conducted to provide details of surface properties for each tennis court.
23 A pendulum test (Slip resistance test, ITF CS 02/01) was conducted to provide a measure of
24 dynamic translational friction of the court surfaces (Miller & Capel-Davies, 2006). The test

1 has previously been used to examine surface friction on clay and acrylic tennis courts (Miller
2 & Capel-Davies, 2006; Damm et al., 2013; Damm et al., 2014). The pendulum test was
3 conducted on five different locations on the baseline of the court. Eight repeats were
4 conducted at each location with the first three repeats being disregarded. Therefore five valid
5 repeats were collected in five locations along the baseline of each court. The Crab III device
6 (developed by the ITF; (Miller & Capel-Davies, 2006) was used to obtain a measure of static
7 translational friction. Data were collected from ten separate locations around the baseline area
8 of each tennis court. Making consistent measurements on the clay court proved challenging
9 with both friction test devices as the surface particles were disturbed between trials, therefore
10 reducing the validity of the test devices.

11 Mechanical hardness and stiffness were measured using the SERG impact hammer, first
12 described by Carré et al., (2006). To simulate actual conditions and to prevent damage to the
13 tennis courts, an outsole of a tennis shoe was attached onto the rigid steel hammer, which has
14 previously been successful in comparing impact characteristics of tennis surfaces (Yang,
15 2010). Peak force was measured during impact with the surface to indicate differences in
16 surface hardness. Average stiffness was reported as the ratio of the peak force and the related
17 displacement. The SERG impact hammer test was conducted on ten separate locations in the
18 baseline area of the court.

19 2.3 Perception data

20 A short questionnaire comprising of five visual analogue scales (VAS; Figure 1) was used to
21 collect perception data following play on each court (Starbuck, 2015). These scales were 100
22 mm in length with two descriptive end phrases, formulated from parameters and language
23 identified in previous qualitative pilot work. Perception parameters included perceived
24 predictability, grip, hardness, ability to change direction, ability to slide.

1 ****Figure 1 near here****

2 2.4 Kinematic data

3 Kinematic data were collected using three video cameras (Sony HDV 1080i mini DV). The
4 video data were then de-interlaced to provide a sampling frequency of 50 Hz with images of
5 720p. Event synchronisation of LED lights were used to synchronise the cameras with a
6 maximum error of 0.02 s. Direct linear transformations (DLT) using Vicon Motus (v9.2)
7 software reconstructed 3-dimensional coordinates from the 2-dimensional digitised
8 coordinates of each camera (Abel-Aziz & Karara, 1971). Reconstruction errors, calculated
9 using Root Mean Square Error (RMSE) of four known markers, were no larger than 0.01 m
10 in the x, y and z direction. Eleven markers (Figure 2) were placed upon the lower limb of the
11 dominant leg, enabling increased accuracy and reliability of manual digitisation as well as
12 defining the joint coordinate systems adapted from (Grood & Suntay, 1983; Soutas-Little,
13 Beavis, Verstraete, & Markus, 1987). The 3-dimensional lower limb coordinates were filtered
14 using a recursive 2nd order Butterworth filter, with an optimum cut off frequency (range of 4-
15 8 Hz) for each coordinate determined using residual analysis .

16 ***Figure 2 near here***

17 Rotations about the ankle and knee joint centres were determined using a custom written
18 Matlab code (2011b, MathsWorks.). All kinematic data were presented relative to a relaxed
19 standing trial. Kinematic variables included initial and peak inversion angles, initial ankle
20 flexion and peak dorsi flexion angles and initial and peak knee flexion angles. Occurrence
21 times of peak angles were reported relative to heel contact. Sliding distance was calculated
22 from the resultant distance covered by the 5th metatarsal during ground contact. Attack angle

1 at impact was defined as the angle between the xy plane and the calcaneus to hip vector.
2 Estimated errors for all angles were less than 1°.

3 2.5 Pressure data

4 ***** Figure 3 near here*****

5 Pressure insoles (Pedar, Novel, GmbH, Munich) were used to obtain pressure data at 100 Hz
6 for the turning step. Eight masks, as previously used by Damm et al. (2012), allowed for a
7 detailed analysis of plantar foot sections (Figure 3), which included the lateral and medial
8 heel, midfoot and forefoot and the hallux and lesser toes. Variables for both whole foot and
9 foot regions included mean and maximum pressures, peak impact and active forces, peak and
10 average loading rates, and impulse. Occurrence times of peak impact and active forces and
11 maximum pressures were also identified. To ensure an accurate assessment, a drift correction,
12 recommended by Hurkmans et al. (2006), was implemented for the pressure data. 2.6

13 Statistical Analysis

14 Comparisons between the clay experience groups and the surfaces were examined for
15 kinematic and perception data using a two-way ANOVA with repeated measures, with
16 Bonferonni's corrected alpha *post hoc* analysis. Standardised effect sizes (ES) were
17 calculated using partial Eta² to provide the degree to which the differences were present
18 (Cohen, 1977). ES were presented for either differences between groups and within groups
19 (court differences) when significance was observed for these effects. Some trials from the
20 pressure data were omitted due to a failed wireless transmission, resulting in data for only
21 four participants in the low-experience group and three participants in the experienced group,
22 meaning group comparisons could not be made for pressure variables. Therefore a paired t-
23 test was conducted to examine differences for the whole cohort of players between the two

1 courts. Statistical analysis was conducted using SPSS (v.19) software. An alpha level of less
2 than 0.05 determined significance.

3 **3. Results**

4 3.1 Mechanical Data

5 ****Table 1 near here****

6 The clay court had lower static and dynamic coefficients of friction compared to the acrylic
7 court (Table 1). Peak force measured by the SERG impact hammer was greater on the
8 acrylic court compared to the clay court, indicating greater hardness of the acrylic court
9 (Clarke, Carré, Damm, & Dixon, 2013). Stiffness was also measured by the SERG impact
10 hammer and was greater on the acrylic court compared to the clay court ($P < 0.05$).

11 3.2 Tennis Court Differences

12 ****Figure 4 near here****

13 The analysis revealed differences between tennis courts for all perception parameters (Figure
14 4). The acrylic court was rated to be more predictable, have more grip, greater hardness and
15 was harder to slide on when compared with the clay court. However, the clay court was
16 perceived to be harder to change direction compared to the acrylic court.

17 Sliding distances were greater ($ES = 0.598$, $P < 0.05$) on the clay court (0.66 ± 0.40 m)
18 compared to the acrylic court (0.35 ± 0.04 m). Ground contact time ($ES = 0.838$, $P < 0.05$)
19 was longer on the clay court (0.54 ± 0.11 s) compared to the acrylic court (0.35 ± 0.04 s).
20 Represented schematically (Figure 5), initial attack angle was higher on the clay court (74.4
21 $\pm 6.1^\circ$) compared to the acrylic court ($64.8 \pm 5.3^\circ$, $ES = 0.572$, $P < 0.05$). Greater initial knee
22 flexion angle, indicating greater flexion, was observed on the clay court ($32.5 \pm 9.4^\circ$; Table 2)

1 compared to the acrylic court ($20.8 \pm 11.2^\circ$, $P < 0.05$). No court differences occurred for peak
2 ankle dorsi flexion angle. However, later peak dorsi flexion ($ES = 0.694$, $P < 0.05$) occurred
3 on the clay court (0.28 ± 0.10 s) compared to the acrylic court (0.16 ± 0.10 s).

4 ****Figure 5 near here****

5 ****Table 2 near here****

6 The acrylic court produced ($P < 0.05$) greater peak impact forces, peak active forces, average
7 loading rates, peak loading rates and impulse compared to the clay court (Table 3). Peak
8 active force occurred earlier on the acrylic compared to the clay court. No differences
9 between the tennis courts were identified for whole foot mean and maximum pressures.

10 ****Table 3 near here****

11 Greater maximum pressure in the hallux region ($ES = 1.73$, $P < 0.05$; Figure 6) occurred on
12 the clay (36.40 ± 9.64 kPa) compared to the acrylic court (24.14 ± 12.13 kPa). Differences
13 between the courts were detected for the maximum pressures at the lateral ($ES = 1.06$, $P <$
14 0.05) and medial heel regions ($ES = 1.49$, $P < 0.05$). Lower maximum heel pressures were
15 produced on the clay court (lateral = 18.36 ± 4.77 kPa and medial = 16.39 ± 4.77 kPa)
16 compared to the acrylic court (lateral = 26.57 ± 7.45 kPa and medial = 24.68 ± 6.88 kPa).
17 Lower mean (Figure 7) lateral midfoot pressures ($ES = 0.334$, $P < 0.05$) were revealed on the
18 clay court (3.83 ± 4.41 kPa) compared to the acrylic court (4.98 ± 4.92 kPa).

19 ****Figure 6 and 7 near here****

3.3 The Influence of Previous Clay Court Experience on Perceptions and Biomechanical Response

All perception parameters except players' perceived ability to change direction were similar between experience groups. The experience group perceived it easier (33.7%) to change direction compared to the low-experience group ($P < 0.05$) irrespective of tennis court. The experience group (0.26 ± 0.03 s) produced later peak knee flexion (ES = 0.456, $P < 0.05$) compared to the low-experience group (0.14 ± 0.03 s). An interaction between group and court was revealed (ES = 0.562 $P < 0.05$) for initial ankle flexion angle. *Post hoc* analysis indicated differences between tennis courts for the experienced group but no differences for the low-experience group. At impact, the experienced group were plantar flexed on clay ($7.7 \pm 9.4^\circ$), whilst this group were neutral or slightly dorsi-flexed on the acrylic court ($-2.5 \pm 7.5^\circ$).

4. Discussion

The main purpose of this 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. Court differences in player perceptions and response were observed, whilst group differences only occurred in tennis players' biomechanical responses and perception of ability to turn on the surfaces.

4.1 Player Perceptions of Tennis Courts

Players' perceptions of the courts inform their response to mechanical differences between surfaces (Milani et al., 1997), therefore measuring perceptions can provide an insight into how tennis players differentiate between court surfaces (Fleming et al., 2005). Similar to previous reports (Lockhart, Woldstad, Smith, & Ramsey, 2002; Stiles & Dixon, 2007), this

1 study revealed differences in perception of the two tennis courts, which corresponded to
2 differences in mechanical data. For instance, the acrylic court, which was mechanically
3 harder and had greater friction, was perceived to be harder and resulted in greater perceptions
4 of grip compared to the clay court. Unlike previous reports, this study examined additional
5 perceptions such as perceived predictability and perceived ability to change direction and
6 slide. Perceived predictability was lower on the low friction surface which was also perceived
7 to be easier to slide on yet difficult to change direction. These additional perception measures
8 provided further information regarding player perception of tennis courts which could alter
9 players' response to the surface, thus influencing injury risks and style of play. Results in this
10 study suggest that the mechanical tests of hardness and friction that were used provided
11 information regarding player perceptions of friction and hardness, yet other perceptions of the
12 surface, such as predictability, were identified and should be considered during the future
13 development of mechanical tests.

14 When developing mechanical tests and characterising tennis court surfaces the collection of
15 perceptions provides an indication of how players' respond to surfaces. Therefore perceptions
16 may reveal associations with biomechanical variables associated with increased injury risk.
17 Measuring perception provides further information regarding players experience of the
18 surface which can supplement mechanical measures but also aid in the development of new
19 mechanical tests (Fleming et al., 2005). This study identified differences in players'
20 perceptions of their ability to perform tasks such as sliding and changing direction between
21 court surf aces which could influence their biomechanical response. Therefore it is
22 recommended that future development of mechanical tests should attempt to replicate sliding
23 and changing of direction type movements, with the use of biomechanical data such as
24 applied loading characteristics and foot placements.

1 4.2 Player Response to Tennis Court Differences

2 Longer braking has previously been associated with high friction surfaces and has been
3 suggested to be an attempt to reduce high loading (Durá et al., 1999). In contrast, the current
4 study reported longer braking on the low friction clay court, observed through later peak
5 active force and ankle dorsi flexion. These differences were attributed to longer contact times
6 as a result of sliding on the court, unlike previous comparisons where sliding was not
7 reported (Durá et al., 1999). The lower loading measured on the clay court compared with the
8 acrylic is attributed to sliding on this court surface, and provides a suggested explanation for
9 the lower injury incidences previously reported on lower friction tennis courts such as clay, in
10 comparison to high friction acrylic courts (Nigg & Segesser, 1988; Bastholt, 2000).

11 Sliding in tennis can be beneficial by allowing braking to occur during stroke production thus
12 allowing players to prepare for the next stroke immediately after ball strike making for a
13 more efficient movement (Miller, 2006; Pavailler & Horvais, 2015). As a result of sliding on
14 clay it was apparent that an altered turning technique (e.g. differences in initial knee flexion,
15 attack angle, pressure distribution) occurred compared to the acrylic court where no sliding
16 was observed, as hypothesised. This study revealed greater knee flexion at ground contact
17 and reduced GRF on clay, both of which have been associated with improved stability on low
18 friction surfaces during walking (Heiden et al., 2006). Flexion at the knee has previously
19 been suggested to improve stability through lowering the COM closer to the base of support
20 (Cham & Redfern, 2002; Marigold & Patla, 2002). High knee flexion during cutting
21 movements has also been suggested to reduce risk of ACL injuries on low friction surfaces
22 (Dowling et al., 2010). Thus the more extended knee at initial ground contact on the acrylic
23 court observed in the current study may increase risk of ACL injuries when performing on
24 this surface compared with low friction clay.

1 Participants approach to the clay court was consistent with results previously reported from
2 walking studies (Heiden et al., 2006). Greater attack angle on the clay suggests a more
3 upright position at ground contact. A more upright attack angle has previously been
4 associated with an anterior COM shift, suggested to improve stability (Clark & Higham,
5 2011) in addition to lower COM through greater knee flexion. In contrast to the clay court, all
6 players had a more aggressive approach through lower attack angle on the acrylic court. This
7 aggressive approach observed on the acrylic court agrees with findings reported by Girard et
8 al. (2007) and reflects the explosive playing style often observed on acrylic courts
9 (O'Donoghue & Ingram, 2001).

10 Unlike previous reports, where greater whole foot mean and maximum pressures on acrylic
11 courts compared to clay courts have been reported (Girard et al., 2007; Damm et al., 2012),
12 few differences were obtained between the acrylic and clay courts. Findings from this study
13 were similar to those reported during walking where altered pressure distributions between
14 surfaces accounted for a lack of whole foot pressure differences (Fong, Mao, Li, & Hong,
15 2008). The greater pressures in the hallux area observed on the clay court compared to the
16 acrylic court suggest increased grip needed to turn on the lower friction surface, which is
17 similar to Fong et al. (2008) who suggested that greater toe grip and lower heel pressures
18 provided balance and grip during walking on slippery surfaces. Players ability to increase
19 grip on the low friction clay court through greater hallux pressures may increase risk of
20 tendinopathy of the flexor hallucis longus, which develops during repetitive loading in the
21 big toe area (Trepman, Mizel, & Newberg, 1995; Lynch & Renström, 2002). In agreement
22 with Damm et al. (2014), greater lateral pressures at the heel, midfoot and forefoot were
23 reported on the acrylic court suggesting a more inverted foot position which has previously
24 been linked to increased risk of ankle inversion injuries (Kristianslund et al., 2011).

1 In contrast to Girard et al. (2007), the current study reported lower midfoot pressures on the
2 clay court compared to the acrylic court. This response has been suggested to facilitate
3 sliding on this type of surface by limiting areas of high pressure to prevent ‘sticking’ (Damm
4 et al., 2012). Girard et al. (2007) reported higher midfoot loading on clay compared with
5 acrylic hardcourt, suggesting this permitted controlled sliding. Additionally, Girard et al.
6 (2007) reported higher hallux pressures on acrylic attributed to a more aggressive play
7 possibly as a result of greater friction. The findings reported in the current study differed to
8 those reported by Girard et al. (2007), likely due to the different methods of analysing
9 pressure data. Girard et al. (2007) examined the global effect of playing surface on pressure
10 during two movements, serve and volley and baseline movements, therefore combining
11 pressure distributions from multiple steps which consisted of accelerations, running and
12 cutting which differ in pressure distribution patterns (Orendurff et al., 2008). Girard et al.
13 (2007) collected data during whole tennis strategies (e.g. serve and volley) whilst this study
14 specifically examined the turning step. Examining pressure distribution during individual
15 steps rather than multiple steps allows more detailed understanding of surfaces affects and the
16 specific implications regarding injury risks.

17 4.3 The Influence of Previous Clay Court Experience on Perceptions and Biomechanical 18 Response

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

1 felt necessary for safety reasons, but may have limited the ability to detect differences
2 between experience groups.

3 It was hypothesised that those with prior experience of clay courts would adapt to increase
4 stability through reduced GRF and further increases in initial knee flexion compared to the
5 low-experience group. However, findings from the current study failed to support this
6 hypothesis. The lack of agreement with previous literature is most likely due to the nature of
7 the population and the movement. Previous literature has focused on walking (Heiden et al.,
8 2006), whilst the current study examined a more dynamic movement.

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

19 **5. Limitations**

20 The use of on court analysis in this study was a limitation regarding reproducibility of the
21 tennis-specific movements. Yet, the benefits of an on court analysis using the tennis specific
22 drills provided realistic conditions which are often difficult to obtain in confined laboratory
23 conditions, thus improving the ecological validity. Even with the limitations regarding

1 reliable reproduction of the movement between trials, statistically differences between
2 surfaces were detected.

3 Low sampling frequency of kinematic (50 Hz) and pressure (100 Hz) data was a limiting
4 factor which increases synchronisation error within the data and reduces accuracy of temporal
5 data. In support of the data collected, values were similar to those reported in the literature. It
6 is possible that the presence of the pressure insoles within the footwear influenced
7 participants movement on the tennis court (Kong & De Heer, 2009). However, it was felt that
8 the data obtained through the use of these insoles was appropriate for obtaining on court
9 loading characteristics, and that the influence on footwear environment was small compared
10 with the large differences in surface characteristics. The Pedar system used for pressure data
11 collection (Pedar, Novel) has been suggested to be acceptably accurate and reliable (Godi,
12 Turcato, Schieppati, & Nardone, 2014; Price, Parker, & Nester, 2014).

13 The anchor words employed in the visual analogue scale, previously deemed a reliable
14 measure of perception (Mündermann, Nigg, Stefanyshyn, & Humble, 2002; Mills, Blanch, &
15 Vicenzino, 2010), may be interpreted differently by different people (Aitken, 1969). However
16 previous pilot work supported that face validity of the questionnaire was achieved, thus
17 minimising the ambiguity of the questionnaire (Starbuck, 2015).

18 **6. Conclusions**

19 Participants in this study were able to perceive differences between tennis courts and
20 produced altered biomechanical responses as a result of different surface properties. As
21 hypothesised, players perceived differences in perceived hardness and perceived grip
22 between the tennis courts, in agreement with the mechanical data collected. Evidence
23 suggests the inclusion of multiple perception measures such as perceived predictability and
24 ability to perform tennis specific tasks, to develop a more global approach to characterising

1 tennis court surfaces. The use of perception and biomechanical data during on court analysis
2 could inform the development of mechanical tests to better replicate player experience. All
3 participants in the current study demonstrated adaptations consistent with providing improved
4 stability on the clay court during sliding, whilst those with greater experience on clay had
5 additional adaptations such as later knee flexion, reducing rate of loading and potentially
6 reducing injury risk. Previous experience does not appear to influence players' perceptions of
7 tennis courts but provides information regarding an appropriate response. Although not
8 directly measured due to a failed wireless transmission, later occurrence of peak knee flexion
9 for the experienced group suggests lower GRF when compared to the low-experienced group,
10 as hypothesised. This evidence suggests that when on clay, players with high previous
11 experience are better able to accommodate to the court, through additional biomechanical
12 responses, highlighting the importance of court familiarisation.

13 **7. References**

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1 **8. Tables with captions**

2

3 Table 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*
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*

4

* denotes a ($P < 0.05$) difference between tennis courts

Table 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 (°)	-2.5 ± 7.7	3.3 ± 8.3	0.4 ± 8.1	7.7 ± 9.4	3.3 ± 8.3	2.5 ± 10.2	0.562 ⁱ
Peak (°)	-20.4 ± 12.8	-27.6 ± 12.8	-24.0 ± 11.9	-14.4 ± 5.0	-22.3 ± 9.2	-18.3 ± 8.1	
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 ± 0.10	0.694*
Ankle inversion							
At impact (°)	-0.3 ± 6.6	-1.7 ± 7.0	-1.0 ± 6.5	3.5 ± 6.7	-4.9 ± 6.1	-0.7 ± 7.5	
Peak (°)	-14.3 ± 10.1	-10.3 ± 4.1	-12.3 ± 7.6	-8.6 ± 4.4	-11.4 ± 3.3	-10.0 ± 4.0	
Time of peak (s)	0.08 ± .01	0.12 ± 0.01	0.08 ± 0.03	0.11 ± 0.09	0.11 ± 0.03	0.11 ± 0.02	
Knee Flexion Angle							
At impact (°)	17.3 ± 9.5	24.3 ± 12.7	20.8 ± 11.2	28.1 ± 9.1	37.0 ± 8.2	32.5 ± 9.4	0.476*
Peak (°)	31.2 ± 18.2	49.6 ± 9.7	40.4 ± 16.8	51.2 ± 17.6	42.7 ± 23.7	47.0 ± 20.2	
Time of peak (s)	0.16 ± 0.12	0.12 ± 0.10	0.14 ± .10	0.36 ± 0.11	0.15 ± 0.12	0.26 ± 0.16	0.456 ^g

* denotes ($P < 0.05$) difference between courts, ⁱ represents a ($P < 0.05$) interaction between court and group, ^g represents a ($P < 0.05$) difference between groups

Table 3: Means and standard deviations for whole foot pressure data during the turn for each tennis court

Variable	Acrylic court	Clay court	ES
Impact force			
Peak (BW)	2.86 ± 0.78	2.14 ± 0.59	1.688*
Time of peak (s)	0.13 ± 0.06	0.12 ± 0.03	
Active force			
Peak (BW)	2.92 ± 0.75	2.37 ± 0.46	1.055*
Time of peak (s)	0.17 ± 0.09	0.29 ± 0.12	0.985*
Loading rate			
Average (BW/s)	32.69 ± 11.44	21.43 ± 6.20	1.110*
Peak (BW/s)	83.62 ± 12.74	65.48 ± 28.50	0.767*
Impulse (BW.s)	11.47 ± 3.80	8.11 ± 2.00	1.22*
Whole foot pressure			
Maximum pressure (kPa)	49.31 ± 10.56	49.5 ± 10.74	
Mean pressure (kPa)	14.29 ± 18.49	13.23 ± 17.29	

*Denotes a ($P < 0.05$) difference between the clay and the acrylic court

9. Figure Captions

Figure 1. Depicts the perception scales including the descriptive end phrases

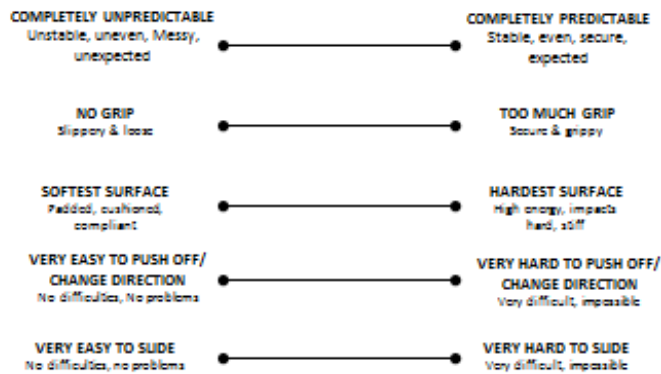


Figure 2. Joint coordinate system marker locations: 1) hip (greater trochanter) , 2) medial knee (medial femoral epicondyle), 3) lateral knee (lateral femoral epicondyle), 4) shin (anterior aspect of shank), 5) Achilles 1 (proximal bisection of posterior shank), 6) Achilles 2 (distal bisection of the 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

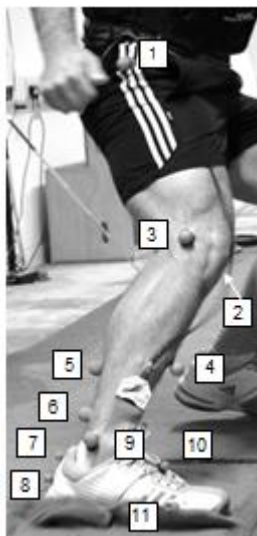


Figure 3. A representation of the eight masks (right foot) used; P1: hallux, P2: lesser toes, P3: medial forefoot, P4: lateral forefoot P5: Medial mid foot, P6: lateral midfoot, P7: medial heel, P8: lateral heel.

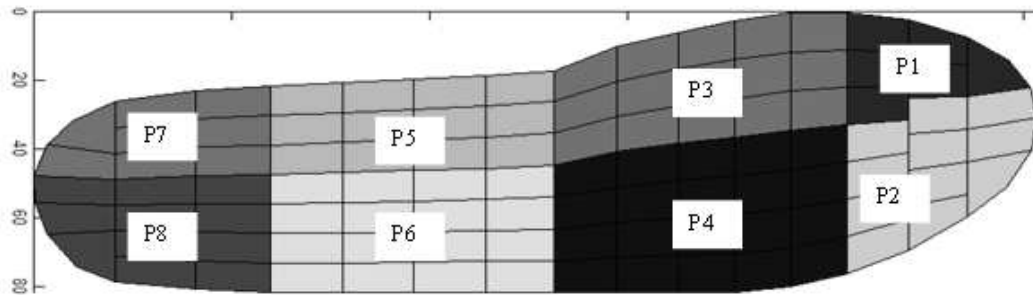


Figure 4. Means and SD for the perception parameters and comparison between the clay court and hard court * Denotes a ($P < 0.05$) difference between court

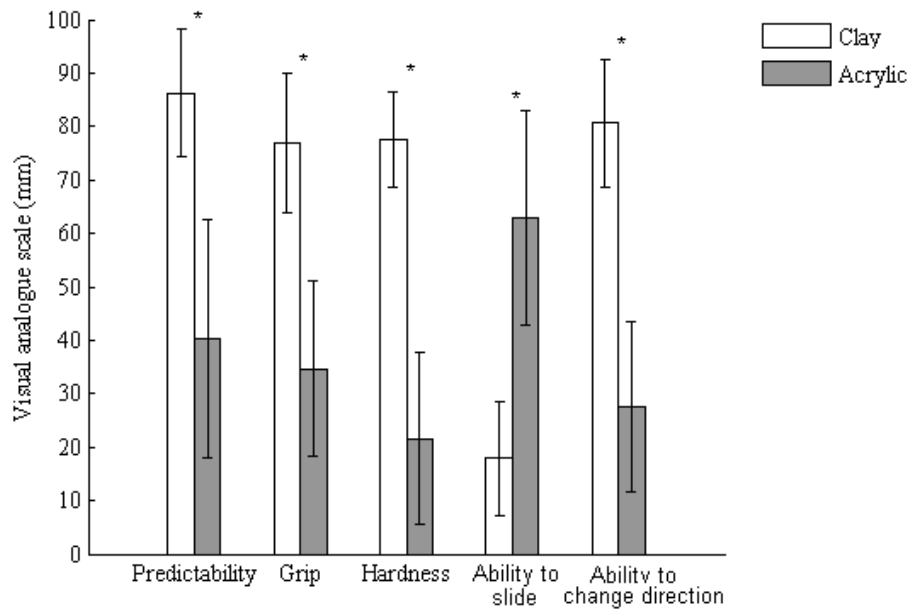


Figure 5. A schematic diagram representing attack angle, where attack angle is defined as the angle between the horizontal axis and calcaneus to hip vector. a) Represents a greater attack angle reported for the acrylic court, b) presents a more upright position observed on the clay court, with a greater hip height compared to the acrylic court.

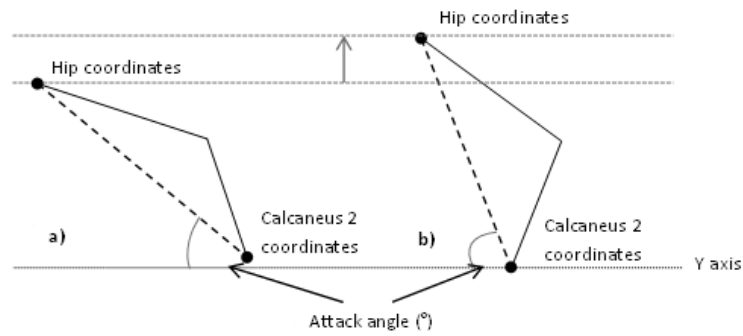


Figure 6. Maximum pressures for the eight masks on acrylic and clay court. * Denotes ($P < 0.05$) difference between courts.

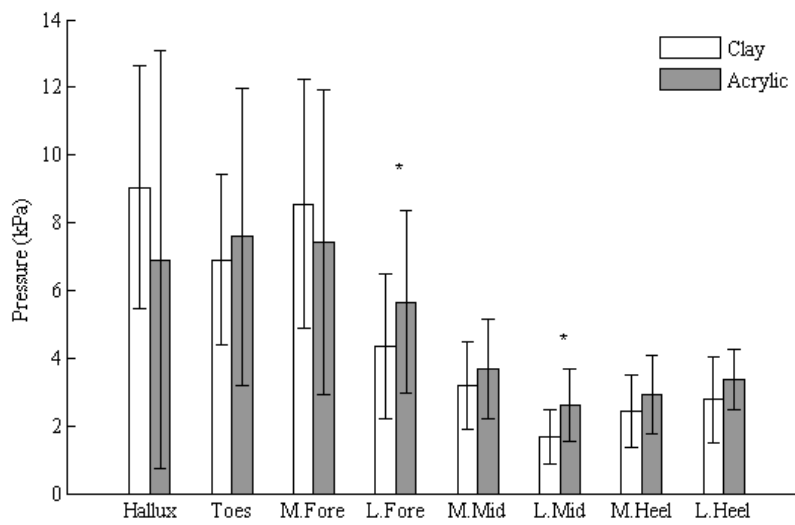


Figure 7. Mean pressures for the eight masks on acrylic and clay court. * Denotes ($P < 0.05$) difference between courts

