Impact forces and torques transmitted to the arm by a tennis racquet

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Introduction

It is commonly believed that stiff racquets and light racquets act to increase the force on the arm when playing tennis, and that flexible racquets and heavy racquets help to reduce arm injuries. There is little data on this subject, and most of the evidence is anecdotal. From a physics point of view, there are several qualitative arguments that can be advanced both for and against the use of stiff or light racquets, so it is not obvious which is better. A heavy racquet is harder to swing but it does not recoil as rapidly when struck by a ball. Stiff racquets vibrate less than flexible racquets, since they are harder to bend, but will obviously exert a larger force on the arm than a racquet with a very flexible, rubber handle. To investigate these issues, we present below some measurements and calculations based on a flexible beam model of the racquet.

Several different approaches can be used to model the interaction of a ball with a tennis racquet, and the consequent interaction of the racquet with the arm. The simplest approach is to treat the racquet as a perfectly rigid object with flexible strings at one end and a hand, wrist joint and arm attached at the other end. This approach was used by the author to examine the effect of the hand on the location of the centre of percussion of a hand-held striking implement [1]. The calculations agreed well with experimental data and indicated that the force on the arm could be reduced by using a heavy, flexible racquet. However, the consequences of replacing the rigid beam with a flexible beam were not fully investigated. Flexible beam models of a tennis racquet have been used to examine effects on the outgoing ball speed [2, 3, 4], but the consequences in terms of the forces transmitted to the arm have not previously been investigated. In this paper we consider the effect of adding a hand and arm to the handle end of a flexible beam in order to determine how changes in mass, mass distribution and stiffness of the beam affect the force and the torque on the hand.

The largest forces on a racquet are generated during the impact of a racquet with the ball, being much larger than the force required to swing the racquet. During and immediately after the impact, impulsive forces are transmitted to the hand and arm as a result of rotation, translation and vibration of the racquet. These forces depend on a large number of factors, including the stiffness of the ball and the stiffness of the strings. We consider in this paper impacts only at points on the long axis of the racquet. Effects due to twisting of the racquet in the hand or rotation of the racquet about its long axis are not considered, despite the fact that they may also contribute to arm injuries. Twisting of the racquet is not a necessary condition for developing tennis elbow. The author developed severe tennis elbow some years ago when polishing the end of a rectangular block of lead for ten minutes on sandpaper to reduce its length by 1 mm. The block shuddered when pulled end-on across the sandpaper, due to its high centre of mass, but not when it was pulled while face-down (with a low centre of mass). In that case, a jerking force was applied axially along the arm.
Effective mass of the hand and arm

The forces transmitted to the hand and arm depend on the coupling between the hand and the handle. The hand is not rigidly attached to the handle since it isolated to some extent by the soft grip attached to the handle and by soft tissue in the hand. The force on the hand depends on the stiffness of the grip and the softness of the hand. Consider, for example, the situation shown in Fig. 1 where the handle is represented by a mass $M_1$, the hand is represented by a mass $M_2$ and the two are separated by a spring with stiffness $k$. Suppose that $M_1$ and $M_2$ are both initially at rest when a constant force $F$ is applied to $M_1$. The initial force acting on $M_2$ is zero since the spring does not compress until $M_1$ starts to move. If $F$ reverses direction while the spring force is still relatively small, then the motion of $M_1$ is not strongly affected by $M_2$, and the acceleration of $M_1$ is essentially $F/M_1$. It is partly for that reason that the effective mass of the hand, in reducing the vibration frequency of a racquet, is less than half of the actual mass. The mass of an adult hand is typically about 500 g but the effective mass of the hand is typically less than 200 g.

![Fig. 1 The hand is separated from the handle by a soft grip and soft tissue](image)

There is an additional reason why the effective mass of the hand is less than the actual mass. If a 500 g point mass is added to the handle at the vibration node point in the handle, then the vibration frequency and amplitude will not change at all. The effect of the additional mass depends on its proximity to the node point. Similarly, if a 500 g point mass is added at the rotation axis of the racquet, then the location of the centre of percussion on the string plane is unaffected. Mass added at the butt end of the handle shifts both the node point and the rotation axis closer to the butt end of the handle. Since the hand extends over a length of about 10 cm of the handle, it does not act as 500 g mass at the butt end, nor does it have zero effect on vibration and rotation of the racquet.

Experimental results showing the effect of the hand and arm on the vibration frequency of a racquet are shown in Fig. 2. The vibration was measured by means of a 15 mm diameter, 0.3 mm thick piezoelectric disk attached to a flat section of the racquet handle 21 cm from the butt end, just beyond the end of the grip. Vibrations were induced by impacting a tennis ball at low speed on the strings near the tip of the racquet when the racquet was (a) freely suspended, (b) held firmly by the handle with one hand and (c) suspended freely with a 40 mm wide, 184 g wood block bolted to the handle grip and centred 6 cm from the butt end of the handle. The decrease in
vibration frequency was essentially the same in cases (b) and (c), although the hand was more effective than the wood block in damping the vibrations.

The racquet used to show the results in Fig. 2 was unusual in that it had a particularly high vibration frequency, being very stiff and light (260 g). Similar percentage changes in the vibration frequency were obtained with other racquets, indicating that the hand and arm together effectively add about 180 g to 200 g to the handle when the handle moves rapidly. The hand also damps the vibrations over time, but does not have a strong damping effect on the amplitude of the first few vibration cycles, at least at the measurement point 21 cm from the butt end.

![Fig. 2](image)

Fig. 2. The hand acts as a mass of about 180 g in lowering the vibration frequency of a racquet.

**Rigid racquet and arm model**

The basic mechanics describing the force, $F_H$, transmitted to the hand (and arm) can be described by assuming that a racquet behaves as a rigid beam of mass $M_R$ with a mass $M_H$ connected to the end of the handle, as shown in Fig. 3. In this model, the force on the hand arises purely from rotation and translation of the racquet. Vibrations of the racquet do not play a significant role, so the model is strictly only appropriate
for impacts at the vibration node near the middle of the strings. Nevertheless, the effect of vibrations at other impact points can be estimated in terms of a reduced coefficient of restitution at the impact point. A significant effect of the additional mass at the handle end is to shift the centre of mass of the racquet-hand system closer to the handle end, so that it is located at a distance \( B \) from the butt end of the handle.

![Fig. 3 Rigid beam model of a racquet with a mass \( M_H \) attached to the handle end. \( M_H \) represents the combined mass of the hand and arm.](image)

It is convenient to study the collision in a reference frame where the racquet is initially at rest. In that case, a ball striking the racquet strings will exert a force \( F \) on the racquet, causing the centre of mass to recoil at speed \( V_{cm} \) and the whole racquet to rotate an angular velocity \( \omega \). The hand and forearm will also rotate, about axes through the wrist and elbow respectively, the net result being that the racquet rotates about an axis at distance \( A \) from the centre of mass [1].

The racquet exerts a force \( F_H = M_H a_H \) on the hand and arm, where \( a_H \) is the acceleration of the hand and handle, and the hand exerts an equal and opposite force on the handle. Here and later in this paper we assume that \( M_H \) represents the combined effective mass of the hand and the arm, and that it can be represented as a single mass element of width 10 cm attached to the handle, as indicated in Fig. 3. A slightly more complicated model, where the hand and forearm are represented by separate mass elements connected by a hinge at the wrist, was not considered since the forearm can be regarded as a mass attached to the end of the handle in the same way that the hand acts as an additional mass attached to the handle [4].

If we regard the hand, arm and racquet as a single, isolated system of total mass \( M = M_R + M_H \), then the only force on that system is the impact force \( F \) of the ball on the strings of the racquet. If the ball impacts at a distance \( b \) from the centre of mass then

\[
F = M \frac{dV_{cm}}{dt} \\
F b = I_{cm} \frac{d\omega}{dt}
\]

where \( I_{cm} \) is the moment of inertia of the racquet-hand system about an axis through the combined centre of mass. Since \( V_{cm} = A \omega \) we find from Eqs. (1) and (2) that
If the centre of the hand is located at a distance \( H \) from the rotation axis, then \( V_H = H \omega \), where \( V_H \) is the velocity of the hand. The force on the hand is then given by \( F_H = M_H dV_H/dt = H M_H d\omega /dt \), so

\[
F_H = \left( b M_H / l_{cm} \right) F
\]

The force on the hand is proportional to \( F \), and is also proportional to \( H \). In theory, the force on the hand decreases to zero if \( H = 0 \), a situation that can arise if the rotation axis coincides with the centre of the hand. The impact point on the racquet is then regarded as the centre of percussion (COP) with respect to the axis through the hand.

Since \( F_H \) is proportional to \( F \), the easiest method of reducing \( F_H \) is not to hit the ball so hard. Since \( F \) acts to change the ball speed from about \(-20 \) m/s to about \(+30 \) m/s in a typical groundstroke, and since \( F \) acts over a time interval of about 5 ms, a typical, average value of \( F \) is 570 N for a 57 g ball. The peak value of \( F \) is about twice the time-average value. If the impact duration is extended to say 7 ms using softer strings or a softer ball, then the average value of \( F \) is reduced to 407 N.

Differences between rigid and flexible racquets can be illustrated by considering a “standard” racquet of mass \( M_R = 300 \) g, modelled as a uniform beam of length \( L = 69 \) cm, with its centre of mass at the centre of the beam and with \( l_{cm} = M_R L^2 /12 = 0.01190 \) kg.m\(^2\). If a hand of effective mass \( M_H = 200 \) g and length 10 cm is located at the end of the handle, then the overall mass increases from 300 g to 500 g, \( B \) decreases from 34.5 cm to 22.7 cm and \( l_{cm} \) almost doubles, to 0.02251 kg.m\(^2\). The response of a hand-held racquet to an impact with a ball might therefore be expected to differ considerably from the response of a free racquet. In fact, the rebound speed of the ball is unaffected and the vibration frequency decreases by only about 12%.

The main effects of the hand are to shift the centre of percussion to a point in the throat region of the racquet, and to damp vibrations.

If the rotation axis is located under the centre of the hand, then \( A = 17.7 \) cm, and we find from Eq. (3) that \( b = 0.254 \) m, corresponding to an impact at distance \( d = 0.209 \) m from the tip of the racquet. Since the head of a racquet is typically about 30 cm long, the COP is located in the throat area, about 6 cm from the middle of the strings. By contrast, the node of the fundamental vibration mode is typically close to the middle of the strings, about 15 cm from the tip, regardless of whether the racquet is freely supported or hand held. The node point is the sweet spot of the racquet [1], a result that will be confirmed when we consider flexible racquets.

The force on the arm can be a significant fraction of the force of the ball on the racquet, especially for impacts near the tip of the racquet. For example, an impact 6 cm from the tip of the standard racquet is described with \( b = 0.403 \) m, \( A = 0.112 \) m and \( H = 0.065 \) m, giving \( F_{H/F} = 0.234 \). If the racquet mass is increased to 350 g, then \( F_{H/F} = 0.222 \). According to the rigid beam model, there is only a 5% reduction in \( F_{H/F} \) when the mass of the racquet is increased by 17%, or a 5% increase in \( F_{H/F} \) when the mass of the racquet is decreased by 17% to 250 g. The model indicates that \( F_H \) is a maximum at the tip of the racquet and decreases to zero at the COP.
A similar type of analysis could be done for off-axis impacts. The moment of inertia of a racquet about its long axis is typically about 0.0015 kg.m$^2$. The hand will increase the moment of inertia only marginally since the racquet head is much larger in diameter than the hand. For an impact near the edge of the racquet frame, say 8 cm from the long axis, the torque about the long axis will be about half of that about the transverse axis through the centre of mass, depending on the distance from the impact point to the centre of mass. However, the rate of rotation about the long axis will be much greater due to the much lower moment of inertia. When combined with rotation about the transverse axis, the result could be a significant stretching of the muscles in the forearm and an increased axial force on the tendons attached to the elbow.

**Flexible racquet model**

A ball impacting on the strings of a racquet acts to stretch the strings while the ball first compresses and then expands, as indicated in Fig. 4. The strings exert a force on the racquet frame, which we assume to be localised at a distance $b$ from the centre of mass, as in Fig. 4. Goodwill and Haake (2002) considered a distributed force and obtained similar results to that for a localised force. We assume that the strings have a stiffness $k_s$ and the ball has a linear stiffness $k_1$ during compression. The force, $F$, on the ball when it expands is taken as $F = k_2 x^p$, where $x$ is the compression of the ball, giving a coefficient of restitution of 0.67 when $p = 3.5$ and when the ball impacts on a concrete slab [4]. In this model, the coefficient of restitution is enhanced when the ball impacts at the vibration node near the middle of the strings, as observed experimentally, since the ball compression and energy loss in the ball is significantly reduced compared to an impact on concrete. The coefficient of restitution may be reduced, however, for impacts at other locations on the strings, due to the energy loss resulting from vibrations of the racquet frame.
Fig. 4 Flexible beam model of a racquet, allowing for flexibility of the ball and the strings as well as the racquet. The beam was divided into 40 segments each of mass \(m\) and length \(s\). An additional 200 g mass was distributed over the last 5 segments to simulate the effect of the hand and arm.

The racquet is modelled as a flexible beam, and was divided into 40 elements of equal length \(s\), and mass \(m\), to obtain a numerical solution of the standard beam bending equation [2]. The force, \(F\), acting on the ball and the strings was applied to one of those elements in the racquet head region, and the effect of the hand was simulated by adding a mass of 0.04 kg to each of the last five elements of the beam. The numerical solutions yielded the transverse velocity and acceleration of each element in the beam. The total force on the hand, \(F_H\), was calculated by summing the forces acting on each 0.04 kg mass at the end of the handle. The torque on the hand, causing it to rotate at the same angular velocity as the racquet, was also calculated by summing the torques acting on each 0.04 kg segment about an axis through the centre of mass of the hand.

The stiffness of a beam can be specified in terms of the parameter \(EI\) where \(E\) is Young’s modulus and \(I\) is the area moment of inertia. Neither \(E\) nor \(I\) are well known for any given racquet but an average value along the length of a racquet can be determined by approximating the racquet as a uniform beam of mass \(M\) and length \(L\). The fundamental vibration frequency, \(f\), of such a beam is given by

\[
f = 3.561 \left( \frac{EI}{ML^3} \right)^{(1/2)}
\]

for a freely supported beam. Modern racquets have \(M\) values around 0.3 kg, \(L\) about 0.7 m and vibrate with a fundamental frequency between about 110 Hz and 200 Hz. Consequently, \(EI\) is typically about 150 Nm to 280 Nm averaged over the length of the racquet. For the standard racquet, \(f = 160.4\) Hz.

When a racquet is held firmly by the hand, the vibration frequency decreases and the vibrations are strongly damped, as shown in Fig. 2. The hand is not sufficiently rigid to clamp the handle or to allow the racquet to vibrate in a low frequency diving board mode [3]. The damping effect of the hand is ignored in the following calculations, since the main effect of damping is to decrease the amplitude of the vibrations over time, but it does not decrease the initial force applied to the hand.

**Typical results**

Numerical solutions for the standard racquet are given in Figs. 5 and 6, showing the force on the racquet at the impact point and the force on the hand and arm. The racquet was assumed to be initially at rest and the ball was incident at right angles to the string plane, at points on the long axis, at 30 m/s. The solutions were obtained for a 57 g ball of stiffness \(k_1 = 30\) kN/m, with \(p = 3.5\), and for a string plane stiffness \(k_s = 20\) kN/m. Fig. 5 shows the time variation of the forces on the ball and the hand for impacts (a) 6.7 cm, (b) 16.3 cm and (c) 25.9 cm from the tip of the racquet. The impact near the tip excites the fundamental vibration mode strongly and causes the racquet to rotate rapidly, thereby generating a large force on the hand and arm. The impact near the middle of the strings does not excite the fundamental mode strongly since the impact is close to the node point. The impact at 25.9 cm is close to the COP for an axis at the butt end of the handle.
An obvious result that can be inferred from Fig. 5 is that the force on the hand is large for impacts near the tip and throat of the racquet and is much smaller for impacts near the middle of the strings. The magnitude of the force on the hand is proportional to the magnitude of the force of the ball on the strings, but the variation of the two forces with time is quite different. The impact of the ball on the strings lasts for only 5 or 6 ms, whereas the force on the hand persists for a longer period of time due to vibration of the racquet. There is a time delay of about 2 ms before the force of the ball on the strings is transmitted to the hand, due to the time delay of the bending wave to arrive at the handle. The wave then reflects off the end of the handle and heads back to the impact point on the strings, but the ball bounces off the strings before the bending wave arrives back at the impact point. For that reason, the bounce speed of the ball off the racquet is largely unaffected by the presence (or absence) of the hand [4].

For the impact at \( d = 6.7 \text{ cm} \), the maximum force on the hand is 273 N and the maximum force on the ball is 599 N, so \( F_H/F = 0.45 \). The force ratio is nearly twice that predicted by the rigid beam model, the reason being that the peak handle velocity is effectively doubled as a result of vibration of the racquet.
Fig. 6  Velocity of the butt end of the handle for the standard, hand-held racquet for impacts at distance d from the tip. The ball is incident at 30 m/s and the effective hand mass is taken as 200 g.

The velocity of the last handle segment, at the butt end of the handle, is shown in Fig. 6 for the same three impact points as in Fig. 5. The velocity of that segment is the same as the velocity of the hand at that point. The time derivative of the velocity yields the acceleration of the handle, and the force on the hand is proportional to the acceleration of the handle. An impact at d = 6.7 cm near the tip of the racquet causes the butt end of the handle to rotate in the same direction as the outgoing ball, the rotation speed varying with time due to vibration of the handle at 160 Hz. An impact at d = 25.9 cm near the throat of the racquet results in a much lower rotation speed, in the direction of the incoming ball, since the impact point is close to the COP point. An impact at d = 16.3 cm, near the centre of the strings, also causes the racquet to translate and rotate, but the resulting handle velocity is relatively small and the vibration amplitude of the racquet is also small.

As shown in Fig. 6, the average or DC component of the handle velocity is close to zero for an impact in the throat region, but the AC component due to vibration is relatively large. For an impact in the throat region, the force on the hand arises primarily as a result of vibration of the handle, rather than rotation of the handle. For an impact near the tip of the racquet, the velocity of the handle has a DC component due to rotation and translation of the whole racquet, consistent with a rigid body prediction, and an approximately equal AC component due to vibration of the handle. For a perfectly rigid beam, the force on the hand arises purely from beam rotation and translation and is zero for an impact at the COP. For a flexible beam, the COP point is of no real significance in determining the force on the hand, apart from the fact that the DC component of the handle velocity is close to zero when the ball impacts in the throat region.
How can the force on the hand and arm be reduced?

Effects of changing various parameters of the standard racquet are shown in Fig. 7, by varying one parameter at a time and keeping all other parameters of the standard racquet and hand fixed. In each case, the force and torque acting on the hand is shown for an impact at $d = 6.7$ cm, assuming that the ball is served at 50 m/s. A different set of results is obtained if one assumes that the ball is incident at a fixed speed on a stationary racquet. For example, if the ball is incident at 30 m/s then the peak force on the hand is about 270 N (as shown in Fig. 5 for the standard 300 g racquet), regardless of the mass or stiffness of the racquet. The latter result agrees with experimental data on the handle acceleration of a wide variety of different racquets. Regardless of the mass or stiffness of the racquet, the handle acceleration is about the same for all racquets if the incident ball speed and string plane stiffness is the same [4]. By contrast, the peak force on the hand in Fig. 7(a) decreases from 443 N to 341 N when the racquet mass is increased from 200 g to 400 g, and it decreases from 388 N at $EI = 100$ Nm to 363 N at $EI = 360$ Nm. The decrease in the hand force in Fig. 7(a), both with increasing mass and stiffness, is due primarily to the increase in ball rebound speed when the racquet mass or stiffness is increased.

A ball incident on a stationary racquet at speed $v_1$ bounces off the racquet at speed $v_2 = e_A v_1$, where $e_A$ is the apparent coefficient of restitution. Alternatively, if the impact point on the racquet approaches a stationary ball at speed $V$ then the ball will be served at speed $v = (1 + e_A)V$. In order to serve the ball at 50 m/s, the racquet must approach the ball at speed $V = 50/(1 + e_A)$. In the racquet frame of reference, the ball approaches the racquet at speed $v_1 = 50/(1 + e_A)$. Numerical solutions of the beam equation for any given value of $v_1$ yield both the force on the hand and the value of $e_A$ at the impact point. The results shown in Fig. 7 were obtained by first calculating the hand force and $e_A$ when $v_1 = 30$ m/s and then proportioning the hand force for an incoming ball speed $v_1 = 50/(1 + e_A)$. For the standard 300 g racquet, $e_A = 0.176$. For the 200 g racquet, $e_A = 0.016$ and for the 400 g racquet, $e_A = 0.283$. When serving at 50 m/s with a 400 g racquet, the racquet does not need to be swung as fast as a lighter racquet, and the resulting force on the hand is smaller.
Fig. 7 Force, $F_H$ (solid curves, left scale) and torque (dashed curves, right scale) on the hand when serving at 50 m/s from a point 6.7 cm from the tip of the racquet, showing (a) changes with racquet mass and stiffness, assuming that the mass and stiffness are uniform along the length of the racquet, (b) variation with the string or ball stiffness (c) the effect of changing the hand mass and (d) the effect of changing the mass distribution of the standard 300 g racquet.

One of the effects of increasing racquet stiffness is that the vibration amplitude decreases, but the first half cycle of the hand force waveform remains relatively large. The effect can be seen in Fig. 2. In the limit where the racquet is infinitely stiff, the vibration amplitude would be zero. The first half cycle would then represent pure translation and rotation of the handle, in direct proportion to the force of the ball on the strings and without a time delay. A flexible racquet obeys the same linear and angular momentum conservation laws as a rigid racquet, and therefore rotates and translates at about the same speed, apart from the fact that the ball rebounds at a lower speed due to the transfer of some of the initial kinetic energy of the ball to vibrational energy in the racquet. The coefficient of restitution is therefore lower for a flexible...
A racquet, which translates to a lower value of $e_A$ for an impact near the tip or throat of a flexible racquet. The value of $e_A$ for an impact near the middle of the strings is essentially the same for both rigid and flexible racquets since the vibration amplitude remains small regardless of racquet stiffness.

Significant increases in the hand force and torque result when the stiffness of the ball or the strings is increased, as shown in Fig. 7(b). Increasing the ball stiffness results in an increase in both the force on the ball and the force on the hand, although it does not have a strong effect on $e_A$, which increased from 0.166 to 0.181 when the ball stiffness was increased from 10 kN/m to 40 kN/m. An increase in string stiffness also results in an increase in the force and torque on the hand, and it resulted in a decrease in $e_A$ from 0.246 to 0.113 when $k_s$ was increased from 10 kN/m to 40 kN/m.

Figure 7(c) shows the effect of changing the effective hand mass. Both the force on the ball and the value of $e_A$ remains constant when additional mass is added to the handle, since the ball rebounds off the strings before the bending wave arrives back from the handle end. Increasing the hand mass acts to decrease the vibration amplitude at the handle end, but the force and torque on the hand increase since a larger mass is accelerated.

In Fig. 7(d), the mass distribution of the standard racquet was varied by increasing the mass of the head region and decreasing the mass of the handle, while keeping the total mass fixed at 300 g. Mass added to the head or removed from the handle acts to shift the centre of mass closer to the head. For example, with a 140 g head, the centre of mass of the racquet (without the added hand) shifted to a point 39.1 cm from the end of the handle. The result is a significant increase in $e_A$ for a head heavy racquet, with $e_A = 0.293$ with a 140 g head and $e_A = 0.007$ with a 60 g head. The ball bounces better off a heavy head than off a light head, so the racquet does not need to be swung as fast if it is head heavy, resulting in a smaller force and torque being transmitted to the hand.

Discussion and Conclusions

The results in Fig. 7 demonstrate that the force and torque on the hand can be reduced by several different means, especially by using a soft ball and soft strings and a head-heavy racquet. From an overall racquet performance point of view, the force on the hand is only one of many factors considered by players and racquet manufacturers. Modern racquets are not designed specifically to reduce the force on the arm. Light racquets are usually head-heavy and heavy racquets are usually head-light so that players can swing them easily and generate high ball speeds. Professional players tend to hit the ball in the middle of the strings more consistently than recreational players, so the force on the arm is not generally a serious issue for them, and they usually prefer to use stiff strings to improve ball control or for extra spin. The force on the arm is not usually an issue even with recreational players, unless they have already experienced pain in the arm and are seeking ways to reduce the pain or to prevent a recurrence. In that case, the main factors that should help to reduce the force on the arm are to use a lower string tension, a heavier racquet or a head heavy racquet. One other factor, not considered in detail here, would be to use a lighter ball. If the cloth cover is removed from a tennis ball, the reduction in ball mass and stiffness makes a
very big difference to the force on the arm. Such a ball was used at Wimbledon in 1877 but it was quickly replaced by a cloth-covered ball to improve its playability, and it has remained cloth-covered ever since.

References


