

# Effect of preparation of organic ferroelectric P(VDF-TrFE) nanostructure on the improvement of tennis performance

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**Abstract.** Organic ferroelectric material found vast application in a verity of engineering and health technology fields. In the present study, we investigated the application of the deformable organic ferroelectric in motion measurement and improving performance in tennis players. Flexible ferroelectric material P(VDF-TrFE) could be used in wearable motion sensors in tennis player transferring velocity and acceleration data to collecting devises for analyzing the best pose and movements in tennis players to achieve best performances in terms of hitting ball and movement across the tennis court. In doing so, ferroelectric-based wearable sensors are used in four different locations on the player body to analyze the movement and also a sensor on the tennis ball to record the velocity and acceleration. In addition, poses of tennis players were analyzed to find out the best pose to achieve best acceleration and movement. The results indicated that organic ferroelectric-based sensors could be used effectively in sensing motion of tennis player which could be utilized in the optimization of posing and ball hitting in the real games.

**Keywords:** artificial neural network (ANN); nano-material; organic ferroelectric P(VDF-TrFE); performance improvement; tennis player

## 1. Introduction

Organic ferroelectric materials was discovered in 1920 by Valasek (1921) in which the Rochelle salt was introduced. The importance of organic ferroelectric materials in comparison to other ferroelectrics grounds in the abundance in nature. Although, a long way is ahead to fully understand and develop organic materials both in their underlying chemistry and in production technology. However, the astonishing properties of ferroelectric materials make them a ideal candidates in application like memories and sensing devices (Horiuchi and Tokura 2008).

Motion sensors have been widely used in industries to detect abnormal vibrations and motion in equipment for a long time. Due to the large size of the conventional motion sensors their applications were limited to heavy equipment and sensor were commonly installed in a stationary position. With emerge of nanotechnology (Seleznev *et al.* 2009, Mehri *et al.* 2016, Singh *et al.* 2021, Naderi *et al.* 2020), it becomes available to the scientists and engineers to devise nano- and micro-size sensors with applications in fast moving objects (Al-Furjan *et al.* 2020, Habibi *et al.* 2019, 2021a, b, Zare *et al.* 2020, Li *et al.* 2020). One notable application in sports is to track ball trajectory to find the impact instance (Melo *et al.* 2021, Conaire *et al.* 2009, Zhao *et al.* 2019, Archana and Geetha, 2015, Yan *et al.* 2014). Recently, wearable devices are developed to monitor athletes' movement in different sports. One of the most agitated sports is tennis in which highly active players changes direction of motion several times in short time

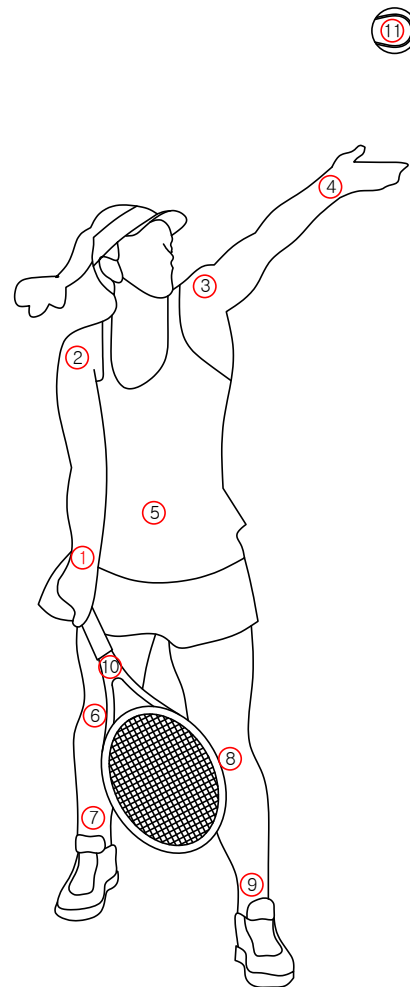
span. Moreover, the pose of the players could affect their performance in ball hitting and transferring energy to the ball. In this regard, wearable sensors to acquire pose and movement of tennis players have crucial importance. Organic ferroelectric materials in nano-scale have been utilized in flexible wearable sensors as reviewed by (Tsikriteas *et al.* 2021). In a notable research, Petritz *et al.* (2021) created ultraflexible sensors with ferroelectric co-polymers P(VDF-TrFE) to be used as attached sensors to human body. This type of sensors has all the energy harvesting, sensing and ultraflexibility which is needed in human body for sensing motion, pulses and air vibrations. They discussed that ferroelectric co-polymers P(VDF-TrFE) could be effectively be utilizes in both nano-generators and motion sensing. Therefore, this type of sensors are ideal candidate in health care systems and sport motion monitoring (Whatmore *et al.* 1990, Lee *et al.* 2018, Muralt 2000).

Motions in each member of a tennis player body is extremely important in determining the performance of the player in terms of accuracy of ball hitting, agitation and transferring energy to the tennis ball. Abrams *et al.* (2011) reviews the research articles on the tennis player motion analysis during three types of serves. Flat, kick and slice serves are three main types of serves being analyzed in recent years using both skin-based marker and markerless techniques. In four stages of the serve, there are potential of occurring injury in the tennis player and it requires detail analysis of movement. They discussed that during kick serves there a higher risk in injury occurrence in shoulder and back. Reid *et al.* (2007) used marker techniques to examine full body motion in tennis players with focus of shoulder joint kinetics. They showed that in both long-term kick and flat serves similar kinetics occurs which may

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results in injuries to shoulders. Hayes *et al.* (2021) tried to find correlation between different parameters in junior tennis players. Hernández-Davó *et al.* (2019) investigated the serve performance in terms of accuracy and speed in different age groups and examined the correlation between serve performance and body position just before ball impact. They found a noticeable effect of relative spatial positions of shoulder and hip on the performance of the serve performance. Colomar *et al.* (2022) reviewed the physical parameters influencing serve velocity. Collecting various results, they concluded that body height, arm length and body mass have favorable influence on the serve velocity. On the other hand, repetitive serve could deteriorate the players' performance during serve. Hornestam *et al.* (2021) experimentally found correlation between knee flexion and racket speed during serve in tennis play. It was declared that groups with greater knee flexion, having similar other parameters, reaches average ~16% higher racket speed. Fett *et al.* (2020) explored effects of physical and technical parameter on the serve speed in junior tennis players containing both male and female players. Over 1000 players were examined for their physical abilities and serve performance. They indicated that both physical parameter like medicine ball throws, body mass, grip force are important in serve performance. In addition to these parameter, technical parameters were well correlated to the serve velocity on the young players. Sánchez-Pay *et al.* (2021) studied two groups of national and professional mal tennis players to analyze effects of anthropometric, physical and functional parameters on the serve velocity. The results demonstrated that there were significant correlation between parameters in each of the three groups of parameter with serve velocity. Moreover, they proposed new functional test to evaluate serve performance in tennis players. Spin rate in tennis ball is important as ball speed in serve performance. Koya *et al.* (2022) investigated the effects of physical strength on the ball speed. They found a new parameter being important in ball speed in serves, depth of impact point was found to have high correlation with ball speed. In their analyses, they utilized tennis radar device. Although there are several studies on the effects of different parameters in tennis performance, there apparatuses used are either limiting the players' movement (attached sensors) or lacking enough accuracy in measurements. Therefore, using nanotechnology based sensors employing organic flexible ferroelectric sensors is becoming a widespread demand.

Regarding the above mentioned issues, organic ferroelectric material found vast application in a verity of engineering and health technology fields. In the present study, we investigated the application of the deformable organic ferroelectric in motion measurement and performance improving in tennis players. Flexible ferroelectric material P(VDF-TrFE) could be used in wearable motion sensors in tennis player transferring velocity and acceleration data to collecting devises for analyzing the best pose and movements in tennis players to achieve best performances in terms of hitting ball and movement across the tennis court. In doing so, ferroelectric-based wearable sensors are used in four different location on the player body to



Organic ferroelectric sensor list:

- 1- Right hand wrist
- 2- Right upper limb
- 3- Left upper limb
- 4- Left hand wrist
- 5- Lumber
- 6- Right knee
- 7- Right ankle
- 8- Left knee
- 9- Left ankle
- 10- Racket handle
- 11- Ball

Fig. 1 Location of organic ferroelectric-based motion sensors on tennis players body, racket and ball

analyze the movement and also a sensor on the tennis ball to record the velocity and acceleration. In addition, poses of tennis players were analyzed to find out the best pose to achieve best acceleration and movement.

## 2. Methodology

### 2.1 Body motion measurement

In the present study, the body motion of tennis player is measured with installing ultraflexible motion sensors on different positions. These position includes wrist, ankle,

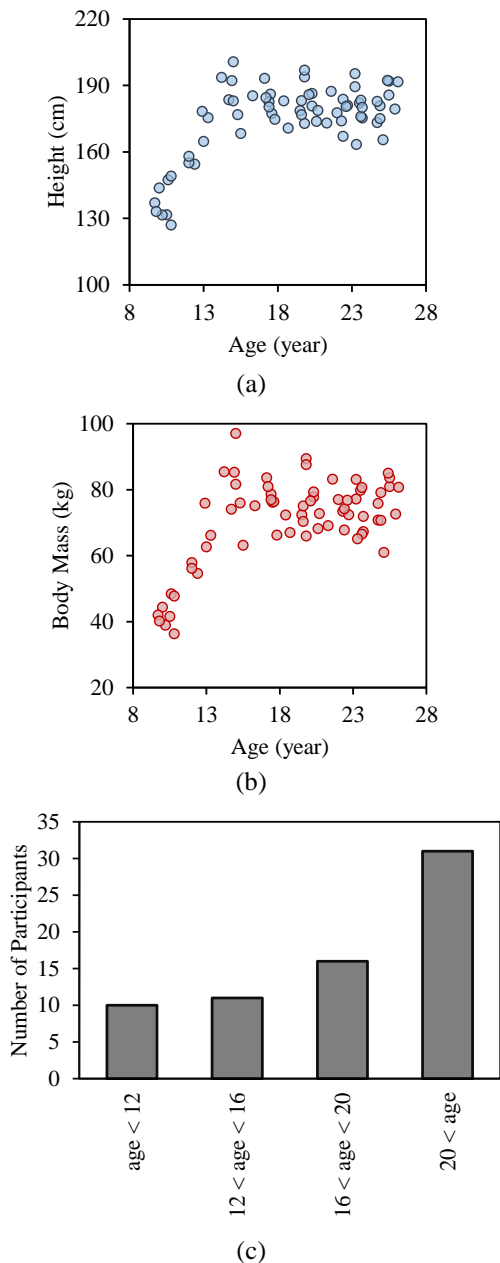


Fig. 2 Distribution of height, body mass and age of total 68 participants in the test; (a) Distribution of height in different ages; (b) Distribution of body mass in different ages; (c) Distribution of number of participants in age groups

knee, upper limb and lumbar of the tennis players, and one sensor on the tennis ball as illustrated in Fig. 1. All the sensors are capable of sending wireless signals at the rate 60Hz to a nearby device which collects the information of the position and time of each sensors. Having all the information of the player posing (relative position of different organs) and speed of the ball, it will be a simple statistical analysis to find correlation between different parameter and optimize the posing gesture during serve. The hitting position of ball to the court ground is another parameter measured with respect to a  $0.5 \times 0.5$  m marked square on the court.

## 2.2 Participants

Participants of this study included 69 male participants from different ages as provided in Fig. 2 and Table 1. All the participants are professional tennis players. On each player, organic ferroelectric-based nano-sensors with less than  $5\mu\text{m}$  thickness are attached as depicted in Fig. 1. The sensors are ultraflexible and ultralight having trivial influences on the tennis players' performance. The participants were asked to do their best to acquire highest speed and accuracy in their flat serves.

The participants were divided into four groups of U12 (under age 12), U16 (between 12 and 16 years old), U20 (between 16 and 20 years old) and +20 (greater than 20). The mean value of age, height and body mass of each group with standard deviations are listed Table 1. The majority of the participants falls in the +20 group. However, there are enough participants in other groups as well to make a conclusion on their performances.

## 3. Results

### 3.1 Physical parameters

Beside two physical parameters of height and body mass, four other parameters of shoulder external rotation (SR), hand speed in the wrist area (HS), knee flexion (KF) and differences between hand and hip vertical position (HH) are measured at 100ms before hitting the ball using data acquired from organic ferroelectric-based nanosensors. To measure the speed of the tennis ball right after racket impact the data from sensor attached to the ball was used. In Table 2, the mean  $\pm$  standard deviation of the measured values from players' bodies are provided. As could be observed, U12 group has the lowest values of all four measured parameters among other groups and +20 groups has the highest values. More specifically, the U12 group members have lowest values of KF parameter which could be correlated to their lower height which also affects HH parameter. On the other hand, both U16 and U20 measured parameters falls between the values of U12 and +20 groups. However, between U16 and U20 there are reciprocating measurements which could be due to close performance of these two groups.

### 3.2 Accuracy and ball speed

Accuracy and ball speed was measured after ball hits the ground and during ball movement, respectively. Accuracy of the serve was evaluated by measuring distance of ball hit point from center of the  $0.5 \times 0.5$  m marked square on the court ground at which players were asked to hit the ball. The lower the values of the accuracy column in Table 3, the higher the accuracy is. It is seen that, players in +20 group exceptionally achieve higher accuracy in comparison to other groups which could be a result of their expertise and experience. Among other groups, the U12 group has the lowest accuracy mostly due to their smaller height and experiences. Since the scale of the court is the same for all groups.

Table 1 Statistical data of the participants (Mean  $\pm$  Standard Deviation)

Group	Number	Age (year)	Height (cm)	Body Mass (kg)
U12	10	10.6 $\pm$ 0.81	141.3 $\pm$ 10.8	45.4 $\pm$ 7.2
U16	11	14.2 $\pm$ 1.05	173.1 $\pm$ 12.9	71.7 $\pm$ 6.4
U20	16	18.3 $\pm$ 1.16	182 $\pm$ 7.2	75.6 $\pm$ 5.8
+20	31	23.2 $\pm$ 1.76	181 $\pm$ 7.7	77.7 $\pm$ 6

Table 2 Physical parameters measurements in different groups (Mean  $\pm$  Standard Deviation)

Group	SR (degree)	HS (km/h)	KF (degree)	HH (cm)
U12	49 $\pm$ 6.2	7.8 $\pm$ 1.2	151 $\pm$ 9.2	72.4 $\pm$ 2.7
U16	51 $\pm$ 5.1	10.1 $\pm$ 2.4	148 $\pm$ 6.5	72.6 $\pm$ 3.6
U20	50.5 $\pm$ 3.9	10.6 $\pm$ 1.3	142 $\pm$ 3.6	83.6 $\pm$ 3.1
+20	53.2 $\pm$ 4.1	11.2 $\pm$ 1.8	137 $\pm$ 5.2	88.3 $\pm$ 5.6

Table 3 Serve performance in tennis players as measured using accuracy and ball speed (Mean  $\pm$  Standard Deviation)

Group	Accuracy (cm)	Ball speed (km/h)
U12	96 $\pm$ 12	90 $\pm$ 16.3
U16	91 $\pm$ 9	93 $\pm$ 17.2
U20	75 $\pm$ 11	105 $\pm$ 15.9
+20	54 $\pm$ 14	118 $\pm$ 14.6

Table 4 Correlation factor between different parameters and serve performance in U12 group

Group	Serve accuracy	Ball speed
SR	0.01	0.16
HS	-0.21	0.71
KF	0.68	-0.018
HH	0.64	0.43
BM	-0.34	0.29
Height	0.41	0.36

Table 5 Correlation factor between different parameters and serve performance in U16 group

Group	Serve accuracy	Ball speed
SR	0.05	0.23
HS	-0.26	0.69
KF	0.65	0.02
HH	0.53	0.38
BM	-0.48	0.31
Height	0.24	0.37

In the case of ball speed which is determinative parameter in serve performance, the body mass is seen to be important at the first glance. However, in the following sections effect of other parameters will be discussed. It should be noted measurement of these parameters simultaneously in a direct consequence of using organic ferroelectric sensors.

### 3.3 Correlation between physical parameter and performance

In this section, we try to find correlation between different physical and functional factors with flat serve performance. Since, there were substantial differences between performances of different age groups, these groups will be analyzed separately. In Table 4, the correlation factors for U12 group is presented. The influencing factor is six parameters of SR, HS, KF, HH, height and body mass (BM) of the players. The dependent parameters are ball speed and accuracy of flat serves. As seen, influence of SR parameter on the accuracy is trivial in U12 group. This observation confirm that rotation of the body directly affect the energy transferred to ball and has no impact on the accuracy. On the other hand, HS parameter has reversal effect on the accuracy in U12 group which indicates that higher power in the hands results in decrease in the accuracy. One interesting results of this correlation analysis is the effects of KF and HH parameters which are significantly correlated with accuracy of serve. These two parameters provides more stability of the player leading to accuracy of ball hitting at the supposed location. Body mass has detrimental effect of the accuracy while height of the player in U12 group is favorable to accuracy of the serve.

Regarding ball speed right after racket impact, it is seen that KF have slight negative influence on the ball speed. All other factors have positive influence on the ball speed with hand speed is the most influential effects on the ball speed with correlation factor 0.71.

In the case of U16 group, ball speed is mostly affected by hand speed with correlation factor 0.69. However, in comparison to U12 group, influences of SR, BM and height have been slightly increased. Effect of KF is also negligible in U16 group since the correlation factor is very small. The effect of BM on the ball speed increased substantially indicating its influential role in achieving high ball speeds. For the case of accuracy there are similar results with the above discussion. Factor BM has more negative effect than before since in this age group strength and mass are not increased proportionally. Same discussion is true for the case of height effect which is decreased in U16 group. Higher hand speed results in decrease in accuracy in U16 group as well.

For higher age group U20, there is seen a moderation of effects of different factors on the serve performances. Increase in body expertise is a major factor in equating influence of all factor on the accuracy and ball speed in flat serve as measures by organic ferroelectric ultraflexible sensors. However, it is noteworthy to focus on influences of each factor on the players' performance. SR factor and HS factor are not important in determining accuracy of the flat serve as their correlations are under 1%. Thus, it is safe to say that these factors are not detrimental in accuracy performance of tennis players. On the other hand, effect of height is increasing and influential in all age groups until now describing the importance of experience along with height of the athlete in accuracy determination. The effect of body mass in U20 group become trivial since with any BM the player could reach enough control on their body to have an accurate shot. On the other side, hand speed also

Table 6 Correlation factor between different parameters and serve performance in U20 group

Group	Serve accuracy	Ball speed
SR	0.08	0.26
HS	0.036	0.65
KF	0.51	-0.12
HH	0.45	0.38
BM	0.01	0.56
Height	0.56	0.47

Table 7 Correlation factor between different parameters and serve performance in +20 group

Group	Serve accuracy	Ball speed
SR	0.06	0.34
HS	0.025	0.77
KF	0.45	-0.02
HH	0.52	0.47
BM	0.12	0.38
Height	0.49	0.51

has the greater correlation with ball speed in U20 group. However, the negative effect of KF factor become noticeable although it is small in comparison to other factors. Both height and BM are greatly affect the ball speed as these two factors are closely related to the strength of athletes in this age range.

In the case of +20 group, ball speed is mostly affected by hand speed with correlation factor 0.77, the greatest among all groups indicating. However, in comparison to other groups, influences of SR and height are increased. Effect of KF is also negligible in +20 group since the correlation factor is very small. The effect of BM on the ball speed decreased in comparison U20 group. For the case of accuracy there are similar results with the above discussion for U20 group. Factor BM in this case has positive effects in contrast to U20 group.

#### 4. Conclusions

Organic ferroelectric material found vast application in a verity of engineering and health technology fields. In the present study, we investigated the application of the deformable organic ferroelectric in motion measurement and improving performance in tennis players. Flexible ferroelectric material P(VDF-TrFE) could be used in wearable motion sensors in tennis player transferring velocity and acceleration data to collecting devises for analyzing the best pose and movements in tennis players to achieve best performances in terms of hitting ball and movement across the tennis court. In doing so, ferroelectric-based wearable sensors are used in four different location on the player body to analyze the movement and also a sensor on the tennis ball to record the velocity and acceleration. In addition, pose of the tennis player were analyzed to find out the best pose to achieve best

acceleration and movement. The results indicated that:

- Ball speed is mostly affected by hand speed with correlation factor higher than 0.65 in all age groups.
- Higher hand speed results in decrease in accuracy in younger players in U12 and U16 groups. However, in mature groups above 16 YoA higher hand speed is not an influential factor on the accuracy of serve.
- It is safe to say that SR and HS factors are not determinative in accuracy performance of tennis players.
- The most influential parameters affecting accuracy of flat serve are the knee flexion and HH as measured by organic ferroelectric-based nano-sensors.
- Using organic ferroelectric nanosensors in detecting motion and speed in athletes could aid the performance of tennis players without affecting their abilities during play.

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