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A mechanical study on tennis racquets to investigate design factors that contribute to reduced stress and improved vibrational dampening

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Abstract

There are a multitude of factors that will affect the mechanical performance and stress transfer to a tennis player's upper extremities. Variations in frame design, materials, string tensioning, ball stiffness, impact locations, and player technique are just some of the potential variables that can result in a significant increase or decrease of stress transfer and vibration from the racquet to the player. To better understand the significant contributing design factors that influence shock and vibration transmission to the racquet handle upon impact, such testing was conducted in a standardized and repeatable manner to evaluate and compare the shock and vibration patterns for multiple frame designs from a variety of high performing tennis racquets. Multiple racquet frame designs from six different manufacturers were mechanically tested in an ISO17025 certified third-party independent test facility by qualified mechanical and biomechanical engineers. A consistent mass drop technique was employed to provide controlled impact to the center of the head of each mounted racquet. The impact load and duration were plotted and a Fourier Transform Analysis was conducted on each data file. The results of this study showed statistically significant reductions in vibrational dampening time and lower vibrational amplitudes following the initial impact shock for the triple core designs. This evaluation provided consistent baseline comparisons for different handle designs in a manner that demonstrated multi-layered cores of the racquet handle performed better than hollow designs with respect to vibration and force attenuation.

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Keywords: Tennis racquet; biomechanics, handle; stress transfer; vibration; dampening; shock

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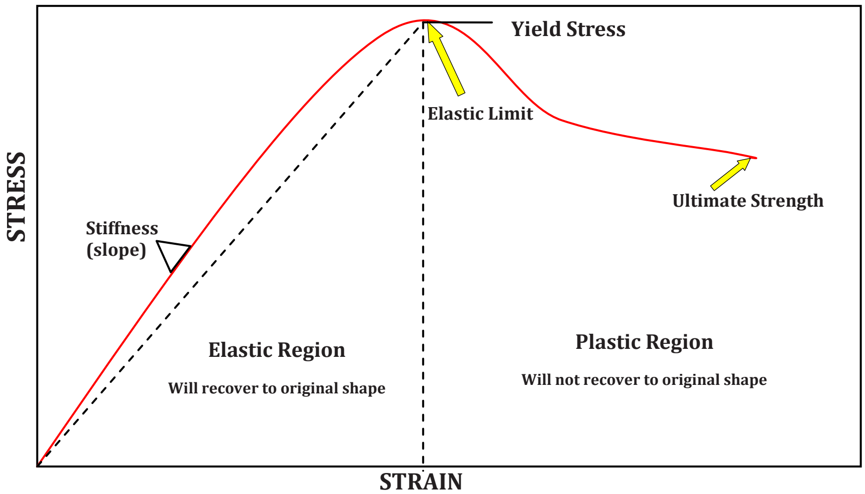
1. Introduction

Repetitive impact and overuse of the upper extremities in racquet sports can increase the risk of tissue fatigue and injury, leading to inflammation of the tendons and soft tissue in the wrist, elbows, and shoulders. Eventually, long term repetitive use can result in small stress fractures and chronic degeneration of the surrounding soft tissues due to microscopic tears that were incompletely healed [1]. There are many human factors such as; compromised muscular strength, poor technique, and increases in duration or intensity of play that may contribute to an increased risk of injury [2, 3]. Modern racquet designs have evolved to compensate for reduced muscular strength through the incorporation of stiffer racquets and harder tennis balls. However, an increased stiffness in the player's equipment can potentially lead to increased shock transmission from the racquet transferred to the tissues of the upper extremities (i.e. wrist, elbow, shoulder). Additionally, prolonged exposure to vibratory oscillations due to racquet displacement has the potential to lead to fatigue injury and tissue degeneration over time [2-4]. Recently, new and innovative technologies and materials have been incorporated into the handle designs of tennis racquets in an effort to reduce shock and prolonged vibration in an effort to reduce injury to the player.

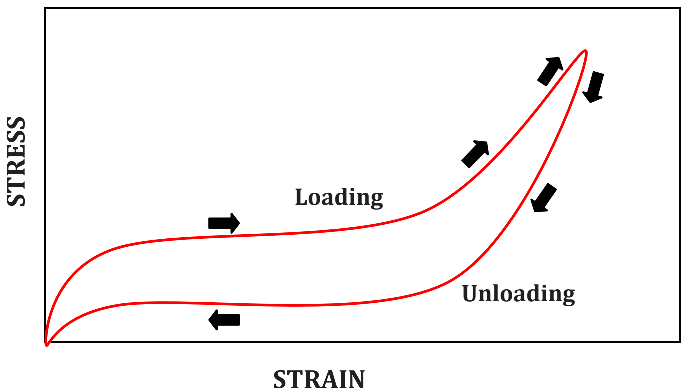
Numerous variations in racquet design, materials, string tensioning, ball stiffness, impact locations, and player technique are just some of the potential variables that when combined, can result in an exponential increase or decrease of impact, stress transfer, and vibration from the racquet to the player. The specifications of a tennis racket play a large part in how the tennis racquet performs. Racquet stiffness measures its flexibility along its longitudinal axis. The stiffness is measured in terms of a rating scale, with the majority of racquets ranging between 55 and 72 on the stiffness rating scale [5, 6]. It is measured by placing a specific amount of weight on a lever, which bends the frame. A stiffer racquet will transfer greater impact energy to the tennis ball, resulting in more power, while flexible racquets return less energy, resulting in less power. The stiffness of a racquet and its relationship with energy transfer is best explained by a stress-strain curve when a tennis racquet is loaded (Fig. 1).

The loading and unloading phase of a stress-strain profile generates a hysteresis curve that defines the mechanical performance of an object. Stiffness is measured as the slope of the stress-strain profile within the linear elastic portion of the curve. Therefore, when loading and unloading an object within this region, the object will undergo deformation and recover when unloaded to maintain its original shape. If an object is more compliant, greater deformation will occur during loading, resulting in a wider hysteresis curve and greater energy loss (Fig. 1a). The hysteresis curve is the sigmoidal curve generated from loading and unloading of an object (Fig. 1b). The area within this curve represents the energy loss. A wider curve represents greater energy loss and is indicative of an object with greater compliance or flexibility. A narrow curve is indicative of a stiffer object. If less energy is lost during the loading and unloading of an object, the hysteresis curve would be narrow when compared to the current graph shown in Fig. 1a. If less energy is lost, the remainder of energy will be directly transferred to the object, thus resulting in higher stress transfer to the object. In essence, a stiffer racquet that has less energy loss will transfer higher stresses from the handle to the tissue gripping the handle. Furthermore, a stiffer racquet will transfer greater impulse forces (shock) [5, 6] to the human tissue, and higher vibratory amplitudes. Lower amplitudes and shock forces indicate greater flexibility.

Many studies have investigated a combination of these variables to quantify shock and/or vibration for a variety of racquet designs. However, variations in the literature exist with respect to study design where controlled comparative studies were difficult to perform, included a multitude of variables that may have masked the study outcomes, and may have provided conflicting or inconclusive comparisons. To better understand the significant contributing factors towards stress and vibration transfer for different tennis racquet frame designs, such testing was conducted in a standardized, consistent, and repeatable manner to provide statistically valid comparisons with minimized variability in the study design. Therefore, the goal of the present study was to provide an initial mechanical evaluation of shock and vibration for multiple frame designs from a variety of high performing tennis racquets to investigate potential design factors that could influence shock and vibration transmission to the racquet handle upon impact. In order to provide a direct comparison between racquet handle designs, the testing conducted was controlled in a manner to isolate specific design factors and eliminate the effects of string material and tension.



(a)



(b)

Fig. 1. Relationship between stiffness and energy through stress-strain curves (a); Typical hysteresis curve (b)

2. Materials and methods

Ten racquet frame designs from five different manufacturers were mechanically tested in an ISO17025 certified third-party independent test facility by qualified mechanical and biomechanical engineers. To minimize variability and provide a well-controlled comparison between tennis racquets, a consistent mass drop technique using a calibrated mass along a drop guide mounted to an electromechanical materials test machine (MTS Corp. Eden Praire, MN) was employed to provide accurate repetitive impact to the center of the head of each mounted tennis racquet. The center was determined through direct measurements and marked for each specific racquet tested. Each racquet handle was secured to a load cell (maximum capacity of 5kN) via gripping plates such that the face of the racquet was perpendicular to the mounted handles. A 2.5lb (11N) weight was dropped at 18 inches (0.46m) with a mean acceleration of 24G's onto the marked center of each racquet for five trials of impact. The mean acceleration of 24 G's for a stationary racquet with a mass drop in this study was slightly less than the 26G's of acceleration measured for a racquet in swing motion impacting a tennis ball with a collision duration of 5ms [6].

The specifications for each racquet, string tension, total handle length, and exposed handle length from the fixed edge of each mounted racquet were recorded. To minimize variability for consistency, the exposed handle length was maintained within the same ratio with respect to the total handle length for the different manufacturers and the string tensions were set to manufacturer specifications. The results were evaluated between racquet handle designs for both normalized and non-normalized of the parameters to the string tension for providing an equilibrated direct comparison. Normalization of each racquet's measured parameter (peak force) were divided by its string tension and statistically compared. This was conducted to remove the variability created by the slightly varied string tensions between tennis racquets for statistical comparisons. The composition and design of each handle was also documented and necessary for the comparative analysis. There were three different types of handles designed (triple core, dual core, hollow) and are outlined in Table 1, which detail the specifications for each racquet type. The internal core designs of the handle were categorized as the triple core, dual core, or hollow design.

Force and dampening times were compared with and without normalization to the string tension. Furthermore, the mounting of the racquets and design of the study minimized such variabilities due to the consistent nature of the test design. Each racquet handle was mounted and rigidly affixed to a calibrated load cell mounted to a materials test machine. The length of the exposed handle to the marked center of the racquet head was measured and the ratio of exposed length to total length to the center was maintained for all of the racquets tested. Five impact tests per racquet were performed. The impact and vibratory forces and duration were continuously sampled using MTS Testworks Software and a Fourier Transform Analysis was conducted on each data file sampled. This allowed for the full sinusoidal oscillation patterns to be sampled and the force at impact, force for each vibration, and time to dampen to be analyzed. The Fourier Transform generated the time domain and frequency domain for each sample. Minimizing variability from the impacting element, impact location, and the string tension in the manner described above allowed for a direct comparison between racquets to better determine the contributing factors towards stress reduction and vibration dampening from the handle of the racquet to the player. The time domain, initial impact force and vibratory forces transferred to the handle, and vibratory duration (time to reduce oscillations to a negligible force <5N) were analyzed. Dampening was considered complete when the vibrational amplitudes (in terms of force) were less than 5N. A one way Analysis of Variance (ANOVA) to a confidence interval of 95% and paired two-tailed t-tests were conducted to identify differences between the racquet handle designs.

Table 1. Racquet parameters categorized by handle design

Racquet Number	Material	Handle Design	Stiffness Rate
1	Carbon Fiber	Triple core	61
2	Graphite	Dual core	63
3	Carbon Fiber	Triple core	57
4	Graphite	Dual core	64
5	Graphite	Dual core	61
Mean (Stdev)			61.2 (2.7)
6	Graphite w basalt planks	Hollow	68
7	Graphite Tungsten	Hollow	67
8	Graphite	Hollow	70
9	Graphite	Hollow	67
10	Graphite Tungsten/Copper/Titanium	Hollow	65
Mean (Stdev)			67.4 (1.8)

3. Results

Table 1 showed that the stiffness per the manufacturers' specifications between the racquet types were lower for the core handle design group when compared to the hollow handle. Statistically the dual and triple core racquets were significantly less stiff than the hollow racquets ($p<0.05$) as shown in Table 1. The time to dampen the vibrations was greatest for the hollow racquets. Contrary to this, the triple core demonstrated the shortest dampening time with respect to the vibratory oscillations. Additionally, the hollow racquets demonstrated greater peak force (shock) than the triple and dual core, with the triple core demonstrating the fastest vibration dampening, lowest shock force, and lowest vibratory forces transmitted to the racquet handles (Figures 2a through 3a).

The Fourier Transform analysis demonstrated significant reductions in the vibrational dampening from the generated time domains for the core handle designs greater than the hollow designs. Additionally, the amplitudes during the vibration oscillations following the initial shock impulse for the core handle design were significantly less than that for the hollow designs, with the triple core handle design demonstrating the greatest decrease in amplitude after the initial shock force, $P<0.05$, (Fig. 2b). The hollow core design reduced shock force by 22%, where the core designs reduced the shock by at least 65% or more.

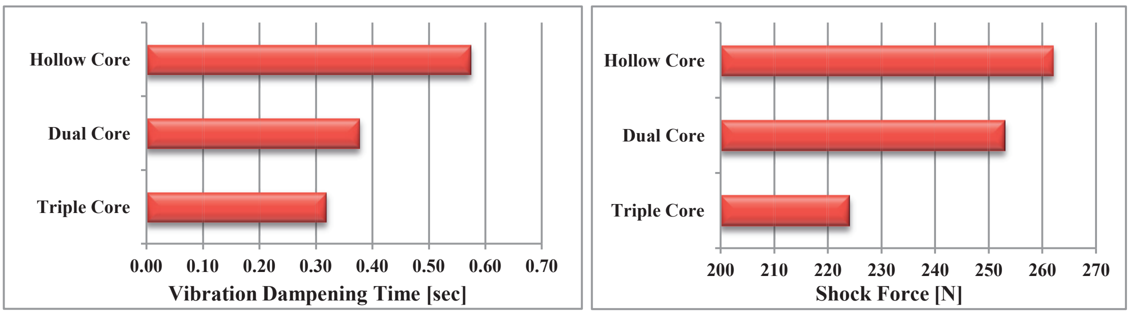
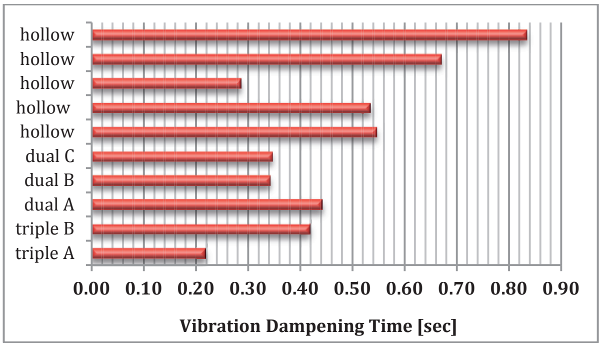


Fig. 2. (a) Mean vibration dampening time at impact for the handle design; (b) Mean shock force at impact for the handle design



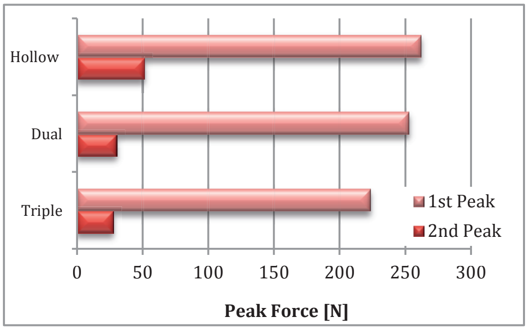


Fig. 3. (a) Vibration dampening times per racquet handle design; (b) Force difference between impulse and 2nd vibratory force

4. Conclusions

The dual and triple core designs demonstrated reduced dampening time where these designs successfully dampened the vibratory oscillations by at least 35% for the dual core and 50% for the triple core design when compared to the hollow handle design. Additionally, the amplitudes during the vibration oscillations following the initial shock impulse force for the core handle design were significantly less than that for the hollow designs, with the core handle designs demonstrating a reduction in these forces by at least 65% and the hollow core design reducing the shock force by 22% (Fig. 3b).

Overall, the dual and triple core designs demonstrated significantly lower shock forces and vibratory forces and dampened vibration quicker than the hollow designs. Although this study provided a controlled and repeatable assessment of racquet design, additional testing is currently underway to further investigate the impact of design factors that have the greatest capacity to reduce shock and vibration while replicating tennis swing kinematics and upon ball impact.

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