Original Article

Button damper reduces the impact force during tennis flat serve.

MASON PORRAMATIKUL¹, THEERABODEE ANEKJUMNONGPORN², THITI MEEOPARTMONGKON³, BOONSAKDI LORPIPATANA⁴, CHALERM CHAIWATCHARAPORN⁵, TOSSAPORN YIMLAMAI⁶

^{1,2,3}Department of Orthopedics, Faculty of Medicine, Vajira Hospital, Navamindradhiraj University, Bangkok, THAILAND

¹Sports Authority of Thailand, Bangkok, THAILAND

^{4,5}Faculty of Sport Science, Kasem Bundit University, Bangkok, THAILAND

⁶Faculty of Sport Science, Chulalongkorn University, Bangkok, THAILAND

Published online: May 30, 2020

(Accepted for publication: May 18, 2020)

DOI:10.7752/jpes.2020.03214

Abstract:

Problem Statement: The effect of damper on the impact force and damping time is still controversial and no literature review has compared dampers with varied string tension. **Approach:** Experimental study **Purpose:** To study the effect of four dampers on tennis rackets on the impact force and damping time at the grip area at low and high tennis racket string tension. **Materials and Methods:** The peak force and damping time were tested on tennis racket grips with five settings: no damper and four different dampers. Tennis balls were served using a tennis strike-simulating machine at a racket speed of 32 m/s. The impact force and damping time were recorded using a force transducer attached to the grip and were compared at the low and high string tensions. **Results:** Button damper reduced the impact force at the grip regardless of the string tension. At low string tension, the force was 144.6 ± 0 N with no damper compared to 133.5 ± 7.8 N when button damper was installed ($p = 0.006$); similarly, at high string tension, the forces were 171.2 ± 6.1 N and 157.9 ± 4.9 N, respectively ($p = 0.00$). Moreover, at low string tension, button damper yielded a 10% decrease in damping time (from 380.2 ± 10.3 ms to 344.0 ± 25.8 ms; $p = 0.013$). Similarly, rubber band damper exhibited a 15% decrease in damping time at low string tension (from 380.2 ± 10.3 to 324.82 ± 6.7 ms; $p < 0.01$). **Conclusion:** Button damper reduced 10% of the racket's impact force and damping time regardless of string tension, whereas rubber band damper reduced the damping time at low string tension only.

Key Words: tennis, impact force, damper, button damper, rubber band damper, flat serve

Introduction

Playing tennis can cause musculoskeletal injury. Over half of tennis players suffer elbow pain at least once in their lifetime. The force from repeated impaction between the ball and string bed is transferred to the tennis player's hand and arm through the racket, which can lead to repetitive stress injuries by either immediate impact force or post-impact vibration (Dines et al., 2015; Hutchinson, Laprade, Burnett, Moss, & Terpstra, 1995; Pluim, Staal, Windler, & Jayanthi, 2006).

The need to decrease vibration and force transfer to the wrist is believed to be important because of the association between vibration and potential injury. String vibration dampers are devices that are installed on racket string beds with the theoretical goal to reduce the reaction force and post-impact vibration. Dampers are commonly divided into three groups: button, rubber band and worm dampers. Button and rubber band dampers are attached to two vertical strings and one horizontal string, whereas worm dampers are long and thin and are attached to multiple vertical strings.

The manufacturers of these dampers claim that they help to decrease vibration transfer to the wrist during ball impact, thus making the impact feel 'more comfortable'. Although there is little evidence to support this benefit, these dampers remain widely used by tennis players. From anecdotal reports, it is controversial whether dampers are beneficial. Some studies have shown benefits from using dampers. Tomosue, Sugiyama, Yoshinari, & Yamamoto (1995) studied the effectiveness of dampers on reducing impact shock during tennis forehand strokes. They found that racket handle accelerations after impact of hand-held rackets were decreased by string vibration dampers. Timme and Morrison (2009) constructed a variety of models to assess string-bed vibration using a simulator speckle-pattern interferometry system.

Their results suggested that dampers can reduce some high-frequency vibrations (>800 Hz) in tennis string; however, these simulations dealt with acoustic vibrations and not real-life tennis ball impacts that generally strike a single point on the string bed. Conversely, Ameer, El-hafez, & Abdalla (2015) used a ball

machine and 30 elite and novice tennis players, and reported that dampers reduce the myoelectric activity of the wrist extensor muscle in less experienced tennis players, but not in experienced tennis players.

However, other studies did not support the usefulness of dampers. Stroede, Noble, & Walker (1999), instructed 20 tennis players to hold the racket firmly and projected tennis balls at them with a pneumatic tennis ball machine. They found that dampers do not reduce the vibration of the frame when hitting the ball. Li, Fewtrell, & Jenkins (2004) assessed the usefulness of dampers with 20 participants and a ball machine, using accelerometers to measure electrical muscle activity at the flexor carpi radialis and extensor digitorum communis; they found that dampers did not reduce vibration for any ball impact location. Mohr et al. (2008) used a finite element model to compare vibrations between frame-excited frequency and string-excited frequency and found that dampers act as string-bed frequency mode shifters but do not dampen the racket vibrations. Hsu and Cheng (2016) used two accelerometers attached at the frame–string interface and grip to measure vibration patterns with and without a damper. Ball–racket impacts were controlled by releasing the ball 3 m above the racket to produce a consistent impact intensity at centre and off-centre locations. They found that dampers can reduce the amplitude of spring-bed acceleration; however, vibration at the racket handle was not affected by the damper. Dampers may change the sound that is generated when a racket comes in contact with the ball; this can be misunderstood by the tennis player as decrease in vibration, which may thus create a sensory confusion for the player.

Studies have shown that racket structural properties, racket velocity, string tension, grip force, stroke form, tennis ball elasticity and ball impact location can influence the force transmitted to the player's hands (Chow, et al., 2003; Dines et al., 2015; Hatze, 1976; Hennig, Rosenbaum, & Milani, 1992; Yoshizawa, Kumamoto, Nemoto, Itani, & Jonsson, 1989). The benefits of dampers in terms of reducing the impact force and racket vibration are controversial because of various confounding factors. Tomosue et al., Stroede et al. and Li et al. could not control factors such as ball position and grip force. Conversely, although Ameer et al. and Hsu and Cheng could control grip force using a machine, they could not control the racket velocity (Ameer et al., 2015; Hsu & Cheng, 2016; Li et al., 2004; Mohr et al., 2008; Stroede et al., 1999; Timme & Morrison, 2009; Tomosue et al., 1995).

The string tension of the tennis racket affects the transmitting force through the tennis racket (Choppin, 2013; King, Kentel, & Mitchell, 2012; Li, Yang, Hwang, & Kim, 2009; Naß, Hennig, & Schnabel, 1998). L. Li et al. (2009) used the finite element method to compare the vibration of tennis rackets during forehand strokes. They determined that reduced string tension decreases the likelihood of arm injuries. Mohandhas et al. (2016) investigated the effect of a string vibration damper on the myoelectric activity of wrist extensors during the impact phase of backhand strokes by 15 elite and 15 novice tennis players. They found that lower string tensions transmit less force to the elbow during backhand strokes. Thus, reducing the string tension may lower the risk of developing lateral epicondylitis (Mohandhas et al., 2016). However, to our knowledge, there is no literature on the association between damper use and string tension regarding the force transmitted to the tennis racket.

The flat serve is considered as the basic (first) serve (Mavvidis et al., 2014). The tennis serve is the most complex movement in this sport that can cause injury to the upper limbs (Abrams, Renstrom, & Safran, 2012). Previous studies have only tested damper effects at racket speeds of 10–20 m/s (Engel, 1995; Hatze, 1992; Hennig et al., 1992; Li et al., 2004; Mohandhas et al., 2016), which is slower than an actual serve by a professional tennis player (approximately 30 m/s) (Chow et al., 2003). Therefore, it would be interesting to study the differences in flat serves with and without a vibration damper.

The objective of the present study was to investigate the effect of four different damper shapes (one button, one rubber band and two worm shapes) on the peak force and damping time at the grip area at different string tensions.

Material and Methods

The study protocol was approved by the ethics committee of our institution. Flat serve strokes were simulated using a tennis strike-simulating machine (TESMA) that can swing the tennis racket at speeds approaching those of professional tennis players (Pavilas & Chaiwatcharaporn, 2014; Pavilas, Suwanthada, & Chaiwatcharaporn, 2015). The study was performed at the Testing and Research Centre for Sports Materials and Equipment, Faculty of Sports Science, Chulalongkorn University, Bangkok, Thailand.

Two Yonex (Ezone Xi 100; Tokyo, Japan) tennis rackets were strung at 42 and 62 lb. tension. After stringing, the rackets were not used for 2 days in order to ensure stable string tension before starting the experiment. The racket handle was clamped to the TESMA rotating swing arm, and the servo motor adjusted the speed of the racket with precise control at 450 rpm, which is similar to professional tennis players' pre-impact racket velocity (32 m/s) according to Chow et al. (2003).

The racket grip was connected to a wireless force transducer (FlexiForce WELF2 system with WB201-H sensor; Tekscan, Boston, MA, USA), which consisted of a piezoelectric sensor that converts force into an electrical signal and can be used to measure impact force. These measurements are presented as a force graph and time spreadsheet after they are wirelessly transmitted to a workstation (Fig.1). A high-speed DMAS 2,000-Hz DVRs camera was positioned behind the racket to confirm that the ball impacts were in the centre of the

rackets (Fig.2). A calibration frame of $0.5 \times 0.5 \times 0.5$ m with 15 markers was used to calibrate the system for high speed, high precision and high accuracy with an estimated error of 0.043%.

The tennis balls were tested for their adherence to the International Tennis Federation specifications. Each tennis ball was used for no more than 30 impact strikes to ensure consistent bouncing of more than 130 cm in height during all experimental trials (Fig.3). Using these experimental settings, the racket type, string type, racket speed, string tension, ball quality and ball impact location could be controlled (Hatze, 1992; Hennig et al., 1994; Hennig et al., 1992; King et al., 2012; L. Li et al., 2009; Mohandhas et al., 2016; Naß et al., 1998; Nesbit, Elzinga, Herchenroder, & Serrano, 2006; Rogowski et al., 2015; Stroede et al., 1999; Tomosue et al., 1995).

Figure 1. The tennis strike-simulating machine consisted of a striker driven by a 5 HP Servo-Motor with 3D motion capture and an analysis system with a 2,000-Hz high-speed camera
Experimental data were captured and recorded using the FlexiForce WELF2 system with a WB201-H sensor attached to the racket's handle.

Figure 2. Ball impact location was determined using a high-speed camera
All of the ball impacts were in the centre of the tennis rackets.

Figure 3. The tennis balls were tested for their bouncing properties

Four dampers were tested in this study, namely button damper (Custom Damp; Babolat, France, Damper D1), rubber band damper (Solaris Shock Off ; Unique sports, USA, Damper D2), worm damper (Shockbuster 2; Gamma, USA, Damper D3) and worm damper (Shock Trap; Wilson, USA, Damper D4) (Fig.4).

Figure 4. The four dampers tested in this study

D1: Damper D1, D2: Damper D2, D3: Damper D3, D4: Damper D4

We conducted five sets of trials at low and high string tension, respectively. The first set of trials was the control, during which we tested rackets without any dampers. The second set of trials tested rackets fitted with Damper D1; this button damper was attached to the two middle vertical strings and the horizontal string nearest to the grip (the first horizontal string). All other conditions were identical to those of the control trials. The third set of trials tested rackets fitted with a Damper D2, which was attached at the same location as the Damper D1. The fourth set of trials tested rackets fitted with a Damper D3, which was attached along the ten vertical strings in the middle of the racket, just below the first horizontal string. Finally, the fifth set of trials tested rackets fitted with a Damper D4, which was attached at the same location as the Damper D3 (Fig.5).

Each trial was repeated ten times. 5 out of 10 trial which have confirmed the location of impact at the centre of string bed were utilized. The string tension was checked using a string metre after each damper change to ensure tension consistency.

Figure 5. Set-up of the five trials in the experiments

A: No damper, B: Damper D1, C: Damper D2, D: Damper D3, E: Damper D4

During each trial, the ball was released from the machine and hit by the tennis racket, which was swung by the servo motor. After contact, the wireless force transducer showed the force and time data in the ELF Multi-handle HS 4.32 programme.

Peak force was defined as the maximum force at the time of impact minus the initial force prior racket moving. Damping time was defined as time between peak force until no reduction of the force amplitude (Fig.6). Damping time reflected the vibration time of tennis racket after ball impactation.

Figure 6. The wireless force transducer showing the force and time data
The y-axis shows the force at the racket handle and x-axis shows the time. Point A indicates the time at which the ball starts to impact the racket strings, and Point B indicates the peak impact force at the racket handle. The force then decreases over time and the force ends at Point C. Thus, we can find the racket vibration time by calculating the duration from Point A to Point C.

Statistical analysis

Data were analysed by SPSS statistical analysis version 22.0 (IBM Corp, Armonk, NY, USA). The peak force and damping time data were compared by one-way analysis of variance using the least significant difference method. Damping conditions were analysed to find the effect of the string tension on the damping process, and *t*-tests were used to compare the peak force and damping time between low and high string tension.

Results

Peak force (Fig.7)

At low string tension, the peak force at the grip was 144.6 ± 0 N when no damper was attached (control). The peak forces were 133.5 ± 7.8 N, 144.6 ± 0 N, 140.2 ± 6.1 N and 144.6 ± 7.8 N when D1, D2, D3 and D4 were installed, respectively. Only D1 significantly reduced the peak force ($p = 0.006$) compared to no damper. At high string tension, the peak force at the grip was 171.2 ± 6.1 N when no damper was attached. The peak forces were 157.9 ± 4.9 N, 169.0 ± 4.9 N, 166.8 ± 7.8 N and 164.5 ± 4.9 N when D1, D2, D3 and D4 were installed, respectively. Similar to the low string tension tests, only D1 significantly reduced the peak force ($p = 0.002$) compared to no damper. When comparing the data at low and high string tension, we found mean overall peak forces of 141.5 ± 6.8 N at low string tension and 165.9 ± 7.1 N at high string tension. Low string tension resulted in significantly lower peak force ($p < 0.01$) than high string tension.

Figure 7. Peak force (N) at various damping conditions and differing string tensions (1 = low tension, 2 = high tension). Only Damper D1 significantly reduced the peak force at both string tensions

Damping time (Fig.8)

At low string tension, the damping time at the grip was 380.2 ± 10.3 ms when no damper was attached (control). Further, the damping times were 344.0 ± 25.8 ms, 324.8 ± 6.7 ms, 359.4 ± 26.0 ms and 367.9 ± 26.8 ms when D1, D2, D3 and D4 were installed, respectively. D1 and D2 significantly reduced the damping time ($p = 0.013$ and $p < 0.01$, respectively) when compared to the control. However, the damping times of D1 and D2 did not significantly differ ($p = 0.165$).

Further, at high string tension, the damping time at the grip was 571.5 ± 28.7 ms when no damper was attached, and the damping times were 547.0 ± 13.1 ms, 566.0 ± 23.2 ms, 544.0 ± 8.2 ms and 569.2 ± 30.3 ms when D1, D2, D3 and D4 were installed, respectively. None of the dampers significantly reduced the damping time at high string tension ($p = 0.098$).

When comparing the damping times at low and high string tension, we found mean overall damping times of 355.3 ± 27.5 ms at low string tension and 559.9 ± 24.0 ms at high string tension. The t -test showed that low string tension resulted in a significantly shorter damping time ($p < 0.01$) than high string tension.

Figure 8. Damping time (milliseconds) at various damping conditions and differing string tensions (1 = low tension, 2 = high tension).

Only D1 and D2 significantly reduced the damping time at low string tension; however, none of the dampers significantly reduced the damping time at high string tension.

Discussion

Many studies have examined the relationship between peak force and damping time on tennis rackets with and without dampers in different setting. Our study used the moving racket impacted to moving tennis ball. However, some experiments did not have realistic hitting conditions comparable to those during actual tennis playing. For example, Mohr et al. (2008) used an acoustic speaker to generate vibrations through the rackets and Timme and Morrison used a percussion hammer to generate vibrations. Stroede et al., Li et al., Ameer et al. and Hsu and Cheng used human subjects holding the racket without motion impacted to the moving ball projected from the machine or dropped the ball from a certain height onto a stationary tennis racket to simulate the tennis ball–racket impact.

Experiments involving human subjects holding the rackets have many disadvantages; the main disadvantage is that human subjects cannot control the grip force so that it is the same during every tennis ball–racket impact. If the subject had a tighter grip on the tennis racket, there would be a stronger vibration through the tennis racket. Further, consistent ball impact locations are not achievable when using human subjects.

Factors affecting the force at the grip include the racket type, racket speed, racket material, string tension, stroke type, type of ball, ball impact location and grip force; our study can control for all these factors. Thus, we could precisely determine the impact of the tennis ball on the string bed.

Impacts were precisely located on the string bed of the racket by adjusting the timing between the ball release above the striker and the angular position of the racket rotating at a constant pre-determined speed. A constant grip force was also able to be maintained throughout the experiments.

Another advantage of our study is that we tested damper effects at racket speeds of approximately 32 m/s, which is similar to that of an actual serve by a professional tennis player. No anecdotal study has been reported the damper effect during high speed impact.

Peak force

The shape of the damper (button, rubber or worm) is an interesting factor that may affect the force at the grip. Tomosue et al. (1995) found that dampers reduce the peak force at the handle; however, subsequent studies reported contradictory results.

At present, the dampers could significantly reduce peak force by changing the mass distribution along the vertical strings in a racket. Only tightness in the two centre vertical strings from button and rubber band dampers have been compared to worm dampers for direct centre hits. The reason for this is that button and rubber band dampers help to absorb more energy because more of the dampers' mass lies along the hitting axis of the racket.

Damping time

We found that both Damper D1 and Damper D2 yielded a 10% significant decrease in damping at low string tension. Low string tension resulted in a shorter damping time at the grip than high string tension. This agrees with the results of Li et al. (2009), who found that the trampoline effect at lower string tension causes a small amount of energy loss from the ball, which results in less energy being transmitted to the grip. Thus, button dampers may not help damping at high string tension because of inconsistency between high damping and a small damper mass.

The damping time was significantly reduced by 35–55 ms; however, some may say that this is not a substantial length of time. Heaven, Goonetilleke, Ferguson, & Shiralkar (2011) described hand–arm vibration syndrome, which is a common occupational hazard in industrialised countries; the extent of the syndrome is related to the strength of the vibrational forces, as well as the duration of exposure to these forces. From the literature, this syndrome can result from exposure to vibrational frequency greater than 2.5 m/s^2 when we compare the vibrational forces of hitting a tennis ball and that of industrialised tools. Theoretically, dampers significantly decrease vibrations, but only by a few milliseconds; however, in a tennis game, players may hit the ball multiple times with a racket. This may subsequently result in injury to the player because the cumulative effect of decrease in vibrations is nullified by the prolonged contact of the racket with the ball.

Comparing high and low tension

In our study, low string tension yielded a 20% significant decrease in force at the grip and a 55% significant decrease in damping. Mohandhas et al. (2016) found that lower string tensions transmit less force to the elbow, although the conditions in their study were different from those of our study, such as backhand stroke with the ball machine hit.

In addition to helping decrease force and damping time, dampers can be used for other reasons, such as noise reduction, ball control or comfort from other effects. Further study is warranted to reveal the physical mechanisms behind players' preference for dampers.

The present study has some limitations. When the TESMA was driven at 450 rpm, the handle had to be clamped to the machine very strongly to prevent the racket from falling off. In practise, players' palms are flexible; therefore, the grip on a tennis racket is also flexible. Also, different models of tennis rackets bend when hitting the ball and vibrate in different ways. Additionally, the sensor used in this experiment was a force sensor that measured in a single plane only; therefore, only the force on one side of the racket handle was measured, whereas in practise, vibrations spread around the racket handle on all sides.

Conclusions

Our results showed that button dampers such as the (Damper D1) may help reduce the impact force on tennis rackets regardless of the string tension. At low string tension, the button damper and rubber damper (Damper D2) could significantly reduce the damping time when the ball was hit at a centre location. Tennis players, especially less experienced players, may consider using dampers for this purpose.

Conflicts of interest

All authors declare no support from any manufacturers or business for the submitted work and no other relationships or activities that could appear to have influenced the submitted work.

References:

- Abrams, G. D., Renstrom, P. A., & Safran, M. R. (2012). Epidemiology of musculoskeletal injury in the tennis player. *British Journal of Sports Medicine*, 46(7), 492-498. doi:10.1136/bjsports-2012-091164
- Ameer MAA, E.-h. S., El-hafez GM, Abdalla AAA. (2015). Effect of string vibration damper on the myoelectric activity of the wrist extensors. *International Journal of Current Research*, 7, 14656-14661.
- Choppin, S. (2013). An investigation into the power point in tennis. *Sports Engineering*, 16(3), 173-180.
- Chow, J. W., Carlton, L. G., Lim, Y. T., Chae, W. S., Shim, J. H., Kuenster, A. F., & Kokubun, K. (2003). Comparing the pre- and post-impact ball and racquet kinematics of elite tennis players' first and second serves: a preliminary study. *Journal of Sports Sciences*, 21(7), 529-537. doi:10.1080/0264041031000101908

- Dines, J. S., Bedi, A., Williams, P. N., Dodson, C. C., Ellenbecker, T. S., Altchek, D. W., . . . Dines, D. M. (2015). Tennis Injuries: Epidemiology, Pathophysiology, and Treatment. *Journal of the American Academy of Orthopaedic Surgeons*, 23(3), 181-189. doi:10.5435/JAAOS-D-13-00148
- Engel, J. (1995). Tennis: dynamics of racket-grip interaction. *Journal of Hand Surgery*, 20(3 Pt 2), S77-81.
- Hatze, H. (1976). Forces and duration of impact, and grip tightness during the tennis stroke. *Medicine and Science in Sports*, 8(2), 88-95.
- Hatze, H. (1992). The effectiveness of grip bands in reducing racquet vibration transfer and slipping. *Medicine and Science in Sports*, 24(2), 226-230.
- Heaver, C., Goonetilleke, K., Ferguson, H., & Shiralkar, S. (2011). Hand-arm vibration syndrome: a common occupational hazard in industrialized countries. *Journal of Hand Surgery (European Volume)*, 36(5), 354-363.
- Hennig, E. M., Milani, T. L., & Rosenbaum, D. (1994). The influence of tennis racket design on impact induced arm oscillations. *Journal of Biomechanics*, 27(6), 669. doi:10.1016/0021-9290(94)90985-7
- Hennig, E. M., Rosenbaum, D., & Milani, T. L. (1992). Transfer of tennis racket vibrations onto the human forearm. *Journal of Biomechanics*, 24(10), 1134-1140.
- Hsu, Y.-C., & Cheng, K. B. (2016). *Effect of attaching string dampers on vibration characteristics of a tennis racket*. Paper presented at the ISBS-Conference Proceedings Archive.
- Hutchinson, M. R., Laprade, R. F., Burnett, Q. M., 2nd, Moss, R., & Terpstra, J. (1995). Injury surveillance at the USTA Boys' Tennis Championships: a 6-yr study. *Medicine and Science in Sports*, 27(6), 826-830.
- King, M. A., Kentel, B. B., & Mitchell, S. R. (2012). The effects of ball impact location and grip tightness on the arm, racquet and ball for one-handed tennis backhand groundstrokes. *Journal of Biomechanics*, 45(6), 1048-1052. doi:10.1016/j.jbiomech.2011.12.028
- Li, F. X., Fewtrell, D., & Jenkins, M. (2004). String vibration dampers do not reduce racket frame vibration transfer to the forearm. *Journal of Sports Sciences*, 22(11-12), 1041-1052. doi:10.1080/02640410410001729982
- Li, L., Yang, S. H., Hwang, C.-S., & Kim, Y. S. (2009). Effects of string tension and impact location on tennis playing. *Journal of Mechanical Science and Technology*, 23(11), 2990-2997. doi:10.1007/s12206-009-0903-5
- Mavridis, A., Manousaridou, A., Grivas, N., Evagelidis, T., & Laios, A. (2014). The effectiveness of serve in tennis depending on the placement of palm across the racket grip inwards or outwards. *Journal of Physical Education & Sport*, 14(4).doi:10.7752/jpes.2014.04089
- Mohandhas, B. R., Makaram, N., Drew, T. S., Wang, W., Arnold, G. P., & Abboud, R. J. (2016). Racquet string tension directly affects force experienced at the elbow: implications for the development of lateral epicondylitis in tennis players. *Shoulder Elbow*, 8(3), 184-191. doi:10.1177/1758573216640201
- Mohr, S., Cotter, R., Lau, D., Gillet, C., Kotze, J., Jolly, M., & Schwenger, R. (2008). Dynamics of a String-Bed Damper on Tennis Rackets (P175). In *The Engineering of Sport 7: Vol. 2* (pp. 179-189). Paris: Springer Paris.
- Naß, D., Hennig, E. M., & Schnabel, G. (1998). *Ball impact location on a tennis racket head and its influence on ball speed, arm shock and vibration*. Paper presented at the ISBS-Conference Proceedings Archive.
- Nesbit, S. M., Elzinga, M., Herchenroder, C., & Serrano, M. (2006). The effects of racket inertia tensor on elbow loadings and racket behavior for central and eccentric impacts. *J Sports Sci Med*, 5(2), 304-317.
- Pavilas, C., & Chaiwatcharaporn, C. (2014). Comparison in maximum ball velocity of 3-structural characteristic rackets using simulated tennis flat serve. *Journal of Sports Science and Technology*, 14(2), 1-16.
- Pavilas, C., Suwanthada, S., & Chaiwatcharaporn, C. (2015). The Tennis Strike Simulation Machine Identified and Confirmed Power Spot Location on Tennis Racket during Flat First Serve. *Journal of Exercise Physiology Online*, 18(3).
- Pluim, B. M., Staal, J. B., Windler, G. E., & Jayanthi, N. (2006). Tennis injuries: occurrence, aetiology, and prevention. *Br J Sports Med*, 40(5), 415-423. doi:10.1136/bjsm.2005.023184
- Rogowski, I., Creveaux, T., Triquigneaux, S., Macé, P., Gauthier, F., & Sevez, V. (2015). Tennis racket vibrations and shock transmission to the wrist during forehand drive. *PloS one*, 10(7), e0132925.
- Stroede, C. L., Noble, L., & Walker, H. S. (1999). The effect of tennis racket string vibration dampers on racket handle vibrations and discomfort following impacts. *Journal of Sports Sciences*, 17(5), 379-385. doi:10.1080/026404199365894
- Timme, N., & Morrison, A. (2009). The mode shapes of a tennis racket and the effects of vibration dampers on those mode shapes. *Journal of the Acoustical Society of America*, 125(6), 3650-3656. doi:10.1121/1.3126343
- Tomosue, R., Sugiyama, K., Yoshinari, K. and Yamamoto, K. (1995). The effectiveness of damping material in reducing impact shock in the tennis forehand drive. In *Science and Racket Sports*, pp. 140 – 145.
- Yoshizawa, M., Kumamoto, M., Nemoto, Y., Itani, T., & Jonsson, B. (1989). Effects of dynamic features of tennis rackets on muscular load of tennis players. *Journal of Biomechanics*, 22(10), 1106. doi:10.1016/0021-9290(89)90532-0