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Interspecific comparisons of C_3 turfgrass for tennis use: II. Investigation of ball friction, ball bounce, and associated factors in replicated grass courts

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Abstract

Tennis is played on many different surfaces including natural grass, which plays fast because of low ball bounce (i.e., coefficient of restitution [COR]) and low ball-to-surface friction (coefficient of friction [COF]) that increase the pace (ball speed) of tennis. Effects of various C_3 turfgrasses on COF and COR have not been investigated. Our objectives were to evaluate eight cultivars of various species randomized within three official size tennis courts: (a) 'Keeneland' Kentucky bluegrass (*Poa pratensis* L., KB), (b) 'Rubix' KB, (c) 'Villa' velvet bentgrass (*Agrostis canina* L., VBG), (d) 'Puritan' colonial bentgrass (*Agrostis capillaris* L., CL), (e) '007' creeping bentgrass (*Agrostis stolonifera* L., CB), (f) fine fescue (*Festuca* sp., FF) mixture, (g) 'Karma' perennial ryegrass (*Lolium perenne* L, PR), and (h) 'Wicked' PR. Friction was measured using a weighted sled and ball bounce (BB) to derive COR was measured using a vertical drop height of 254 cm. Bounce (i.e., COR) to satisfy the International Tennis Federation (ITF) minimum of 50% BB (COR = 0.70) was not observed on any of the species evaluated. Species such as FF and PR were able to achieve BB to satisfy the ITF 80% BB minimum to that observed on smooth concrete. Linear regression indicated that 170g of surface hardness for FF and PR to as much as 200g on KB and higher on BG may be needed to achieve a COR = 0.70. Hemi- and lignocellulose cell wall fractions were correlated with COR and COF but exhibited significant and opposite relationships. Achieving higher COF may be a more practical means to slow court pace of notoriously fast grass courts. Future research will be needed to investigate the effects of cultural practices on COF.

Abbreviations: AB, annual bluegrass; BB, ball bounce; BG, bentgrass; CB, creeping bentgrass; CL, colonial bentgrass; COF, coefficient of sliding friction for tennis ball; COR, coefficient of restitution; CPR, court pace rating; FF, fine fescue; hemi, hemicellulose; HOC, height of cut; ITF, International Tennis Federation; KB, Kentucky bluegrass; LCC, Longwood Cricket Club; ligno, lignocellulose; PR, perennial ryegrass; TDR, time domain reflectometry; VBG, velvet bentgrass; VWC, soil volumetric water content.

1 | INTRODUCTION

There are as many as 14.68 million participants playing tennis in the United States (TIA, 2018). Unlike other sports, tennis is played on many different surfaces including natural grass, clay, and acrylic/asphalt (hard court), with >160 different surfaces and types available for tennis play (Lehrer, 2011). Each surface can influence play because of variations in ball bounce (BB; i.e., coefficient of restitution, COR) and ball-to-surface interaction due to friction (coefficient of friction, COF) that affect the pace (ball speed) at which tennis is played. These coefficients are affected by surface type, moisture, grass type, level of wear, and weather.

The International Tennis Federation (ITF) uses the Sestée, which is capable of measuring court pace using photometric analysis and theoretical models, to calculate COR and COF from tennis balls projected onto the court surface (ITF, 2019; CS 01/02). The Sestée device is expensive and not very portable, requires trained individuals to operate, and is also limited by grass height of cut because of the height of the optical sensors. As such, alternative methods have been proposed to measure friction and restitution (Goodwill, Haake, Spurr, & Capel-Davies, 2008). Researchers have used friction sleds, where a weighted sled with fixed tennis balls are in contact with the court surface and towed at a constant speed. Friction coefficients can be measured simply as the ratio of the horizontal force (N) required to move a ball across a surface to the total normal force (weight) on the sled (Brody, 1984; Cross, 2010). This simple method has been used to measure COF of a surface to tennis balls (Thorpe & Canaway, 1986a) and cricket balls (Adams, Baker, James, & Young, 2005; James, Carré, & Haake, 2005). As suggested by Cross (2005, 2010), however, friction sleds may not provide COF measurements equivalent to photometric analysis of the Sestée because the ball speed and contact area can be different from actual playing conditions.

Typical COF values using various methods are 0.49–0.70 for hard courts (Brody, 1984; Brody, Cross, & Lindsey, 2002; Cross, 2003), 0.60 for grass courts (Cross, 2003), and 0.80 for clay courts (Brody et al., 2002; Cross, 2003). Higher COFs slow ball horizontal velocity after impact, resulting in slower court pace. Therefore, grass courts can exhibit faster pace because of their lower COF, and clay courts are slower because of their higher COF. Significant variations in COF for hard courts and grass courts are observed (Thorpe and Canaway, 1986a) because of variations in the roughness of these surfaces due to the different types of hard courts (45 different types; Lehrer, 2011) and numerous grass species and their maintenance (Newell & Wood, 2000; Newell, Crossley, & Jones, 1996) that may affect friction. To our knowledge, studies directly comparing the effect of different species on COF have not been conducted.

Core Ideas

- Coefficient of restitution (COR) and surface friction in tennis have received little attention.
- Perennial ryegrass and fine fescue were the highest in COR among eight turf species evaluated.
- Bentgrass species were among the highest in surface friction.

The COR is derived from ball rebound height and requires fresh tennis balls to be released from a standard height of 254 cm (100 inches). Coefficient of restitution is expressed as the square root of the ratio of rebound-to-drop height. Higher COR indicates higher rebound height, allowing more time between successive bounces that slow play and court pace. Grass surfaces are less rigid (softer) than other surfaces (clay and hard court) with lower COR, which gives the player less time to complete their stroke in relation to the net and therefore play faster. Coefficient of restitution measured by ITF may range on grass from 0.60 to slightly below 0.90 (ITF average = 0.73), from 0.73 to 0.90 on clay (ITF average = 0.83), and from 0.73 to 0.95 on hard court (ITF average = 0.80) (Fog Mountain Tennis, 2014).

Surfaces with a COR less than 0.70 are not recommended for use as tennis courts (Cross, 2010; ITF, 2019). Restitution of 0.70 is equivalent to BB of ~50% of the drop height ($0.70^2 = 0.49$ or ~50%). Typical COR for grass may be <0.70, with restitution ranging from 0.65 to 0.69 (Thorpe & Canaway, 1986a) to as low as 0.50 (Thorpe & Canaway, 1986b) to 0.60 (Pallis & Mehta, 2000). As noted by Cross (2003), this variation in COR indicates the condition of the grass and the underlying soil and the role that soil moisture and soil compaction or hardness may play. The previously cited research on COR did not compare species or offer details on the maintenance practices used, which needs further investigation. For example, the work conducted by Thorpe and Canaway (1986a, 1986b) and Pallis and Mehta (2000) consisted of bermudagrass [*Cynodon dactylon* (L.) Pers.] overseeded with *Festuca rubra* L. var. *commutata* Gaudin and *Lolium perenne* L.

Holmes and Bell (1986) and Baker and Isaac (1987) reported a strong correlation between BB and soil hardness measured as gravities using the Clegg impact soil tester (Clegg, 1976). The Clegg impact soil tester using a 0.5-kg missile has been shown to be most effective with players' perception of surface hardness (Canaway, Bell, Holmes, &

Baker, 1990) and most sensitive to the presence of verdure that varies with the species (Rogers & Waddington, 1993). Soil moisture and soil hardness have been shown to be inversely related in lawn tennis (Newell & Wood, 2000) and other sport surfaces (Brosnan, McNitt, & Serenstis, 2009). Holmes and Bell (1986) measured soil hardness and BB on nine grass tennis courts. Soil hardness ranged from 40*g* to 200*g*, which varied with the level of play (i.e., wear) and soil compaction. In this study, it was found that soil hardness on good-quality grass courts range from 124*g* at the side lines with a COR of 0.66 (43% BB) to 208*g* at the baselines with a COR of 0.73 (53% BB). Holmes and Bell (1986) found an 8% increase in BB per 50*g* increase in soil hardness. Furthermore, Newell and Wood (2000) reported a 5.5*g* increase in soil hardness per 1% decrease in soil moisture. The relationship between BB (COR) and soil hardness is likely to vary with the species and soil moisture. Further research is needed to investigate the covariation of soil moisture and soil hardness on COR, which has not been investigated at the species level.

The objectives of Part 2 of this companion study were (a) to evaluate six different turfgrass species (eight turfgrass species–cultivar combinations) at the interspecies level for their ball-to-surface friction and restitution maintained as grass tennis courts, (b) to investigate the variation of soil hardness on COR to develop appropriate soil hardness recommendation at the species level to achieve ITF standard for restitution of 0.70 (BB ≈ 50%), (c) to evaluate cell wall components from Part 1 of this companion study (Ebdon, James, DaCosta, & Lu, 2020) as they relate to COF and COR, and (d) to calculate court pace ratings (CPR, slow to fast) at the species level according to ITF guidelines (ITF, 2019) derived from measured friction (COF) and restitution (COR).

2 | MATERIALS AND METHODS

2.1 | Treatments, grass court setup, and maintenance

Detailed descriptions of the experimental design and construction of three grass tennis courts are provided in Ebdon et al. (2020). As such, only a brief description will be provided here. Three official-size single courts were constructed at the Joseph Troll Turf Research and Education Center in South Deerfield, MA. Grass tennis courts were established on Hadley silt-loam (coarse-silty, mixed, superactive, nonacid, mesic, Typic Udifluents) characterized as 23.5% sand, 63.8% silt, and 12.7% clay.

Single courts followed recommended court dimensions (23.77 × 8.23 m, length × width, respectively). Eight different species–cultivars were planted on 17 May 2016 as main plots. All main plots measured 13.41 × 2.06 m with sufficient grass area between the service line and net for measurements in the service box (i.e., minimal-wear area). The following eight species–cultivars were randomized within the three courts (replicates as blocks): (a) 'Keeneland' Kentucky bluegrass (*Poa pratensis* L., KB), (b) 'Rubix' KB, (c) 'Villa' velvet bentgrass (*Agrostis canina* L., VBG), (d) 'Puritan' colonial bentgrass (*Agrostis capillaris* L., CL), (e) '007' creeping bentgrass (*Agrostis stolonifera* L., CB), (f) fine fescue (FF) mixture consisting of approximately 60–40% (by weight) 'Bridgeport II' Chewings fescue (*Festuca rubra* var. *commutata*) and 'Barcrown' slender creeping red fescue (*Festuca rubra* ssp. *littoralis* Vasey ex Beal), (g) 'Karma' perennial ryegrass (PR), and (h) 'Wicked' PR.

Grass courts were mowed at 8-mm height of cut (HOC) and were maintained at this HOC from 2017 to 2019. Courts were mowed daily and immediately before any measurements. Beginning in 2017, courts were rolled three to four times per week using a 1,000-kg roller (3.05-m length and 0.254-m diam.; Smithco, Ultra Fairway Roller) to maintain uniform BB and firmness. Courts were fertilized using foliar and granular N corresponding to total N of 166.5, 162, and 102 kg ha^{-1} in 2017, 2018, and 2019, respectively. All plots were treated uniformly with preventative fungicides, insecticides, and herbicides to maintain uniform and actively growing turf.

2.2 | Coefficient of restitution

Coefficient of restitution was derived directly from tennis ball vertical rebound height (BB) after impact using a 254-cm (100-inch) drop height where BB = rebound height/drop height and COR = (BB)$^{1/2}$. According to ITF rules (ITF, 2019) the tennis ball rebound height after impact with the surface was measured from the bottom of the ball. Before the ball rebound-to-drop height ratio was measured on grass court main plots, BB (COR) was first measured on smooth concrete using fresh (Type 2) tennis balls (Wilson, U.S. Open Grass Court) in order to satisfy ITF rule that BB off smooth concrete for new tennis balls must range from 53 to 58% (COR = 0.73 to 0.76, respectively).

New (fresh) tennis balls (Type 2, Wilson, U.S. Open Grass Court) were used every 12 bounces or impacts during the study. Three BB measurements, which were normal (vertical to the surface) after impact, were measured on main plots and smooth concrete. All measurements of BB on main plots were made within the service area (minimal-wear areas) when main plots were free of any surface moisture. Grass courts were mowed and rolled during the morning hours the day BB was measured. Three

BB subsamples were used to calculate COR on each main plot and averaged before data analysis. Coefficient of restitution derived from BB was measured on nine dates in 2018 (3, 10, 16, 24, and 31 July; 7, 15, 20, and 27 August) and 10 dates in 2019 (4, 14, 20, and 28 June; 5, 10, 15, and 26 July; 2 and 6 August).

2.3 | Tennis ball coefficient of friction

Sliding (dynamic) friction between the tennis ball and the grass court surface was measured using a friction sled similar to that described by Adams et al. (2005), Thorpe and Canaway (1986a), and James (2005). The triangular shaped friction sled used in the current study allowed tennis balls to be fitted (clamped) between two plates with tennis balls positioned at each apex. The friction sled was pulled parallel to the court surface at a constant speed (0.7 m s^{-1}) using pulleys and a constant speed electric motor (Kaman Automation). The sled was weighted with a normal force of 111.3 N (11.35 kg barbell plate) and the total weight (sled + weight) on the tennis balls was 12.23 kg (120.0 N). The weight was positioned on the sled with a location pin attached to the sled. The friction sled was placed on a polished stainless steel surface of low static friction (0.208 ± 0.004, mean ± SE) to eliminate the higher static friction of initiating movement on grass. All three tennis balls of the sled were in contact with the grass surface over a measurement length of 100 cm. The horizontal force (N) required to maintain motion of the weighted sled was measured using a digital force gauge (C.S.C. Force Measurement) with a digital accuracy of ±0.5%. The coefficient of sliding friction (COF) of the weighted sled on the grass surface was calculated as follows: measured force (N) to maintain horizontal motion/120.0 N (normal force) on the sled.

In 2018 and 2019, two COF measurements were made on each main plot. All COF measurements were made on the same day as BB (COR) and within the service area. Measurements were taken in the afternoon when main plots were dry and after courts were mowed and rolled. The friction sled was pulled by the electronic drive in opposite directions and from opposite ends of the service area (between the service line and net). The friction sled was pulled in a direction parallel to the sideline of the single court. New (fresh) tennis balls were used and then rotated on the friction sled between replicated courts. The two COF subsamples to measure sliding friction were averaged before data analysis. Coefficient of sliding friction was collected on five dates in 2018 (30 July; 6, 17, 21, and 28 August) and on 10 dates in 2019 (4, 14, 20, and 28 June; 5, 10, 15, and 26 July; 2 and 6 August).

2.4 | Court pace rating

Court pace rating was derived (calculated) directly from COR and COF measurements according to ITF calculations (ITF, 2019) for court pace (CS 01/02):

$$\text{CPR} = 100\,(1 - \text{COF}) + 150\,(0.81 - \text{COR}) \quad (1)$$

where the multiplier 150 is the pace perception constant and 0.81 is the mean COR for all surface types measured by ITF. Court pace rating categories according to ITF are as follows: slow (CPR ≤ 29); medium-slow (CPR 30–34), medium (CPR 35–39), medium-fast (CPR 40–44), and fast (CPR ≥ 45). Court pace ratings were calculated on five dates in 2018 and 10 dates in 2019.

2.5 | TDR soil volumetric water content and court hardness

Soil volumetric water content (VWC) using time domain reflectometry (TDR, Trase System I, Soilmoisture Equipment Corporation) was measured in all years (2018, 2019) and on the same dates in both years as COR measurements. Rod lengths were 7.5 cm, and three TDR measurements were made on each main plot and then averaged. Surface hardness was measured as the peak deceleration (unit of gravities, *g*) of plots using a Clegg impact soil tester equipped with a 0.5-kg missile (Lafayette Instruments) (Clegg, 1976).

Hardness measurements were taken on the same dates in both years (2018, 2019) as COR. Three measurements were made on each main plot and on all courts and then averaged before analysis.

2.6 | Related measurements

Measurements such as shoot density (aerial shoots cm^{-2}), total cell wall content (TCW), hemicellulose (hemi), and lignocellulose (ligno) were previously described and presented in part 1 of this companion study (Ebdon et al., 2020). These measurements are also discussed as part of the current study, as they relate to court pace (COF, COR).

Measurements of COR, COF, and surface hardness described in sections above were also measured at Longwood Cricket Club (LCC, Chestnut Hill, MA) on 17 Aug. 2019. Three court surface types were measured, including PR (blend of Karma + Wicked), annual bluegrass (AB, *Poa annua* L.), and one clay court. Grass courts at Longwood were mowed at the same HOC as our current study (8 mm). Twelve samples of each measurement were taken on each court surface. In addition, measurements were taken from two areas of an AB court where (a) the grass along the baseline was worn to ∼30% cover, and (b) from an area worn to no grass cover (i.e., bare soil).

2.7 | Statistical analysis

Eight species and associated cultivars were randomized within the three individual grass courts (replicates) and analyzed as randomized complete blocks. Subsamples taken on main plots were averaged, and ANOVA was performed on those averages using Minitab. Sum of squares for all reported data including COF, COR, CPR, and soil hardness were partitioned into single-df orthogonal contrasts to test for interspecific difference between the combined means of various species.

Seven single-df orthogonal contrasts were computed and are reported in tables as follow: FF mixture vs. all other species (KB +VB + CL+ CB + PR) (Contrast 1); KB + PR vs. all *Agrostis* (BG) species (VB + CL + CB) (Contrast 2); among *Agrostis* species (CB vs. VB + CL) (Contrast 3); among *Agrostis* species (VB vs. CL) (Contrast 4); KB vs. PR (Contrast 5); within KB (Keeneland vs. Rubix) (Contrast 6); within PR (Karma vs. Wicked) (Contrast 7). Results for measured responses were analyzed and reported by individual dates and year because of the interactions detected between year (2018 and 2019) and treatment main effect and associated contrasts for measured response variables. Treatment means were separated using Fishers protected LSD at the .05 level.

Simple linear regression was used to compute regression coefficients (slope estimates) for individual species (KB, PR, FF, and BG) and pooled across all species. To that end, observed data (all replicates) for COR and BB were regressed on soil hardness to compute slope estimates (95% confidence interval) for individual years (2018, 2019) and pooled across both years. Ball bounce per 50g increase in soil hardness and soil hardness to achieve 50% BB (COR ≈ 0.70) were computed using simple linear regression analysis. Correlation coefficients (*r* values) were computed between soil hardness, TDR VWC, various cell wall components, and shoot density, as well as their relationship with court pace, COF, and COR. No departures from the assumptions of ANOVA were detected in homogeneity of variance or normality.

3 | RESULTS AND DISCUSSION

3.1 | Coefficient of restitution

Ball bounce was used to derive COR and restitution is reported for 2018 and 2019 in Tables 1 and 2, respectively. For all years and measurement periods, significant differences were observed between species–cultivars, and for contrasts comparing FF vs. all and BG vs. KB + PR. Fine fescue mixture generally exhibited higher COR averaging from 0.621 to 0.689 in 2018 and from 0.634 to 0.688 in 2019. During 2018 and 2019, KB + PR afforded higher COR and therefore higher BB than BG species (Tables 1 and 2). In 2018, PR exhibited higher COR on average than KB on six occasions from 24 July to 27 August (Table 1) and on 14 and 20 June in 2019 (Table 2). During six measurement periods in 2018 (Table 1) and two in 2019 (Table 2), VBG exhibited the lowest restitution among all turfgrass species–cultivars evaluated. Turfgrass species–cultivars with higher restitution measurements are expected to play slower. Therefore, VBG is expected to play faster than FF, PR, and KB because of its lower COR (Tables 1 and 2).

In both years, FF plots exhibited the highest observed COR of 0.69, whereas the highest observed COR for PR was 0.68 in 2018 and 0.67 in 2019 (Table 3). None of the turfgrass species evaluated in our study ever achieved a restitution of 0.70 or BB of 50% of the dropped height as recommended by the ITF. In all cases, fresh tennis balls dropped onto smooth concrete using a 254-cm drop height satisfied ITF standards for rebound, which ranged from a COR of 0.74 to 0.77 (Table 3). The ITF uses a predictive method for COR where the height of BB onto a test surface (i.e., grass, in our case) is expressed relative to the height of BB off a reference surface of smooth concrete. The ITF recommends no less than 80% BB off a test surface to that observed on concrete. Therefore, any grass surface exhibiting a COR ≥0.68 would satisfy the 80% BB rule of tennis, which included only FF and PR in our current study (Table 3).

Measurements conducted in 2019 on various court surfaces at LCC indicated that clay courts had the highest COR ranging from 0.76 to 0.78 (Table 3). Annual bluegrass courts at LCC exhibited COR similar to VBG ranging from 0.52 to 0.57 (Table 3). Perennial ryegrass courts at LCC exhibited COR ranging from 0.59 to 0.65 (Table 3) and were similar to PR grass courts reported in this current study (Table 3). At LCC, clay courts exhibited a COR that exceeded AB courts by a factor $(0.77/0.543)^2 = 2.0$, and PR exceeded AB courts by a factor $(0.622/0.543)^2 = 1.3$ (Cross, 2003). Interestingly, partially worn AB courts (30% grass cover) and completely worn AB courts (no grass cover) exhibited COR ranging from 0.63 to 0.72 and from 0.74 to 0.76 (Table 3), respectively. Therefore, worn grasses along the baselines were the only grass surfaces to satisfy the minimum standard for COR of 0.70. This agrees with the work conducted by Holmes and Bell (1986), who reported that areas on grass courts receiving greater wear were observed to have the highest COR.

Surface hardness and shoot density (reported in Ebdon et al., 2020) were found to be inversely related (Table 4).

TABLE 1 Results from ANOVA of coefficient of restitution (COR)[a] measured weekly in 2018 on eight turfgrass species and cultivars maintained as tennis courts

Cultivar and species	df	(Rebound height-to-drop height ratio)$^{1/2}$ 3 July	10 July	16 July	24 July	31 July	7 Aug.	15 Aug.	20 Aug.	27 Aug.
‘Keeneland’, Kentucky bluegrass (KB)		0.633a[b]	0.632abc	0.645a	0.580bc	0.638cd	0.628bc	0.622cd	0.638cd	0.650c
‘Rubix’, KB		0.613b	0.620c	0.625a	0.572c	0.619d	0.620c	0.610d	0.633d	0.640c
‘Villa’, velvet bentgrass (VBG)		0.547d	0.545e	0.537c	0.495e	0.549f	0.545e	0.539f	0.565f	0.577f
‘Puritan’, colonial bentgrass (CL)		0.560cd	0.570d	0.581b	0.517de	0.574e	0.567de	0.579e	0.611e	0.602e
‘007’, creeping bentgrass (CB)		0.567c	0.590d	0.577b	0.552cd	0.593e	0.590d	0.576e	0.607e	0.621d
‘Bridgeport II’ + ‘Barcrown’, fine fescue mixture (FF)		0.623b	0.650a	0.649a	0.621a	0.680a	0.674a	0.673a	0.681a	0.689a
‘Karma’, perennial ryegrass (PG)		0.623b	0.641ab	0.640a	0.607ab	0.661ab	0.659a	0.660ab	0.674ab	0.678ab
‘Wicked’, PG		0.610b	0.623bc	0.633a	0.599ab	0.652bc	0.652ab	0.646bc	0.658bc	0.668b
		ANOVA								
Source of variation										
Species and cultivars	7	***	***	***	***	***	***	***	***	***
Orthogonal contrasts[c]										
1. FF vs. all	1	***	***	***	***	***	***	***	***	***
2. BG vs. KB + PR	1	***	***	***	***	***	***	***	***	***
3. CB vs other	1	†	**	NS‡	**	**	**	NS	*	***
4. VBG vs. CL	1	NS	*	**	NS	*	†	**	***	**
5. KB vs. PR	1	NS	NS	NS	*	***	**	***	***	***
6. Among KB	1	*	NS	NS	NS	*	NS	NS	NS	NS
7. Among PR	1	NS	†	NS	NS	NS	NS	NS	NS	NS

[a] Derived as the square root of the rebound height-to-drop height ratio of tennis ball vertical impact using a 2.54 m (100 inch) drop height.
[b] Values followed by a common letter are not statistically different at the $\alpha = .05$ level according to Fishers protected LSD.
[c] 1. Fine fescue vs. all other species and cultivars; 2. all bentgrass species vs. the combined mean of Kentucky bluegrass and perennial ryegrass cultivars; 3. creeping bentgrass vs. the combined mean of velvet bentgrass and colonial bentgrass; 4. velvet bentgrass vs. colonial bentgrass; 5. combined mean of Kentucky bluegrass cultivars vs. perennial ryegrass cultivars; 6. contrast comparing cultivars of Kentucky bluegrass; 7. contrast comparing cultivars of perennial ryegrass.
† Significant at the .10 probability level. * Significant at the .05 probability level. ** Significant at the .01 probability level. *** Significant at the .001 probability level. ‡ NS, nonsignificant.

TABLE 2 Results from ANOVA of coefficient of restitution (COR)[a] measured weekly in 2019 on eight turfgrass species and cultivars maintained as tennis courts

Cultivar and species	df	(Rebound height-to-drop height ratio)$^{1/2}$									
		4 June	14 June	20 June	28 June	5 July	10 July	15 July	26 July	2 Aug.	6 Aug.
'Keeneland', Kentucky bluegrass (KB)		0.602ab[b]	0.622b	0.604b	0.620b	0.643a	0.660ab	0.647b	0.634b	0.644a	0.643ab
'Rubix', KB		0.590b	0.626b	0.595bc	0.626b	0.646a	0.653b	0.647b	0.632b	0.623b	0.636a
'Villa', velvet bentgrass (VBG)		0.550c	0.554d	0.526d	0.553d	0.564c	0.577d	0.570d	0.556d	0.569c	0.581c
'Puritan', colonial bentgrass (CL)		0.575bc	0.582c	0.572c	0.595c	0.601b	0.609c	0.587cd	0.577cd	0.590c	0.586c
'007', creeping bentgrass (CB)		0.560c	0.572cd	0.566c	0.585c	0.588bc	0.601cd	0.595c	0.590c	0.586c	0.592c
'Bridgeport II' + 'Barcrown', fine fescue mixture (FF)		0.634a	0.652a	0.649a	0.657a	0.667a	0.688a	0.666a	0.659a	0.661a	0.666a
'Karma', perennial ryegrass (PG)		0.598ab	0.630ab	0.623ab	0.632b	0.660a	0.661ab	0.655ab	0.644ab	0.641a	0.648ab
'Wicked', PG		0.597ab	0.614b	0.614b	0.624b	0.638a	0.648b	0.638b	0.637ab	0.643a	0.636b
		ANOVA									
Source of variation											
Species and cultivars	7	**	†	**	***	***	***	***	***	***	***
Orthogonal contrasts[c]											
1. FF vs. all	1	***	*	**	***	***	***	***	***	***	***
2. BG vs. KB + PR	1	***	NS‡	**	***	***	***	***	***	***	***
3. CB vs other	1	NS	NS	*	NS	NS	NS	*	*	NS	NS
4. VBG vs. CL	1	NS	NS	NS	***	*	*	†	†	†	NS
5. KB vs. PR	1	NS	*	**	NS	NS	NS	NS	NS	NS	NS
6. Among KB	1	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
7. Among PR	1	NS	NS	NS	NS	NS	NS	†	NS	NS	NS

[a] Derived as the square root of the rebound height-to-drop height ratio of tennis ball vertical impact using a 2.54-m (100-inch) drop height.
[b] Values followed by a common letter are not statistically different at the $\alpha = .05$ level according to Fishers protected LSD.
[c] 1. Fine fescue vs. all other species and cultivars; 2. all bentgrass species vs. the combined mean of Kentucky bluegrass and perennial ryegrass cultivars; 3. creeping bentgrass vs. the combined mean of velvet bentgrass and colonial bentgrass; 4. velvet bentgrass vs. colonial bentgrass; 5. combined mean of Kentucky bluegrass cultivars vs. perennial ryegrass cultivars; 6. contrast comparing cultivars of Kentucky bluegrass; 7. contrast comparing cultivars of perennial ryegrass.
†Significant at the .10 probability level. *Significant at the .05 probability level. **Significant at the .01 probability level. ***Significant at the .001 probability level. ‡NS, nonsignificant.

TABLE 3 Summary statistics for surface hardness (gravities, g), coefficient of restitution (COR), coefficient of sliding friction (COF), and court pace rating (CPR) measured on various surfaces. Means, standard errors (±SE) of the mean, and ranges are included

	Gravities[a]		COR[b]		COF[c]		CPR[d]	
Surface	**Mean ± SE**	**Range**	**Mean ± SE**	**Range**	**Mean ± SE**	**Range**	**Mean ± SE**	**Range**
Bentgrass species								
2018, $n = 81$	103.9 ± 1.6	59–136	0.568 ± 0.004	0.48–0.63	0.649 ± 0.011	0.50–0.80	70.3 ± 1.2	57.5–91.3
2019, $n = 90$	115.4 ± 1.3	84–145	0.577 ± 0.003	0.51–0.64	0.760 ± 0.005	0.65–0.87	59.0 ± 0.5	47.1–68.7
Fine fescue mixture								
2018, $n = 27$	124.6 ± 2.3	95–146	0.660 ± 0.005	0.62–0.69	0.594 ± 0.020	0.45–0.67	60.0 ± 1.8	53.1–74.4
2019, $n = 30$	141.3 ± 2.3	121–167	0.660 ± 0.003	0.63–0.69	0.685 ± 0.007	0.60–0.74	54.0 ± 0.8	47.3–62.6
Kentucky bluegrass cultivars								
2018, $n = 54$	120.8 ± 1.4	99–145	0.623 ± 0.003	0.55–0.66	0.633 ± 0.010	0.54–0.71	63.7 ± 0.9	55.5–73.5
2019, $n = 60$	135.3 ± 1.4	113–161	0.630 ± 0.003	0.58–0.67	0.706 ± 0.005	0.59–0.77	56.4 ± 0.6	46.8–65.7
Perennial ryegrass cultivars								
2018, $n = 54$	121.6 ± 1.7	84–143	0.644 ± 0.003	0.58–0.68	0.618 ± 0.011	0.51–0.69	60.5 ± 1.1	52.1–72.8
2019, $n = 60$	132.8 ± 1.6	110–157	0.634 ± 0.003	0.57–0.67	0.755 ± 0.007	0.61–0.90	50.9 ± 0.5	42.0–60.8
Smooth concrete								
2019, $n = 27$	865.4 ± 2.0	852–880	0.762 ± 0.001	0.74–0.77	0.416 ± 0.012	0.34–0.49	–	–
Dead grass								
2019, $n = 18$	137.4 ± 3.4	112–164	0.662 ± 0.004	0.63–0.69	0.397 ± 0.016	0.32–0.48	–	–
Longwood Cricket Club, 2019, $n = 12$								
Annual bluegrass court	86.3 ± 2.1	77–102	0.543 ± 0.004	0.52–0.57	0.866 ± 0.019	0.69–0.93	–	–
Perennial ryegrass court	98.8 ± 1.9	88–112	0.622 ± 0.005	0.59–0.65	0.736 ± 0.014	0.65–0.81	–	–
Clay court	342.8 ± 12.5	291–448	0.770 ± 0.002	0.76–0.78	0.580 ± 0.009	0.51–0.63	–	–
Worn grass, baseline	129.9 ± 5.0	112–169	0.681 ± 0.008	0.63–0.72	–	–	–	–
No grass, baseline	246.3 ± 10.2	206–283	0.753 ± 0.003	0.74–0.76	–	–	–	–

[a] Measured in gravities using the Clegg impact hammer (0.5-kg mass hammer) dropped from 60-cm height.
[b] Derived as the square root of the rebound height-to-drop height ratio after tennis ball vertical impact using a 254-cm (100-inch) drop height.
[c] Derived as the ratio of the force (kg) to sustain motion of a weighted sled (12.44 kg) with tennis balls in contact with the surface.
[d] Derived from COF and COR as $CPR = 100(1 - COF) + 150(0.81 - COR)$.

TABLE 4 Selected correlation (r) values between surface hardness (gravities, g), coefficient of restitution (COR), coefficient of sliding friction (COF), time domain reflectometry (TDR), volumetric soil moisture content (VWC), shoot density (no. cm^{-2}, SHT), total cell wall content (TCW), hemicellulose (hemi), lignocellulose (ligno), and court pace rating (CPR) measured on various grass surfaces in 2018 and 2019

Correlation	Bentgrass species		Fine fescue mixture		Kentucky bluegrass		Perennial ryegrass		All species		
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	2-yr avg.
g–COR	.586***	.721***	.712***	.698***	.292	.728***	.680***	.591***	.723***	.823***	.722***
g–COF	−.193	−.390**	.251	−.276	−.249	−.239*	.118	−.237*	−.262**	−.462***	−.132*
COF–COR	.181	−.325**	.290	−.050	−.128	−.082	.207	−.619***	−.206*	−.487***	−.339***
VWC–COR	−.374***	.003	−.280	.034	−.528***	.026	−.416**	−.137	−.590***	−.126*	−.094
VWC–COF	−.117	.323**	−.086	.232	.235	.132	.177	.286	.219*	.264***	.691***
VWC–g	.023	−.151	−.193	−.104	−.113	.100	−.299*	.023	−.341***	−.159*	.310***
CPR–COR	−.634***	−.465***	−.406	−.507**	−.427*	−.588***	−.500***	−.041	−.671***	−.557***	−.454***
CPR–COF	−.875***	−.686***	−.992***	−.836***	−.842***	−.758***	−.951***	−.759***	−.588***	−.454***	−.684***
CPR–g	−.152	−.217*	−.326	−.146	−.128	−.283*	−.340*	−.188	−.488***	−.400***	−.464***
TCW–COR	NR[a]	NR	NR	NR	NR	NR	NR	NR	.147	−.185	−.069
TCW –COF	NR	NR	NR	NR	NR	NR	NR	NR	−.169	−.188	.083
TCW–g	NR	NR	NR	NR	NR	NR	NR	NR	−.169	−.099	−.047
Hemi–COR	NR	NR	NR	NR	NR	NR	NR	NR	−.564**	−.528**	−.690***
Hemi–COF	NR	NR	NR	NR	NR	NR	NR	NR	.399*	.420*	.620***
Hemi–g	NR	NR	NR	NR	NR	NR	NR	NR	−.571**	−.396*	−.588**
Ligno–COR	NR	NR	NR	NR	NR	NR	NR	NR	.672***	.741***	.818***
Ligno–COF	NR	NR	NR	NR	NR	NR	NR	NR	−.536**	−.501**	−.716***
Ligno–g	NR	NR	NR	NR	NR	NR	NR	NR	.555**	.640***	.707***
SHT–COR	NR	NR	NR	NR	NR	NR	NR	NR	–	−.828***	–
SHT–COF	NR	NR	NR	NR	NR	NR	NR	NR	–	.576**	–
SHT–g	NR	NR	NR	NR	NR	NR	NR	NR	–	−.860***	–

[a] Not reported. Correlation (r) values are not reported for shoot density and cell wall components (TCW, hemi, ligno); these variables were measured once each year of the test. n ranged from three to nine for fine fescue and bentgrass species, respectively.

*Significant at the .05 probability level. **Significant at the .01 probability level. ***Significant at the .001 probability level.

TABLE 5 Results from ANOVA of surface hardness (gravities, *g*)[a] measured weekly in 2018 on eight turfgrass species and cultivars maintained as tennis courts

Cultivar and species	df	Gravities 3 July	10 July	16 July	24 July	31 July	7 Aug.	15 Aug.	20 Aug.	27 Aug.
'Keeneland', Kentucky bluegrass (KB)		108.3ab[b]	106.7ab	125.1ab	116.4a	123.3a	127.2ab	114.0d	124.3bc	136.7ab
'Rubix', KB		113.1a	104.5ab	125.2ab	117.6a	129.6ab	124.8abc	120.7bcd	120.6c	136.9ab
'Villa', velvet bentgrass (VBG)		80.2d	70.5c	98.3d	87.5c	90.9c	100.3d	101.8f	102.2e	112.2e
'Puritan', colonial bentgrass (CL)		97.4c	89.8b	100.5cd	101.8b	109.0bc	115.0c	108.6ef	113.8d	120.5de
'007', creeping bentgrass (CB)		97.2c	88.9b	115.4bc	108.5ab	121.0ab	117.8bc	115.3cde	114.1d	127.1cd
'Bridgeport II' + 'Barcrown', fine fescue mixture (FF)		113.6a	104.7ab	125.2ab	117.2a	130.4a	125.8abc	131.5a	130.9ab	142.2a
'Karma', perennial ryegrass (PG)		104.8abc	110.1a	131.6a	117.6a	130.7a	130.9a	125.1ab	133.2a	137.2ab
'Wicked', PG		103.3bc	103.1ab	121.0ab	111.7ab	125.9ab	124.9ac	121.3bc	125.1bc	131.1bc
		ANOVA								
Source of variation										
Species and cultivars	7	***	**	**	***	***	**	***	***	***
Orthogonal contrasts[c]										
1. FF vs. all	1	**	NS[†]	NS	*	**	NS	***	***	***
2. BG vs. KB + PR	1	***	***	***	***	***	***	***	***	***
3. CB vs other	1	*	NS	*	**	***	*	**	‡	*
4. VBG vs. CL	1	**	*	NS	**	**	*	**	**	‡
5. KB vs. PR	1	*	NS	NS	NS	NS	NS	‡	*	NS
6. Among KB	1	NS	NS	NS	NS	NS	NS	‡	NS	NS
7. Among PR	1	NS	NS	NS	NS	NS	NS	NS	*	NS

[a] Measured in gravities using the Clegg impact soil test (0.5-kg missile) dropped from 60-cm height.
[b] Values followed by a common letter are not statistically different at α = .05 level according to Fishers protected LSD.
[c] 1. Fine fescue vs. all other species and cultivars; 2. all bentgrass species vs. the combined mean of Kentucky bluegrass and perennial ryegrass cultivars; 3. creeping bentgrass vs. the combined mean of velvet bentgrass and colonial bentgrass; 4. velvet bentgrass vs. colonial bentgrass; 5. combined mean of Kentucky bluegrass cultivars vs. perennial ryegrass cultivars; 6. contrast comparing cultivars of Kentucky bluegrass; 7. contrast comparing cultivars of perennial ryegrass.
[†] NS, nonsignificant. [‡] Significant at the .10 probability level. [*] Significant at the .05 probability level. [**] Significant at the .01 probability level. [***] Significant at the .001 probability level.

TABLE 6 Results from ANOVA of grass hardness (gravities, g)[a] measured weekly in 2019 on eight turfgrass species and cultivars maintained as tennis courts

		Gravities									
Cultivar and species	**df**	**4 June**	**14 June**	**20 June**	**28 June**	**5 July**	**10 July**	**15 July**	**26 July**	**2 Aug.**	**6 Aug.**
'Keeneland', Kentucky bluegrass (KB)		124.6ab[b]	122.1abc	121.2ab	133.1a	141.0a	148.5ab	153.2a	131.9ab	136.0ab	140.6a
'Rubix', KB		130.9a	128.0ab	125.5ab	129.3a	143.2a	151.5ab	147.9ab	128.9abc	129.0b	138.8a
'Villa', velvet bentgrass (VBG)		95.4c	97.1e	99.7d	99.3c	112.9c	111.3e	113.4d	100.8d	109.0d	110.8b
'Puritan', colonial bentgrass (CL)		111.9b	113.2cd	118.0bc	117.6b	124.9bc	130.6d	134.1bc	119.3b	124.2c	119.0b
'007', creeping bentgrass (CB)		118.3ab	105.3de	109.9cd	114.5b	124.9bc	135.3cd	130.3c	117.5c	122.1c	121.8b
'Bridgeport II' + 'Barcrown', fine fescue mixture (FF)		130.6a	134.1a	131.0a	132.9a	144.2a	157.1a	159.3a	139.6a	137.4ab	146.3a
'Karma', perennial ryegrass (PG)		119.4ab	117.0bcd	117.6bb	128.1a	133.3ab	143.0c	146.8ab	135.0a	138.2a	140.3a
'Wicked', PG		120.8ab	118.8bc	119.9abc	129.9a	140.8a	148.3ab	149.7a	136.0a	135.2ab	138.2a
		ANOVA									
Source of variation											
Species and cultivars	7	**	***	***	***	**	***	***	***	***	***
Orthogonal contrasts[c]											
1. FF vs. all	1	*	***	**	**	*	***	**	**	**	**
2. BG vs. KB + PR	1	***	***	***	***	***	***	***	***	***	***
3. CB vs other	1	*	NS[†]	NS	‡	NS	*	NS	NS	NS	NS
4. VBG vs. CL	1	*	*	NS	***	NS	**	**	**	**	NS
5. KB vs. PR	1	NS	‡	NS	NS	NS	NS	NS	NS	NS	NS
6. Among KB	1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
7. Among PR	1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a] Measured in gravities using the Clegg impact soil tester (0.5-kg mass missile) dropped from 60-cm height.

[b] Values followed by a common letter are not statistically different at $\alpha = .05$ level according to Fishers protected LSD.

[c] 1. Fine fescue vs. all other species and cultivars; 2. all bentgrass species vs. the combined mean of Kentucky bluegrass and perennial ryegrass cultivars; 3. creeping bentgrass vs. the combined mean of velvet bentgrass and colonial bentgrass; 4. velvet bentgrass vs. colonial bentgrass; 5. combined mean of Kentucky bluegrass cultivars vs. perennial ryegrass cultivars; 6. contrast comparing cultivars of Kentucky bluegrass; 7. contrast comparing cultivars of perennial ryegrass.

[†] NS, nonsignificant. [‡] Significant at the .10 probability level. [*] Significant at the .05 probability level. [**] Significant at the .01 probability level. [***] Significant at the .001 probability level.

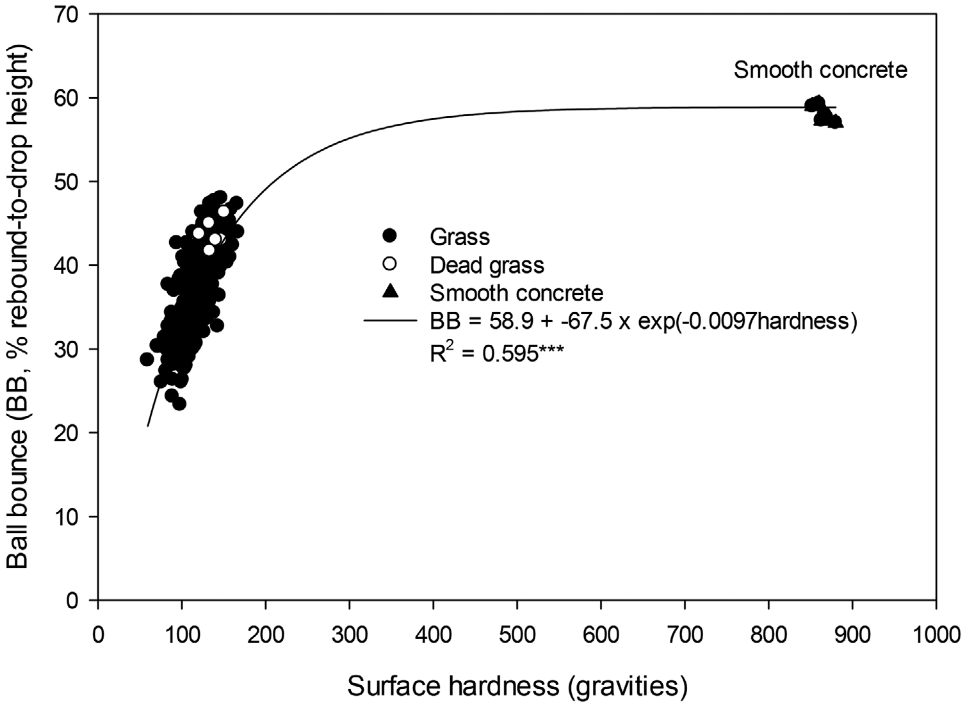

FIGURE 1 General relationship between soil hardness (gravities, *g*) and tennis ball rebound measured on grass tennis courts and smooth concrete. Hardness converges with ball bounce at 58.9% rebound on concrete. Rebound of 50% of the drop height corresponds to 210*g*. All species and years are shown ($n = 456$). ***Regression significant at the .001 probability level

Greater green biomass (verdure) softens the court surface and increases the energy absorbed by the surface with less energy returned as BB. As such, COR was strongly and inversely related to shoot density (Table 4). For all species evaluated, COR increased with soil hardness. Clay court surfaces at LCC were observed to exhibit the highest soil hardness (342.8 ± 12.5*g*) and COR (Table 3), whereas BG as a species in our study exhibited the lowest soil hardness (103.9 ± 1.6*g*) (Table 3) and COR (Tables 1 and 2).

Velvet bentgrass as a species showed the lowest soil hardness in 2018 (Table 5) and 2019 (Table 6). Alternatively, FF plots were consistently among the highest in surface hardness in 2018 (Table 5) and 2019 (Table 6). Similarly, PR afforded the hardest surfaces equivalent to FF, and on average PR provided harder surfaces than KB cultivars on 3 July and 15 and 20 August in 2018 (Table 5). Newell and Wood (2000) also found PR to produce the hardest surface, with PR averaging 188*g* and KB averaging 178*g*. The greatest observed soil hardness in our study was 167*g* for FF, 161*g* for KB, and 157*g* for PR, which were all observed in 2019 (Table 3). Smooth concrete exhibited the hardest surface ranging from 852 to 880*g* (Table 3).

Figure 1 reports all species and cultivars ($n = 456$) and the relationship between surface hardness and BB on natural grass. The relationship was linear on natural grass with 50% BB (i.e., COR ≈ 0.70) occurring at 210*g*. The fitted line converged towards its asymptote of 58.9% BB (COR = 0.767) on concrete averaging 865*g* (Table 3). Holmes and Bell (1986) reported similar results with BB increasing linearly with hardness to values of 200*g* on natural grass surfaces. These same authors observed 53% BB to occur around 208*g* on worn grass. We observed completely worn areas of the baselines at LCC to range from 206 to 283*g* and BB to range from 55 to 58% (Table 3). Partially worn areas at LCC ranged from 112 to 169*g* in hardness, with BB ranging from 40 to 52%.

Close examination of the linear regression between BB (and COR) as Y response variables and soil hardness (g) as X independent variables revealed that species varied in slope estimates for COR and BB with soil hardness (Table 7). Most linear regressions were statistically significant at the $\alpha = .001$ level for the pooled regression (i.e., years 2018 + 2019) and for regressions of individual years (2018 and 2019). According to the pooled regression, BG exhibited a steeper slope estimate for COR and BB with soil hardness than other species (FF, KB, PR), indicating that greater increases in COR or BB were observed per unit increase in soil hardness for BG species. For example, BB increase per 50*g* increase in soil hardness was 7.1% for BG (95% confidence interval: 6.5–7.7%) and was significantly greater than the increase in BB per 50*g* increase in soil hardness observed for other species. The greatest observed increase in BB per 50*g* increase in soil hardness was 9.6% for FF (2018), 9.3% for KB (2019), 8.8% for PR

TABLE 7 Results from linear regression analysis of coefficient of restitution (COR[a]) and ball bounce (BB[b]) regressed on soil hardness (gravities, *g*). Statistics including slope estimates, soil hardness (*g*) to achieve 50% BB, linear increase in BB per 50g, and associated 95% confidence intervals (CIs) are reported for four species and two years (2018, 2019)

			95% CI (mid-point)		95% CI	
Species and year	r^2	***n***	**COR slope**	**BB slope**	**BB increase per 50g**	**Soil hardness for 50% BB**
			$\times 10^{-3}$		% (mid-point)	*g* (mid-point)
All species						
2018 + 2019	0.520***	456	1.71–1.87 (1.79)	0.206–0.226 (0.216)	10.3–11.3 (10.8)	171–187 (179)
2018	0.523***	216	1.98–2.25 (2.11)	0.239–0.271 (0.255)	12.0–13.6 (12.8)	154–175 (165)
2019	0.678***	240	1.92–2.09 (2.01)	0.233–0.255 (0.244)	11.7–12.7 (12.2)	170–186 (178)
Bentgrass						
2018 + 2019	0.417***	171	1.13–1.35 (1.24)	0.129–0.155 (0.142)	6.5–7.7 (7.1)	212–253 (233)
2018	0.344***	81	1.07–1.46 (1.26)	0.122–0.166 (0.144)	6.1–8.3 (7.2)	197–267 (232)
2019	0.520***	90	1.26–1.54 (1.40)	0.145–0.178 (0.162)	7.3–8.9 (8.1)	198–243 (221)
Fine fescue						
2018 + 2019	0.319***	57	0.63–0.94 (0.78)	0.082–0.123 (0.102)	4.1–6.1 (5.1)	164–245 (205)
2018	0.514***	27	1.17–1.76 (1.46)	0.154–0.231 (0.192)	7.7–11.5 (9.6)	132–197 (165)
2019	0.488***	30	0.72–1.08 (0.90)	0.095–0.142 (0.119)	4.8–7.1 (5.9)	163–244 (204)

(Continues)

TABLE 7 (Continued)

Species and year	r^2	n	95% CI (mid-point) COR slope	BB slope	95% CI BB increase per 50g	Soil hardness for 50% BB
Kentucky bluegrass						
2018 + 2019	0.245***	114	0.74–1.03 (0.89)	0.094–0.130 (0.112)	4.7–6.5 (5.6)	193–267 (230)
2018	0.087*	54	0.36–0.97 (0.67)	0.046–0.121 (0.083)	2.3–6.0 (4.2)	175–462 (319)
2019	0.536***	60	1.29–1.65 (1.47)	0.163–0.209 (0.186)	8.2–10.4 (9.3)	170–217 (194)
Perennial ryegrass						
2018 + 2019	0.232***	114	0.72–1.01 (0.87)	0.091–0.128 (0.109)	4.5–6.4 (5.5)	181–255 (218)
2018	0.462***	54	1.17–1.58 (1.38)	0.150–0.203 (0.177)	7.5–10.1 (8.8)	147–200 (174)
2019	0.349***	60	0.91–1.30 (1.10)	0.112–0.163 (0.137)	5.6–8.1 (6.8)	171–249 (210)

[a] COR is the ratio of tennis ball velocity measured as the ratio immediately after and before ball impact on various grass surfaces and is derived as the square root of BB.
[b] BB is the ratio of tennis ball vertical rebound height-to-drop height measured from a 254-cm (100-inch) drop height.
*Significant at the .05 probability level. ***Significant at the .001 probability level.

(2018), and 8.1% for BG (2019) (Table 7). Holmes and Bell (1986) reported an 8% increase in BB per 50g increase in soil hardness. These authors evaluated 81 pairs of points but did not specify the species evaluated. The lowest observed gravities (soil hardness) to achieve 50% BB (COR ≈ 0.70) averaged 165g for FF (2018), 174g for PR (2018), 194g for KB (2019), and 221g for BG (2019) (Table 7). These values for soil hardness were derived from data taken from the minimal-wear areas of the service box where BB and COR are expected to be lowest (Holmes & Bell, 1986). Disproportionately less surface hardness would be needed with FF and PR species to establish a COR of 0.70 (50% BB) than would be needed for KB and especially with BG species. Although not measured in this study, the thatch and mat tendencies of KB and BG species are likely to soften the surface and tends to inhibit soil drying, compaction, and soil hardness (Baker, Cook, & Binns, 1999; Baker, Cook, Binns, Carré, & Haake, 1998; Newell & Wood, 2000; Rogers & Waddington, 1993).

Surface hardness is negatively influenced by soil moisture (Newell & Wood, 2000). No significant relationship was observed in 2018 and 2019 in our study between VWC and soil hardness (Table 4); actual TDR VWC data are not reported. In Newell and Wood (2000), higher clay content (23%) was observed compared with the soil used in this study (12.7% clay), which would explain the greater sensitivity of soil hardness to VWC that was observed in their study (James, 2015). However, COR was negatively correlated with TDR VWC measured in 2018 for BG ($r = -.374$, $p \leq .001$), KB ($r = -.528$, $p \leq .001$), and PR ($r = -.416$, $p \leq .001$). No significant relationship between COR and TDR VWC was observed in 2019 for any species or for FF in 2018 (Table 4). Thus, irrigation practices to promote soil drying are practical strategies for most cool-season turfgrass to increase COR and slow court pace.

Interestingly, cell wall components (hemi and lingo fractions) reported in Ebdon et al. (2020) covaried with surface hardness and COR, which exhibited opposite associations (Table 4). Lignocellulose fractions possess high mechanical rigidity and therefore serve to strengthen both stems and vascular tissues (Taiz & Zeiger, 1972) and physical toughness (Van Soest, 1994), whereas greater hemi content increases fiber flexibility (Sitch & Marshall, 2011). Greater flexibility afforded by higher levels of hemi content in leaf tissue decreased soil hardness (r ranged from $-.396$ [$p \leq .05$] to $-.588$ [$p \leq .01$], Table 4), and in turn decreased COR (r ranged from $-.528$ [$p \leq .01$] to $-.690$ [$p \leq .001$], Table 4). Alternatively, greater leaf rigidity associated with higher ligno content increased both soil hardness (r ranged from .555 [$p \leq .01$] to 0.707 [$p \leq .001$], Table 4) and COR (r ranged from .672 [$p \leq .001$] to .818 [$p \leq .001$], Table 4). No significant relation was observed between total cell wall content (TCW) and surface hardness or COR.

3.2 | Tennis ball coefficient of sliding friction

In 2018, little difference was observed between species–cultivars in COF between the ball and grass surface, whereas in 2019, numerous differences were observed (Tables 8 and 9). On one date (30 July) in 2018 (Table 8), BG species were associated with greater friction with the ball than KB + PR, whereas in 2019, BG species produced greater ball-to-surface friction than KB + PR on 7 of the 10 measurement dates (Table 9). Greater ball-to-surface friction of BG species reduces the outbound velocity of the ball after impact and therefore slows tennis pace (play) on BG courts. The FF mixture exhibited the lowest COF in 2018 and was among the lowest on many dates in 2019 (Tables 8 and 9). Therefore, FF has the potential to promote faster pace compared with BG species. In 2019, PR exhibited higher COF than KB on 8 of 10 evaluation dates, indicating that pace of tennis play can be slower with PR because of the greater surface friction between the ball and PR grass courts (Table 9).

Ball-to-surface friction increased with shoot density ($r = .576$ [$p \leq .01$], Table 4). Greater resistance offered by more tillers with BG species is consistent with the greater overall COF of this species. Based on averages, most species–cultivars in 2018 (Table 8) would be categorized as medium in overall friction (0.56–0.70; ITF, 2019) with FF, smooth concrete, and dead grass categorized as low (≤0.55) (Tables 3 and 8). Most species–cultivars in 2019 (Table 9) would be categorized as high (≥0.71) in overall friction according to ITF rules. The greater friction observed in 2019 is most likely the result of the 60% greater shoot density (see Ebdon et al., 2020) observed in 2019 compared with previous years, which is the result of an aggressive overseeding program to reestablish baselines and other areas worn from traffic caused by tennis play.

Similar to results observed between cell wall fractions (ligno and hemi) and COR, cell wall fractions (ligno vs. hemi) also had opposite effects on ball-to-surface friction (Table 4). Greater leaf rigidity due to higher levels of ligno in leaf tissues decreased surface friction between the ball and grass surface (r ranged from -0.501 [$p \leq .01$] to -0.716 [$p \leq .001$], Table 4). Alternatively, greater amounts of hemi in leaf tissues provided more flexible leaf tissues that increased COF (r ranged from 0.399 [$p \leq .05$] to 0.620 [$p \leq .001$], Table 4).

3.3 | Calculated court pace rating

All grass surfaces exhibited a calculated CPR (see Equation 1) averaging above 45 (i.e., categorized as fast) for all years (2018 and 2019, Tables 10 and 11, respectively). Only

TABLE 8 Results from ANOVA of coefficient of sliding friction (COF)[a] between the tennis ball and grass surface measured in 2018 on eight turfgrass species and cultivars maintained as tennis courts

Cultivar and species	df	Ratio of force to maintain motion to normal force on friction sled				
		30 July	6 Aug.	17 Aug.	21 Aug.	28 Aug.
'Keeneland', Kentucky bluegrass (KB)		0.617b[b]	0.574a	0.611	0.663abc	0.613ab
'Rubix', KB		0.615b	0.631a	0.675	0.675ab	0.658a
'Villa', velvet bentgrass (VBG)		0.715a	0.601a	0.621	0.656abc	0.558b
'Puritan', colonial bentgrass (CL)		0.638b	0.570a	0.680	0.663abc	0.648a
'007', creeping bentgrass (CB)		0.638b	0.630a	0.662	0.710a	0.644a
'Bridgeport II' + 'Barcrown', fine fescue mixture (FF)		0.623b	0.489b	0.617	0.647bc	0.608ab
'Karma', perennial ryegrass (PG)		0.615b	0.586a	0.624	0.675ab	0.629a
'Wicked', PG		0.636b	0.590a	0.605	0.613c	0.614ab
		ANOVA				
Source of variation						
Species and cultivars	7	NS[†]	*	NS	NS	NS
Orthogonal contrasts[c]						
1. FF vs. all	1	NS	**	NS	NS	NS
2. BG vs. KB + PR	1	*	NS	NS	NS	NS
3. CB vs other	1	NS	NS	NS	*	NS
4. VBG vs. CL	1	*	NS	NS	NS	*
5. KB vs. PR	1	NS	NS	NS	NS	NS
6. Among KB	1	NS	NS	NS	NS	NS
7. Among PR	1	NS	NS	NS	*	NS

[a] Derived as the ratio of the force (kg) to sustain motion of a weighted sled (12.44 kg) with tennis balls in contact with the surface.

[b] Values followed by a common letter are not statistically different at $\alpha = .05$ level according to Fishers protected LSD.

[c] 1. Fine fescue vs. all other species and cultivars; 2. all bentgrass species vs. the combined mean of Kentucky bluegrass and perennial ryegrass cultivars; 3. creeping bentgrass vs. the combined mean of velvet bentgrass and colonial bentgrass; 4. velvet bentgrass vs. colonial bentgrass; 5. combined mean of Kentucky bluegrass cultivars vs. perennial ryegrass cultivars; 6. contrast comparing cultivars of Kentucky bluegrass; 7. contrast comparing cultivars of perennial ryegrass.

*Significant at the .05 probability level. **Significant at the .01 probability level. [†]NS, nonsignificant.

TABLE 9 Results from ANOVA of coefficient of sliding friction (COF)[a] between the tennis ball and grass surface measured weekly in 2019 on eight turfgrass species and cultivars maintained as tennis courts

		Ratio of force to maintain motion to normal force on friction sled									
Cultivar and species	**df**	**4 June**	**14 June**	**20 June**	**28 June**	**5 July**	**10 July**	**15 July**	**26 July**	**2 Aug.**	**6 Aug.**
'Keeneland', Kentucky bluegrass (KB)		0.700b[b]	0.694ab	0.728bc	0.753cd	0.648cde	0.711bc	0.688	0.761a	0.716cd	0.744bc
'Rubix', KB		0.701b	0.665b	0.694c	0.720d	0.643de	0.688c	0.680	0.718bc	0.728bcd	0.745bc
'Villa', velvet bentgrass (VBG)		0.738ab	0.776a	0.776a	0.826ab	0.706ab	0.761ab	0.744	0.774a	0.772ab	0.774ab
'Puritan', colonial bentgrass (CL)		0.730ab	0.726ab	0.761b	0.776bc	0.707ab	0.719abc	0.701	0.766a	0.756abc	0.774ab
'007', creeping bentgrass (CB)		0.780a	0.766a	0.820a	0.837a	0.694abc	0.778a	0.719	0.767a	0.778a	0.789a
'Bridgeport II' + 'Barcrown', fine fescue mixture (FF)		0.678b	0.667b	0.691c	0.713d	0.622e	0.674c	0.672	0.708c	0.704d	0.723c
'Karma', perennial ryegrass (PG)		0.779a	0.749ab	0.776ab	0.768c	0.675bcd	0.730abc	0.732	0.756a	0.747ab	0.764ab
'Wicked', PG		0.773a	0.780a	0.763ab	0.771c	0.743a	0.738ab	0.739	0.759ab	0.769ab	0.782a
		ANOVA									
Source of variation											
Species and cultivars	7	*	*	**	***	**	*	NS†	**	*	*
Orthogonal contrasts[c]											
1. FF vs. all	1	*	*	**	**	**	*	NS	**	*	**
2. BG vs. KB + PR	1	NS	NS	**	***	‡	*	NS	*	*	*
3. CB vs other	1	§	NS	*	‡	NS	NS	NS	NS	NS	NS
4. VBG vs. CL	1	NS	NS	NS	*	NS	NS	NS	NS	NS	NS
5. KB vs. PR	1	**	*	**	‡	**	NS	*	NS	*	*
6. Among KB	1	NS	NS	NS	NS	NS	NS	NS	*	NS	NS
7. Among PR	1	NS	NS	NS	NS	*	NS	NS	NS	NS	NS

[a] Derived as the ratio of the force (kg) to sustain motion of a weighted sled (12.44 kg) with tennis balls in contact with the surface.
[b] Values followed by a common letter are not statistically different at α = .05 level according to Fishers protected LSD.
[c] 1. Fine fescue vs. all other species and cultivars; 2. all bentgrass species vs. the combined mean of Kentucky bluegrass and perennial ryegrass cultivars; 3. creeping bentgrass vs. the combined mean of velvet bentgrass and colonial bentgrass; 4. velvet bentgrass vs. colonial bentgrass; 5. combined mean of Kentucky bluegrass cultivars vs. perennial ryegrass cultivars; 6. contrast comparing cultivars of Kentucky bluegrass; 7. contrast comparing cultivars of perennial ryegrass.
*NS, nonsignificant. ‡Significant at the .10 probability level. *Significant at the .05 probability level. **Significant at the .01 probability level. ***Significant at the .001 probability level.

TABLE 10 Results from ANOVA of calculated court pace rating (CPR)[a] derived from coefficient of friction (COF) and coefficient of restitution (COR) measured in 2018 on eight turfgrass species and cultivars maintained as tennis courts

		CPR				
Cultivar and species	**df**	**30 July**	**6 Aug.**	**17 Aug.**	**21 Aug.**	**28 Aug.**
'Keeneland', Kentucky bluegrass (KB)		64.0abcd[b]	69.9a	67.1ab	59.5bcd	62.8bcd
'Rubix', KB		67.2abc	65.4b	62.5b	59.0bcd	59.7cd
'Villa', velvet bentgrass (VBG)		67.7abc	79.7a	78.6a	71.2a	79.1a
'Puritan', colonial bentgrass (CL)		71.6a	79.5a	66.7b	63.6b	66.4b
'007', creeping bentgrass (CB)		68.7ab	70.0ab	68.9ab	59.4bc	64.0bc
'Bridgeport II' + 'Barcrown', fine fescue mixture (FF)		57.2d	71.5ab	58.9b	54.7cd	57.5d
'Karma', perennial ryegrass (PG)		60.9bcd	64.0b	60.1b	52.9d	56.9d
'Wicked', PG		60.1cd	64.6ab	64.2b	61.4bc	59.9cd
		ANOVA				
Source of variation						
Species and cultivars	7	*	*	*	**	***
Orthogonal contrasts[c]						
1. FF vs. all	1	*	NS[†]	‡	*	***
2. BG vs. KB + PR	1	*	**	*	**	***
3. CB vs other	1	NS	*	NS	**	**
4. VBG vs. CL	1	NS	NS	*	*	*
5. KB vs. PR	1	‡	‡	NS	NS	***
6. Among KB	1	NS	*	NS	NS	NS
7. Among PR	1	NS	NS	NS	*	NS

[a] CPR calculated as $100(1 - COF) + 150(0.81 - COR)$: slow, ≤29; medium-slow, 30-34; medium, 35–39; medium-fast, 40–44; fast, ≥45.

[b] Values followed by a common letter are not statistically different at $\alpha = .05$ level according to Fishers protected LSD.

[c] 1. Fine fescue vs. all other species and cultivars; 2. all bentgrass species vs. the combined mean of Kentucky bluegrass and perennial ryegrass cultivars; 3. creeping bentgrass vs. the combined mean of velvet bentgrass and colonial bentgrass; 4. velvet bentgrass vs. colonial bentgrass; 5. combined mean of Kentucky bluegrass cultivars vs. perennial ryegrass cultivars; 6. contrast comparing cultivars of Kentucky bluegrass; 7. contrast comparing cultivars of perennial ryegrass.

[†] NS, nonsignificant. [‡] Significant at the .10 probability level. [*] Significant at the .05 probability level. [**] Significant at the .01 probability level. [***] Significant at the .001 probability level.

TABLE 11 Results from ANOVA of calculated court pace rating (CPR)[a] derived from coefficient of friction (COF) and coefficient of restitution (COR) measured in 2019 on eight turfgrass species and cultivars maintained as tennis courts

		CPR									
Cultivar and species	**df**	**4 June**	**14 June**	**20 June**	**28 June**	**5 July**	**10 July**	**15 July**	**26 July**	**2 Aug.**	**6 Aug.**
'Keeneland', Kentucky bluegrass (KB)		61.1ab[b]	58.8ab	58.2bcd	53.1abc	60.2bc	51.4b	55.7bcd	50.4de	53.3bcde	50.7bc
'Rubix', KB		62.9ab	61.1a	62.8ab	55.5a	60.3bc	54.7ab	56.5bcd	54.9bcd	55.3abcd	51.6bc
'Villa', velvet bentgrass (VBG)		65.3a	60.8a	65.0a	56.0a	66.3a	58.8a	61.6ab	60.7a	58.9a	57.0a
'Puritan', colonial bentgrass (CL)		62.3ab	61.6a	59.7bc	54.6ab	60.6b	58.3a	63.4a	58.4ab	57.5ab	56.3a
'007', creeping bentgrass (CB)		59.6bc	59.0ab	54.6cde	50.0c	63.9ab	53.6ab	60.3abc	56.2bc	55.9abc	53.9ab
'Bridgeport II' + 'Barcrown', fine fescue mixture (FF)		58.6bcd	57.0ab	55.1cde	51.7abc	59.3bc	50.9b	54.4cd	51.9cde	52.0cde	49.3bc
'Karma', perennial ryegrass (PG)		53.9d	52.1b	50.4e	49.9c	55.0cd	49.4b	50.1d	49.3e	50.6de	47.9c
'Wicked', PG		54.7cd	51.5b	53.1de	50.9bc	51.6d	50.4b	52.0d	50.1e	48.2e	47.9c
		ANOVA									
Source of variation											
Species and cultivars	7	**	†	***	*	***	*	**	***	**	**
Orthogonal contrasts[c]											
1. FF vs. all	1	NS‡	NS	NS	NS	NS	NS	NS	NS	NS	†
2. BG vs. KB + PR	1	**	*	*	NS	***	**	***	***	***	***
3. CB vs other	1	§	NS	**	*	NS	*	NS	†	NS	NS
4. VBG vs. CL	1	NS	NS	*	NS	*	NS	NS	NS	NS	NS
5. KB vs. PR	1	***	**	***	*	**	NS	*	†	*	*
6. Among KB	1	NS	NS	†	NS	NS	NS	NS	†	NS	NS
7. Among PR	1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a] CPR calculated as $100(1 - COF) + 150(0.81 - COR)$: slow, ≤29; medium-slow, 30-34; medium, 35–39; medium-fast, 40–44; fast, ≥45.
[b] Values followed by a common letter are not statistically different at $\alpha = .05$ level according to Fishers protected LSD.
[c] 1. Fine fescue vs. all other species and cultivars; 2. all bentgrass species vs. the combined mean of Kentucky bluegrass and perennial ryegrass cultivars; 3. creeping bentgrass vs. the combined mean of velvet bentgrass and colonial bentgrass; 4. velvet bentgrass vs. colonial bentgrass; 5. combined mean of Kentucky bluegrass cultivars vs. perennial ryegrass cultivars; 6. contrast comparing cultivars of Kentucky bluegrass; 7. contrast comparing cultivars of perennial ryegrass.
†Significant at the .10 probability level. *Significant at the .05 probability level. **Significant at the .01 probability level. ***Significant at the .001 probability level. ‡NS, nonsignificant.

one observation had a calculated CPR <45 (i.e., 42; classified as medium-fast), which was observed for PR in 2019 (Table 3). Bentgrass species consistently averaged higher CPRs and therefore exhibited the potential to play faster than KB + PR in 14 of 15 measurement periods in 2018 and 2019 (Tables 10 and 11, respectively). Furthermore, PR cultivars on average afforded significantly slower CPR than KB on four dates in 2018 (Table 10) and nine dates in 2019 (Table 11). Velvet bentgrass was among the highest (fastest) in overall CPR on three of five dates in 2018 (Table 10) and 9 of 10 dates in 2019 (Table 11).

Compared with restitution, friction between the ball and court surface was more closely associated with CPR (higher r values, Table 4). For example, r^2 for COF accounted for as much as 70.9% ($p \leq .001$, KB) to 98.4% ($p \leq .001$, FF) of the variation in CPR. Alternatively, COR only accounted for as much as 40.2%($r = -.634$, $p \leq .001$) in grass court CPR, which was observed for BG. With the possible exception of BG and PR in 2019, COR and COF were generally uncorrelated and little covariation (collinearity) existed between these two measured coefficients (Table 4). According to Equation 1, to slow grass court pace to play more like clay and hard-court surfaces (Fog Mountain Tennis, 2014), higher friction between the ball and court surface would be needed. To a lesser extent, higher COR can also slow grass court pace.

The COR is a straightforward measurement for practitioners because it is derived directly from BB. From a turf management perspective, higher COR and thereby slower pace can be promoted with lower soil moisture (Newell & Wood, 2000), greater soil hardness and soil compaction (Bell, Baker, & Canaway, 1985; Canaway et al., 1990; Holmes & Bell, 1986), lower annual N (Bell et al., 1985; Canaway, 1984, 1985), lower HOC (Bell et al., 1985; Pallis & Mehta, 2000), lower thatch and mat tendencies, and in areas receiving greater wear and soil exposure (Canaway et al., 1990; Holmes & Bell, 1986). Grass court maintenance such as fertility, mowing, rolling, irrigation, overseeding, and cultivation practices are important factors affecting COR. Friction between the ball and grass surface requires specialized equipment and is not well understood from a management perspective. Management practices to slow court pace by promoting greater COF is an area of future research. It is important to recognize, however, that cultural practices to slow court pace need to be implemented without compromising wear tolerance, as discussed in Ebdon et al. (2020).

4 | CONCLUSIONS

Grass courts investigated for surface friction (i.e., COF) and BB (i.e., COR) indicated that species selection is an important factor. Restitution to satisfy the ITF minimum of 50% BB and COR of 0.70 was not observed on any of the species evaluated. Species such as FF and PR were able to achieve sufficient BB to satisfy the ITF 80% minimum to that observed on smooth concrete. Results indicated that 170g of surface hardness for FF and PR to as much as 200g on KB and higher on BG may be needed to achieve a COR = 0.70. Cell wall fractions including hemi and ligno were correlated with COR and COF. These two cell wall fractions exhibited significant but opposite associations with COF and COR. Friction between the ball and grass surface accounted for 70 (FF) to 98% (BG) of the variation in court pace. Achieving higher COF may be a more practical means to slow court pace of notoriously fast grass courts. Future research will be needed to investigate cultural practices that promote slower pace by increasing ball-to-surface friction.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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