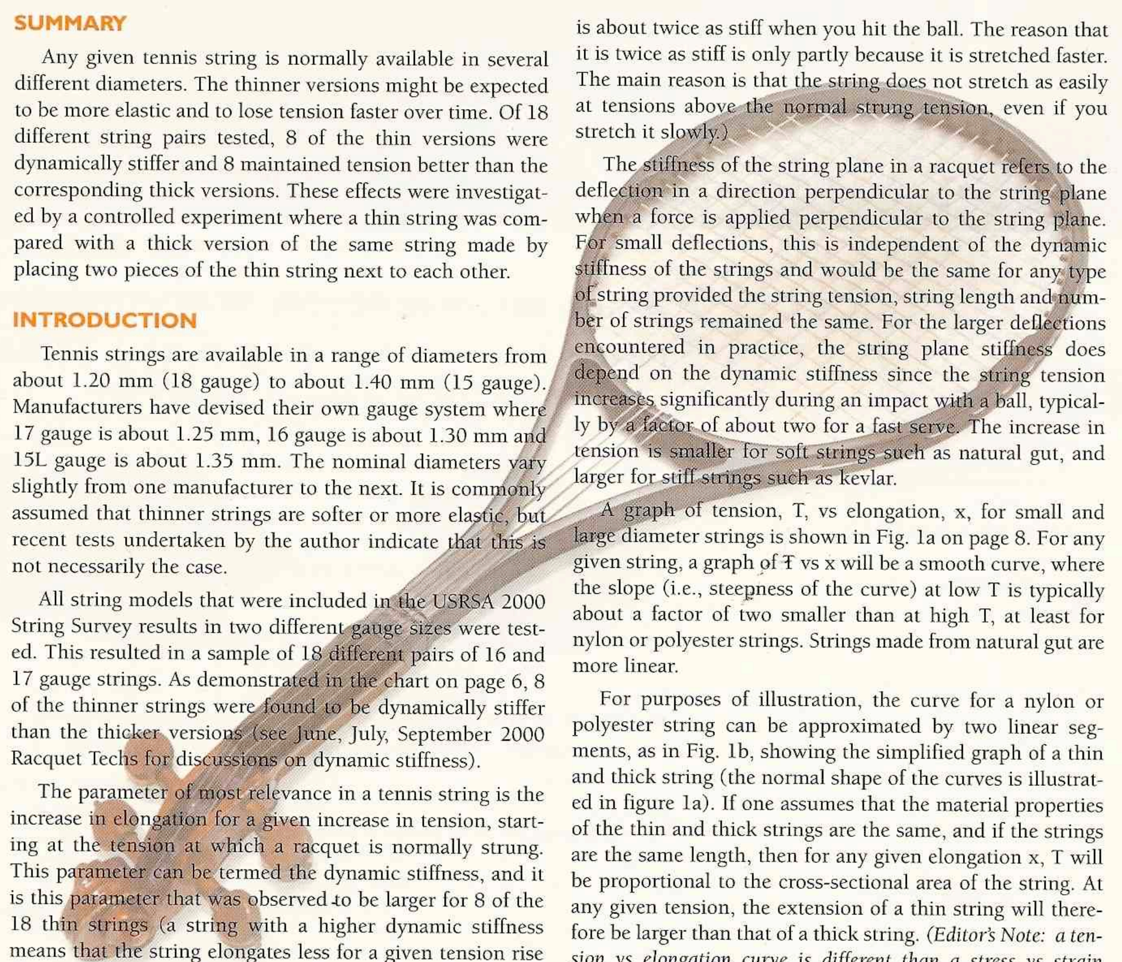
STRING GAUGES

Are Thin Strings Softer or Stiffer?

Rod Cross



SUMMARY

Any given tennis string is normally available in several different diameters. The thinner versions might be expected to be more elastic and to lose tension faster over time. Of 18 different string pairs tested, 8 of the thin versions were dynamically stiffer and 8 maintained tension better than the corresponding thick versions. These effects were investigated by a controlled experiment where a thin string was compared with a thick version of the same string made by placing two pieces of the thin string next to each other.

INTRODUCTION

Tennis strings are available in a range of diameters from about 1.20 mm (18 gauge) to about 1.40 mm (15 gauge). Manufacturers have devised their own gauge system where 17 gauge is about 1.25 mm, 16 gauge is about 1.30 mm and 15L gauge is about 1.35 mm. The nominal diameters vary slightly from one manufacturer to the next. It is commonly assumed that thinner strings are softer or more elastic, but recent tests undertaken by the author indicate that this is not necessarily the case.

All string models that were included in the USRSA 2000 String Survey results in two different gauge sizes were tested. This resulted in a sample of 18 different pairs of 16 and 17 gauge strings. As demonstrated in the chart on page 6, 8 of the thinner strings were found to be dynamically stiffer than the thicker versions (see June, July, September 2000 Racquet Techs for discussions on dynamic stiffness).

The parameter of most relevance in a tennis string is the increase in elongation for a given increase in tension, starting at the tension at which a racquet is normally strung. This parameter can be termed the dynamic stiffness, and it is this parameter that was observed to be larger for 8 of the 18 thin strings (a string with a higher dynamic stiffness means that the string elongates less for a given tension rise than does another). Neither the elongation nor the dynamic stiffness, at tensions lower than that at which the racquet is strung, are of any consequence regarding the performance of tennis strings. (So don't go by the stretchiness of a string during stringing. This occurs in a tension range below the strung tension and is irrelevant. When you hit the ball, the tension rises rapidly above the strung tension, and the string stretches by an amount that depends on the dynamic stiffness. Typically, a nylon string that is soft when you string it is about twice as stiff when you hit the ball. The reason that it is twice as stiff is only partly because it is stretched faster. The main reason is that the string does not stretch as easily at tensions above the normal strung tension, even if you stretch it slowly.)

The stiffness of the string plane in a racquet refers to the deflection in a direction perpendicular to the string plane when a force is applied perpendicular to the string plane. For small deflections, this is independent of the dynamic stiffness of the strings and would be the same for any type of string provided the string tension, string length and number of strings remained the same. For the larger deflections encountered in practice, the string plane stiffness does depend on the dynamic stiffness since the string tension increases significantly during an impact with a ball, typically by a factor of about two for a fast serve. The increase in tension is smaller for soft strings such as natural gut, and larger for stiff strings such as kevlar.

A graph of tension, T, vs elongation, x, for small and large diameter strings is shown in Fig. 1a on page 8. For any given string, a graph of T vs x will be a smooth curve, where the slope (i.e., steepness of the curve) at low T is typically about a factor of two smaller than at high T, at least for nylon or polyester strings. Strings made from natural gut are more linear.

For purposes of illustration, the curve for a nylon or polyester string can be approximated by two linear segments, as in Fig. 1b, showing the simplified graph of a thin and thick string (the normal shape of the curves is illustrated in figure 1a). If one assumes that the material properties of the thin and thick strings are the same, and if the strings are the same length, then for any given elongation x, T will be proportional to the cross-sectional area of the string. At any given tension, the extension of a thin string will therefore be larger than that of a thick string. *(Editor's Note: a tension vs elongation curve is different than a stress vs strain curve, though they look the same. The former plots how tension changes with a given elongation in any given piece of string — thick or thin. The stress vs strain curve looks similar but it takes the size of the string into account — factoring in the cross-sectional area and length of the string. As a result, the stress vs strain curve will be the same for any string length or diameter of a given material. It measures the property of the material of a standardized dimension. The tension vs elongation curve measures the behavior of string of a particular dimension.*

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Stiffness, Elongation, and Tension Loss for 16-17 String Gauge Pairs

Numbers shown in ***red*** *are measurements that are contrary to conventional wisdom.*

Brand	String Name	Diameter mm	Stiffness (k) lb/in	Stretch (mm) at 62 lb	Tension Loss lbs
Babolat	Super Fine Play 16	1.32	208	35.0	11.3
Babolat	Super Fine Play 17	1.26	202	34.5	10.5
Babolat	VS Power 16	1.29	108	26.0	7.5
Babolat	VS Power 17	1.24	100	29.2	7.8
Gamma	Live Wire 16	1.31	177	33.5	11.2
Gamma	Live Wire 17	1.27	180	34.0	13.5
Gamma	Live Wire XP 16	1.32	161	32.0	12.8
Gamma	Live Wire XP 17	1.27	183	29.8	13.0
Gamma	Synthetic Gut 16	1.30	214	31.5	8.5
Gamma	Synthetic Gut 17	1.24	211	31.0	9.1
Gamma	TNT 16	1.32	188	33.0	8.9
Gamma	TNT 17	1.25	207	34.3	10.2
Gamma	TNT 18	1.16	197	43.0	12.5
Gamma	TNT Pro Plus 16	1.31	187	38.5	10.8
Gamma	TNT Pro Plus 17L	1.23	163	40.5	10.9
Gosen	OG-Sheep Micro 16	1.33	209	35.0	11.0
Gosen	OG-Sheep Micro 17	1.30	207	31.0	9.3
Prince	DNA Helix 16	1.30	192	31.0	9.4
Prince	DNA Helix 17	1.25	192	32.8	9.9
Prince	Perfection 16	1.29	206	27.5	11.4
Prince	Perfection 17	1.25	204	27.5	11.3
Prince	Sweet Perfection 16	1.295	183	34.0	12.2
Prince	Sweet Perfection 17	1.25	178	37.0	11.7
Prince	Synthetic Gut 16 w/Duraflex	1.29	202	33.5	8.9
Prince	Synthetic Gut 17 w/Dura flex	1.25	198	32.0	10.1
Prince	Synthetic Gut Original 16	1.32	194	41.5	10.8
Prince	Synthetic Gut Original 17	1.24	212	30.0	9.1
Prince	Synthetic Gut Soft 16	1.29	213	30.0	8.7
Prince	Synthetic Gut Soft 17	1.23	207	32.8	9.3
Tecnifibre	NRG^2 SPL 16	1.34	170	31.5	8.4
Tecnifibre	NRG^2 SPL 17	1.23	184	30.0	8.3
Wilson	Extreme Control 16	1.29	210	29.0	8.8
Wilson	Extreme Control 17	1.23	196	29.5	9.2
Wilson	Sensation 16	1.32	183	29.0	9.0
Wilson	Sensation 17	1.25	213	29.8	10.1
Wilson	Sensation Ice 16	1.32	194	34.0	11.4
Wilson	Sensation Ice 17	1.25	204	33.0	11.3
Wilson	Sensation NXT 16	1.32	208	29.0	10.5
Wilson	Sensation NXT 17	1.24	202	29.8	10.4
Wilson	Syn Gut Extreme Control 16	1.30	198	29.5	9.3
Wilson	Synth Gut Extreme Control 17	1.25	218	29.4	8.3

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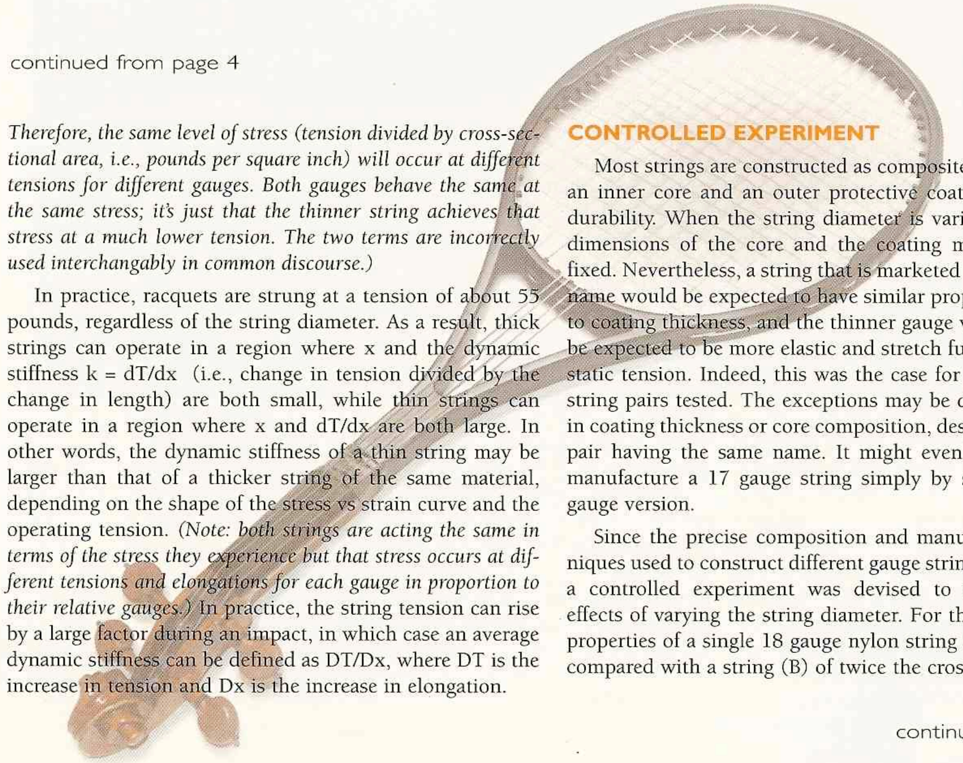

Therefore, the same level of stress (tension divided by cross-sectional area, i.e., pounds per square inch) will occur at different tensions for different gauges. Both gauges behave the same at the same stress; it's just that the thinner string achieves that stress at a much lower tension. The two terms are incorrectly used interchangably in common discourse.)

In practice, racquets are strung at a tension of about 55 pounds, regardless of the string diameter. As a result, thick strings can operate in a region where x and the dynamic stiffness k = dT/dx (i.e., change in tension divided by the change in length) are both small, while thin strings can operate in a region where x and dT/dx are both large. In other words, the dynamic stiffness of a thin string may be larger than that of a thicker string of the same material, depending on the shape of the stress vs strain curve and the operating tension. *(Note: both strings are acting the same in terms of the stress they experience but that stress occurs at different tensions and elongations for each gauge in proportion to their relative gauges.)* In practice, the string tension can rise by a large factor during an impact, in which case an average dynamic stiffness can be defined as DT/Dx, where DT is the increase in tension and Dx is the increase in elongation.

CONTROLLED EXPERIMENT

Most strings are constructed as composite materials with an inner core and an outer protective coating to enhance durability. When the string diameter is varied, the relative dimensions of the core and the coating may not remain fixed. Nevertheless, a string that is marketed under the same name would be expected to have similar proportions of core to coating thickness, and the thinner gauge would normally be expected to be more elastic and stretch further at a given static tension. Indeed, this was the case for most of the 18 string pairs tested. The exceptions may be due to a change in coating thickness or core composition, despite each string pair having the same name. It might even be possible to manufacture a 17 gauge string simply by stretching a 16 gauge version.

Since the precise composition and manufacturing techniques used to construct different gauge strings is unknown, a controlled experiment was devised to investigate the effects of varying the string diameter. For this purpose, the properties of a single 18 gauge nylon string (string A) were compared with a string (B) of twice the cross-sectional area

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Tension vs Elongation
(When thin is stiff and thick is soft)

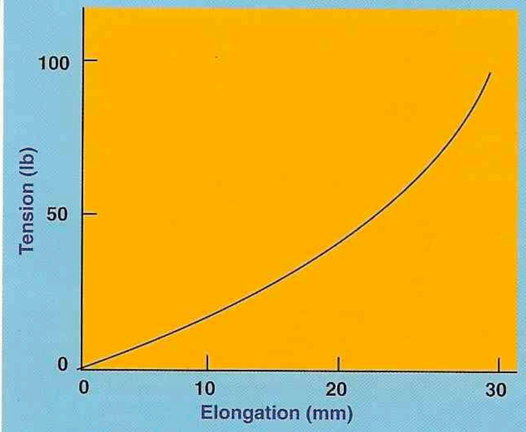

Figure 1a: A typical tension vs elongation curve is an J-shape with a varying slope at different amounts of elongation. The string gets stiffer the more it is stretched, indicated by the steeper slope of the line.

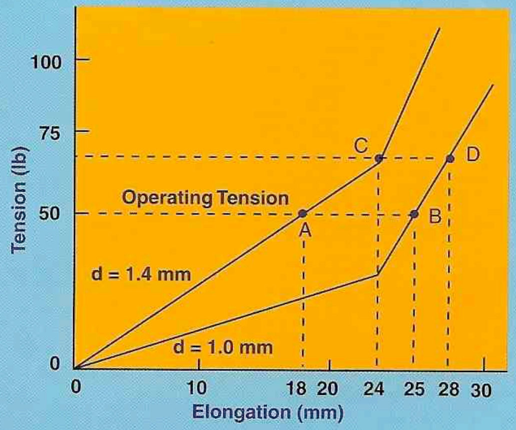

Figure 1b: A simplified version of the tension vs elongation curves for two nylon strings of different diameter.

As shown in Fig 1b, when the thick string is strung at 50 lb, it stretches by 18 mm (point A). When the thin string is strung at 50 lb, it stretches by 25 mm (point B). Up to that point the thin string is softer than the thick string, since it stretches futher, which is what everyone would expect.

Now suppose a ball hits the string and the tension suddenly rises from 50 lb to 70 lb and then back to 50 lb, all during the 5 ms impact with the ball. If it hits the thick string, the string stretches from point A to point C, or an extra 6 mm. If the ball hits the thin string, it stretches from point B to point D, or an extra 3 mm. This time, the thick string stretches more than the thin string, so the thin string is stiffer.

In this example, the dynamic stiffness of the thin string is twice as large as the thick string since it stretches by an extra 3 mm, while the thick string stretches an extra 6 mm (for the same increase in tension from 50 to 70 lb).

mounted in the test device as two lengths of string A in parallel. Strings A and B were both tensioned, in separate experiments, to 62 pounds and then clamped at a fixed length (320 mm). The tension in each string decreased with time due to stress relaxation. The tension in string A dropped by 9.2 lb to 52.8 lb after 1000 seconds. The tension in string B dropped by 11.9 lb to 50.1 lb after 1000 seconds. This result is consistent with the common observation that thin strings often hold tension better than thick strings, despite the fact that the stress in a thin string is larger. It is also consistent with the observation that when string A was tensioned to 31 lb, the tension dropped by 6.1 lb to 24.9 lb after 1000 seconds. When string B was tensioned to 62 lb, each "half" of the string was tensioned to 31 lb. If the tension in each half drops by 6.1 lb after 1000 seconds, then the total tension in string B would drop by 12.2 lb, essentially as observed.

The dynamic stiffness of strings A and B was measured immediately after the 1000 second delay, by impacting ten times with a hammer as described in June 2000 Racquet Tech. In theory, one should be able to determine the dynamic stiffness of a string simply by measuring its elongation curve under quasi-static conditions using an Instron or similar materials testing device (these devises are like stringing

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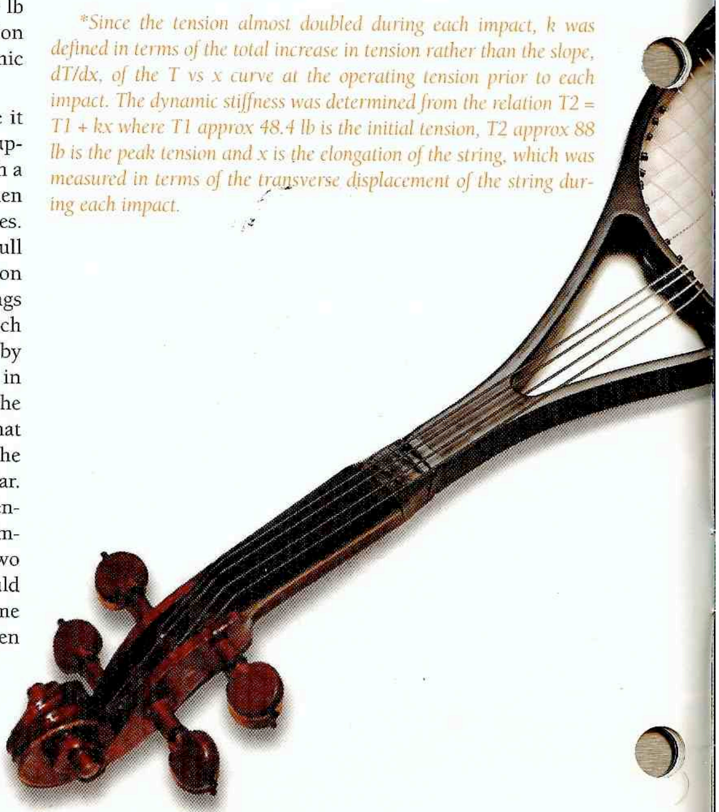
machines — they pull relatively slowly and at a constant rate of elongation. That's why the rate of pulling is always specified in testing. These rates are typically 10 mm to 500 mm per minute.). In practice, this is not as accurate or as relevant as an impact method since the elongation curve depends on the rate of stretch. For example, if a string is stretched by an additional 1 mm and then clamped, the tension may increase by say 2 lb while the string is being stretched, but it immediately starts to decrease as soon as the string is clamped, typically by about 0.4 lb in the first two seconds. This problem can be avoided if the string is stretched sufficiently rapidly (a hammer impact stretches the string at a rate of about 1000 inches per minute).

For the impact tests, the impact duration was about 29 milliseconds for each string, and the impact energy was 1.63 Joules per impact (equivalent to the energy on one string in a 120 mph serve). The increase in tension during each impact was 37.8 lb on average for string A and 43.1 lb for string B. Calculations (see note at right*) revealed that string A had a dynamic stiffness $k = 196.6$ lb/in averaged over 10 impacts, at an average tension of 49.7 lb. For string B, $k = 235.5$ lb/in averaged over 10 impacts, at an average tension of 48.2 lb. An average tension is quoted since the tension decreased slightly following each impact. In this case, the thinner string was softer, but not by the factor of two that one would expect if the stress vs strain curve were linear. For string A, one can infer that the dynamic stiffness at a tension of about 48.4 lb is a factor of 1.7 larger than the dynamic stiffness at a tension of 24.2 lb. If it were a factor of two higher, then the dynamic stiffness of strings A and B would have been the same.

To understand this, consider a simple spring. Suppose it stretches one inch when you pull it with a force of 25 lb. Suppose also that it stretches by 2 inches when you pull it with a force of 50 lb. Such a spring is said to be linear since when you double the force you double the amount it stretches. Now suppose you put two such springs in parallel, and pull with a force of 50 lb. Then there is a force of 25 lb acting on each spring, so they each stretch by 1 inch. The two springs in parallel are twice as stiff as only spring since they stretch only one inch at 50 lb, whereas one spring alone stretches by 2 inches at 50 lb. Similarly, two identical tennis strings in parallel would be twice as stiff as one string alone, if the strings behaved as linear springs. In fact, it turned out that strings A and B (i.e., two A strings in parallel) had about the same stiffness, which means that the strings were not linear. For string A, one can infer that the dynamic stiffness at a tension of about 48.4 lb is a factor of 1.7 larger than the dynamic stiffness at a tension of 24.2 lb. If it were a factor of two higher, then the dynamic stiffness of strings A and B would have been the same. If the stiffness at 48.4 lb was the same as the stiffness at 24.2 lb (i.e., the strings were linear) then string B would be twice as stiff as string A.

CONCLUSIONS

A surprising result of testing thin and thick versions of commercially available tennis strings is that thin strings can be dynamically stiffer and they can maintain tension better than the corresponding thick versions. In this paper it has been shown how this can arise. Two linear strings connected in parallel will be twice as stiff as one. Tennis strings are nonlinear and have the property that the stiffness increases with tension. Consequently, the stiffness of two parallel strings can be larger, smaller, or the same as that of a single string depending on the stress vs strain curve and the operating tension. Similarly, the rate at which a string loses tension is a nonlinear function of tension. The rate of tension loss increases with tension, but the loss rate may not increase in proportion to the tension. As a result, two strings in parallel can lose tension at a faster rate than a single string. ■



**Since the tension almost doubled during each impact, k was defined in terms of the total increase in tension rather than the slope, dT/dx, of the T vs x curve at the operating tension prior to each impact. The dynamic stiffness was determined from the relation* $T2 = T1 + kx$ *where T1 approx 48.4 lb is the initial tension, T2 approx 88 lb is the peak tension and x is the elongation of the string, which was measured in terms of the transverse displacement of the string during each impact.*