Player sensitivity to changes in string tension in a tennis racket

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Forty-one advanced recreational tennis players were tested to determine their ability to detect differences in string tension in a tennis racket. Subjects were given pairs of rackets that varied in tension by up to 98 N (10 kg) and were asked whether they noticed a difference in tension and if so, which racket was strung at a higher tension. Only 11 (27%) of those tested could correctly identify a tension difference of 5 kg (11 lb) or less. Fifteen (37%) could not pick a difference of 10 kg (22 lb). To examine the importance of sound as a means of discrimination, an additional test was undertaken where participants wore earplugs. Of the 26 subjects undertaking this additional test, only 6 (23%) were successful. It was concluded that advanced recreational tennis players demonstrated limited ability to correctly identify differences in string tension and that impact sound was an important factor for those participants who were successful at various levels of discrimination.

Introduction

In tennis, it is commonly thought that changes in string tension have a significant effect on racket performance and feel. Advanced tennis players are especially particular about the tension at which their racket is strung. Whilst most rackets are strung at a tension typically between 50 and 70 pounds (23 kg and 32 kg), advanced players will often request their racket to be strung to the nearest one pound (0.5 kg). It is doubtful that stringing machines are accurate enough to meet such a request. Even if they were, it is questionable whether players can actually detect a difference of 0.5 kg in string tension. On the other hand, one might expect that experienced players could easily pick a difference of say 10 kg (22 lb) in string tension, but this has never been tested.

Previous investigations suggest that differences in racket performance can be expected when string tension is varied [1,2,3]. It is generally accepted that one should string a racket at low tension (loose strings) for increased power or at high tension (tight strings) for better control. The explanation for the increase in power is that the ball deforms less when it impacts on looser strings and will rebound at higher speed due to the decreased energy loss in the ball. The strings store and return energy much more efficiently than the ball. Ball control and rebound angle are also affected by string tension [4,5]. For a groundstroke, the racket will rotate about its longitudinal axis if it impacts on a ball either above or below this axis. The amount of rotation about the longitudinal axis of the racket is reduced as the string tension is increased due to the shorter impact duration [6], resulting in better control of the ball trajectory in the vertical direction. Whilst these explanations are valid, the inference is that the increase in power or control is substantial. However, recent estimates indicate that the increase in power for a 20% decrease in tension is typically less than 2% [7]. The effect on racket control was also found to be very small. The question therefore arises as to whether these effects are even detectable by players. This was the primary motivation for the present study.

The feel and performance of a racket must ultimately be related to the mechanical forces acting between the ball and the strings and the consequent forces transmitted to the hand and arm by the racket handle. The most significant factors determining these forces are the mass, stiffness and weight distribution of the racket, the mass and stiffness of the ball and the stiffness of the string plane. String tension is only one of several factors affecting string plane stiffness. Other factors include head size, number and spacing of the strings, string diameter and string type. Consequently, the implications of the present study extend beyond the direct effects of changes in string tension. If players are unable to differentiate between rackets with different string tension, then it is also likely that they will be unable to distinguish differences in string plane stiffness arising from any of the other factors listed above. Such a result is indicated by laboratory tests of physical properties of strings [8], which show that all strings made from the same basic material (gut, nylon, polyester or kevlar, in increasing order of stiffness) have very similar physical properties. This is evident despite the fact that players often have a strong preference for one particular brand of string over another, even when the string is made from the same material. Factors such as "playability", "touch", "feel" and "responsiveness" are commonly used by players and string manufacturers to distinguish different strings, but laboratory tests generally show no correlation with subjective assessments by players. Similarly, recent laboratory tests [9] show that the amount of spin imparted to a ball is essentially independent of string type, string tension, string diameter and spacing between the strings, despite the commonly held views of players and string manufacturers that all these factors do have a strong effect on ball spin. One aspect of tennis that is significantly affected by string tension is the ball's angle of rebound [3,4]. As the string tension is lowered, the ball rebounds at an angle closer to the normal.

The ability of advanced recreational players to detect both small and large changes in string tension during play conditions was examined. It was hypothesised, on the basis of the small calculated change in racket power and control with string tension, that players would not be able to detect small differences in string tension if the influence of the impact sound could be eliminated.

Experimental methods

No attempt was made in this study to make an accurate determination of the threshold ability of individual subjects to distinguish different string tensions. That would have required a relatively large number of trials for each subject and it would have taken several hours to test each subject. Since subjects were available for only a limited time, the approach adopted was to use a small number of trials and a large number of subjects. The fundamental question addressed was whether most players can confidently pick a specified difference in string tension. The precise threshold of any particular individual was not a major concern.

Five identical, Volkl Pro Comp model graphite rackets were used for the tests. When strung, each racket had of mass 307±4 gm, length 690 mm and a balance point 338 mm from the butt end of the handle. The head size was rated as medium with a strung area of 630 cm^2. The fundamental vibration frequency of each racket was measured to be 133±2 Hz indicating a racket of medium stiffness. By contrast, old wooden rackets have a vibration frequency typically about 90Hz while modern wide-body graphite rackets are very stiff and light by comparison and have a vibration frequency typically around 180Hz [10]. This was considered relevant as the stiffness of a racket also influences the rebound characteristics of the ball [4].

The rackets were strung using a 1.40 mm diameter nylon string at tensions 18, 21, 23, 25 and 28 kg (from 40 to 62 lbs). The tension increments were respectively 3, 2, 2 and 3 kg. This enabled combinations of rackets to be compared that varied in tension by as little as 2 kg (4.4 lbs) and as large as 10 kg (22 lbs). The rackets were identifiable only to the investigator by a small code placed on the frame. The rackets were otherwise identical in appearance. The tension of the stringing machine was calibrated with a load cell immediately prior to stringing. The string tension was monitored over the 9 days of testing by measuring the vibration frequency of the strings [11]. The string tension in each racket decreased marginally over the 9-day period but the tension differences were closely preserved at the nominal increments of 3, 2, 2 and 3 kg.

All tests were conducted with a string dampener installed to make it more difficult for players to detect changes in string tension from the sound of the strings vibrating. String dampeners have no effect on the vibration of the racket frame since the mass of the dampener (<5 gms) is too small to be significant [12,13]. For the same reason, a dampener is not likely to have a significant effect on racket power or control, but it may have a strong psychological effect by changing the duration of the impact sound. Many players claim to be unable to play comfortably with a racket if it is not fitted with a string dampener. The significance of the impact sound on the sensitivity to string tension was determined by testing certain subjects with and without earplugs and by avoiding conversation during the tests.

As part of the test procedure, apparatus was set up on a tennis court as shown in Figure 1. Twenty-four Slazenger tennis balls were removed from their pressurised container 24 hours prior to the beginning of testing. The balls were launched at a speed of 19.2±0.6 ms^{-1} from a ball machine set up on one baseline so that each ball landed approximately in the centre of the opposing court. Each subject stood in the centre of the opposite baseline and was instructed to hit a cross-court forehand towards a radar gun positioned next to the ball machine. The radar gun was used to monitor the consistency of speed from the ball launcher and to measure the speed of the ball returned by the player.

Tests were conducted on two consecutive weekends at a local tennis club which conducts a regular tennis competition on synthetic grass courts. A

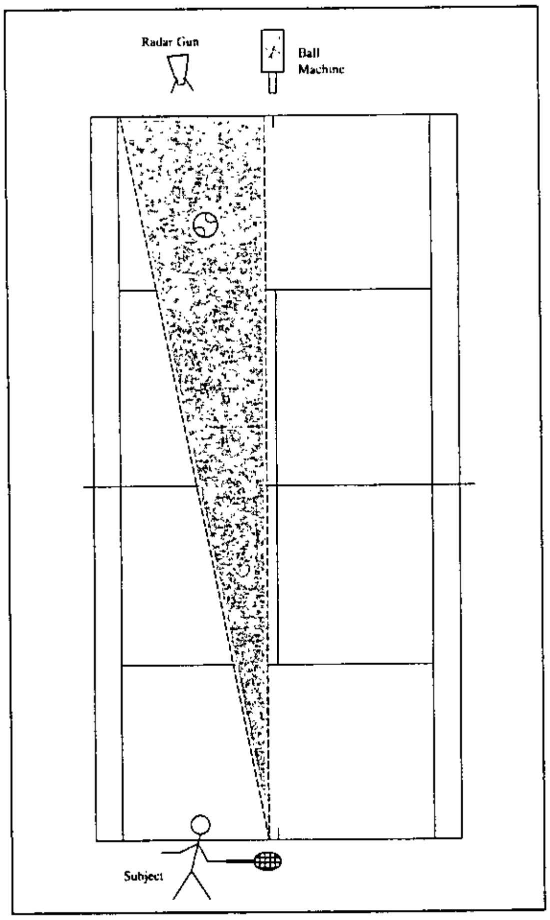

Figure 1: Set-up on the tennis court.

summary of the test procedure was distributed to the top grade players at the beginning of the afternoon. Volunteers were tested after they had completed a competition set which was considered to be an adequate warm-up. A total of 41 subjects (26 male, 15 female) were tested. These players were all "A grade", experienced players who could hit the ball consistently well, but none was of professional standard, and most played tennis only once or twice a week in a local competition. An indication of the general standard was estimated by measuring the serving speeds of those tested. Prior to testing, each player completed a short questionnaire regarding his or her previous tennis experience.

The order of testing (Figure 2) was derived for both logistical reasons and to randomise the sequence. The order was also dependent on the success or failure of each trial. Each trial involved a subject comparing two rackets in succession and stating whether they could detect a difference in string tension. If a difference was noticeable, the subject was asked to identify which racket had the higher tension. Prior to starting the test, players were

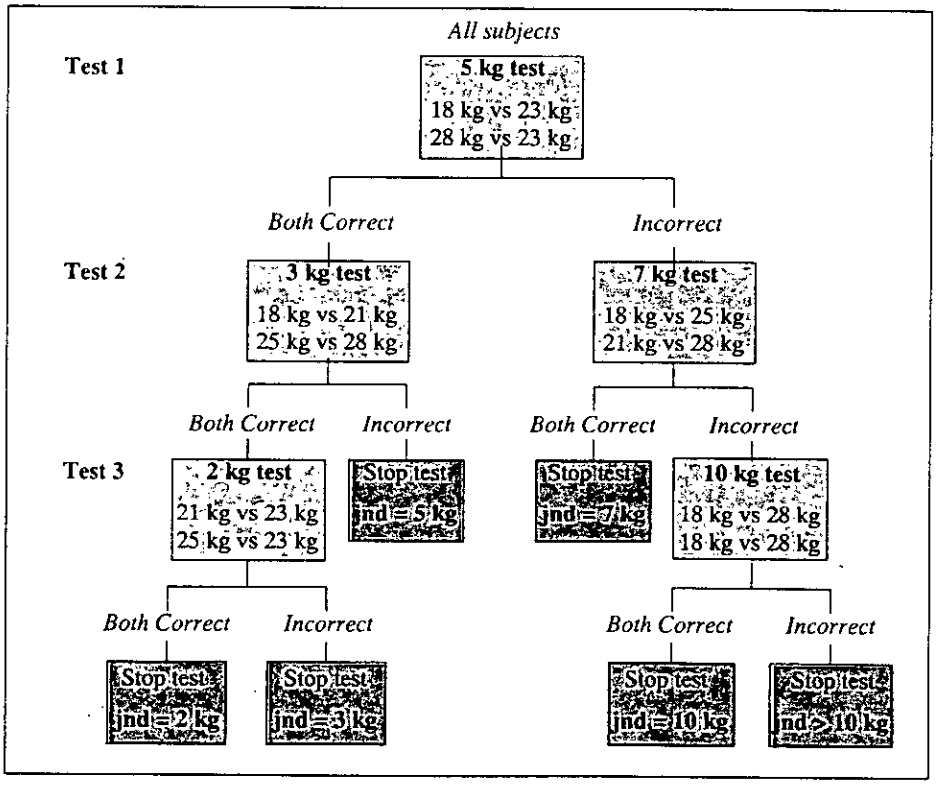

Figure 2: Decision tree for testing.

instructed to concentrate on the string tension of each racket and not the speed of impact. Subjects were not informed of ball rebound speeds at any stage of the test.

Each subject was given the opportunity to hit four balls for each racket before a decision was required. This provided subjects with enough trials to establish the "feel" of each racket, but not so many that the "feel" was forgotten during the second set of trials. The test was then repeated with another two rackets that varied in tension by the same amount. If the subject correctly determined the order of tension both times, he/she was considered to have successfully passed and was then tested using two pairs of rackets with a smaller tension differential. If they failed one or both of the first tests, they were provided with rackets that were strung with a larger tension differential. This was continued until the player's discrimination level was determined. The term "just noticeable difference" (jnd) is commonly used in this context [14,15] and will be used henceforth despite the limited number of trials.

Once a player's jnd was determined, an additional test was undertaken where the subject wore earplugs and repeated the last comparison where a difference was correctly noted. This was conducted with the dampeners remaining in position in each racket. Subjects who failed every test and therefore did not have a measured jnd were not required to complete this additional test.

Participants were not informed of the specific details of the testing procedure. Prior to the test, they were told that all racket frames were identical but the string tensions in any given pair of rackets might be different. They were also instructed not to hit the strings with their hand in an attempt to gauge the sound or feel of the strings.

Further to the above tests, an additional laboratory based experiment was undertaken to assist in the interpretation of the player sensitivity tests. This involved the measurement of the frequency spectrum of the impact sound emanating from the strings when struck by a ball. For this purpose, a microphone was located near the impact point and its output was recorded using a spectrum analyser. This was done for the rackets strung at 21 kg and 28 kg both with and without a dampener.

All data from the subject questionnaire and string tension sensitivity tests were entered into the Statistical Package for Social Sciences (SPSS) for further analysis. This included both descriptive and analytical tests. A Pearson's Chi-Square test was used to determine whether gender, age, playing experience or preferred tension had any effect on a player's jnd or whether they were more successful at detecting a difference for lower tension rackets compared to the higher tension rackets.

Results

The mean age of the 41 players tested was 26 years and the mean number of years experience in tennis was 16 years. Males were able to serve at an average speed of 44.7 ms^{-1} (161 km/hr) and females at 36.1 ms^{-1} (130 km/hr). Fifty nine percent of those participating had a preferred string tension, the average of which was 26 kg (57 lbs). All 41 subjects were tested at the 5 kg

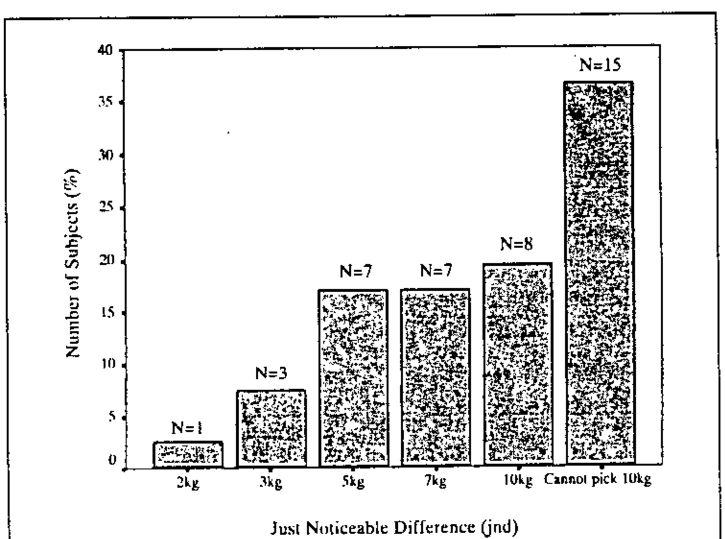

Figure 3: Distribution of jnd with string tension.

	Just Noticeable Difference			Tension Range Factor		
	χ^2	df	p-value	χ^2	df	p-value
Gender (m/f)	1.37	5	0.93	1.29	3	0.73
Age Range (≤ 20/>20)	2.60	5	0.76	0.22	3	0.98
Experience (<5, 5-10,>10)	5.72	10	0.84	1.68	6	0.95
Preferred Tension (Low, Med, High)	14.42	15	0.49	6.65	9	0.67

Table 1: Chi-square statistics for just noticeable difference and tension range (no earplugs).

Tension difference	Number of subjects attempting test	Number of subjects passing test (%)
10 kg	23	8 (35%)
7 kg	30	7 (23%)
5 kg	41	11 (27%)
3 kg	11	4 (36%)
2 kg	4	1 (25%)
Various (ear plugs)	26	6 (23%)

Table 2: Number of subjects attempting and passing each test.

discrimination level and only 11 (27%) could pick the difference in the two successive trials (Figure 3). In other words, 30 (73%) of the subjects could not reliably discriminate between a racket strung at say 23 kg (51 lbs) and 28 kg (62 lbs). Fifteen (37%) of the subjects failed to correctly detect a 10 kg difference. Therefore, of the 41 subjects originally tested, only 26 (63%) could be identified as having a jnd of 10 kg or less. When these subjects were re-tested at their jnd wearing earplugs, only 6 (23%) were successful.

There were no significant differences in jnd between players for gender, age, playing experience or preferred tension (Table 1). Likewise, no significant differences were found regarding the ability of subjects to discriminate between pairs of rackets strung at the higher range of tensions when compared to the lower range of tensions (Table 1). When analysing the distribution of the results, the data were evenly split between identifying a) both correctly, b) both incorrectly, c) the lower tension pair correctly and d) the higher tension pair correctly. Table 2 presents the number of subjects attempting and passing each test.

Laboratory measurements of the impact sound produced strings that vibrated for 1 to 2 seconds with a well-defined frequency of 545 Hz for the racket strung at 21 kg and 640 Hz for the racket strung at 28 kg. This occurred after the initial impact sound which lasted about 6 ms. When a dampener was used, the largest amplitude component in the frequency spectrum was centred around 200 Hz arising from the initial impulse lasting around 4 ms. This was the same for both the 21 kg and 28 kg racket.

Discussion

(a) Random nature of outcomes

Threshold measurements are commonly made using a forced choice method whereby subjects are forced to guess if they are unsure of their choice. Because of the small number of trials in the present study, there was concern that some players may have enhanced their discrimination level through guessing. While guessing was actively discouraged and all players appeared to have given an honest assessment, the results are still similar to that of pure chance (Table 2). Given that each test requires two pairs of rackets to be correctly ranked, there was a 25% chance of guessing correctly. If chance was a factor in some participants' results, one must conclude that the ability of players to discriminate between tensions is actually less than those presented in Figure 3, as guessing could only have falsely enhanced the success rate. Regardless of whether subjects were guessing or whether the data reflect a valid statistical distribution of discrimination levels, the main experimental results are clear. That is, (a) surprisingly large fractions of subjects were unable to pick tension differences as large as 7 kg or 10 kg with certainty and (b), the ability to discriminate tension differences is diminished strongly when subjects wear earplugs.

(b) Detecting a difference

In order to pass a test, players were required to correctly detect not only a difference in string tension, but also the direction of that difference. It was interesting to note that most players showed no uncertainty in detecting a string tension difference, but were unable to detect whether the string tension had increased or decreased. In relation to hearing tests, Moore [15] found that listeners sometimes have difficulty in assigning a direction to a change in pitch, even though they hear that two tones are different. Moore noted that such people show considerable improvement with practice. Whilst all of the subjects tested were experienced tennis players, few would change their string tension more than twice a year. One might expect that the ability to distinguish small differences in tension could be learnt or improved by experience. The test results described above can be regarded as typical of players with limited previous experience in detecting changes in string tension. With respect to age and general playing experience, no significant correlation was found between these and the ability of a subject to successfully detect tension differences. In fact, the one player who detected the 2 kg difference, both with and without earplugs, happened to be the youngest subject tested (15 years old).

The fact that many players were unable to pick differences as large as 7 or 10 kg in the above tests indicates not only that such players were insensitive to the difference in feel or performance of the rackets, but that they were also unable to pick the differences in the impact sound under the conditions of the test. Whilst the influence of sound on the results was somewhat minimised by the presence of string dampeners, subjects became less successful when using earplugs (Table 2). This result demonstrates that, despite the presence of a dampening effect, sound was still a source of information useful in discriminating between string tensions. In the context of the current results, one may conclude that 77% of the players discriminated primarily on the basis of the impact sound and that the other 23% discriminated primarily on the basis of racket feel or performance.

(c) Effect of string tension on impact sound

In any strung device (such as a racket or musical string instrument), the vibration frequency of the strings increases in proportion to the square root of the string tension. Most people can easily detect a frequency change of 6%, which is the difference in frequency of adjacent notes on a piano. A 6% change in string frequency corresponds to a change of about 12% in string tension. Consequently, if a racket is strung at say 25 kg, it should be easy to detect a change in tension of 3 kg simply by listening to the string vibrations. In fact, studies concerning the ability of subjects to discriminate tones of different frequency show that for a steady tone at around 500 Hz, most subjects can detect a difference of about 1 Hz (0.2%) when one tone is presented immediately after the other and no other sounds intervene [14,15]. If the tone duration is less than about 0.1s, then the just noticeable difference (jnd) in frequency increases as the duration decreases to about 10 Hz for a 6 ms tone. Sipovsky et al [16] showed that, for a tone at 1500 Hz, the jnd in frequency increases to about 30 Hz as the duration decreases to a point where only a single cycle is present.

In the current context, the sound made by the ball impacting on the strings of the racket consists of a relatively loud "thud" lasting about 6 ms, followed by a short tone of 545 Hz for the racket strung at 21 kg and 640 Hz for the racket strung at 28 kg. The ear detects the initial loud impact followed by the fainter string vibrations. The effect of the dampener was that it reduced the amplitude and the duration of the string vibrations. No significant difference was observed in the sound spectrum in this region for either racket. The peak in the frequency spectrum due to string vibrations was still clearly evident, but the spectrum was much broader with the result that both rackets contain frequency components that overlap. This, together with the fact that the dominant components in the spectrum are at frequencies around 200 Hz, makes it more difficult to discriminate between the two rackets on the basis of the impact sound.

Since about half of the players could detect a 7 kg difference in string tension with a string dampener installed and, since most of these players relied on the sound of the impact to pick the difference, one can conclude that the jnd in frequency is about 100 Hz. This is considerably larger than the jnds described above, but the conditions were quite different from normal hearing sensitivity tests. For example, players had to contend with both the ball machine and any other extraneous noise present. Furthermore, players were not specifically instructed to listen for differences in the impact sound and may not even have focused their attention on the sound as a means of discrimination. In fact, it appeared to the authors that some players focused more attention on hitting the ball at high speed over the net than on picking the differences in tension. Evidence for this was found in the data on return speeds. None of the 6 male players returning the ball at an average speed greater than 116 kph were able to detect a 7 kg difference in tension, but 5 of the 7 male players returning the ball at an average speed less than 106 kph were able to pick the difference. This factor suggests that players' technique contributes to their ability to differentiate between string tensions.

(d) Effect of string tension on racket power

The most obvious conclusion that one can draw from the above results is that a moderately large change in string tension does not have a strong effect on the feel of a racket. This is in fact what one might expect from an analysis of the dynamics. If a ball is incident normally on a racket at speed υ_1, and if the racket approaches the ball at speed *V*, then the speed, υ_2, of the ball off the racket is given by

$$\upsilon_2 = e_A\upsilon_1 + (1 + e_A)\,V$$

where e_A is the apparent coefficient of restitution [17]. The value of e_A is typically about 0.45 for an impact at the centre of the strings. As shown by Cross, a factor of two decrease in string tension leads to an increase in e_A of about 7% under conditions where the stiffness of the ball is about the same as the string plane stiffness [7]. A decrease in tension from 28 to 18 kg would therefore result in an increase in e_A of about 5%. In the trials described above, υ_1 was about 12 ms^{-1} after the ball bounced off the court and *V* was about 17 ms^{-1}. If e_A is increased by 5% from 0.450 to 0.473 then υ_2 will increase by only 2.4% from 30.0ms^{-1} (108 kph) to 30.7ms^{-1} (110.5 kph). Since players returned the ball at speeds varying typically by about 10%, most of this variation was due to changes in racket speed. Given that it is difficult to detect small changes in ball speed by eye and that the observed distance travelled by the ball depends on both ball speed and the initial angle to the horizontal, it seems unlikely that players would be able to detect any change in ball speed due to string tension differences.

The primary effect of a change in string tension in a racket is that it changes the stiffness of the string bed. For very small deflections of the string bed, the stiffness is directly proportional to the *initial* string tension. However, this is not the case for medium or large deflections of the string bed since any extension of a string acts to increase the string tension. More generally, the stiffness of the string bed is proportional to the *instantaneous* tension and therefore varies during an impact. For a very fast serve, the stiffness may even double during the impact. Since strings at low tension deflect more than strings at high tension, the increase in tension is larger when the strings are initially at low tension. As a result, the average or peak stiffness of the string bed during an impact does not depend strongly on the initial string tension. Similarly, the impact duration and the force acting on the ball or on the strings does not depend strongly on the initial string tension [8].

The ball remains on the strings for a period of approximately 5 ms but the handle itself undergoes rotation, translation and vibration for a period of about 30 ms following the impact [18]. The handle motion itself is therefore not simply related to the force on the strings or the duration of the impact and it depends primarily on the total impulse (the product of the force and the duration) given to the racket. At any given racket speed, the outgoing ball speed and hence the impulse will increase by about 2% when the string tension decreases from 28 to 18 kg as described above. As a result, the force acting on the hand would increase by only 2%. An increase of 2% in the impulse would also arise if the racket speed were increased by 2%. Frame vibrations are more sensitive to changes in string tension than changes in ball speed [7], but if a player hits the ball in the middle of the strings, there are no frame vibrations at all. It is therefore not obvious how a player would be able to distinguish a change in string tension from a change in racket speed using only the feel of the racket as a guide.

The possibility that some players are sensitive to changes in the feel of a racket when the tension is changed suggests that a biomechanical mechanism operates to detect not only the change in the peak or average force on the racket but also the rate at which the force is applied. Such a mechanism must be sufficiently sophisticated that a player can recognise the difference between an increase in racket speed and an increase in string tension, since in both cases the force transmitted to the hand increases as well as the rate of this force application. It may therefore be the combination of the player's knowledge of swing speed and biomechanical "feel" of the force application that enables the performer to discriminate between string tensions.

Conclusions

Advanced tennis players demonstrated limited ability to detect differences in string tension during playing conditions. Only 27% of the subjects tested were sensitive to a tension difference of 5 kg (11 lbs). When earplugs were added, the ability to correctly identify the tighter racket dropped considerably. Despite the muffling effect of the string dampener, these results indicate that sound was still a factor in the decision making process. No significant differences were found between gender, age, playing experience, preferred tension or upper and lower test ranges.

The results described above are likely to surprise the many tennis players who are apparently quite particular about their string tension. Nevertheless, other evidence exists that indicates these results are at least plausible and are not entirely unexpected. A decrease in string tension from 28 kg to 18 kg results in an increase in ball speed of only 2%, which would be difficult to detect by players. The change in the force on the strings and hence the change in the force on the hand is about 2% and would also be difficult to detect. Consequently, the physical attributes of the impact are such that it is very difficult for players to differentiate between rackets of different string tension.

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