INERTIAL AND VIBRATIONAL CHARACTERISTIC OF PADDLE RACKETS, AND THEIR RELATION WITH THE FREQUENT IMPACT AREAS

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INTRODUCTION: Racket designers aim is to obtain a racket with the best characteristics in areas where players usually hit the ball. We are looking for these ideal impact areas and the physical principles which determine them. One of the first works that involved several parameters related to the physics of tennis rackets was that of Brody (1979). In his paper racket-ball interaction was analyzed and three points or areas that can be considered sensitive or critical were determined: *center of percussion* (COP), *node of vibration* (NV) and maximum *apparent coefficient of restitution* (ACOR).
The goal of this work was to determine the most common impact location of drive, volley and smash during a paddle game, and to correlate these locations with racket physical parameters and their qualitative biomechanical characteristics.

METHODS AND PROCEDURES: The sample consisted of 14 last generation graphite frame paddle rackets. *Center of mass* (COM) location was determined swinging the rackets about three different points. The classical pendulum method was used to locate the racket COP; this is an indirect method which consists of using the racket as a physical pendulum, making it oscillate with respect to an axis located 60 mm from the grip bottom. Using equation $l=\tau^2 g/4\pi^2$, with gravitational acceleration g and oscillation period τ, the distance l between the oscillation center and the COP can be calculated. Oscillation time was measured within 1ms precision, using a high speed video camera (180Hz), allowing us to locate the COP within a 1mm interval.
Rackets NV were located using accelerometer techniques, impacting hanging rackets instrumented by two piezoelectric transducers near their ends. Impacts were performed over the racket longitudinal axis with a system based on the pendulum principle and a bidimensional adjustable platform with scales 1/10 millimeters of resolution which enables good impact intensities and location control. Signals from the piezoelectric transducers were analyzed with the help of a Yokogawa digital oscilloscope. When the impact area where the fundamental mode of vibration (lowest frequency and slower dumping) was less excited, impacts were performed around this region, determining in this way a 4 mm segment were the NV could be located within 95% confidence. To identify a racket's natural frequency, impacts were performed near an antinode of the fundamental mode and then the fast Fourier transform (FFT) algorithm was used to calculate the frequency spectrum from the data acquired with the oscilloscope.
A field study was done with four advanced paddle players, chosen from among the players in the 1st and 2nd State category, to locate areas on the racket face which they often use for *drive*, *volley*, and *smash* shots. The characteristics of paddle racket impact surfaces enabled the location of contact points by covering the

racket with strips of carbon paper 200 x 30 mm located over the longitudinal rackets axis. The players were instructed to practice for a couple of minutes with each racket in order to become comfortable with them, then executing 5 to 10 specific shots (*drive*, *volley*, or *smash*) with the carbon paper covered racket. Marks from the carbon paper made possible the location of impacts, thus helping to define the point of greater impact incidence.

RESULTS AND DISCUSSION:

Table 1 – Racket natural frequency f_0, NV (l_1) and COP (l_2) location measured from the racket top.

Racket	f_0 (Hz)	l_1 (mm)	l_2 (mm)	$l_1 - l_2$ (mm)
Dunlop	287 ± 2	113 ± 2	-	-
Extender (2-A)	360 ± 2	108 ± 2	114 ± 1	6
Extender (2-C)	343 ± 2	107 ± 2	114 ± 1	7
Proto Fina	215 ± 2	106 ± 2	113 ± 1	7
Kennex Asymm. v.	292 ± 2	114 ± 2	115 ± 1	1
Prince 3B	330 ± 2	115 ± 2	117 ± 1	2
Smashing (cinza)	305 ± 2	118 ± 2	112 ± 1	6
Smashing (S1)	317 ± 2	103 ± 2	111 ± 1	7
Smashing (S2)	314 ± 2	103 ± 2	110 ± 2	7
Smashing Oca Rota	310 ± 2	104 ± 2	-	-
Steel Amarela	230 ± 2	109 ± 2	110 ± 1	1
Steel Preta	280 ± 2	109 ± 2	113 ± 1	4
Steel Vermelha	248 ± 2	109 ± 2	114 ± 1	5
Proto Oriav	305 ± 2	110 ± 2	113 ± 1	3

Table 2 – Impact location of *drive, volley,* and *smash* shots measured from the racket top**.**

Player	Racket	*Drive* (mm)	*Volley* (mm)	*Smash* (mm)
1	*Dunlop*	145	153	90
	Extender 2A	133	141	100
	Proto 3B	165	173	79
2	*Dunlop*	129	138	81
	Extender 2A	140	150	86
	Proto 3B	136	146	91
Player	Racket	*Drive* (mm)	*Volley* (mm)	*Smash* (mm)
3	*Dunlop*	115	132	80
	Extender 2A	121	140	92
	Proto 3B	115	139	91
4	*Dunlop*	78	143	63
	Extender 2A	109	131	82
	Proto 3B	115	153	74

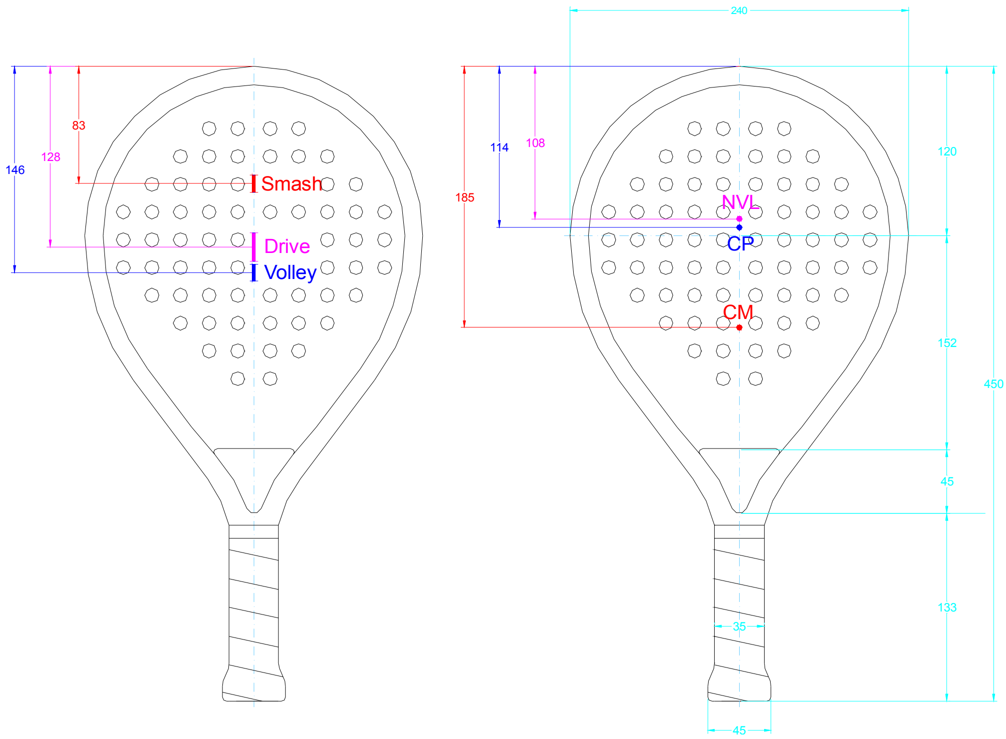
The average natural frequency for the 14 paddle rackets was f_0 = 280.4 Hz with s_f = 80.5 Hz standard deviation. The highest natural frequency was f_0 = 360 $\pm$ 2 Hz and the lowest f_0 = 215 $\pm$ 2 Hz. These natural frequencies are higher than those of tennis rackets (100 to 250 Hz) as a consequence of their length (Figure 1b). Hennig (1993) found that vibrational load at the arm decreases with the increase in the resonance frequency of tennis rackets. Results are consistent with Hatze (1993), who determined that the tennis racket frame was responsible for 58 to 64% of the kinetic energy loss during impact. Hennig (1996) estimated that rackets with natural frequencies around 400 Hz might be able to restitute part of the energy loss to the ball in the post-impact recoil motion and the internal vibrations of the racket frame. It is very difficult to make a tennis racket with a 400 Hz natural frequency, but it is feasible to make paddle rackets with frequencies of these of higher orders and test their responses.

The 14 paddle rackets' COP average location was l_{CP} = 115 mm from the racket top, with s_{CP} = 3 mm standard deviation; the NV average location for the same rackets were l_{NV} = 109 mm with s_{NV} = 4 mm, so the average distance between the COP and the NV was just 6mm (Figure 1a), therefore impacts near this region transmit low force and vibration to the player's arm.

Field study results showed that advanced paddle players use different areas on the racket face for *drive*, *smash* and *volley* shots: l_d = 128 mm, l_s = 83 mm and l_v = 146 mm are their average location measured from the racket top, with s_d = 22 mm, s_s = 11 mm, s_v = 14 mm, standard errors respectively (Figure 1b). A t-test was used to check whether location differences could be statistically significant, resulting t = -2.6 and p = 0.014 between *drive* and *volley ;* t = -11.4 and p = $1.2\text{x}10^{11}$ between *volley* and *smash* and t = -6.2 and p = $1.4\text{x}10^{-6}$ between *drive* and *smash.* These results indicate the existence of statistically significant difference between impact places used in different types of shots.

Paddle rackets have their COP and NV located between 100 and 120 mm from the racket top, so impacts in this region do generate vibrations and forces of small amplitude which are transferred to the player's arm. Impacts between this region and the racket CM have high apparent coefficients of restitution (ACOR). Impacts near the racket top (as in *smash* shots) have low ACOR’s and they do not have the COP and NV advantages, transferring larger vibrations and forces to the player's arm.

Smash shots are characterized by low approach ball speed and high racket angular velocities, in *volley* shots the approach ball speed is normally high and the racket has slower angular velocity. *Drive* shots do have variable characteristics, in between *volley* and *smash.* Field study showed that *smash* impacts normally occur near the top, and *volley* impacts near the COM. Further studies with electronic instrumented rackets and motion analysis systems with high speed video will be necessary in order to correlate approach ball velocity, racket motion and impact location.



a b

Figure 1 – a) Impact places for *drive*, *volley* and *smash* shots. b) Dimensions of *Extender 2A* racket and COM, COP and NV locations.

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