APPARENT COEFFICIENT OF RESTITUTION OF IMPACTS IN PADDLE RACKETS WITH DIFFERENT CHARACTERISTICS

Federico J. Viollaz, Universidade Federal de Santa Maria, Brazil and
Universidade do Estado de Santa Catarina, Florianópolis, Brazil,
Aluisio O. V. Avila, José C. Pio da Fonseca,
Universidade do Estado de Santa Catarina, Florianópolis, Brazil,
Aldo J. Viollaz, Universidad Nacional de Tucumán, Tucumán, Argentina

INTRODUCTION: The advantage of a high *coefficient of restitution* (COR) is double, because apart from high ball speed rebound, it is clear that a smaller part of the kinetic energy before collision would be transformed in other forms of energy, some of which can potentially cause injury to the player's arm. Hatze (1993) defined the *apparent coefficient of restitution* (ACOR) of a tennis racket whose handle is constrained under specified conditions to be the ratio of the rebound to the approach velocity of a tennis ball having certain properties and impacting the stationary racket normal to its string surface at a specific point on the string at a specific speed.

Several authors, such as Baker & Wilson (1980), Brody (1979) and Elliott (1982), observed that tennis rackets with increased string tension resulted in decreased ball velocities after impact. Hatze (1993) showed that in the racket-ball interaction, the larger part (58 to 64%) of the transformed kinetic energy is due to the spatial post-impact recoil motion and the internal vibrations of the racket frame, and a substantial part (15% or more) is lost within the ball itself; however, the kinetic energy lost in the strings represents only 2 to 4%. According to these findings, the suggestion was made to construct hollow paddle rackets with softer and more elastic impact surfaces, which could work as a tennis racket with lower string tension in comparison with conventional paddle rackets.

The aim of this paper was to study the influence of racket characteristics, type of grip constraint and the pre-impact ball velocity on the apparent coefficient of restitution (ACOR).

METHODS AND PROCEDURES: Laboratory experiments were carried out on 14 paddle rackets of three different groups (conventional, hollow and prototype), by means of a set-up to measure ball velocity and point of impact, with a *Peak Modus* motion analysis system, based on 180 Hz video cameras and an automatic tracking software. Measurements were done for two impact velocities (30 and 17 m/s) and three different types of grip constraint (free, hand held and clamped). The ACOR shows important changes according to the impact location, so collisions were distributed on the racket face, making possible the construction of a three-dimensional mesh to represent it. Elliptic paraboloids were adjusted to the experimental data using the least square method. In order to study the influence of racket, grip constraint, and impact velocity on the ACOR of the points of frequent impact for the *drive* s*mash* and *volley*, the following equation is suggested:

$$e_{aijk} = \mu + R_i + \beta_j + \gamma_k + r_{ijk}$$

where e_{aijk} is the ACOR obtained from racket i, using an impact velocity j ($j=H$: high, $j=L$: low) and grip constraint k ($k=F$: free, $k=A$: held in the hand); μ is a general average; R is a coefficient related racket characteristics; β is a coefficient related to impact speed; γ is a coefficient related grip constraint, r_{ijk} are random variables which supposedly do not correlate with a mean value zero and variance σ^2.

RESULTS AND DISCUSSION:

Table 1 Coefficients of the elliptical paraboloids representing the ACOR surface, and the general standard error of data.

Racket	Grip	Vel** (m/s)	$N^‡$	s***	B_0*	B_2 E-05	B_3 E-05	B_5 E-05
Extender (2-A)	Free	18.58	19	0.008	0.450	11	-3.9	-1.27
Extender (2-C)	Arm	29.09	19	0.013	0.393	-68	-4.7	-0.79
Dunlop Impact	Arm	27.06	11	0.010	0.398	-80	-3.5	-0.49
Dunlop Impact	Arm	17.55	12	0.010	0.497	-68	-4.8	-0.76
Kennex Asym.	Arm	29.38	16	0.007	0.372	-21	-4.3	-1.00
Proto 3B	Arm	29.49	15	0.011	0.400	-18	-3.4	-1.15
Pro. Fina C1,6	Arm	29.11	15	0.013	0.373	12	-3.7	-1.04
Prot Fina C4,5	Arm	15.90	23	0.014	0.442	116	-2.9	-1.64
Smashing cinza	Arm	28.72	12	0.004	0.398	-55	-5.1	-0.89
Smashing (S1)	Arm	16.30	11	0.008	0.524	-41	-4.0	-0.96
Smashing (S1)	Free	17.57	13	0.011	0.484	53	-4.0	-1.68
Smashing (S2)	Arm	16.33	22	0.012	0.505	-36	-4.4	-1.04
Smas Oca (S0)	Arm	15.94	11	0.007	0.517	39	-4.1	-1.58
Smas Oca (S0)	Free	18.41	16	0.007	0.498	26	-4.8	-1.56
Smash Oca R.	Arm	29.36	16	0.014	0.432	-13	-3.8	-1.14
Smash Oca R.	Clamp	17.42	7	0.013	0.613	-118	-5.3	-0.78
Steel Amarela	Arm	29.77	16	0.008	0.364	4	-3.0	-1.11
Steel Amarela	Free	17.08	16	0.007	0.445	53	-5.1	-1.43
Steel Amarela	Clamp	17.97	6	0.017	0.535	-118	-5.7	-0.51
Steel Vermelh	Arm	30.02	12	0.016	0.389	3	-4.3	-1.10
Tecno A (Oca)	Arm	26.50	11	0.011	0.448	-48	-4.2	-1.05
Tecno A (Oca)	Arm	17.38	11	0.007	0.547	-66	-7.3	-0.81

* Quadric coefficients $e_a = B_0 + B_1x + B_2y + B_3x^2 + B_4xy + B_5y^2$.

** Average pre-impact velocity data in each series

*** General standard error of data.

‡ Number of impact for the series.

Data in Table 1 do not allow us to compare racket performances, because the series of measurements were done using two different approach ball velocities and three different types of handle constraints. The influence of racket characteristics on the ACOR is proportional to $\mu + R_i$, and this can be estimated by $\mu + R_i = e_{aijk} - \beta_j - \gamma_k - r_{ijk}$. When more than one measurement was done on a racket, quantities $\mu+R_i$ were obtained as an average of them. In Table 2 these average values are shown.

Table 2 Average μ + *Ri* for each of the rackets.

Racket	Type	$\mu+R_i$ Smash*	$\mu+R_i$ Drive*	$\mu+R_i$ Volley*
Extender (2-A)	Conventional	0.288	0.373	0.393
Extender (2-C)	Conventional	0.290	0.375	0.400
Dunlop Impact	Conventional	0.308	0.384	0.407
Kennex Asymm.	Conventional	0.282	0.365	0.388
Proto 3B	Conventional	0.291	0.387	0.412
Proto Fina C4.5	Conventional	0.271	0.365	0.389
Smashing (cinza)	Prototype	0.297	0.383	0.408
Smashing (S1)	Prototype	0.330	0.418	0.439
Smashing (S2)	Prototype	0.312	0.399	0.422
Smashing Oca (S0)	Hollow	0.327	0.425	0.447
Smashing Oca R.	Hollow	0.332	0.424	0.448
Steel Amarela	Conventional	0.295	0.376	0.394
Steel Vermelha	Conventional	0.279	0.373	0.398
Tecno Air (Oca)	Hollow	0.341	0.430	0.456

* Average location of impacts for *drive. volley* and *smash* shots were: l_d = 128 mm. l_v = 146 mm and l_s = 83 mm respectively.

Figure 1 shows the three hollow rackets at the top of the graphic for the drive impact point (the same is valid for *smash* and *volley* impact points). Average ACOR for the 8 conventional rackets was equal to 0.374, while the average for the three hollow rackets equals 0.426; where 0.052, the difference, represents more than seven standard errors $s_{\mu+R}$ = 0.007, which means a 14% increase. For the smash and volley points, increases were 16% and 13% respectively, percentages high enough to introduce a noticeable difference in the performance of the hollow rackets under playing conditions.

The impact velocity has an important influence in the ACOR: an increase from 17 m/s to 29 m/s (70%) generates a decrease of 0.10 (25%) on ACOR. The difference in ACOR due to the type of grip constraint is 0.016 (4%), which is less important than the influence of impact velocity. On two rackets, measurements were done with the racket grip clamped, increasing the ACOR about 25% with respect to the free racket. This last result is not considered of relevant practical importance, since the experimental condition was not sufficiently close to the real grip support of a player arm.

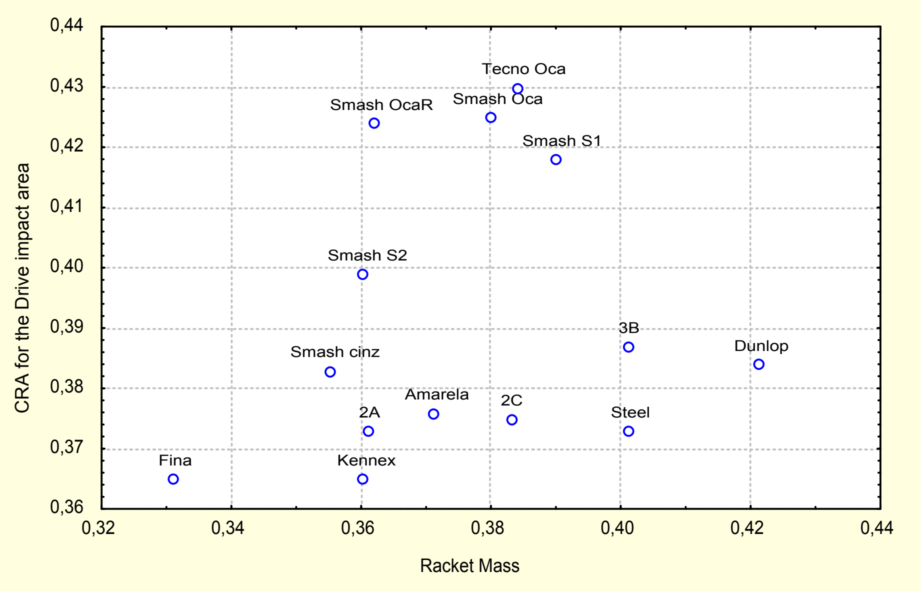

Figure 1 Relationship between racket mass and the ACOR for the *Drive* frequent impact point.

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