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Characterisation of ball degradation events in professional tennis

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Abstract Tennis balls are acknowledged to degrade with use and are replaced at regular intervals during professional matches to maintain consistency and uniformity in performance, such that the game is not adversely affected. Balls are subject to the international tennis federation's (ITF) ball approval process, which includes a degradation test to ensure a minimum standard of performance. The aim of this investigation was to establish if the ITF degradation test can assess ball longevity and rate of degradation and determine if there is a need for a new degradation test that is more representative of in-play conditions. Ball tracking data from four different professional events, spanning the three major court surfaces, including both men's and women's matches were analysed. The frequency of first serves, second serves, racket impacts and surface impacts were assessed and the corresponding distribution of ball speed and (for surface impacts) impact angle was determined. Comparison of ball impact frequency and conditions between in-play data and the ITF degradation test indicated the development of a new test, more representative of in-play data, would be advantageous in determining ball longevity and rate of degradation with use. Assessment of data from different surfaces highlighted that grass court subjected the ball to fewer racket and surface impacts than hard court or clay. In turn, this appears to influence the distribution of ball speed on impact with the surface or racket, suggesting a surface-specific degradation test may be beneficial. As a result of these findings a new test protocol has been proposed, utilising the in-play data, to define the frequency of impacts and impact conditions to equate to nine games of professional tennis across the different surfaces.

Keywords Tennis · Ball · Impact · Hawk-Eye · Surface · Speed · Angle · Degradation

1 Introduction

Approximately 360 million tennis balls are manufactured each year [1], with wholesale sales figures in the region of $92 million in the United States alone in 2015 [2]. It is, therefore, important for tennis brands to be able to produce consistent, durable products to satisfy consumers worldwide. Ball performance and durability is also important to professional players, event organisers and the media to produce the highest quality tennis to entertain spectators. Tennis balls are subjected to the ball approval process, conducted by the International Tennis federation's (ITF) Technical Commission, to ensure a minimum standard and consistency in ball performance. Balls must be approved annually, a list of which is published by the ITF [3], and the mass, size, rebound, deformation and durability of the ball are scrutinised against the standard tests defined in the ball approval specification [4].

The properties of tennis balls are known to degrade with use [5], consequently professional events outline a ball change policy to maintain a consistent level of ball performance during matches. It is commonplace that a set of six balls are in play at any given time. The first set of balls

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is used for the warm-up and the first seven games, with ball changes occurring every nine games thereafter.

Comparison of new and used balls has shown general trends in the change in properties of tennis balls. Used balls exhibited increased bounce height, mass reduction and reduced stiffness [6]. Mass reduction is dominated by a loss of felt and has been shown to increase with both impact speed and number of impacts [5]. The felt cover has been shown to degrade causing mass reduction and changes in fuzziness, in turn affecting the aerodynamic properties of the ball [7, 8]. Furthermore, it has been acknowledged that balls may fall out of specification during use if the initial properties were close to the allowable limits when approval tested [9].

Changes in material composition (felt and rubber), normal impact forces, contact distance and speeds are all relevant factors in tennis ball wear [8] and are determined by a combination of the pre-impact conditions (speed, angle and spin) and the surface interaction between the ball and court. To achieve an accurate representation of how a ball degrades during play it would appear necessary to simulate these phenomena as close as possible.

The ITF durability test was based on the typical ball change policy and sets out to determine if the ball in question can withstand the demands of nine games of professional tennis [6]. The test was established based on research into the properties of worn, unworn, new and used tennis balls, as well as investigating different methods to replicate changes in mass, rebound height and deformation in the laboratory [6, 9]. The test itself is twofold; 20 normal impacts at 40 m s^{-1} against a rigid surface to replicate softening, and 2 min of artificial felt wearing to replicate felt loss. Post-wear regime results for mass, size, rebound and deformation are compared to the initial test results for the balls in question and a maximum allowable change is defined [4]. The ball approval process is not surface-specific although it does accommodate for use at altitude and on different paced courts. Slight differences in specification are defined as type 1 (fast), 2 (medium), 3 (slow) and high-altitude balls designed for use slow, medium and fast-paced courts, respectively. Although the approved ball list is dominated by type 2 balls (with very few type 1 and no type 3 approved balls) [3], it is commonplace to see brands market balls as clay specific or suitable for all court surfaces.

Elements of what a tennis ball endures during its life span in professional tennis have been determined, particularly for matches played on hard court. Impact frequencies for serves, racket impacts and surface impacts and corresponding distributions for ball speed and surface impact angle were assessed by Lane et al. [10]. Similarly, Reid et al. [11] utilised ball tracking data from the Australian Open (2012–2014) comparing aspects of the men's and women's game. Lane et al. [10] found an average of 105 impacts per ball over nine games of professional tennis on hard court, of which, 40 were racket impacts and 53 were surface impacts, the remainder of which were serves. Notational analysis techniques have also been used to assess rally length [12] and strokes per game at the 2003 US Open [13]. Many studies assessing ball impact conditions during play aimed to measure in-play characteristics of specific impact scenarios to more realistically replicate a given scenario in the laboratory [14, 15]. Others aimed to measure a given parameter over time to assess if the nature of the game was changing [16, 17]. Choppin et al. [15] measured ball and racket parameters at the 2006 Wimbledon qualifying tournament to replicate typical values for a baseline top spin forehand shot in laboratory testing. Ball spin rates have also received much attention, mostly to ensure that spin rates were not greatly increasing over time and changing the nature of the game [16, 17]. Typical spin rates and spin axis for flat, slice and kick serves have also been analysed [18].

The ITF durability test fulfils its intended purpose of ensuring that manufactured balls meet the basic quality levels and minimum standards for ITF accreditation. However, a binary pass–fail test can only assess the degree of degradation against the correlated level of use. This is ineffective if the level of use is less than or greater than the correlated value. The ITF test, therefore, is not effective at determining degradation of ball performance over time, nor is it able to assess how long a ball remains within specification, due to its binary nature. While the ITF test has proven effective for maintaining minimum ball standards, it is unable to assess degradation in ball performance with use, across multiple surfaces and at representative impact speeds and angles.

A ball degradation protocol is, therefore, needed to determine ball longevity in the modern game. The results could then be used to evaluate ball degradation performance and influence changes in ball design and material composition. A new effective ball degradation test would be able to assess how long a ball remains within the approval specification, as well as assess the rate of ball degradation with use.

1.1 Aims

- Evaluate the current ITF durability test with respect to ball duress in modern tennis.
- Establish if there is a need for a surface-specific ball degradation test.
- Propose test conditions to enable ball evaluation for each surface type.

2 Methods

Ball tracking data collected by the automatic line-calling system (Hawk-Eye Innovations Ltd., Basingstoke, UK) from the following events were analysed:

- ATP 250 Thailand Open 2011–2013 [hard court (HC), indoor, male event];
- ATP 500 Gerry Weber Open 2011–2013 [grass court (GC), outdoor with retractable roof, male event];
- Roland Garros French Open 2011–2014 [clay court, outdoor, male (MC) and female (WC)].

The Hawk-Eye data analysed spanned all rounds of each event although men's and women's clay court data were limited to matches played on the two show courts, Court Phillipe Chatrier and Court Suzanne Lenglen. All the matches analysed were best of three set matches, apart from men's clay court matches which were best of five sets. Men's and women's clay data also comprised an additional year (2014). The Hawk-Eye system is calibrated to the dimensions of the court, utilising ten cameras (operating at 50–60 Hz) and corresponding software to track the three-dimensional Cartesian coordinates of the ball with respect to time. The system is officially accredited by the ITF (with a mean reported error of 2.6 mm [19]); however, it was not used as an officiating aid at Roland Garros; instead umpires checked the marks left on the surface by the ball to determine contentious line calls.

Each point had a file (.trj) containing the ball tracking information which was processed using a custom MATLAB (Mathworks, Natick, MA, USA) script. File nomenclature allowed the determination of the set, game and serve number (1st or 2nd) enabling the frequency of different impact events to be determined. The information contained enabled the reconstruction of ball position with respect to time, from which ball velocity was derived in the global X-, Y- and Z-axes. Ball position and speed were calculated at an arbitrary frequency of 1000 Hz in aid of
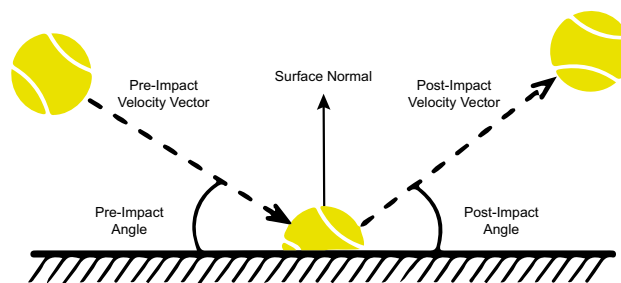

Fig. 1 Ball-surface impact schematic showing angles measured

three-dimensional visualisation. Serves (1st and 2nd), racket impacts (not including serves) and surface impacts were then isolated and the corresponding ball speed and, for surface impacts, angle pre-impact and post-impact were calculated. Ball speed on impact with the surface and racket were taken from the end point of the trajectories immediately pre and post where impact occurred; the specific value was calculated from the first derivative of ball position with respect to time. Surface impact angle was calculated using the dot product between the surface normal and the resultant velocity vector at the end of the trajectory (Fig. 1). Change in either ball speed or impact angle was defined as the post-impact value minus the pre-impact value. Checks were made to ensure the ball contacting the net was not counted as racket impacts. The data were split in terms of the type of impact (serve, racket impact and surface impact) which enabled ball speed for serves, surface impacts and racket impacts and impact angle for surface impacts to be analysed. The mean number of impacts per ball over nine games were deduced on a per match basis from the total number of the given impact scenario and the total number of games. The mean per surface was calculated in the knowledge that six balls were in play for a period of nine games for each event.

Checks were made to ensure the serve was the initial trajectory in each file. All serves, irrespective of legality, were included in the analysis along with additional surface

Table 1 Per surface totals (mean per match ± SD), where *HC* hard court, *GC* grass court, *MC* men's clay court and *WC* women's clay court

	HC	GC	MC	WC
Tournaments	3	3	4	4
Courts covered	1	1	2	2
Match length (best of)	3	3	5	3
Matches	65	69	168	161
Games	1505 (23 ± 6)	1528 (22 ± 7)	5659 (34 ± 10)	3257 (20 ± 6)
1st serves	9790 (151 ± 44)	9898 (143 ± 43)	36,448 (217 ± 66)	22,058 (137 ± 44)
2nd serves	3367 (52 ± 18)	3479 (50 ± 17)	13,621 (81 ± 28)	8071 (50 ± 18)
Racket impacts	40,240 (619 ± 249)	28,003 (406 ± 134)	150,922 (898 ± 336)	87,756 (545 ± 229)
Surface impacts	52,770 (812 ± 297)	41,010 (594 ± 184)	200,707 (1,195 ± 418)	118,432 (736 ± 286)

and racket impacts occurring after the point was won as these contribute to degradation of the balls. Surface impacts were also categorised into impacts post-serve (1st and 2nd), multiple bounce, bounce after net contact and other (including post-groundstroke) for further analysis. It was possible to split serves into first serves and second serves; however, it was not possible from ball tracking data alone to classify the type of stroke played such as forehand, backhand, top spin or slice, for example.

2.1 Statistical analysis

The mean frequency of games per match and the mean frequency of first serves, second serves, racket impacts and surface impacts per game were analysed using one-way ANOVA. Per match means for ball speed and impact angle were first tested for normality using the Shapiro–Wilk test before the per surface means were compared using either one-way ANOVA or Kruskal–Wallis non-parametric test, depending on the result of the normality test. Paired comparisons were conducted using the Bonferroni approach. Two-sample Kolmogorov–Smirnov tests were also utilised to compare the distribution of ball speed and impact angle between surfaces using an adjusted alpha value. All Shapiro–Wilk, ANOVA, Kruskal–Wallis and Bonferroni tests were conducted with a significance level, alpha, of 0.01, whereby a significant result was determined when the test statistic was less than alpha. Kolmogorov–Smirnov tests used an adjusted alpha value (alpha = 0.01 ÷ number of comparisons), to account for using a two-sample test.

3 Results

The mean number of games per match was highest for men's clay court matches at 34 (Table 1) and was significantly higher than the remaining data sets (Table 2). Clay court data (men's and women's) was comprised of an additional tournament's worth of matches in addition to coverage of two courts rather than one, resulting in the analysis of approximately 100 more matches for men's and women's clay than hard court or grass court (Table 1). Hard court, men's clay and women's clay had a total number of impacts between 105.5 and 107.3 per ball during nine games, of which approximately 52 were impacts with the court, 40 racket impacts, 4 s serves and 10 first serves (Fig. 2). Mean impacts per ball on grass court were much fewer at 81.7. The mean number of serves was similar to the other surfaces, but there were approximately 12 fewer racket impacts and 13 fewer surface impacts.

Mean first and second serve speed was fastest on grass court (1st: 53.21 ± 3.87 m s^{-1}; 2nd: 44.53 ± 3.83 m s^{-1})

Table 2 One-way ANOVA results for comparison of mean frequency per match or game

	Games/match		1st serves/game		2nd serves/game		Racket impacts/game		Surface impacts/game	
	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig
ANOVA result	$F(3,459) = 97.13$	<0.001*	$F(3,459) = 8.37$	<0.001*	$F(3,459) = 7.16$	<0.001*	$F(3,459) = 32.98$	<0.001*	$F(3,459) = 30.53$	<0.001*
Paired comparison	Sig	d	Sig	d	Sig	d	Sig	d	Sig	d
HC–GC	1	0.16	1	0.01	1	0.14	<0.001*	1.34	<0.001*	1.17
HC–MC	<0.001*	1.18	1	0.13	0.030	0.43	1	<0.01	1	0.07
HC–WC	0.055	0.50	0.028	0.38	<0.001*	0.55	1	0.02	1	0.12
GC–MC	<0.001*	1.29	1	0.14	.261	0.32	<0.001*	1.49	<0.001*	1.39
GC–WC	0.483	0.32	0.032	0.36	0.007*	0.46	<0.001*	1.32	<0.001*	1.32
MC–WC	<0.001*	1.67	<0.001*	0.54	.599	0.18	1	0.02	1	0.06

Where games per match is represented by games/match; 'F' is the ANOVA test statistic; 'Sig' is the significance value and 'd' is Cohen's d effect size

Denotes a significant result, Paired comparison results between surfaces given in the form 'HC–GC' where HC hard court, GC grass court, MC men's clay court and WC women's clay court

* Denotes a significant result

Fig. 2 Mean number of impacts per ball during nine games of use for each surface, split by impact type
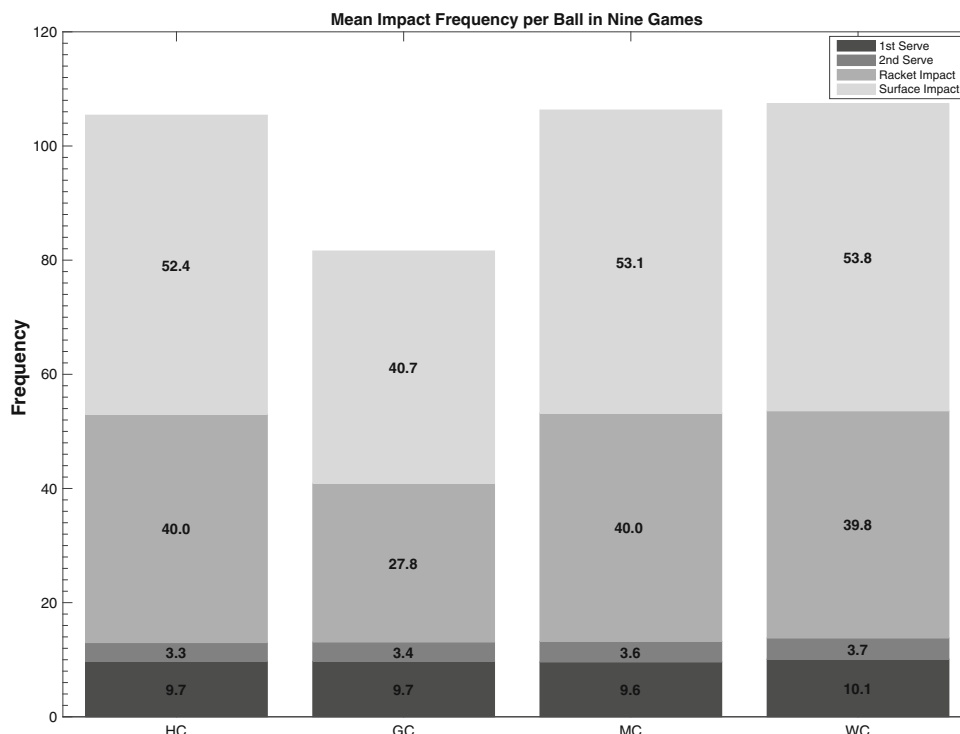
and slowest for women's clay court (1st: 44.36 ± 3.75 m s^{-1}; 2nd: 38.01 ± 3.45 m s^{-1}) (Fig. 3). Women's clay court mean serve speed was significantly slower than men's results for both first and second serve. All mean second serve speeds other than the comparison between hard court and men's clay were significantly different (Table 2). The range in men's mean serve speed was 1.24 m s^{-1} for first serve and 2.47 m s^{-1} for second serve.

Ball speed pre-racket impact was also fastest on grass court at 14.12 m s^{-1}, 1.52 m s^{-1} faster than both hard court and men's clay court, and 2.39 m s^{-1} faster than women's clay court. Post-racket impact grass court displayed the slowest mean speed, resulting in the smallest change in speed (post: 29.07 m s^{-1}; change: 14.95 m s^{-1}). The fastest mean ball speed post-racket impact was 31.53 m s^{-1} for men's clay court, resulting in the largest change in velocity of 18.93 m s^{-1}, consequently mean change in ball speed was 3.98 m s^{-1} greater on men's clay court than grass court (Fig. 4). Only two paired comparisons of mean ball speed during racket impacts were not significant, both of which were comparing hard court to men's clay court (pre-impact speed and post-impact speed) (Table 2). Pre-racket impact ball speed and change in ball speed were the only variables to return significantly different results when comparing the shape of the distributions (Table 3).

Mean ball speed pre-surface impact ranged by 1.71 m s^{-1} from 20.76 m s^{-1} for women's clay court to 22.46 m s^{-1} on grass court. Similarly, ball speed post-impact was fastest on grass court with a mean ball speed of 15.94 m s^{-1} and women's clay court was the slowest at 13.76 m s^{-1}, differing by 2.18 m s^{-1}. The ball reduced in speed due to impact by a mean of 6.69 m s^{-1}, 6.52 m s^{-1}, 7.06 m s^{-1} and 7.00 m s^{-1} on hard court, grass court, men's clay court and women's clay court, respectively (Fig. 5). Mean pre-impact angle was the only variable not deemed to differ significantly between surfaces (Table 2). The pre-impact mean ranged by 0.29° from 18.80° on grass court to 19.09° for women's clay court. A greater range was evident for post-impact angle (2.91°) from 21.41° on grass court to 24.34° for women's clay court. All surfaces exhibited a mean increase in angle (i.e. steeper) post-impact compared to pre-impact. Grass court displayed the smallest mean change in angle of 2.63° with women's clay court displaying the largest at 5.25°, a difference between surfaces of 2.62° (Fig. 6). Change in angle results were further analysed to investigate the cause of the large peak between 0° and 0.2° of change, prominent across all surfaces. Figure 7 shows the frequency distribution by impact type for this range.

3.1 Statistics results
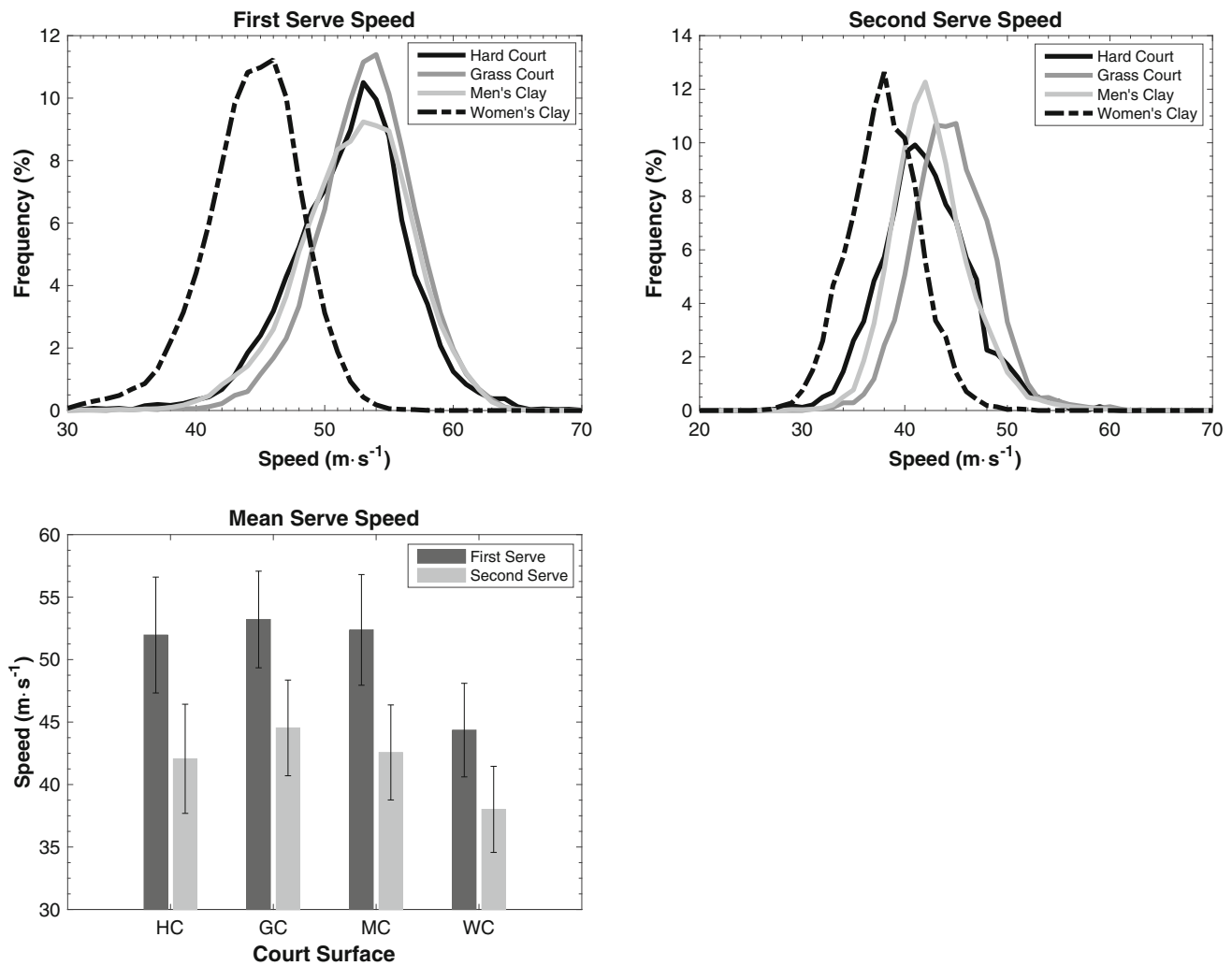
See Tables 2, 3 and 4.

Fig. 3 **a** First serve speed distribution; **b** second serve speed distribution; **c** Mean ± SD serve speed. Distribution bin size = 1 m s^{-1}

4 Discussion

The results of this investigation indicate the ITF durability test is not representative of play in modern professional tennis. The high-velocity impacts defined by the test only involve impacts with a smooth rigid surface, not representative of a surface on which professional tennis is played. The ball is not subjected to any impacts with a racket, be it under serve or groundstroke conditions. Subjecting the ball to 20 impacts is also significantly fewer than the mean number of surface impacts a ball endured on any surface, the least of which was 41 on grass court (Fig. 1). In total the mean number of impacts a ball endured during nine games ranged from 82 on grass court to 107 for women's clay court, resulting in a minimum difference of 62 impacts between in-play results and the number defined by the ITF durability test.

The impact speed and angle of pre-surface impact differs significantly between the ITF durability test and the in-

play results. The durability test impacts the ball at 40 m s^{-1}, normal to the target surface. Figure 6a indicates the majority of surface impacts (92%) have a pre-impact angle between 10° and 30°. Similarly Fig. 5a shows most surface impacts (84%) have a pre-impact speed less than 30 m s^{-1}. There are, however, a small proportion of impacts where the impact speed is in the region of 40 m s^{-1}. The high speed of these impacts would suggest they represent the first impact with the surface after the ball has been served; therefore, the angle at which these are occurring will be much less than the normal impacts used in the ITF durability test.

These differences between the ITF durability test and in-play results are likely to arise from the need to produce the minimum acceptable levels of degradation in a controlled, short and concise manner. After all the tests are designed to produce a known level of degradation and output a binary pass–fail result, it is not designed to replicate play itself, nor be able to determine ball quality over a set period of
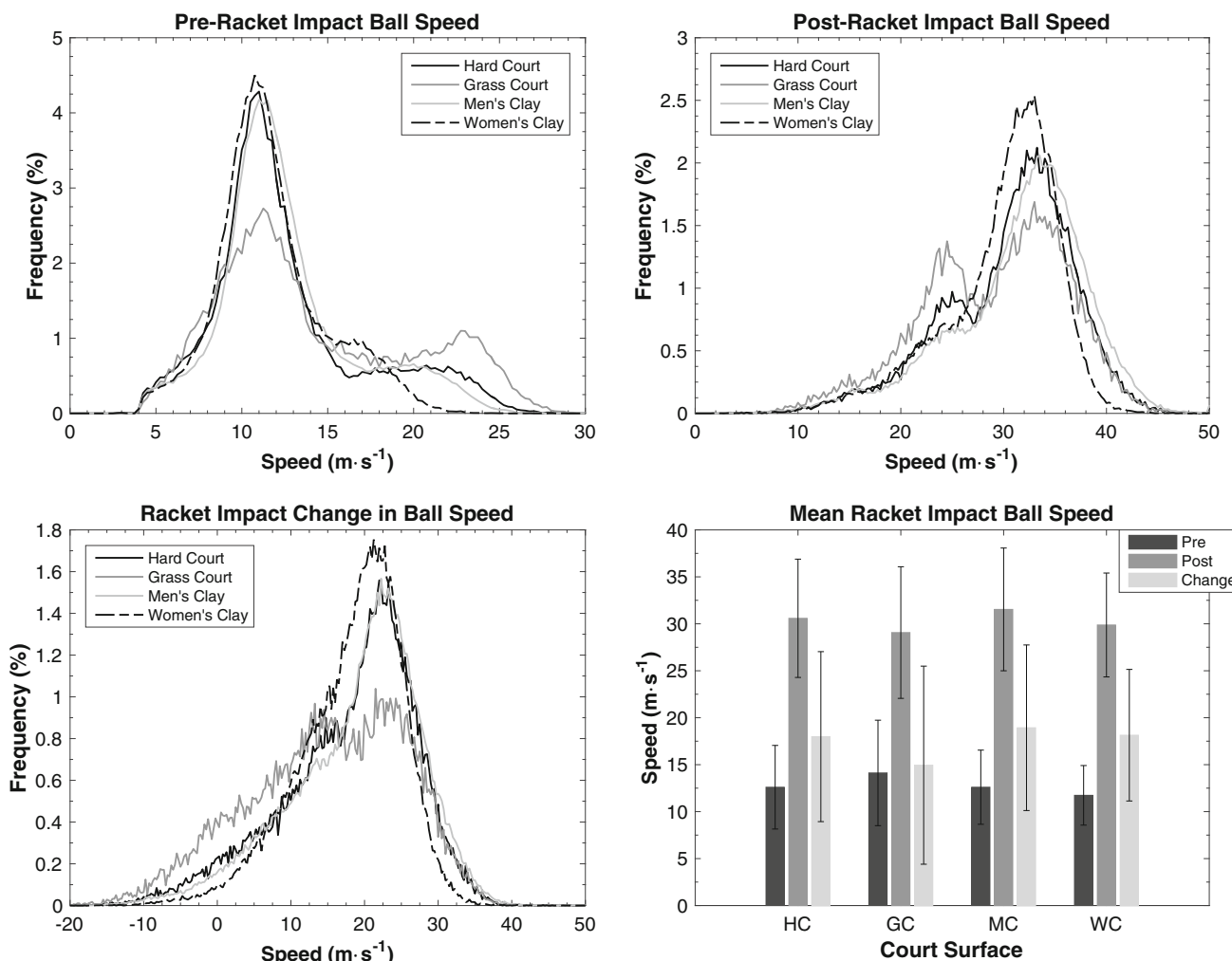
Fig. 4 a Distribution of ball speed pre-racket impact; **b** distribution of ball speed post-racket impact; **c** distribution of change in ball speed; **d** Mean ± SD ball speed pre-, post- and change for racket impacts. Distribution bin size = 0.25 m s^{-1}

real play. For the same reasons this investigation has established that the ITF durability test should not be used to evaluate ball degradation performance, indicating a new test is required to assess ball longevity and rate of degradation in a manner that correlates to modern professional play.

Having established the need for a new degradation test it is necessary to determine if a new test should be specific to the court surfaces used in professional tennis, particularly as brands market "clay" and "all court" variations of their balls. The most notable difference between surfaces was the mean number of impacts per ball for nine games of use (Fig. 2). Analysis of impact frequencies clearly showed the ball is subjected to fewer impacts during its life span on grass than it was on hard court or clay (men's or women's). The number of first and second serves was consistent across surfaces yet the ball was subjected to approximately 25 fewer impacts on grass than hard court or clay court; all of which were racket impacts and surface impacts rather

than serves. Table 2 highlights the significant differences and large effect sizes between grass court and the remaining surfaces for the number of racket and surface impacts per game. Consequently, rally length on grass court appeared shorter on average than on hard court and clay court (which appear very similar), resulting in shorter points. It also suggests that any given ball should be capable of enduring more games on grass than on hard court or clay, assuming the impact conditions are no more severe.

Variation in impact conditions were also found between surfaces. Women's first serve speed on clay was significantly slower than hard court, grass court and men's clay court results (Table 3). Mean first and second serve speed on hard court were both within 0.8 m s^{-1} of the results of Reid et al. [11] albeit the results of this investigation had larger standard deviations, likely a result of Reid et al. only including serves hit in play. Second serve speed results were much more variable, with all comparisons, other than

Table 3 Comparison of mean serve, racket impact and surface impact parameters between court surfaces with paired comparison post hoc results

Test result

	Serve speed		Racket impact ball speed		
	1st serve	2nd serve	Pre-	Post-	Change
Stat	F = 688.12	F = 207.85	χ² = 244.00	χ² = 203.33	χ² = 185.74
Sig	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*

Paired comparison (each cell: Sig / d)

Paired comparison	1st serve Sig	1st serve d	2nd serve Sig	2nd serve d	Pre- Sig	Pre- d	Post- Sig	Post- d	Change Sig	Change d
HC–GC	0.004*	0.61	<0.001*	0.96	<0.001*	1.53	<0.001*	1.35	<0.001*	1.73
HC–MC	1	0.17	1	0.17	1	0.16	<0.001*	0.86	1	0.70
HC–WC	<0.001*	4.03	<0.001*	1.90	<0.001*	1.41	0.006*	0.60	<0.001*	0.34
GC–MC	0.022	0.43	<0.001*	0.94	<0.001*	2.11	<0.001*	2.17	<0.001*	2.57
GC–WC	<0.001*	4.82	<0.001*	3.08	<0.001*	3.43	<0.001*	0.99	<0.001*	2.90
MC–WC	<0.001*	4.30	<0.001*	2.29	<0.001*	1.43	<0.001*	1.51	<0.001*	0.57

Test result

	Surface impact ball speed			Surface impact angle		
	Pre-	Post-	Change	Pre-	Post-	Change
Stat	χ² = 190.36	χ² = 289.04	χ² = 164.50	F = 1.62	F = 167.70	F = 479.71
Sig	<0.001*	<0.001*	<0.001*	.185	<0.001*	<0.001*

Paired comparison (each cell: Sig / d)

Paired comparison	Surface impact ball speed Pre- Sig	Pre- d	Post- Sig	Post- d	Change Sig	Change d	Surface impact angle Pre- Sig	Pre- d	Post- Sig	Post- d	Change Sig	Change d
HC–GC	<0.001*	0.67	<0.001*	1.01	0.048	0.75	–	–	<0.001*	1.79	<0.001*	2.31
HC–MC	0.003*	0.49	1	0.07	<0.001*	1.21	–	–	<0.001*	1.10	<0.001*	1.38
HC–WC	<0.001*	1.12	<0.001*	1.99	<0.001*	1.08	–	–	<0.001*	1.19	<0.001*	1.92
GC–MC	1	0.30	<0.001*	1.23	<0.001*	1.90	–	–	<0.001*	3.04	<0.001*	5.38
GC–WC	<0.001*	1.90	<0.001*	3.31	<0.001*	1.78	–	–	<0.001*	2.76	<0.001*	5.99
MC–WC	<0.001*	1.75	<0.001*	2.40	1	0.14	–	–	0.011	0.34	<0.001*	0.76

'Stat' represents the test statistic; either 'F' for one-way ANOVA comparison of means or 'χ²' for Kruskal–Wallis non-parametric comparison of means

'Sig' represents the significance value where '*'denotes a significant result, 'd' represents Cohen's d effect size. Paired comparison results between surfaces given in the form 'HC–GC' where HC hard court, GC grass court, MC men's clay court and WC women's clay court
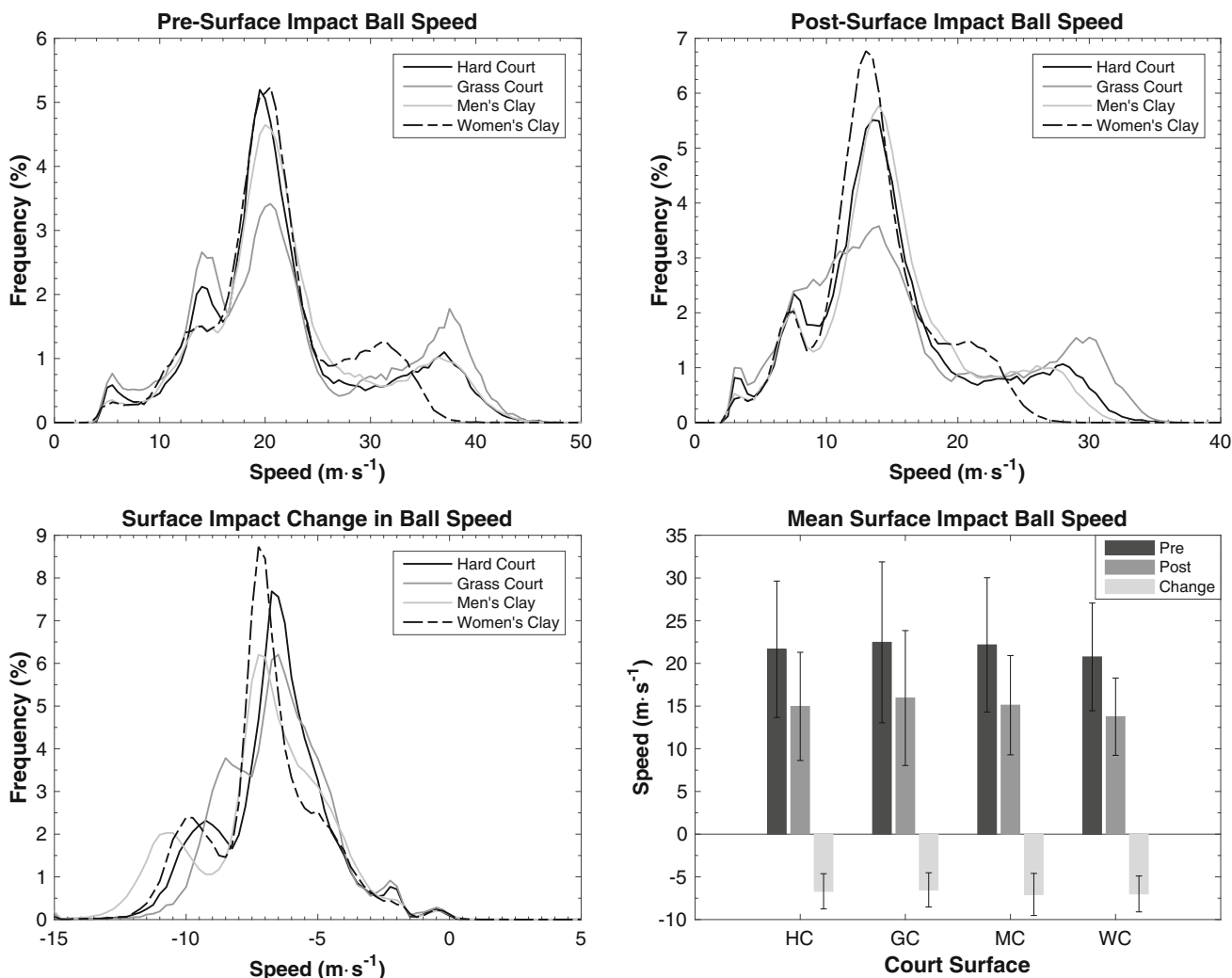
Fig. 5 a Distribution of ball speed pre-surface impact; **b** distribution of ball speed post-surface impact; **c** distribution of change in ball speed; **d** Mean $\pm$ SD ball speed pre-, post- and change for surface impacts. Distribution bin size $= 0.5$ m s^{-1} for pre- and post-impact, 0.25 m s^{-1} for change in speed

hard-court men's clay court comparison, found to have significantly different means.

Although the surface has no physical influence on impact between the racket and the ball whilst serving, it may influence serve tactics, resulting in differing speeds and levels of spin. Sakurai et al. [18] identified a clear trade-off between ball spin rate and velocity for different types of serve. This finding could be evident here with players attempting to maximise the effectiveness of the second serve by opting for faster, flatter serves on grass as this is perceived to be the fastest paced surface on tour [20]. Different serve strategies may lead to differences in the rate of ball degradation between surfaces.

Ball speed for racket impacts showed the most variation in results across surfaces and provided the only variables with significantly different distributions between surfaces (pre-racket impact ball speed and change in ball speed,

Table 4). Many statistical differences between means further highlighting the variation found between surfaces for ball speed pre- and post-racket impact. Mean post-impact ball speed for hard court (30.6 ± 6.3 m s^{-1}), however, was very similar to that of mean groundstroke speed from the Australian Open (30.9 ± 1.5 m s^{-1}) [11]. Results from Choppin et al. [15] indicated faster post-racket impact ball speed (33.9 ± 5.0 m s^{-1}) than the mean grass court result (29.1 ± 7.0 m s^{-1}), albeit standard deviations overlap. The results from Choppin et al. [15] were taken during practice conditions rather than in play and confined to a 2 m^3 capture volume at the baseline; however, they were able to measure racket velocity, finding a modal velocity of 28 m s^{-1}, ranging from 17 to 36 m s^{-1} for male players.

Ball speed during surface impacts was similar in nature to racket impacts in that many differences in mean ball speed were found between surfaces (Table 3). The
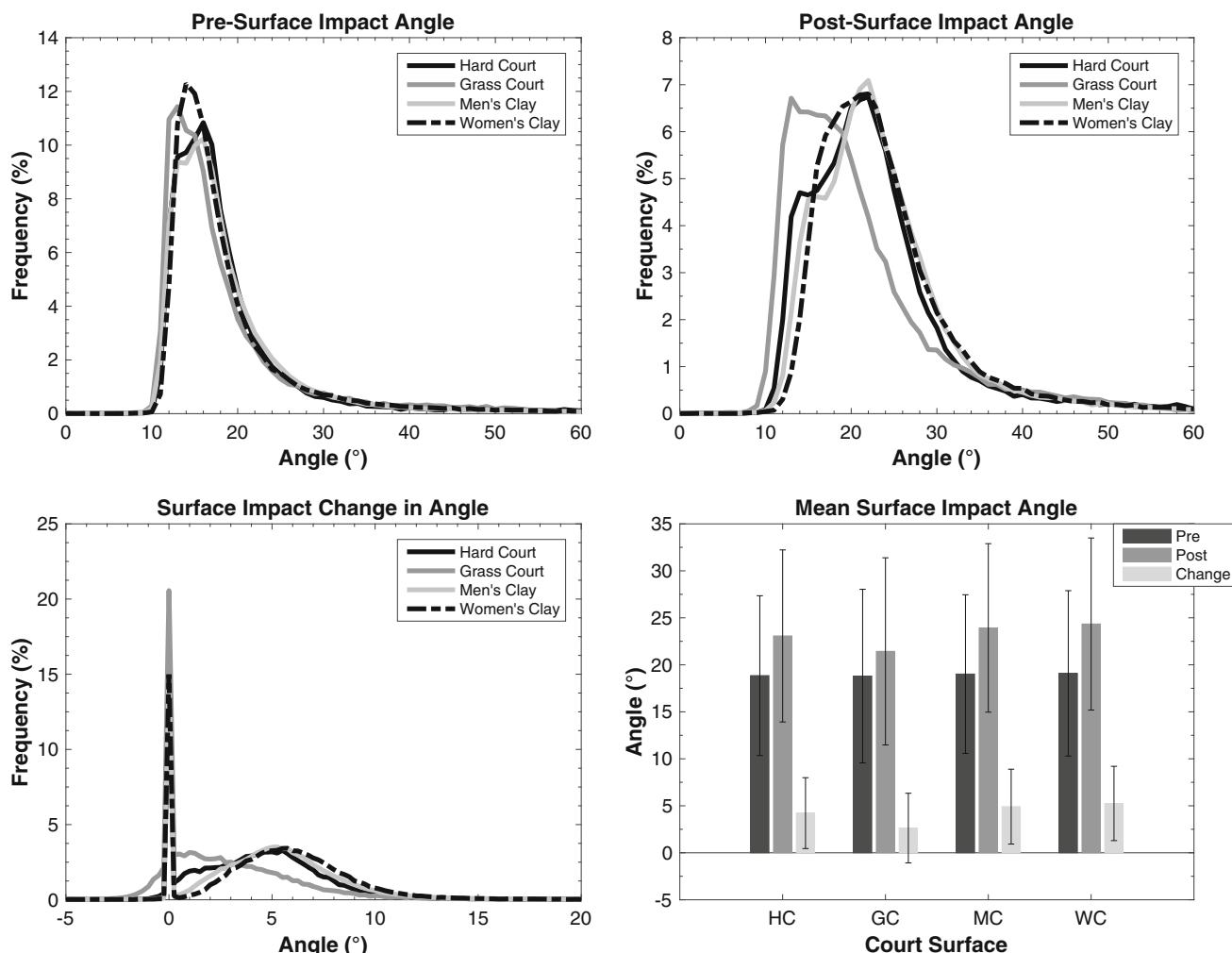
Fig. 6 **a** Distribution of angle pre-surface impact; **b** distribution of angle post-surface impact; **c** distribution of change in angle; **d** Mean ± SD angle pre-, post- and change for surface impacts. Distribution bin size = 1° for pre- and post-impact, 0.25° for change in angle

distribution of ball speed was not found to differ significantly, however, in the same manner as for racket impacts, albeit distribution of ball speed for grass court results differ most when compared visually (Fig. 5). Subtle differences were found between surfaces indicating grass court slowed the ball down the least on impact (6.52 m s^{-1}), followed by hard court (6.69 m s^{-1}) and then clay court (men's: 7.06 m s^{-1}; women's: 7.00 m s^{-1}).

Mean pre-impact angle only ranged by 0.29° across surfaces, yet the post-impact value increased to 2.91° (Fig. 6). Statistical tests supported this finding and revealed no significant difference between pre-impact angle whilst all but one paired comparison was not significant for all comparisons of post-impact angle and change in angle (Table 3). Distribution of angle prior to impact is very similar across all court surfaces, yet these distributions become misaligned post-impact, consequently, the ball appeared to interact differently across the major surfaces used in professional tennis.

When assessing the change in angle distribution a large peak was present across all surfaces between 0° and 0.2° of change. Even though the ball having a similar inbound to outbound angle with the surface is not an abstract concept, the nature of the peak appeared somewhat artificial. Figure 7 shows all change in angle results within this range of interest as a function of impact type. A low percentage of these impacts were from surface impacts occurring directly from the serve (3.1%) and were from impacts with the surface caused by the ball dropping to the floor after contact with the net (6.4%). A reasonable proportion was from the ball bouncing consecutively with the surface without any contact from a player's racket or the net (23.5%).

The majority (67%), however, termed 'other', are from impacts with the surface from a subsequent groundstroke, indicating many impacts occurred with the surface whereby the change in angle was less than 0.2°. As such a high percentage of impacts fell within this window, combined with visualising the distribution of the peak by

Fig. 7 Change in angle by impact type where the change in angle is between 0° and 0.2°. Percentage of all impacts where change in angle is between 0° and 0.2° given in brackets in the legend. 'Other' results on *secondary axis*. Distribution bin size = 0.002°
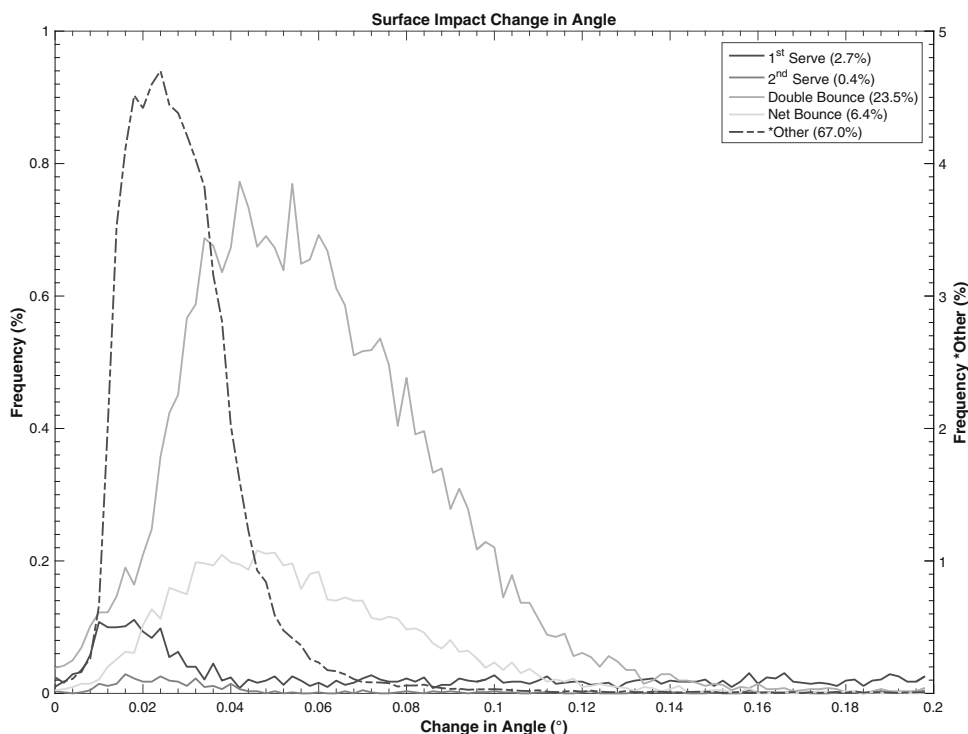

Table 4 Significance values for two-sample Kolmogorov–Smirnov comparison of distributions (significant results only)

Comparison	Racket impact ball speed	
	Pre-	Change
HC–GC	<0.001*	–
HC–WC	–	0.001*
GC–MC	<0.001*	–
GC–WC	–	<0.001*
MC–WC	–	0.001*

* denotes signifcant result

Paired comparison results given in the form 'HC–GC' where *HC* hard court, *GC* grass court, *MC* men's clay court and *WC* women's clay court

impact type, it would appear the result is genuine. It is worth noting that the files analysed are comprised of polynomial curves fitted to the raw tracked points of the ball with time and are not comprised of the raw data itself, which may induce a degree of error. A further investigation using an alternative measurement method may be necessary if a higher level of accuracy was required.

The differences in results comparing ball speed and impact angle across the major surfaces used in professional tennis indicate that any new degradation test may benefit from being specifically adapted to the desired surface. This is most prevalent if the surface in question is grass as the racket and surface impact frequencies were found to be significantly less than that on hard court and clay court. In turn this appears to slightly affect the distribution of ball speed on impact as serves and bounces directly after serves have a larger representation than they do on hard court or clay court, warranting the possible need for a surface-specific degradation test.

It is proposed a new degradation test is required to enable the assessment of ball longevity and rate of ball degradation with use, correlated to professional play. Consequently, it is deemed that the new test must better replicate the impact conditions experienced during play than the ITF durability test, whilst offering a test length in terms of number of games rather than a pass–fail result. The proposed test should try to match, as closely as possible, the court surface, number of impacts of each impact type and the corresponding impact conditions for ball speed and impact angle. Table 5 shows a proposed new durability test whereby the ball is subjected to impact frequencies and conditions matching that found in this investigation. For simplicity, the ball speed and surface impact angle have been stated as a mean±one standard deviation. To replicate the conditions seen in-play more precisely, the distributions of ball speed and impact angle could be represented more closely. Racket impacts would most likely be replicated using a fixed racket and ball cannon. Ball speed post-racket impact and ball speed and angle post-surface impact could be monitored and compared to the corresponding results of

Table 5 Proposed new durability test conditions based on analysis of impact conditions and frequencies, equating to nine games of use

Impact type	Surface-specific test conditions			
	Hard court	Grass court	Clay court (men's)	Clay court (women's)
1st serve: post-impact ball speed	10 @ 52 ± 5 m s^{-1}	10 @ 53 ± 4 m s^{-1}	10 @ 52 ± 4 m s^{-1}	10 @ 44 ± 4 m s^{-1}
2nd serve: post-impact ball speed	3 @ 42 ± 4 m s^{-1}	3 @ 45 ± 4 m s^{-1}	4 @ 43 ± 4 m s^{-1}	4 @ 38 ± 3 m s^{-1}
Racket impacts: pre-impact ball speed	40 @ 13 ± 4 m s^{-1}	28 @ 14 ± 6 m s^{-1}	40 @ 13 ± 4 m s^{-1}	40 @ 12 ± 3 m s^{-1}
Surface impacts: pre-impact ball speed and impact angle	52 @ 22 ± 8 m s^{-1} 19° ± 8°	41 @ 22 ± 9 m s^{-1} 19° ± 9°	53 @ 22 ± 8 m s^{-1} 19° ± 8°	54 @ 21 ± 6 m s^{-1} 19° ± 9°
Total	105	82	107	108

Includes the number of impacts and the mean ball speed (±1 standard deviation) for each impact type and mean impact angle for surface impacts

this investigation to validate if the test is matching that of in-play.

The findings of this investigation are not without limitations, one of which is the nature of the data set whereby it is specific to only one event per surface, played over consecutive years. It is, therefore, not possible to assume that these results are truly representative of tennis played on each surface in general. While the events were all professional tour events, they were not all of the same standing or match length, which could influence the quality of the players on show as not all players compete in all events. There is also the matter of players prioritising events, such as grand slams, over smaller less prestigious events. Furthermore, the data will naturally be skewed towards the individuals who contributed most to the data set. As the event followed a knockout style, players who made it furthest through the event were involved in more matches, resulting in an overrepresentation of those players. Similarly, the same players did not necessarily compete in the event across all years, nor did they necessarily compete across all the events analysed, adding variation to the results. The type of data analysed is also limited in what can be extracted from it. Parameters relating to the racket (speed, impact angle and contact location) and ball spin could not be determined from ball tracking alone.

Future investigations should look to determine the frequency distribution of racket parameters (impact velocity and angle) and ball spin during professional play. The addition of these parameters to the ball speed and angles analysed in this investigation would provide a more complete picture of what a ball endures during play; enabling a more representative degradation test whilst potentially highlighting any differences between surfaces and further supporting the need for a surface-specific test. It may be possible to accurately estimate racket and ball spin parameters based on pre- and post-impact speed and angle

of the ball, removing the need for further data capture using alternative measurement systems.

5 Conclusions

Ball tracking information has been utilised to determine that the ITF degradation test is ineffective for assessing the degradation performance of tennis balls except, when determining basic quality levels and minimum standards for ITF accreditation. The ITF test is an accelerated aging test; consequently, it cannot be used to determine ball longevity and rate of degradation in a manner that correlates to modern professional play, warranting the need for a new degradation test.

Comparison of ball speed and impact angles across the four major court surfaces used in professional tennis indicated that any new degradation test would benefit from being specific to the court surface. Particularly if the surface of interest is grass due to the fewer impacts the ball was subjected to and the effect of the different composition of serves, racket impact and surface impacts on the distribution of ball speed during pre- and post-impact.

A new degradation test protocol, specific to each surface, has been proposed based on the findings of this investigation. The proposed test is correlated against in-play findings enabling the assessment of ball longevity and rate of degradation. The new test may benefit further from the addition of ball spin racket trajectory information.

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