Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 147 (2016) 787 – 792

Procedia Engineering

www.elsevier.com/locate/procedia

11th conference of the International Sports Engineering Association, ISEA 2016

The Development of a Methodology to Determine the Relationship in Grip Size and Pressure to Racket Head Speed in a Tennis Forehand Stroke.

Jonas Christensen[a,b,*], John Rasmussen[a] , Ben Halkon[b], Sekiya Koike[b,c]

[a]*Department of Health Sciences & Technology, Aalborg University, Fredrik Bajers Vej 5, Aalborg 9100, Denmark*
[b]*Wolfson School of Engineering, Loughborough University, Loughborough LE11 3TU, United Kingdom*
[c]*Faculty of Health and Sports Sciences. Tsukuba University, Ten-nodai 1-1-1, Tsukuba, Ibaraki, 305-8577, Japan*

Abstract

This study developed a methodology to examine the effects of grip size and grip firmness on the kinematic contribution of angular velocity (KCAV) to the generation of racket head speed during a topspin tennis forehand. The KCAV is subdivided into kinematic contribution of joint angular velocity and kinematic contribution of the body segments in the upper trunk translational and angular velocities. Two Babolat Pure Storm GT rackets, with grip sizes 2 and 4 respectively, were used with Tekscan 9811E pressure sensors applied to the handles to examine pressure distribution during the stroke. Upper body kinematic data taken from the racket arm and trunk were obtained by means of a Vicon motion capture system. One elite male tennis player was recruited. Fifty topspin forehand strokes per grip at two nominal grip pressures were performed in a laboratory environment with balls being tossed towards the player and struck on the bounce towards a target on a net in as consistent a way as practically achievable.

Processing of the results showed that the firm grip condition led to a significant ($p<0.001$) increase in average racket head speed compared to a normal grip condition. The normal gripping condition resulted in a significant ($p<0.001$) increase in average racket head speed for grip size 2 compared to grip size 4. A trend in negative linear relationships was found between upper trunk and shoulder joint in KCAV across conditions. Using the smaller grip also led to a trend in negative linear relationship between shoulder joint and wrist joint in KCAV across grip conditions. Grip pressure for grip size 2 showed the same pattern across gripping conditions. From 50-75% of completion in forward swing, the pressure difference due to grip firmness decreased. This feasibility study managed to quantify the KCAV while performing a topspin forehand, with respect to changing of grip size and grip pressure in an elite male tennis player for the first time.

© 2016 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license
(http://creativecommons.org/licenses/by-nc-nd/4.0/).

Peer-review under responsibility of the organizing committee of ISEA 2016

Keywords: Kinematic contribution of joint angular velocity; kinematic contribution of upper trunk translation and angular velocity; grip size; grip pressure; topspin forehand; tennis biomechanics

---

1. Introduction

The topspin forehand in tennis is a product of a kinetic chain movement of body segments; a motion-dependent transfer of energy between articulated segments [1]. The complex nature of the kinetic chain movement leads to a summation of speed from proximal to distal links [2]. Maximizing this summation of speed in the aim of increasing racket head speed is important when wanting to dictate play and stress your opponent. Success in tennis, however, requires the ability to perform a topspin forehand so that variation in post-impact ball speeds can be achieved [3]; it is not all about maximizing racket head speed. Players' exploitation of the linked biomechanical system in terms of stroke technique has changed dramatically due to the technological developments and dynamic behavior of tennis rackets [4] in recent years.

Several studies have investigated how grip firmness affects post-impact ball velocity. However results have been inconsistent. One study reported that grip firmness does not affect rebound velocity and that the coefficient of restitution between tennis ball and racket is superior in its impact on rebound velocity [5]. Meanwhile, another finding indicated that grip tension does affect

* Corresponding author. Tel.: +44-0770-447-3443.
E-mail address: jonasc1989@hotmail.com

1877-7058 © 2016 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license
(http://creativecommons.org/licenses/by-nc-nd/4.0/).

Peer-review under responsibility of the organizing committee of ISEA 2016
doi:10.1016/j.proeng.2016.06.317

both rebound velocity and reaction impulse to ball impacts, especially during off-center impacts [6]. Lastly, studies have also concluded that there is no difference to be found in rebound ball velocity due to grip firmness, and that grip firmness only has a potential positive effect on post impact control of the racket [7]. According to previous studies however, guidelines have been established in trying to optimize grip size [8,9]. These differing findings have led to the 1) hypotheses and 2) the research question of this study:

1. It is possible to quantify the kinematic contribution of angular velocity (KCAV) in the upper body when performing a topspin forehand whilst changing the grip conditions as either being normally or firmly gripped.
2. How does changing grip firmness and circumference affect racket head speed as well as the KCAV?

2. Experimental arrangement

2.1. Test equipment preparation

Two Babolat Pure Storm GT rackets (unstrung weight 295 grams, balance point 32.5 cm) with grip sizes 2 and 4 were used. The rackets were strung with new SG SpiralTek 1.35 strings with a crosses and mains tension of 25 kg. Prior to the test session, a Tekscan 9811E medical pressure sensor with a range of 75 psi, a pressure "sensel" spatial resolution of 0.6 cm^{-1} and a thickness of 0.2 mm, was applied to each of the racket handle surfaces, as shown in Fig. 1. In accordance with the sensor system manufacturer's built-in equilibration and calibration procedure, the sensors were equilibrated and calibrated in a "bladder" via a 2-point calibration prior to application. The sensors were then cut along the columns in order that they had six "fingers" that could be attached to 6 of the 8 faces of the grip in order to avoid twisting of the sensors during attachment. A sensor finger was attached to each of the grip faces from 8 to 5 going counter-clockwise around the handle when viewed from below. As a reference, faces 1 and 5 run perpendicular to the stringbed, whilst faces 3 and 7 run parallel with the stringbed. The remaining 4 faces are positioned in between the parallel and perpendicular faces. The upper 4 sensels on each finger were removed such that the sensor covered the length of the grip effectively with a total of 72 discrete pressure sensing regions therefore being realised.

Between the grip handle and the medical pressure sensors, a thin layer of double-sided tape was fixed to minimize movement of the medical pressure sensors and minimize air gaps. The pressure sensors were mounted to cover the gripping area of a semi western forehand grip. After having secured the sensors, two grips were laid on top of each grip handle; the inner grip was the original grip while the outer grip was as standard overgrip. The result was to minimise any influence of the embedded sensor on the feel of the grip.

Kinematic data were captured with a Vicon motion capture system comprising 13 cameras. Ten cameras were fixed near the ceiling, while three tripod-mounted cameras were placed on the floor. Two of the three cameras on the floor were placed on the right hand side of the forward swing with one camera directly behind the volume of interest. This was done in order to minimize marker drop-out while rotating the racket around the body.

2.2. Subject information, preparation and experimental protocol

One male participant was recruited for the study. The participant's age was 24, weight 63 kg and height 1.83 meters. He was a former Davis Cup player for Sri Lanka (2009) and current Loughborough Mens 1st Team player (2015). Before testing, the participant gave informed consent for the procedures required for data collection as approved by the Loughborough University Ethical Advisory Committee.

Forty-one retro-reflective markers were attached to the participant at anatomical landmarks as shown in Fig. 2. Initially, a static capture was made after which the participant was asked to put on shorts, socks and shoes which resulted in kinematic analysis of 25 markers located on the upper trunk, head, right arm and racket in accordance to the marker protocol.

A "cuff", attached to the pressure sensor, was subsequently placed on the forearm of the participant, as also shown in Fig. 2, such that pressure data could be gathered during the stroke. The total weight of sensor, cuff and armband was 177 grams. Cabling to the cuff from the acquisition system is on the form of an Ethernet. While care needed to be taken to not trap the cable etc., the level of inhibition was minimised as much as possible by careful routing and definition of the play area. The maximum possible sample rate of 160 Hz was used during testing. Tekscan's Fscan research version 6.60 was used to investigate pressure data.

The motion capture data were synchronized by detecting spike signals in pressure cell signal output at impact. A sampling rate of 500 Hz was used. Vicon's Nexus software version 1.8.5 was used to reconstruct three dimensional coordinate data. Broken trajectories, marker mergence and smoothing was undertaken following capture. Higher frame rates should assist the smoothing program such that true and spurious accelerations can be easier to distinguish [10].

The test area consisted of a hanging net on which a square target was highlighted towards which the participant aimed his shots. The midpoint of the target was fixed at 1.45 m from the ground and had an area of 1.13 m^2. The distance from the hitting position to the hanging net was 4.15 m. The feeding of balls was done by underarm throw, so that one bounce occurred before topspin forehand execution. The throwing position was 3 m from the hitting position. As shown in Fig. 3, a reference point for the ball bounce was set on the floor, in order to make throwing as consistent as possible. At the hitting position, several reference points were placed on the floor so that investigators could ensure a consistent hitting length.

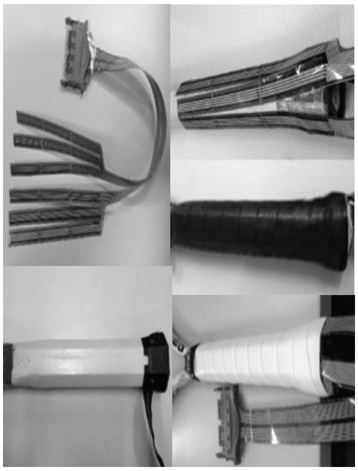

Fig. 1. Modifications of the Tekscan sensor 9811E and the corresponding chronological steps illustrating its application on the grip of the racket handle.

Fig. 2. Tekscan "cuff" attachment, upper body and racket marker protocol.

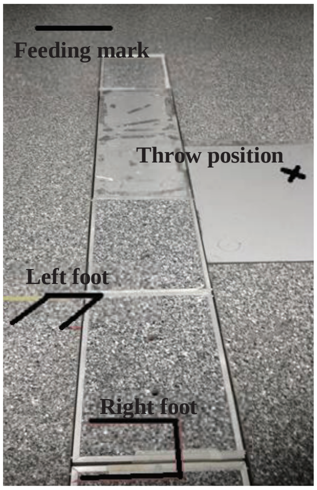

Fig. 3. Reference points showed. 1) denotes food position, 2) aiming mark for feeding, 3) position of thrower.

The participant was asked to not to be physically active from 24 hours prior to testing. Upon arrival the participant was asked to warm up for 5 minutes. A Babolat Pure Storm GT racket with an intermediate grip size of 3 was used for the warm up. After having warmed up, the participant hit forehands towards the designated target for 5 minutes. The participant was instructed to hit the balls as hard as possible. For a stroke to be considered successful, it had to hit the highlighted square. For each racket a total of 50 successful shots were made; 25 with a "normal" gripping condition and 25 with a "firm" grip condition. Collecting sample sizes of five topspin forehands were chosen in order not to tire the participant. A previously unused set of Slazenger Open balls were used for the test.

3. Data analysis

Forward swing phase was defined as a period from the start of swing to the ball impact, where the start of swing was determined as the instance when forward movement of the racket top coordinate showed local minimum value before the ball impact. Fig. 4. shows a rigid-segment model of the upper body with a racket. This model consists of upper trunk, upper arm, forearm, hand and racket.

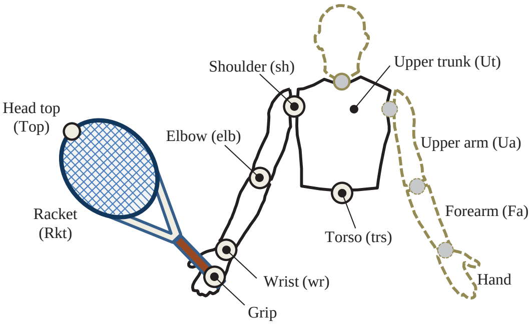

Fig. 4. A Schematic representation of the rigid-segment model consisting of a racket and the upper-body segments.

The position vector of the racket head top $\boldsymbol{x}_{\text{Top}}$ can be expressed as the sums of the position vector of the torso joint $\boldsymbol{p}_{\text{trs}}$ and relative position vectors, which connect neighboring points as:

$$\boldsymbol{x}_{\text{Top}} = \boldsymbol{p}_{\text{trs}} + \left(\boldsymbol{p}_{\text{sh}} - \boldsymbol{p}_{\text{trs}}\right) + \left(\boldsymbol{p}_{\text{elb}} - \boldsymbol{p}_{\text{sh}}\right) + \left(\boldsymbol{p}_{\text{wr}} - \boldsymbol{p}_{\text{elb}}\right) + \left(\boldsymbol{p}_{\text{grip}} - \boldsymbol{p}_{\text{wr}}\right) + \left(\boldsymbol{p}_{\text{Top}} - \boldsymbol{p}_{\text{grip}}\right) \tag{1}$$

where the vectors $\boldsymbol{p}_{\text{sh}}$, $\boldsymbol{p}_{\text{elb}}$ and $\boldsymbol{p}_{\text{wr}}$ denote the position vectors of the shoulder, elbow and wrist joints; the vector $\boldsymbol{p}_{\text{grip}}$ is the position vector of a virtual joint set between the hand and the racket segments; the vector $\boldsymbol{p}_{\text{Top}}$ denotes the position vector of the racket head top.

The relationship between the position vectors (eq.(1)) can be converted into the relationship between the linear and angular velocity vectors [11] with temporal differentiation of eq.(1) under the assumption that the racket is fixed to the hand, i.e. does not move with respect to the hand, during the forward swing motion such that:

$$\boldsymbol{\omega}_{\text{Hand}} = \boldsymbol{\omega}_{\text{Rkt}} \tag{2}$$

where the vectors $\boldsymbol{\omega}_{\text{Hand}}$ and $\boldsymbol{\omega}_{\text{Rkt}}$ denote the angular velocity vectors of the hand and racket segments. The relationship between the angular velocity vectors is expressed as follows:

$$\dot{\boldsymbol{x}}_{\text{Top}} = \dot{\boldsymbol{p}}_{\text{trs}} + \boldsymbol{\omega}_{\text{Ut}} \times \left(\boldsymbol{p}_{\text{sh}} - \boldsymbol{p}_{\text{trs}}\right) + \boldsymbol{\omega}_{\text{Ua}} \times \left(\boldsymbol{p}_{\text{elb}} - \boldsymbol{p}_{\text{sh}}\right) + \boldsymbol{\omega}_{\text{Fa}} \times \left(\boldsymbol{p}_{\text{wr}} - \boldsymbol{p}_{\text{elb}}\right) + \boldsymbol{\omega}_{\text{Hand}} \times \left(\boldsymbol{p}_{\text{Top}} - \boldsymbol{p}_{\text{wr}}\right) \tag{3}$$

where the vectors $\boldsymbol{\omega}_{\text{Ut}}$, $\boldsymbol{\omega}_{\text{Ua}}$ and $\boldsymbol{\omega}_{\text{Fa}}$ denote the angular velocity vectors of the upper trunk, upper arm and forearm segments, respectively. The joint angular velocity vectors of the individual joints are calculated as the difference of angular velocity vectors of the neighboring segments:

$$\boldsymbol{\omega}_{\text{sh}} = \boldsymbol{\omega}_{\text{Ua}} - \boldsymbol{\omega}_{\text{Ut}}, \quad \boldsymbol{\omega}_{\text{elb}} = \boldsymbol{\omega}_{\text{Fa}} - \boldsymbol{\omega}_{\text{Ua}}, \quad \boldsymbol{\omega}_{\text{wr}} = \boldsymbol{\omega}_{\text{Hand}} - \boldsymbol{\omega}_{\text{Fa}} \tag{4}$$

Substituting eqs.(1) and (4) into eq.(3) yields an equation which relates the joint angular velocity vectors to the racket head top velocity vector as:

$$\dot{\boldsymbol{x}}_{\text{Top}} = \dot{\boldsymbol{p}}_{\text{trs}} + \boldsymbol{\omega}_{\text{ut}} \times \left(\boldsymbol{p}_{\text{Top}} - \boldsymbol{p}_{\text{trs}}\right) + \boldsymbol{\omega}_{\text{sh}} \times \left(\boldsymbol{p}_{\text{Top}} - \boldsymbol{p}_{\text{sh}}\right) + \boldsymbol{\omega}_{\text{elb}} \times \left(\boldsymbol{p}_{\text{Top}} - \boldsymbol{p}_{\text{elb}}\right) + \boldsymbol{\omega}_{\text{wr}} \times \left(\boldsymbol{p}_{\text{Top}} - \boldsymbol{p}_{\text{wr}}\right) \tag{5}$$

The unit vector, expressing the direction of racket head top velocity, was obtained by dividing the velocity vector with its magnitude as:

$$\boldsymbol{e}_{\text{Top}} = \frac{\dot{\boldsymbol{x}}_{\text{Top}}}{\left|\dot{\boldsymbol{x}}_{\text{Top}}\right|} \tag{6}$$

Finally, operating the inner product of eq.(5) with eq.(6) yields the kinematic contribution of individual terms to the generation of the racket head top speed shown as:

$$C_{\text{trs}} = \boldsymbol{e}_{\text{Top}}{}^{\text{T}} \dot{\boldsymbol{p}}_{\text{trs}}, \quad C_{\text{ut}} = \boldsymbol{e}_{\text{Top}}{}^{\text{T}} \left\{\boldsymbol{\omega}_{\text{ut}} \times \left(\boldsymbol{p}_{\text{Top}} - \boldsymbol{p}_{\text{trs}}\right)\right\}, \quad C_j = \boldsymbol{e}_{\text{Top}}{}^{\text{T}} \left\{\boldsymbol{\omega}_j \times \left(\boldsymbol{p}_{\text{Top}} - \boldsymbol{p}_j\right)\right\}, \quad (j = \text{sh}, \text{elb}, \text{wr}) \tag{7}$$

where C_{trs}, C_{ut} and C_j respectively denote the contributions to the speed due to 1) translation of the torso point, 2) the absolute angular velocity vector of the upper trunk, and 3) the joint angular velocity vectors at the shoulder, elbow and wrist joints.

4. Results and Discussion

A total of nine topspin forehands were discarded due to inconsistencies in marker trajectory. Pressure data from grip size 4 were discarded due to inconsistency in output and lack of data from multiple pressure sensels. Total pressure distribution with respect to a normalized time history was obtained as shown in Fig. 5. The pressure distribution from the start of the forward swing until the point of impact showed nominally the same pressure distribution pattern across all grip conditions. A significant ($p<0.001$) increase in average racket head speed was found during the firm grip condition compared to the normal gripping condition. The difference in racket head speed was also significantly ($p<0.001$) different between grip sizes when gripping the racket with a normal grip firmness as can be seen in Fig. 6. The relationships in KCAV were also investigated. Fig. 7 shows the investigated relations in KCAV and their inter-relation to the generation of racket head speed. The upper trunk (ut) and shoulder joint (sh) showed a significant negative linear relationship in KCAV to the generation of racket head speed at impact across all conditions. The statistical methods used on the investigation of average racket head speed and the KCAV to the generation of racket head speed at impact were an n-way analysis of variance and a linear correlation test, respectively.

The main findings have led to the following observations:

1) The negative linear relationship found in KCAV of the ut and sh could be of main importance when performing a topspin forehand. This is the case because the negative linear relationship in KCAV is present across all conditions. In being so, the implication is that the main KCAV to racket head speed for an elite player is governed by large muscular groups and flexible skeletal regions able to produce, respectively, large torques over a prolonged period of time and a high range of motion in order to adjust skeletal rotations in optimizing chance of success in performing the topspin forehand.
2) Changing of grip size during normal gripping did lead to a significant ($p<0.001$) increase in average racket head speed for grip size 2 compared to grip size 4. Also the relationship found in KCAV during the use of grip size 2 on the sh and wr is of interest, and signifies the fact that grip size does matter. The negative linear relationship in KCAV as well as the significant ($p<0.001$) increase in average racket head speed, found when using grip size 2, could be explained due to the participant using a grip size 2 with one over grip attached as his preferred grip size. Thereby showing the participant's accustomed use of upper body kinematics and their KCAV to that exact grip size. This is emphasized by the fact that the negative linear relation in sh and wr is kept constant even whilst changing grip firmness.
3) The KCAV interrelation in sh and wr can be the reason why a significant ($p=0.001$) increase in average racket head speed was found across grip sizes when using a normal grip firmness condition. Meanwhile, when increasing grip firmness the grip size did not matter, as there was only a significant ($p<0.001$) difference in average racket head speed between grip firmness conditions, thereby implying that increasing grip firmness decreases the effect grip size has on producing racket head speed.

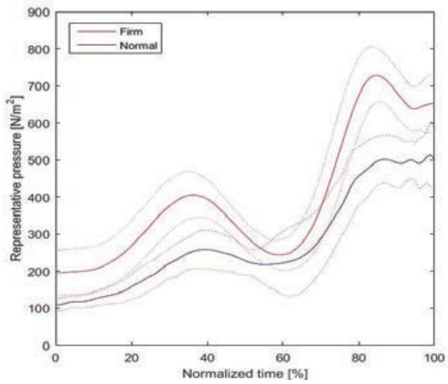

Fig. 5. Mean and standard deviation from start of topspin forehand forward swing until point of impact across grip conditions.

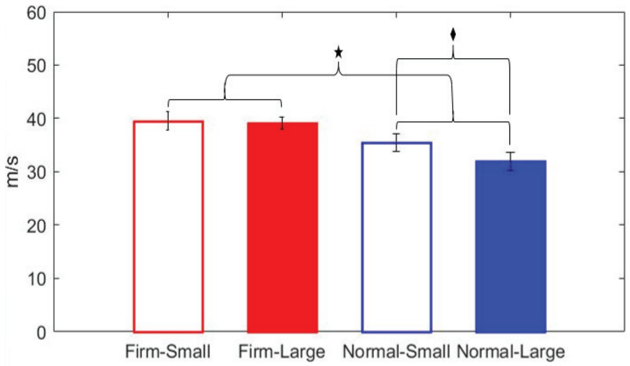

Fig. 6. Average racket head speed in m/s at impact across grip conditions.★, significant difference (p-value<0.001) between grip firmness conditions.♦, significant difference (p-value<0.001) between normal grip firmness.

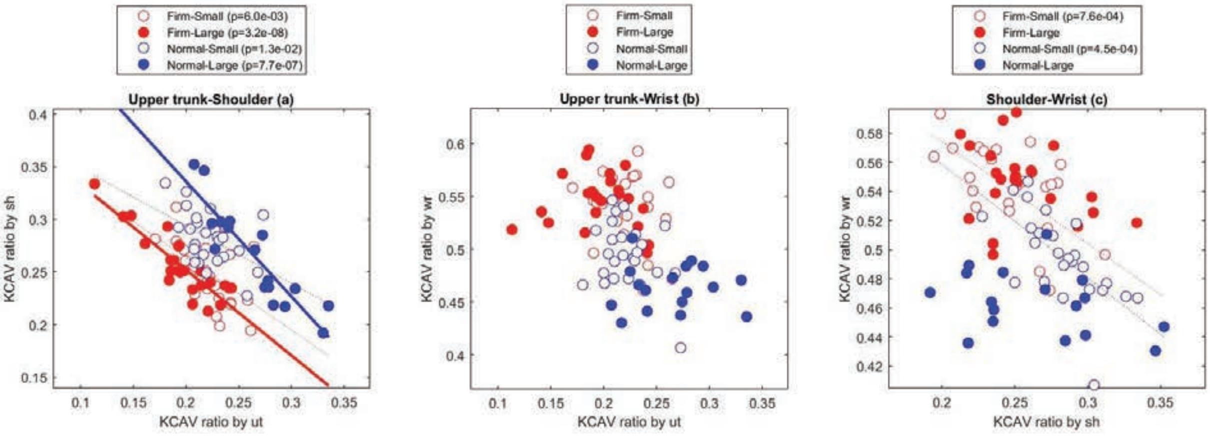

Fig. 7. Relationships between KCAV ratios to racket head speed at impact. From the left is shown a) upper trunk (ut) and shoulder (sh) relation, b) upper trunk and wrist (wr) relation and c) shoulder and wrist relation. The further along an axis the more KCAV ratio.

The proposed methodology, i.e. investigation of the kinematic contribution of angular velocity (KCAV) as a function of grip size and pressure and its resultant effect on racket head speed, shows promise and is the principal contribution of the investigation. Quantification of the effect of these parameters by means of KCAV analysis in a topspin forehand has never before been conducted. However, with only one test subject, the results of the study cannot be generalized to players in general. A larger scale study, on court with representative ball trajectory and velocity, must be conducted to investigate KCAV on a cohort of participants. This will enable the establishing of inter-relations in KCAV and investigating its usefulness in optimizing racket-player fit.

Further investigation of the data from Fig. 5 may provide a better understanding of grip firmness and its relation to racket head speed. The statistical data provide no causality for the effects, but the combination of pressure profile with kinematic data represents an opportunity to understand how racket characteristics influence the stroke. Furthermore, it may illuminate the relationship between perceived player experience and a quantitative performance measure. Increase in dynamic response rate, spatial resolution and durability of the sensors would improve these opportunities. A data-logging solution should be used in future studies when collecting pressure data to further minimize influence on the perception of participants.

Further, subjective player evaluation using a questionnaire could be employed to rate kinematics and racket characteristics, thus relating qualitative player perception with quantitative measurements.

Finally, the current kinematic analysis of the racket angular velocity was obtained by assuming the rotation center at the wrist joint and neglecting the possible degree-of-freedom between the hand and the racket. This modelling assumption should be tested in the design of future studies.

5. Conclusion

The investigation of the kinematic contribution of angular velocity (KCAV) as a function of the parameters, such as grip size and pressure, shows promise, and indicate that these parameters affect racket head speed. Quantification of the effect of these parameters by means of KCAV analysis in a topspin forehand has never before been conducted. Since the results of the study are obtained with only one test subject, they cannot be generalized to players in general. To this end, a larger scale study on a cohort of participants, on court with representative ball trajectory and velocity, is recommended.

Acknowledgements

The authors wish to acknowledge Babolat VS who kindly supported this research project with the provision of rackets, strings and over-grips.

References

[1] Koike S, Harada Y. Dynamic Contribution Analysis of Tennis-Serve-Motion in Consideration of Torque Generating Mode. *P. Engineering*. 2014;72:97-102.

[2] Putnam AC. Sequential Motions of Body Segments in Striking and Throwing Skills: Descriptions and Explanations. *J. Biomechanics*. 1993;26:125-135.

[3] Seeley KM, Funk DM, Denning MW, Hager LR, Hopkins TJ. Tennis Forehand Kinematics Change as Post-Impact Ball Speed is Altered. *S. Biomechanics*. 2011;10(4):415-426.

[4] Banwell HG, Roberts RJ, Halkon JB, Rothberg JS. Understanding the Dynamic Behaviour of a Tennis Racket under Play Conditions. *Exp. Mechanics*. 2014;54:527-537.

[5] LIU KY. Mechanical Analysis of Racket and Ball during Impact. *Med. and Sports in Sports and Exercise*. 1983;15:388-392.

[6] Elliott CB. Tennis: The Influence of Grip Tightness on Reaction Impulse and Rebound Velocity. *Med. and Sports in Sports and Exercise*. 1982;14:348-352.

[7] Grabiner DM, Groppel LJ, Campbell RK. Resultant Tennis Ball Velocity as a Function of Off-Center Impact and Grip Firmness. *Med. and Sports in Sports and Exercise*. 1983;15:542-544.

[8] Plium B, Safran M. From Breakpoint to Advantage: A Practical Guide to Optimal Tennis Health and Performance. *Racquet Tech Publishing*; 2004.

[9] Nirschl RP, Ashman ES. Elbow tendinopathy: Tennis Elbow. *Clin Sports Med*. 2003;22:813-836.

[10] Gordon JB, Dapena J. Contributions of Joint Rotations to Racquet Speed in the Tennis Serve. *J. Sports Sciences*. 2006;24(1):31-49.

[11] Sprigings E, Marshall R, Elliott B, Jennings L. A Three-Dimensional Kinematic Method for Determining the Effectiveness of Arm Segment Rotations in Producing Racquet-Head Speed. *J. Biomechanics*. 1994;27:245-254.