Tennis Conditioning Blueprint 2021

GROUNDSTROKES

ATHLETIC PERFORMANCE ACADEMY

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Disclaimer

The information in this book is offered for educational purposes only; the reader should be cautioned that there is an inherent risk assumed by the participant with any form of physical activity. With that in mind, those participating in strength and conditioning programs should check with their physician prior to initiating such activities. Anyone participating in these activities should understand that such training initiatives may be dangerous if performed incorrectly. The author assumes no liability for injury; this is purely an educational manual to guide those already proficient with the demands of such programming.

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Tennis Conditioning Blueprint 2021

Tennis is considered to be one of the most popular sports in the world today. Increasing popularity and professionalism inspire sport scientists to carry out more research related to the factors affecting performance in tennis. These factors include stroke production, physical fitness, on-court movement, and mental fitness (Groppel, 1992). According to Elliott and collaborators (2003), success in tennis is related to the effective combination of tennis strokes and on-court movements.

This Ebook will examine the aspects of performance that contribute to groundstroke performance and specifically velocity, with the hope that it will direct training approaches that can produce a positive change in groundstroke performance.

To quote Stephanie Kovalchik ''Speed is only one dimension of a shot and rankings show us that the best players aren't necessarily the players that hit the hardest. Quality of a shot has to do with many factors: how close it comes to a line, how open the court is, and how much it takes the opponent by surprise. Although the pace of a shot can't tell us everything about a shot's quality, it does, I think, give us insight into a player's style. Players with a flatter and more attacking game should feature high on the pace charts, whereas the players with more variety, spin, or who wait for their opportunities should not.''

Transfer of Training

Much has been written about the importance of determining methods that will transfer to improved sports performance. Tennis is considered a 'skill dominant' sport with a greater heterogeneity of physical profile amongst athletes. This is represented by a greater emphasis on tactical and technical training than physical training in determining elite levels of performance.

Notwithstanding the obvious need to invest significant time in skill acquisition this document aims to establish what one would expect to 'see' when observing someone hitting a groundstroke at a world class level. It will also consider some of the underpinning physical (structural adaptations) and mechanical (coordination) characteristics that are required to hit at a world class level.

Tennis Groundstroke Research

A combination of personal communication with the Lawn Tennis Association (LTA) and a literature search of nearly thirty peer reviewed journal articles was performed in order to examine the latest research. For ease of understanding the review has been broken down into three key areas that influence tennis groundstrokes:

1. **Anthropometric**- includes body height and body mass
2. **Structural**- includes ground reaction force and torso/pelvis range of motion/strength
3. **Mechanical**- includes motor coordination of general and specific movements

This is not a literature review in the academic sense of the word, meaning this is not a critique of the underlying methodologies used, nor is there a desire to compare and contrast findings in an effort to find points of difference.

This is simply a highlights reel of personal communication from the LTA and passages of nearly thirty journal articles, which have been selectively taken from the original source and included in their original format. Some effort has been made to highlight key findings, with a summary of findings in bullet point format for those that just want the headlines. Full references are provided at the end of the document for those who want to go to the source!

APA would like to give a special thank you to Chris McLeod, Head of Strength & Conditioning at the LTA. Chris has been instrumental in providing the wider British Tennis S&C community with updates on the LTA framework for profiling athletes, research on the demands of the game and a range of continued professional development (CPD) opportunities during the period 2019-2021.

This Ebook is not simply a guide on how to produce more force in a rotational plane (although that's part of it!). It's about the factors that are most within the scope of the strength & conditioning coach to enhance in the tennis stroke itself. It's about discovering the factors that can have the biggest impact on groundstroke hitting power, notwithstanding the obvious priority that technical mastery has on groundstroke performance.

It aims to present up to date facts on Tennis Groundstroke Research. It is ultimately the job of the reader to then decide how to apply the information contained here to inform their practices. A strong case is made for the importance of trunk rotational velocity for developing high racket velocity so logically then the next step would be to ask what would be the underlying exercises we can use in the gym to develop capacity in this action?

If you would like further information, look out for the course '*Functional Anatomy for Tennis*,' which contains in depth analysis of the functions of the anatomical structures used most in Tennis Groundstrokes. This will then inform the rational for choosing exercises to enhance specific aspects of the movement framework presented in this Ebook. If this Ebook is the 'WHAT,' the *Functional Anatomy for Tennis* Course will be the definitive HOW!

We leave you with this quote:

''**Without data you are just another person with an opinion.``**

– W. Edwards Deming –

Groundstrokes- Racket Velocity

In the professional game, the forehand is perceived as the most important stroke after the serve. However, the level of success by a tennis player is often determined by the mechanical efficiency of an individual's stroke.

Racquet velocity has been stated to be the principal performance limiting factor in the speed that can be imparted to the ball, and is therefore considered as one of the main reasons for the constantly high pace in the modern game.

The ability to produce high racquet velocities seems to be the key element of successful play on a professional level because it affects ball velocity. Faster balls take time away from the opponent who is put under more stress and forced to alter their movements, thus more likely to mishit. Consequently, anatomical contributions to racquet head velocity in the forehand are of great interest to researchers.

Groundstrokes- A Caveat

This Ebook will focus on groundstrokes that are hit from a balanced position. These shots will usually occur at low to moderate movement speeds and will be defined by the athlete's ability to maintain their centre of mass (COM) inside their base of support (BOS). It could be argued that there is a lower emphasis on 'physical qualities' in terms of intensity of movement. However, it will be assumed that there will always be maximum intent with the racket work.

Tennis coaches often refer to being 'behind the ball,' or 'on the run.' It is possible to be behind the ball and unbalanced and it is also possible to be on the run and be balanced, if the definition of balance is having one's COM inside their BOS.

Unlike the serve, which takes place from a stationary position and will have a fairly consistent technique, there are a number of different ways that the body can move when hitting a groundstroke from a balanced position. This includes pivoting, hopping, jumping and transferring.

It is beyond the scope of this Ebook to examine in detail all the possible movements that take place when hitting a groundstroke. In the Movement edition (Part 2) of this Tennis Conditioning Blueprint, a case was made for paying special attention to conditioning of the penultimate step (which at high intensity takes place during a running step as you move to the ball). If you perform it well, you can hit on the run and still be in a state of balance by keeping your COM inside your BOS.

A greater amount of hip flexion (upper body flexed) in the penultimate step might equate to higher muscle activity in the hamstring semitendinosus. A greater amount of hip flexion in the penultimate step requires more eccentric force of the semitendinosus to stop the torso from collapsing forward.

Therefore, a flexed upper body could be an indication of hamstring weakness. As it relates to groundstroke performance, the flexed upper body and foot, knee and hip position will significantly affect the ability to transfer energy through the kinetic chain from the lower limbs, through the trunk and to the racket.

Tennis coaches describe this hitting action as more of a ‘block’ with the racket as the upper body is not able to rotate around the hips, and it becomes more of an arm action.

As stated earlier this Ebook will focus on groundstrokes that are hit from a balanced position where the player is ‘behind the ball,’ and can complete a full rotation of the body. These shots will usually occur at low to moderate movement speeds and hit within the tramlines. More on this later.

Anthropometric Factors

Bodyweight and Velocity

Bodyweight is also an important variable for increasing ball velocity, but only when that bodyweight is coupled with the ability to produce power. Greater bodyweight increases the potential energy available to transfer to the ball, but because fat mass is unable to generate power, increased bodyweight should come in the form of lean body mass.

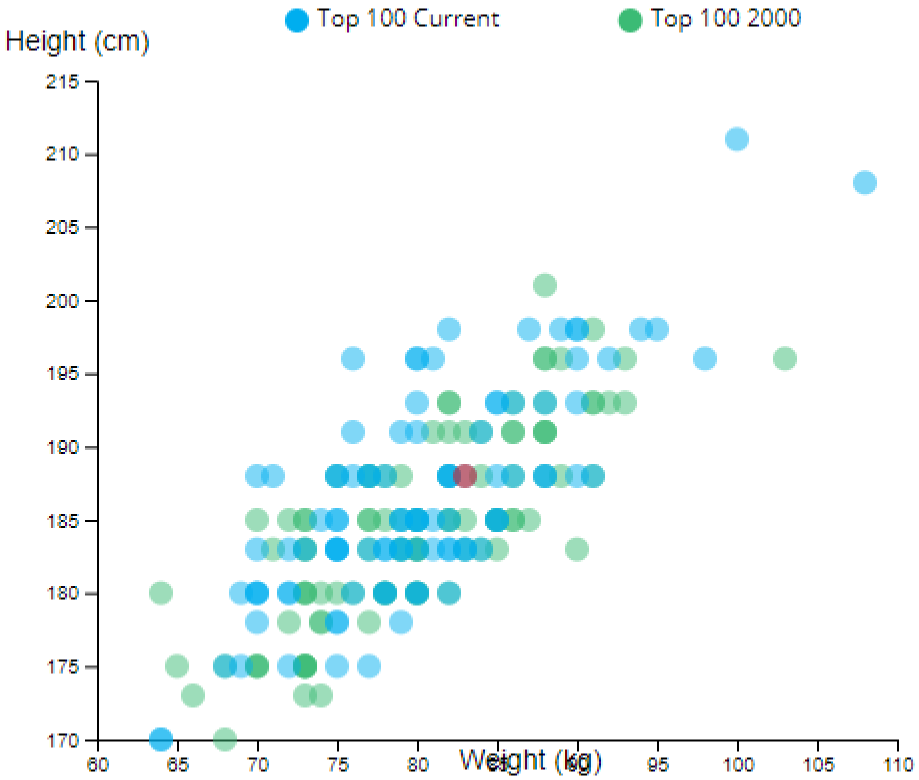


Figure - Build of Top 100 ATP Players 2000 (green) vs 2020 (blue)

Click here to see the article

Notable to the class of 2020 we can see the huge range from 64kg Yoshihito Nishioka to John Isner at 108kg.

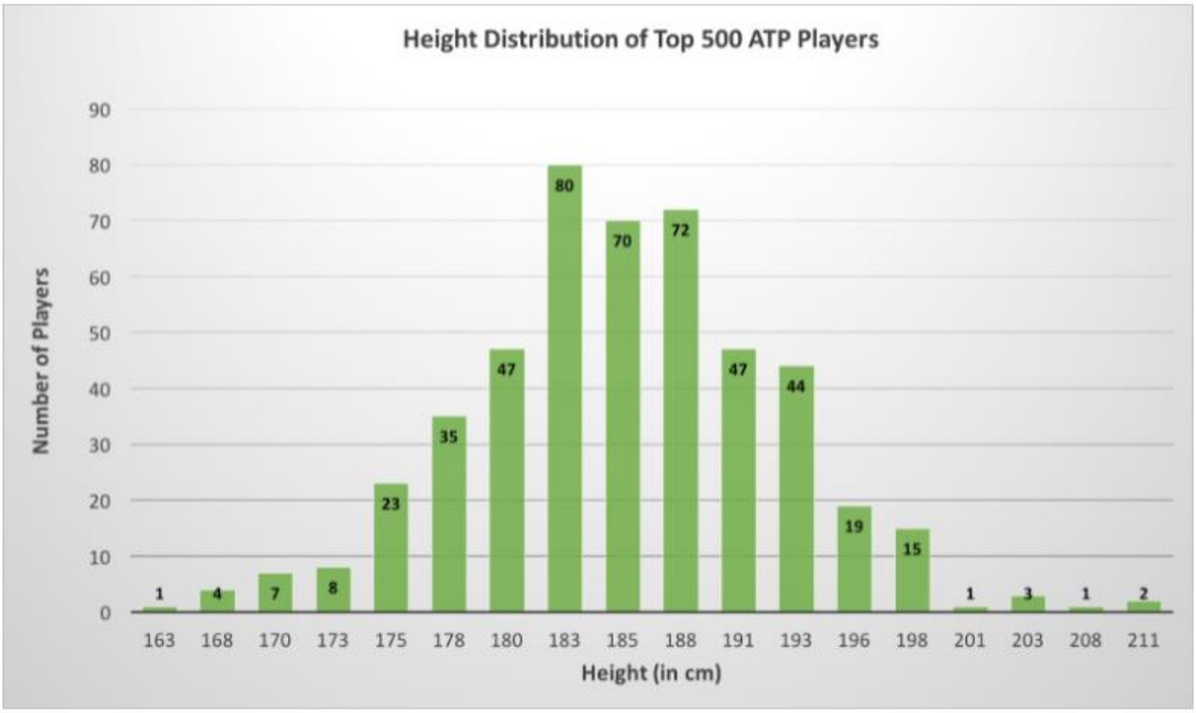
Height and Velocity

For this section it will be useful to first establish the facts around the average height of pro players. The average height of the ATP top 100 is exactly 6'1" (1.85m). Inside the top ten, the average is a bit higher at 6'2" (1.88m). The average height of the WTA top 100 best female players in the world is 5'7" (1.69m). Just like the men the top 10 women were taller averaging 5'8" (1.75m). Based on Data analysis Dec 2019 from Nikola Aracic. See full article here

This is supported from an Analysis in November 2019 (see below) from the website MyTennisHQ.com. See the full Article

We can see that 4 out of the top 10 ATP players are taller than 6 feet 5. In addition, 13 out of the top 50 players (26%) are taller than the same mark. So as we can see, taller tennis players are finding increasing success and height is playing a stronger role in tennis year after year.

The average height of the top 500 male tennis players in the world is 185.5 centimetres (6-feet-1). 222 of the top 500 players measure between 183 cm to 188 cm, so that can be considered to be the average height of professional male tennis players.



The average height of the top 500 ATP tennis players

While a large number of the top tennis players falls within the 183-188cm height range, it is not to say that height does not matter in tennis – as it actually does.

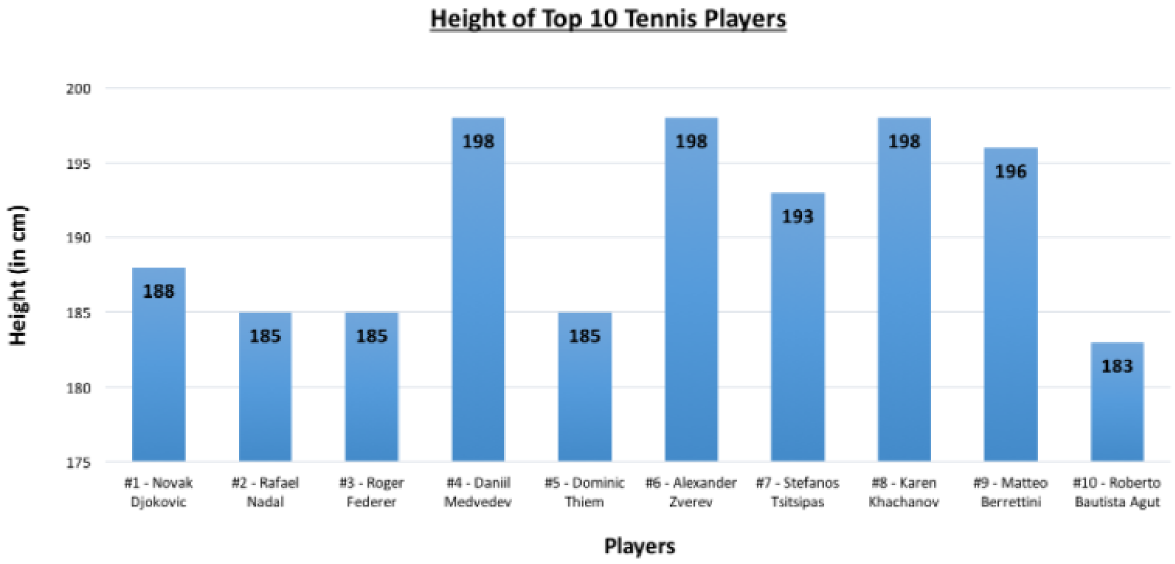
The average height of the top 10 players is 190.9 cm (6-feet-3), while the average height for the players ranked between 401 – 500 is only 183.5 cm (6 feet).

Top 10 – Average Height of Professional Tennis Players

The average height of the top 10 ATP players is 190.9 cm (6’3), a surprising 6.3 cm (3 inches) taller than the average player ranked between the top 50 and 100.

While Djokovic, Federer, and Nadal are not extremely tall, new players in the top 10 like Alexander Zverev, Mateo Berrettini, Karen Khachanov, and Daniil Medvedev are all taller than 196 cm (6’5) – which brings the whole top 10 average to the previously mentioned 190.9 cm.

In November 2019 (when our analysis was conducted), the shortest top 10 players was Roberto Bautista Agut, who measures 183 cm (6 feet). On the other hand, the tallest players were Zverev, Khachanov, and Medvedev, all at 198 cm (6’6).



Does Height Matter in Tennis?

As you were able to see, the height of professional tennis players is all over the place. There are successful players who measure 211 cm and others who measure 170 cm.

Height is an important matter in tennis. Shorter players generally tend to move better, but taller players can serve faster and hit better angles. While players at the ends of the spectrum will excel in one aspect but fail in another, players with a height between the optimal 185 – 190 cm can usually excel at both.

The chart below compares the average height of players in different ranking ranges. As you can see, the trend is that the higher the ranking goes, the tallest players are.

Who is the Shortest ATP Tennis Player?

Just to add some fun facts at the end of this article, I wanted to come up with a list of the 10 shortest players in the top 500 of the ATP rankings. Here they are:

1. Yuta Shimizu (#367) – 163 cm
2. Hiroki Moriya (#224) – 168 cm
3. Roberto Ortega Olmedo (#248) – 168 cm
4. Shuichi Sekiguchi (#272) – 168 cm

5. Rio Noguchi (#398) – 168 cm
6. Diego Schwartzmann (#15) – 170 cm
7. Yoshihito Nishioka (#72) – 170 cm
8. Oscar Jose Gutierrez (#371) – 170 cm
9. Evan Furness (#407) – 170 cm
10. Sebastian Baez (#430) – 170 cm

Who is the Tallest ATP Tennis Player?

On the other end of the spectrum, here is a list of the 10 tallest players on the top 500 of the ATP:

1. Reily Opelka (#31) – 211 cm
2. Ivo Karlovic (#101) – 211 cm
3. John Isner (#17) – 208 cm
4. Kevin Anderson (#45) – 203 cm
5. Danilo Petrovic (#172) – 203 cm
6. Michael Redlicki (#321) – 203 cm
7. Christopher Eubanks (#201) – 201 cm
8. Daniil Medvedev (#4) – 198 cm
9. Alexander Zverev (#6) – 198 cm
10. Karen Khachanov (#8) – 198 cm

In terms of a relationship between height and velocity it is difficult to establish as there is limited public domain data for ATP and WTA matches. Groundstroke speed isn't a difficult thing to calculate with tracking data but tournaments rarely if ever do. Occasionally, we might see a broadcast display the speed of a shot during a rally but this doesn't give us enough information to say what is a *typical* speed of a shot or which players hit the fastest shot on average. That needs to change.

However, there are signs that this is changing with more data becoming available and in particular from the Australian Open. Therefore, we will look at the fastest forehands and backhands taken from an analysis of the Australian Open 2014-2016 from Tennis Australia's Game Insight Group (GIG) and also from an Infosys Beyond the Numbers Insight of the AO 2021.

In addition, we will include an Infosys ATP Beyond The Numbers analysis of players who competed in a minimum of 10 ATP matches on Hawk-Eye courts from 2018-2020 as well as statistics taken from Miami Open 2021.

At the end of this analysis we will look at the height of some of the top performers and make some conclusions about the role of height on hitting velocity in groundstrokes.

Australian Open 2014-2016

Forehand Speed Characteristics for ATP Players

Analysis of speed at impact (in mph) for groundstroke forehands (shots landing within 3 meters of the baseline) observed at the 2014 to 2016 AO show most male players reach average speeds of 71 to 83 mph on the forehand.

Though there weren't many deep forehand shots observed for American Jack Sock, he did have the highest average speed at 86 mph. Dominic Thiem and Stan Wawrinka are two other players in the above 80 mph club, with big-hitting Davis Cup hopeful Juan Martin Del Potro (who only had 2 matches at the 2014 to 2016 AO) is just behind at an average of exactly 80 mph.

Forehand Speed Characteristics for WTA Players

The difference between typical men's and women's speeds on groundstrokes isn't large. Women also are hitting speeds of 70 - 79 mph on their forehand, though fewer of them are hitting speeds of 80 mph or higher frequently. One exception is American Madison Keys who has an average forehand speed of 81 mph.

See the full article here for Forehand Speed

Backhand Speed Characteristics for ATP Players

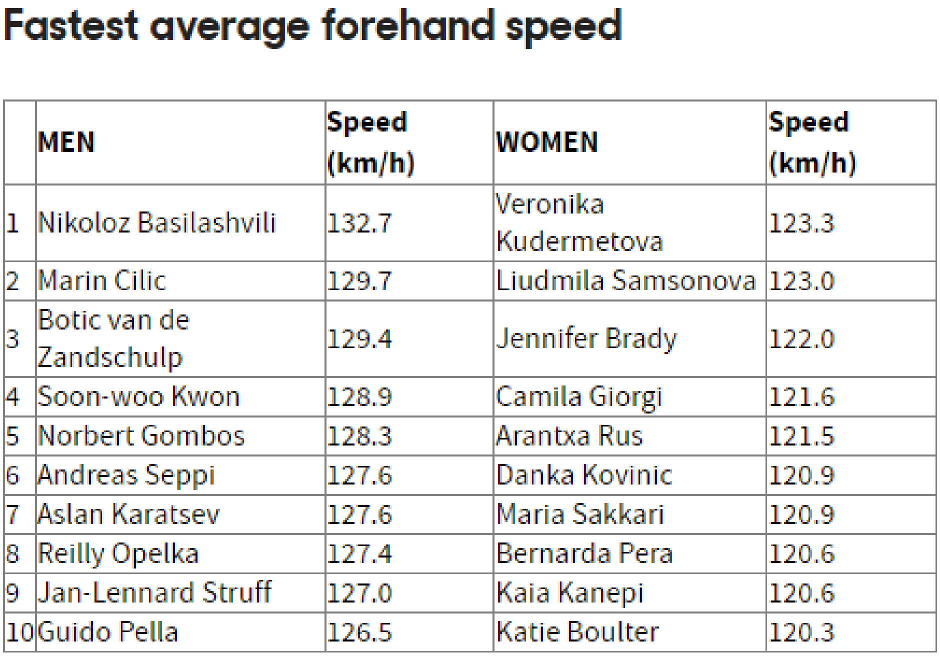
Among the men, these data suggest that player averages on the pace of the backhand range from 60 to 75 mph. Much less than the speed of a first serve but still impressive when one considers that it is the shot that is the most difficult to generate power.

Backhand Speed Characteristics for WTA Players.

When we turn to the WTA, we find median impact speeds that are in the same range of the men's, from 60 to 75 mph. It is also interesting to see that the spread in the backhand speed among the female players is much tighter at the top, suggesting somewhat more consistency in the speed characteristics on the WTA than the ATP. Both of these suggest that flat two-handed backhands are more of a norm for the WTA while the ATP might have more variety of spin on the backhand that could slow the pace but increase the unpredictability of their shots.

See the full article here for Backhand Speed

Australian Open 2021 – InfoSys Analysis

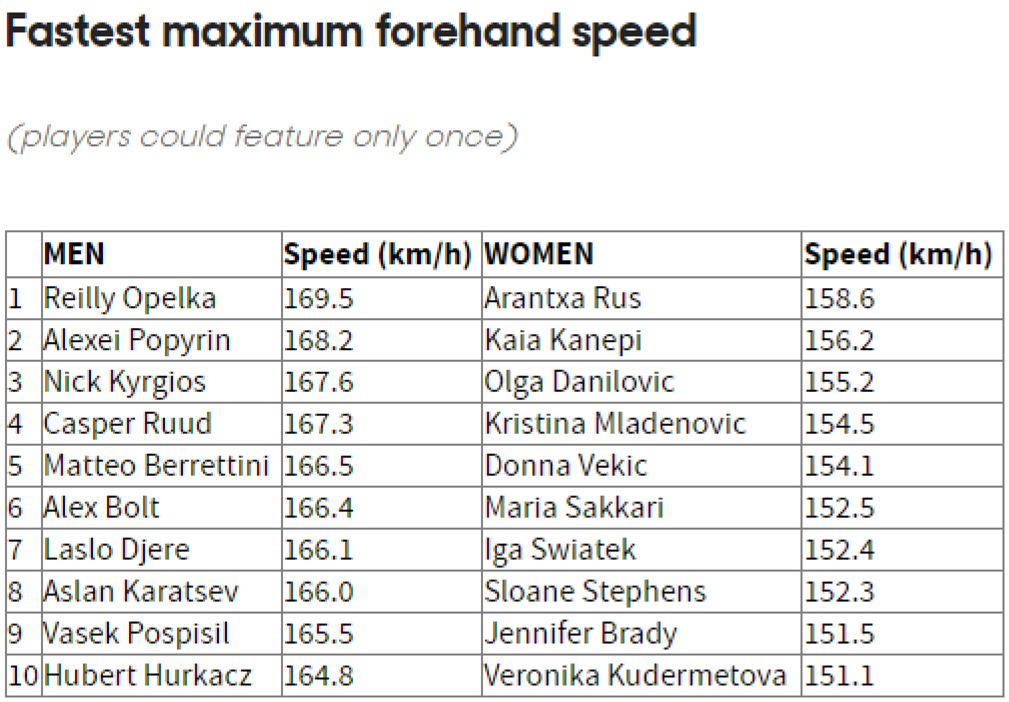


Fastest average forehand speed

	MEN	Speed (km/h)	WOMEN	Speed (km/h)
1	Nikoloz Basilashvili	132.7	Veronika Kudermetova	123.3
2	Marin Cilic	129.7	Liudmila Samsonova	123.0
3	Botic van de Zandschulp	129.4	Jennifer Brady	122.0
4	Soon-woo Kwon	128.9	Camila Giorgi	121.6
5	Norbert Gombos	128.3	Arantxa Rus	121.5
6	Andreas Seppi	127.6	Danka Kovinic	120.9
7	Aslan Karatsev	127.6	Maria Sakkari	120.9
8	Reilly Opelka	127.4	Bernarda Pera	120.6
9	Jan-Lennard Struff	127.0	Kaia Kanepi	120.6
10	Guido Pella	126.5	Katie Boulter	120.3

132.7 km/h = 82.3 mph

123.3 km/h = 76.4 mph



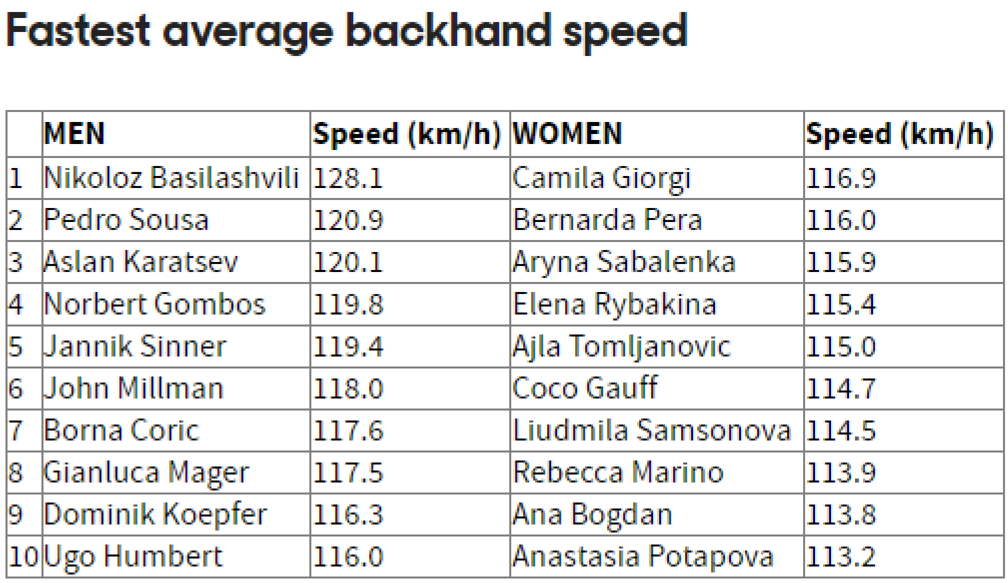
Fastest maximum forehand speed

(players could feature only once)

	MEN	Speed (km/h)	WOMEN	Speed (km/h)
1	Reilly Opelka	169.5	Arantxa Rus	158.6
2	Alexei Popyrin	168.2	Kaia Kanepi	156.2
3	Nick Kyrgios	167.6	Olga Danilovic	155.2
4	Casper Ruud	167.3	Kristina Mladenovic	154.5
5	Matteo Berrettini	166.5	Donna Vekic	154.1
6	Alex Bolt	166.4	Maria Sakkari	152.5
7	Laslo Djere	166.1	Iga Swiatek	152.4
8	Aslan Karatsev	166.0	Sloane Stephens	152.3
9	Vasek Pospisil	165.5	Jennifer Brady	151.5
10	Hubert Hurkacz	164.8	Veronika Kudermetova	151.1

169.5 km/h = 105 mph

158.6 km/h = 98.3 mph

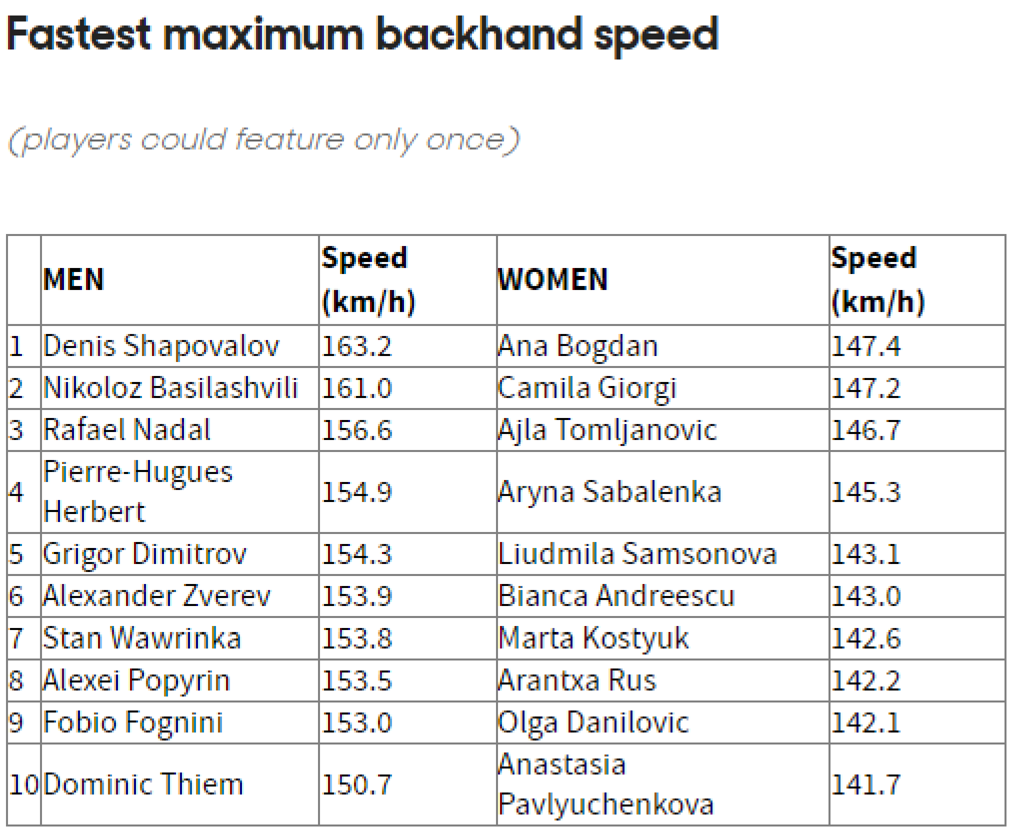


Fastest average backhand speed

	MEN	Speed (km/h)	WOMEN	Speed (km/h)
1	Nikoloz Basilashvili	128.1	Camila Giorgi	116.9
2	Pedro Sousa	120.9	Bernarda Pera	116.0
3	Aslan Karatsev	120.1	Aryna Sabalenka	115.9
4	Norbert Gombos	119.8	Elena Rybakina	115.4
5	Jannik Sinner	119.4	Ajla Tomljanovic	115.0
6	John Millman	118.0	Coco Gauff	114.7
7	Borna Coric	117.6	Liudmila Samsonova	114.5
8	Gianluca Mager	117.5	Rebecca Marino	113.9
9	Dominik Koepfer	116.3	Ana Bogdan	113.8
10	Ugo Humbert	116.0	Anastasia Potapova	113.2

128.1 km/h = 79.4 mph

116.9 km/h = 72.5 mph



Fastest maximum backhand speed

(players could feature only once)

	MEN	Speed (km/h)	WOMEN	Speed (km/h)
1	Denis Shapovalov	163.2	Ana Bogdan	147.4
2	Nikoloz Basilashvili	161.0	Camila Giorgi	147.2
3	Rafael Nadal	156.6	Ajla Tomljanovic	146.7
4	Pierre-Hugues Herbert	154.9	Aryna Sabalenka	145.3
5	Grigor Dimitrov	154.3	Liudmila Samsonova	143.1
6	Alexander Zverev	153.9	Bianca Andreescu	143.0
7	Stan Wawrinka	153.8	Marta Kostyuk	142.6
8	Alexei Popyrin	153.5	Arantxa Rus	142.2
9	Fobio Fognini	153.0	Olga Danilovic	142.1
10	Dominic Thiem	150.7	Anastasia Pavlyuchenkova	141.7

163.2 km/h = 101.2 mph

147.4 km/h = 91.4 mph

Read the full article here

Infosys ATP Beyond The Numbers analysis of players who competed in a minimum of 10 ATP matches on Hawk-Eye courts from 2018-2020

Average Backhand Topspin - Revolutions Per Minute (RPM)

Adding spin to the ball helps create more margin for error and, in turn, allows for more power to be added to the shot as the spin helps keep it in. Sinner was the leader of the pack in hitting the most spin off his backhand wing, averaging 1858 rpm from 17 matches in the data set.

The leading five players in the spin category were:

1. Jannik Sinner = 1858 rpm
2. Martin Klizan = 1840 rpm
3. Felix Auger-Aliassime = 1825 rpm
4. Pablo Cuevas = 1735 rpm
5. John Millman = 1680 rpm

Out of the current Top 10, Gael Monfils (1551 rpm), Stefanos Tsitsipas (1280 rpm) and Daniil Medvedev (1262 rpm) led the way. Rafael Nadal led The "Big Three" with the most backhand topspin (1252 rpm), followed by Novak Djokovic (1148 rpm) and Roger Federer (548 rpm). Federer traditionally employs more slice backhands than the others, which lowers his overall rating here.

Average Backhand Speed (MPH)

The ability to "rock" a backhand is not a problem for the teenage Italian, as he had the fifth-highest average on tour with backhand speed, averaging 69 mph.

The leading five players in the data set are listed below.

1. Nikoloz Basilashvili = 71.2 mph
2. John Millman = 70.2 mph
3. Rafael Nadal = 69.8 mph
4. Ugo Humbert = 69.2 mph
5. Jannik Sinner = 69.1 mph

Dominic Thiem led the current Top 10 with average backhand speed at 67.4 mph, followed by Djokovic (67.3 mph) and Alexander Zverev (67.0 mph). Federer was around the middle of the ATP pack, averaging 66.1 mph. The average backhand speed for the 94 players in the data set was 66.0 mph.

Miami Open 2021 - Average Forehand and Backhand Speeds of Players who Competed in this Year's Masters 1000 tournament

Average forehand speed in Miami (mph)

1. Sinner = 81
2. Korda = 80
3. Raonic = 78
4. Rublev = 77
5. Tsitsipas = 74
6. Medvedev = 73

Average backhand speed in Miami (mph)

1. Sinner = 74
2. Korda = 70
3. Rublev = 67
4. Medvedev = 67
5. Hurkacz = 66
6. Raonic = 65

Based on all the data presented we will now look at a final analysis of Height versus Ranking using the data for the men and women who had the Fastest Average Forehand speed during the Australian Open 2021.

This stroke has been chosen as it is the more frequent groundstroke to be hit and is hit harder than the backhand in most cases. We have also chosen the 'average' forehand speed as it is more representative of what happens in a match.

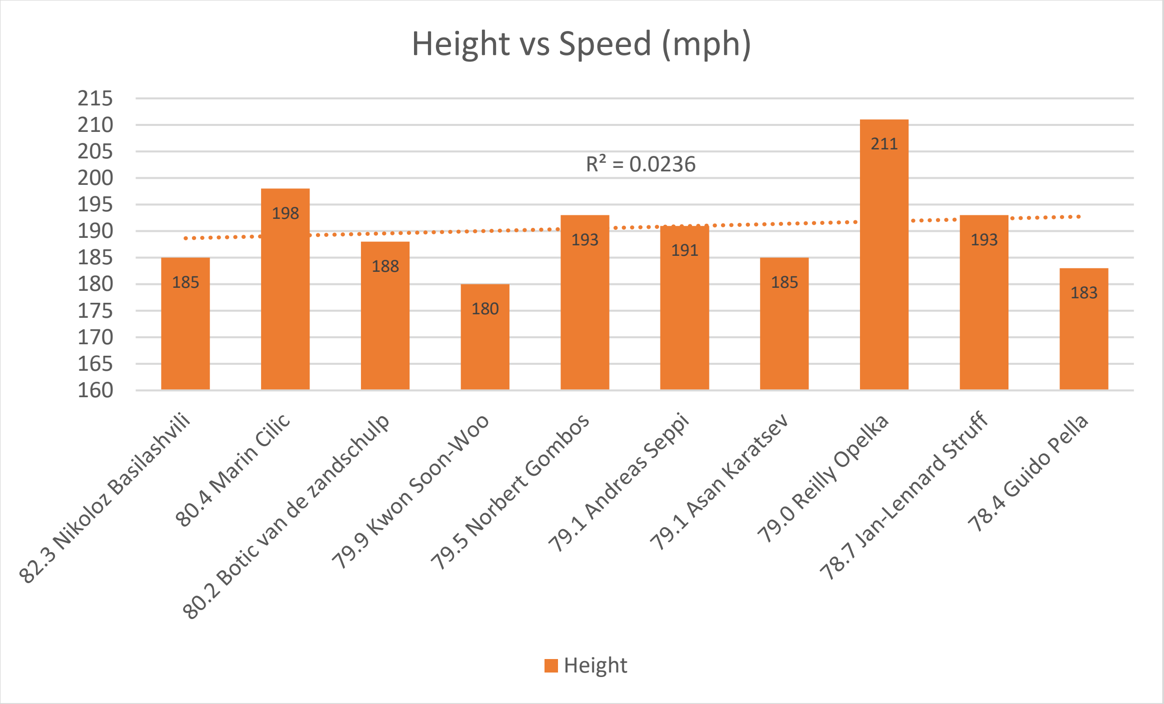


Figure - Fastest Average Forehand Speed Australian Open 2021 (Men)

In the figure above we have presented the data with the fastest hitting player Nikoloz Basilashvili plotted on the left, moving from left to right for the top 10 fastest forehands.

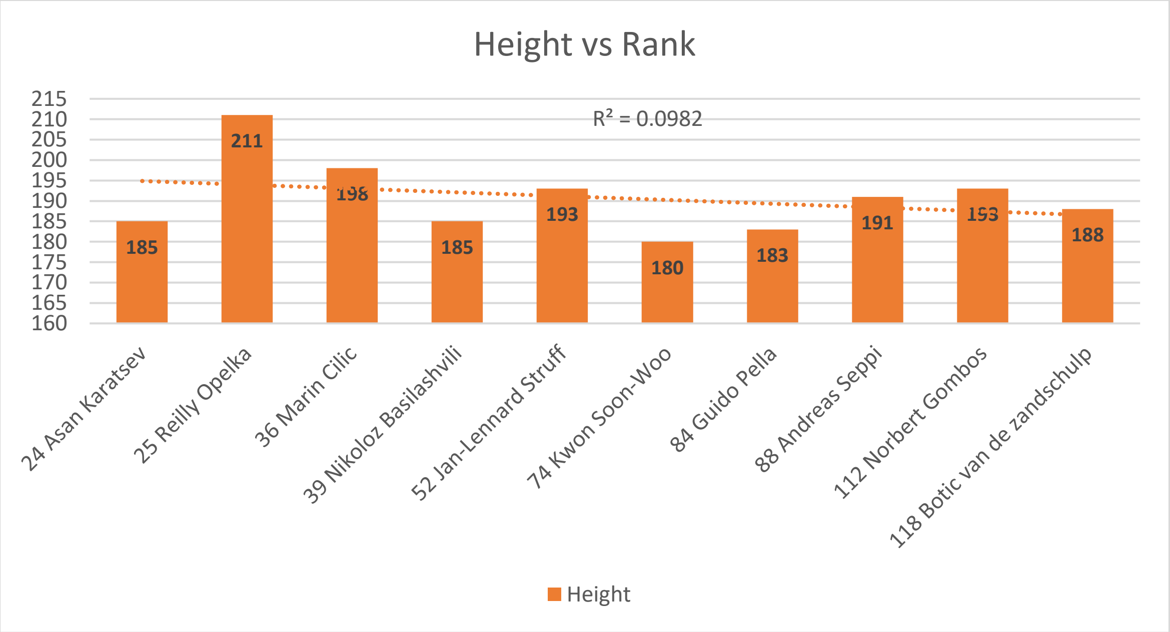


Figure - Fastest Average Forehand Speed Australian Open 2021 (Men)

In the figure above we have presented the data with the highest ranked player Aslan Karatsev plotted on the left, moving from left to right from highest ranked to lowest ranked.

As we can see, there is no relationship between speed, height and ranking. Two things that are notable; firstly, none of the players who hit the fastest average forehand speed were inside the top 20.

Secondly, Kwon Soon-Woo who at 5’11 (1.80m) is the only player under 6 foot (1.83m) to make the list of fastest average forehand hitters at the Australian Open 2021.

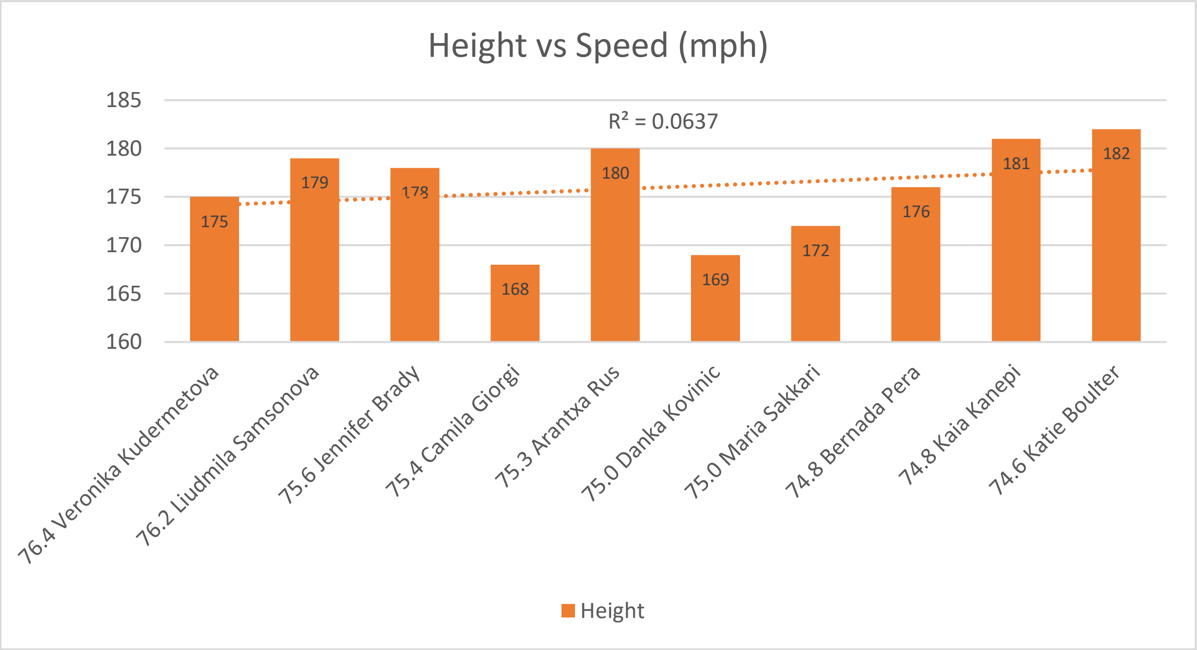


Figure - Fastest Average Forehand Speed Australian Open 2021 (Women)

In the figure above we have presented the data with the fastest hitting player Veronika Kudermetova plotted on the left, moving from left to right for the top 10 fastest forehands

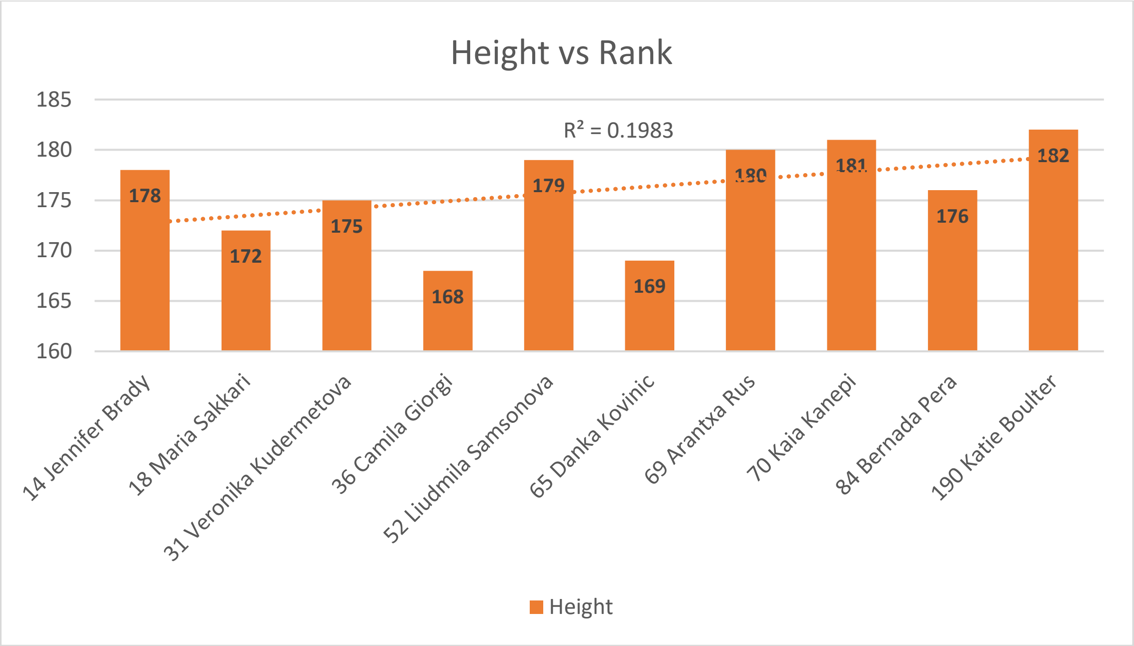


Figure - Fastest Average Forehand Speed Australian Open 2021 (Women)

In the figure above we have presented the data with the highest ranked player Jennifer Brady plotted on the left, moving from left to right from highest ranked to lowest ranked**.**

As we can see, there is no relationship between speed, height and ranking. Two things that are notable; firstly, none of the players who hit the fastest average forehand speed were inside the top 10.

Secondly, only two players under 5”7 foot (1.70m) made the list of fastest average forehand hitters at the Australian Open 2021.

It seems that the velocity that the ball leaves the racket doesn’t tell the whole story. Quality of a shot has to do with many factors: how close it comes to a line, how open the court is, and how much it takes the opponent by surprise. There are other aspects such as “Time pressure’’ measured as the time taken for the ball to travel past the net, which for the best players at applying pressure is around 0.4 seconds for men and women. There is also the matter of average impact location which is how close the baseline you are impacting the ball. A negative value indicates the ball was on average impacted inside the baseline. The best players are impacting the ball within 0.5m of the baseline.

Summary of Anthropometric Factors

- Based on data from 2020 we can see the huge range in body mass of the professional male players from 64kg Yoshihito Nishioka to John Isner at 108kg.
- The average height of the ATP top 100 is 6'1" (1.85m). The average height of the WTA top 100 is 5'7" (1.69m).
- Height is an important matter in tennis. Shorter players generally tend to move better, but taller players can serve faster and hit better angles. While players at the ends of the spectrum will excel in one aspect but fail in another, players with an optimal height (e.g., between 185 – 190 cm for men) can usually excel at both.
- In the men’s game, taller tennis players are finding increasing success and height is playing a stronger role in tennis year after year. The trend is that the higher the ranking goes, the tallest players are.
- There is there is no relationship between ball speed, height and ranking. None of the players who hit the fastest average forehand speed at the Australian Open 2021 were inside the Top 10 (men or women).

Structural Factors

Roetert, P.E et al., (2009). Biomechanics of the Tennis Groundstrokes: Implications for Strength training.

BASED ON THE AVAILABLE RESEARCH, IT WAS DETERMINED THAT TRAINING EXERCISES SHOULD EMULATE THE SEQUENTIAL COORDINATION INVOLVED IN GROUND STROKE PRODUCTION, AS WELL AS STABILIZING MUSCULATURE THAT MIGHT BE INVOLVED IN DEVELOPING FORCE OR IN PROTECTING BODY PARTS FROM STRESSFUL ACTIONS.

-Modern players often hit aggressive high-speed groundstrokes to overpower their opponent.

-This strategy places extra stress on the player's body that strength and conditioning professionals should consider in designing training programs.

- Traditional tennis groundstrokes were hit from a square or closed stance with a long flowing stroke using simultaneous coordination of the body. The modern forehand and even the backhand (particularly the 2-handed backhand) are more often hit from an open stance using sequential coordination of the body.

- It is generally accepted that most of the energy or force used to accelerate a tennis racket is transferred to the arm and racket from the larger muscle groups in the legs and trunk.

- Knudson and Bahamonde reported non-significant differences in racket path and speed at impact between open and square stance forehands of tennis teaching professionals.

- The most common situations where open stance forehands are applied include wide and deep balls when the player is behind the baseline or requires greater leverage to produce the stroke.

- Well coordinated sequential rotations up the kinetic chain through the trunk and upper extremity take advantage of the stretch-shortening cycle of muscle actions.

- The main kinetic chain motions that create racket speed in the forehand are trunk rotation, horizontal shoulder adduction, and internal rotation.

- Following impact in all tennis strokes, the racket and arm retain the vast majority of the kinetic energy from before impact, so the eccentric strength of the musculature active in the follow-through should also be trained. Eccentric strength both in the upper and in the lower body can assist in maximizing tennis performance as well as to aid in the prevention of injuries.

- Particularly, the catching phase of the medicine ball (MB) tosses helps in improving both upper- and lower body eccentric strength.

- Movement to the ball (Fig 1a-c) consists of horizontal linear momentum used to preload the outside leg for a stretch-shortening cycle action to initiate the stroke. Some of the energy stored in this leg is converted to predominantly upward (vertical linear) momentum but also forward (horizontal linear) momentum. This leg drive utilizes ground reaction forces and is critical for linear to angular momentum transfer and the development of high racket speed.

- In Figure 1d–f, we can see the forward swing. The pronounced hip and shoulder rotation from Figure 1c–f is evidence of the use of angular momentum. Energy from the left leg is transferred as the hips open up first, followed by the shoulders. The completion of the swing shows a follow-through in the direction of the target until well after contact is made followed by the racket swinging back over the head as a result of the forceful rotational component of the swing.

- This follow-through, where the racket actually finishes over the head, is an adaptation that many players have implemented, and although the follow-through is initially still toward the target (Figure 1e), the overall pathway of the stroke (Figure 1f) ending up over the shoulder allows the player to impart greater spin on the ball. This adaptation is partially the result of technology changes in the tennis racket and strings allowing for more power and spin generation resulting in more margins for error on the strokes.

One-handed and Two-handed backhand

- Training the wrist extensors is particularly important for tennis players using a 1-handed backhand.

- There are differences in the use of the legs, trunk, and upper extremity between the 1- and 2-handed backhands. One-handed backhands have the hitting shoulder in front of the body and rely less on trunk rotation and more on coordinated shoulder and forearm rotations to create the stroke.

- Front-leg extensor torques are larger in the 1-handed backhand than the 2-handed backhand.

- Two-handed backhands have larger extension torques in the rear leg, which result in larger axial torques to rotate the hips and trunk than 1-handed backhands.

- Greater upper-trunk rotation has been observed in 2-handed backhands than in 1-handed backhands.

- Despite these differences, skilled players can create similar levels of racket speed at impact in 1- and 2-handed backhands.

- In general, there are 2 styles of coordination in 2-handed backhands. One essentially involves straight arms and 4 major kinetic chain elements (hips, trunk, shoulder, and wrist), while the other adds rotations at the elbow joints.

- Whatever the technique adopted, the strength and conditioning professional should work with the tennis coach to customize training programs for the specific techniques used by players.

Exercises:

All designed to produce greater weight transfer, trunk rotation, and more effective stroke production.

- MEDICINE BALL DEEP GROUNDSTROKE (Open stance) - while maintaining dynamic balance produce a forceful hip turn and throw that will mimic the muscle contractions and movements required for a deep defensive forehand stroke.

- MEDICINE BALL SHORT GROUNDSTROKE (open or square)- The purpose was to train the athlete to move forward and in a balanced fashion transfer energy from the lower extremities (open or square stance) to weight transfer and hip/trunk rotation for more effective stroke production.

- MEDICINE BALL WIDE- The purpose was to train the athlete to move sideways and to be able to produce greater energy transfer from an open stance position.

- MEDICINE BALL WALL OPEN STANCE- The purpose was to develop rotational hip and core strength in movement patterns and planes that are most used during tennis strokes.

- CABLE ROTATION IN THE TRANSVERSE PLANE - The purpose was to develop rotational core strength in the transverse plane.

- WRIST ROLLER - The purpose was to increase grip strength and endurance via forearm flexion and extension.

- WEIGHTED FOREARM PRONATION AND SUPINATION - The purpose was to develop forearm strength and endurance in pronation and supination.

Terraza-Rebello et al (2017). Effects of Strength Training on Hitting Speed in Young Players

-20 youth tennis players (15.5+/- 0.9 yrs) randomly divided into 3 groups during 8-week training study with a frequency of 3 days per week

-Group 1 Overload group (SC) performed one additional session with 'overloads' (weights); Group 2 Explosive group (L) performed one additional session with medicine ball and elastic bands; and Group 3 only completed the tennis technical-tactical training.

-Hitting speed is a determining performance factor in modern tennis. In order to increase this speed, strength training should focus on maintaining or improving the levels of USEFUL or APPLIED strength, increasing the power developed in the competitive skill.

Overload method:

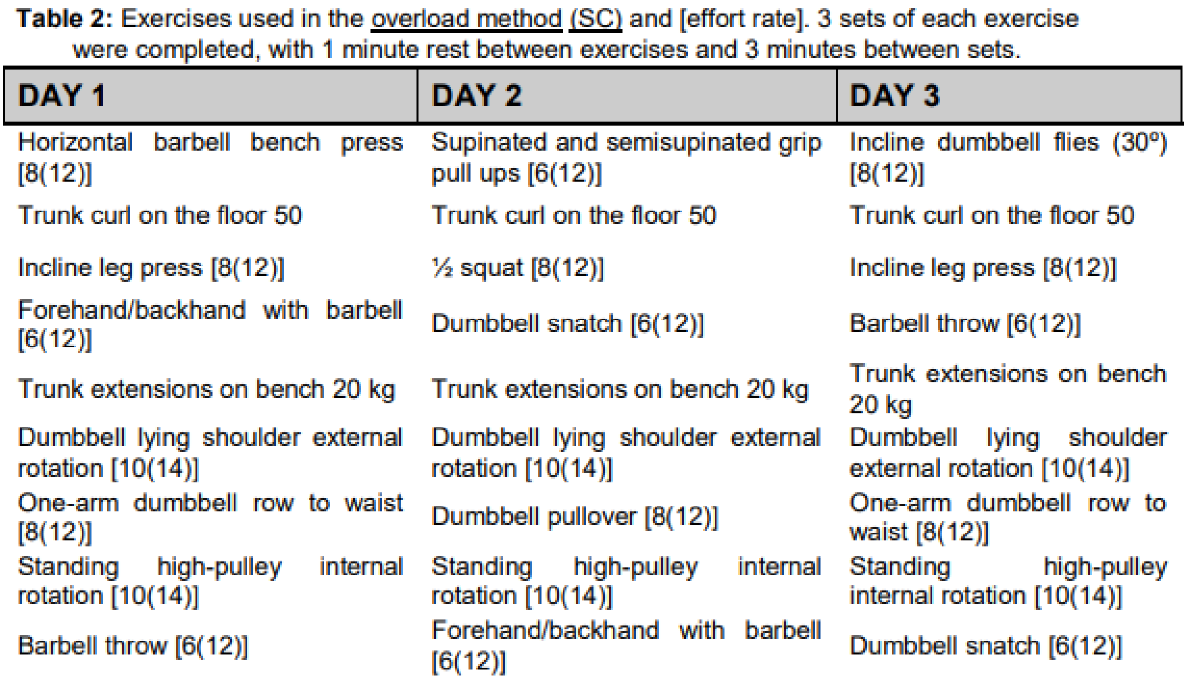


Table 2: Exercises used in the overload method (SC) and [effort rate]. 3 sets of each exercise were completed, with 1 minute rest between exercises and 3 minutes between sets.

DAY 1	DAY 2	DAY 3
Horizontal barbell bench press [8(12)]	Supinated and semisupinated grip pull ups [6(12)]	Incline dumbbell flies (30º) [8(12)]
Trunk curl on the floor 50	Trunk curl on the floor 50	Trunk curl on the floor 50
Incline leg press [8(12)]	½ squat [8(12)]	Incline leg press [8(12)]
Forehand/backhand with barbell [6(12)]	Dumbbell snatch [6(12)]	Barbell throw [6(12)]
Trunk extensions on bench 20 kg	Trunk extensions on bench 20 kg	Trunk extensions on bench 20 kg
Dumbbell lying shoulder external rotation [10(14)]	Dumbbell lying shoulder external rotation [10(14)]	Dumbbell lying shoulder external rotation [10(14)]
One-arm dumbbell row to waist [8(12)]	Dumbbell pullover [8(12)]	One-arm dumbbell row to waist [8(12)]
Standing high-pulley internal rotation [10(14)]	Standing high-pulley internal rotation [10(14)]	Standing high-pulley internal rotation [10(14)]
Barbell throw [6(12)]	Forehand/backhand with barbell [6(12)]	Dumbbell snatch [6(12)]

Explosive Method:

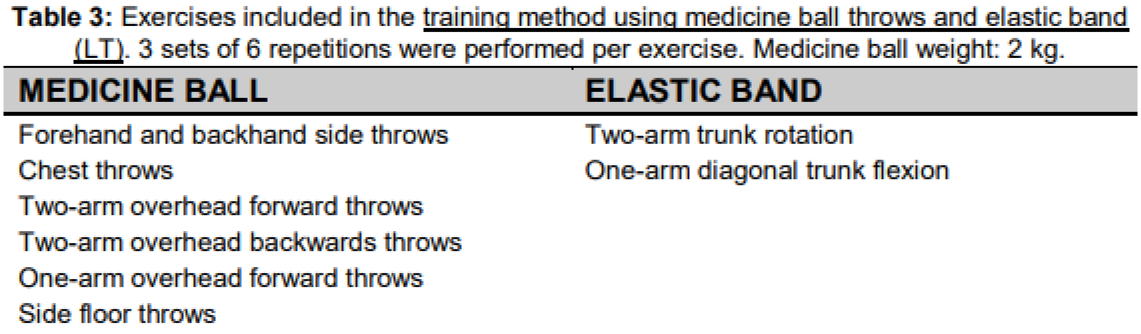


Table 3: Exercises included in the training method using medicine ball throws and elastic band (LT). 3 sets of 6 repetitions were performed per exercise. Medicine ball weight: 2 kg.

MEDICINE BALL	ELASTIC BAND
Forehand and backhand side throws	Two-arm trunk rotation
Chest throws	One-arm diagonal trunk flexion
Two-arm overhead forward throws	
Two-arm overhead backwards throws	
One-arm overhead forward throws	
Side floor throws	

-The hitting assessment consisted of assessing speed of:

- 12 flat serves (6 on each court side)

- 12 backhands (6 parallel and 6 cross court)

- 12 forehands (6 parallel and 6 cross court)

- 3 two-arm overhead throws with a 2-kg medicine ball

- 3 single-arm throws

-Significant correlations were observed among most of the studied speed variables although the correlations between the one-arm medicine ball throwing speed, and both forehand and backhand stroke speeds were not as high.

-There was no significant correlation between the two-arm overhead ball throwing speed and backhand stroke speed.

-In forehand hitting speed significant differences were only observed in the explosive group between pre- and post-test (-6.29km/h).

-Daz comment [there was an insignificant *trend* for forehand hitting speed to increase in the overload group between pre- and post-test (2.43km/h) and the control group (3.5km/h)].

-No significant differences were found in backhand hitting speed among groups. Daz comment [there was an insignificant *trend* for backhand hitting speed to increase in the overload group between pre- and post-test (2.15km/h) and to decrease in explosive group (-3.43km/h)].

-Explosive group: significant differences were identified in the mean serve hitting speed between pre- and post-test (2.16km/h)

-Overload group: significant differences were identified in the mean serve hitting speed between pre- and post-test (6km/h) and between the inter- and post-test (4.86km/h)

-Explosive group: Two-arm medicine ball throwing speed showed significant differences between pre- and inter-test (2.86km/h) and pre- and post-test (2.71km/h).

-Overload group: Two-arm medicine ball throwing speed showed significant differences between pre- and inter-test (1.34km/h) and pre- and post-test (1.55km/h).

- Explosive group: One-arm medicine ball throwing speed showed significant differences between pre- and post-test (1.71km/h).

- Overload group: Two-arm medicine ball throwing speed showed significant differences between pre-and post-test (3.00km/h) and inter- and post-test (1.86km/h).

-The lack of improvement in strength levels observed in the control group in one- and two-arm medicine ball tests suggests that neither the on court technical-tactical training nor the natural development of the player in this age range had an influence on the strength increase measured in the tests performed. This means the differences in performance were caused by the intervention protocol.

-The serve speed experienced the greatest improvement, the biggest increase being detected in the overload group. In this study the improvement in medicine ball throwing speed did not imply an increase in forehand hitting speed.

-In summary, the present study shows that an eight-week training programme with overloads, medicine balls and elastic bands has positive effects on serve speed, as well as one- and two-arm medicine ball throwing capacity.

Genevois et al (2012). Effects of Two Training Protocols on the Forehand Drive Performance in Tennis

-The aim of this study was to examine the effects of two training modalities on the tennis forehand drive performance. Forty-four tennis players (age = 26.9 ± 7.5 years; height = 178.6 ± 6.7 cm; mass = 72.5 ± 8.0 kg; International Tennis Number = 3) were randomly assigned into three groups.

During six weeks, the first group (HMB) performed <u>handled-medicine-ball throws</u> included in the regular tennis practice, the second group (OWR) played tennis forehand drives with <u>overweighed racket</u> during the regular tennis practice; and the third group (RTT) practiced <u>only tennis</u> training as usual. Before and after the 6-weeks program, velocity and accuracy of tennis crosscourt forehand drives were evaluated in the three groups. The main results showed that after 6-weeks training, the maximal ball velocity was significantly increased in HMB and OWR groups in comparison with RTT ($p < 0.001$ and $p = 0.\ 001$, respectively).

-The estimated averaged increase in ball velocity was greater in HMB than in OWR (11% vs 5%, respectively; $p = 0.017$), but shot accuracy tended to be deteriorated in HMB when compared to OWR and RTT ($p=0.043$ and $p=0.027$, respectively).

-The findings of the present study highlighted the efficiency of both training modalities to improve tennis forehand drive performance, but also suggested that the handled medicine ball throws may be incorporated into the preseason program preferably, while the overweight racket forehand drives may be included in the in-season program.

Chalakov (2014). Study of the Ball Speed During Forehand and Backhand Hit in Tennis Training of 12-Year-Old Players.

- Top players achieve average ball speeds of about 130 km/h (80mph). The highest speed measured so far is 199 km/h (124 mph) reached by Andy Murray in 2011 of the Us Open (Willis, 2011).

- Mean rates of the individuals achieved in our study varied between 85 to 110 km/h (53 to 68 mph) and were found to be relatively good for their age.

- Average growth rate for boys between the first and the second study are not very big - from 7 to 12 km/h (one year later).

- The total growth of the boy's performing forehand was 12 km/h. The backhand stroke had a total increase of 7 km/h and is significantly different from the forehand. The subjects who achieved good results in forehand, show moderate and low growth in backhand.

- In girls performing forehand, the total average increase is 10 km/h, and performing backhand there was average growth of group 7 km/h.

Baiget, E. (2011). Strength training for improving hitting speed in tennis. [translated from Spanish]

-Hitting the ball at high speeds is a determining factor for modern tennis performance. Changes in the modern game have resulted in the use of powerful serves and groundstrokes.

-The objective of this study is to review the basic criteria for doing strength training correctly aimed at improving hitting speed of the ball.

-The literature seems to point towards adequate maximum dynamic force (FDM) exerting positive effects on the increase of hitting speed in tennis.

-Useful strength workouts should use means that permit the execution of technique, involving the same muscle chains, range of movement or execution speeds. In this sense, one has proposed the utilization of medicine balls, light dumbbells, elastic bands, multifunctional pneumatic resistance machines, or pulleys.

-A tennis player hits an average of 2.5-3 shots per exchange, depending on your style of play, type of ball, surface, gender or strategy.

-In professional men's tennis one has observed a hitting frequency of 44 +/- 0.6 strokes per minute. This requires a high display of explosive strength both in the upper limbs to accelerate the racket, as well as in the lower body to transmit the final force to the arms by means of the kinetic chain.

-In striking actions, there is mainly a reactive manifestation of force, but also there is a static manifestation at the level of the arm dominant in the grip of the racket. The needs for FDM are low, being important is the ability to apply force to light resistance (racket and ball). The ball weighs between 56.0-56.4g and the racket currently ranges from 250-350g.

-Most technical executions are performed with a previous stretching phase being determinant of the manifestation of explosive elastic force. On the other hand, we must consider that game actions (groundstrokes) are performed an average of 270 times during a match, between 300 and 500 if it is the best of 5 sets.

-FDM is the maximum force that the neuromuscular system can perform with voluntary contraction within the motor sequence. However, it's not always the one that manifests the most force with a high load, it's the one that manifests the most force with a relatively light load. In this sense, it is questionable if greater forces produce in a natural way, an increased acceleration of the racket.

-However, the scientific literature seems to point to some adequate levels of FDM having positive effects on the increase of hitting speed of tennis strokes, although this relationship is not concordant; that is to say that similar increases in FDM do not have to correspond to similar increases in useful force.

-Moderate correlations between FDM and service speed suggest that strength is not the only factor involved in speed production in the serve.

-For comparison, the maximum force for a bench press is reached around 400ms, while the movement forward of the racket with a forehand lasts a little over 120ms. In this sense, although training at these high intensities normally mean that the contractions are performed at low or moderate speed, it is argued the intention to act quickly, rather than actual speed achieved in the movement, is crucial for the development of elevated rates of power.

-In explosive sports like tennis, FDM training can positively influence power output by reducing the relative resistance of loads, increasing muscle size and type II muscle fibres, and by activating motor units.

-Some authors point out the drawbacks of development of FDM aimed at increasing muscle hypertrophy so FDM should be done without excessive repetitions per set so as not to stimulate hypertrophy. It should focus on nerve activation, optimal synchronization of motor units and the joint activation of different muscle groups improving the intra and intermuscular coordination.

-In a study by Sarabia et al (2010) with junior tennis players, it was found that doing overload training grounded on the principle of maintaining speed within limits optimal for the individual (in the range of 90% of the maximum power development) produced improvements in the kinetic chain both in the upper and lower body.

-Because in tennis FDM needs are medium or low, it is not necessary to develop it by maximum percentages of a repetition maximum (1RM). Depending on the level and experience of the player it has been proposed to use loads between 50-80%, 70-85% or 65-85% of 1RM.

-The ultimate goal of strength training is to improve your hitting speed in tennis to improve the useful force or specific expression of explosive force, and therefore improve the ability to apply more force in the time that the action lasts in the concentric acceleration of the racket towards the ball.

-Orientation of training towards useful strength in tennis can be combined with FDM or maximum power training. Various authors propose the combination of useful strength exercises with exercises with high and/or medium loads looking for a transfer to a specific movement.

-A combination going from exercises with higher (not maximal) loads performed at slower speeds, with exercises with light loads or no loads affecting the specific speed and useful force, where in both cases the execution speed is the maximum possible.

-For example, simultaneous maximum strength training with ‘fast force’ exercises using clean and power snatches (medium-low weights), going later to training specific and competition like exercises with very light loads.

-Within such a structure one might expect to provoke a synergistically higher effect than you would get from training each of the exercises separately. Another example could include:

- Bench press
- Medicine ball throw from bench press position
- Lateral medicine ball throws with a lower weight (simulating groundstroke)

- Forehand stroke with racket at full speed execution

-It is proposed that exercises are performed common to the structure of specific movement, looking for effects of the strength training and its later transfer to explosive strength and maximum power under medium and light loads. This may include the pairing of strength exercises with exercises of mechanically comparable speeds such as medicine ball throws with racket strokes.

-**Training Means**: sports such as tennis rely heavily on proprioception and stability during movement, therefore it is recommended that the exercises be free and dynamic in order to develop and increase balance, while working on strength and speed.

-Since technical actions of hitting in tennis (groundstrokes) starts with the legs, it is advisable to perform closed chain exercises (those that the subject keeps their feet on the ground) instead of open chain exercises (usually done on machines).

-Along these lines, learning exercises of intermuscular coordination (e.g., Olympic lifting movements) can help the player to achieve a greater force transfer between the lower body and upper body.

-Regarding the means used for useful strength training, different authors highlight the great utility of training through medicine balls. In tennis it is vitally important to create the maximum angular speed of the implement for hitting the ball efficiently. The use of medicine balls allows the execution of a complex and sport-specific movement with greater resistance to that observed during regular competition.

-Pulleys, plyometrics and medicine ball exercises could all be part of the training because they all incorporate stretch-shortening (SSC) actions, in addition to multifunctional pneumatic resistance machines for power work through specific exercises performed at maximum power (>90% of maximum voluntary effort), ensuring a precise and efficient movement performed at maximum speed.

-Within the methods utilised for the training of useful force in tennis, one can differentiate between those that use equal, higher or lower resistance than that used in competition itself.

- EQUAL: racket shadowing/hitting- hitting the ball with maximum speed of execution

- HIGHER: shadowing with a weighted racket (without hitting), light dumbbells, elastic bands, medicine balls, multifunctional pneumatic resistance machines, or pulleys (versapulley).
- LOWER: shadowing with a lighter racket (without hitting).

- There may also be a place for mechanical vibration training when it is correctly planned, as it improves muscle pre-activation and hitting performance. Also inclusion of proprioceptive training exercises, work with dynamic tasks like hitting and jumping, as well as whole body vibration training using ones own body weight and with additional weight.

-Eccentric means of training both of the upper and lower body may contribute to maximising the performance of the groundstroke, as well as assist injury prevention. This means of training takes on a more and more important role in tennis. The isoinertial resistance machine uses the inertia of the flywheel to provide resistance, and allows specific hitting actions to be performed in an eccentric action.

-On the other hand, there are some means used to a greater extent for the prevention of injuries, such as unstable surface training, rubber bands, or low weight balls, but they can also contribute to the improvement of hitting speed. Exercises that lead to an increased stabilisation of force and an Improvement in body alignment, will help the player to create effective and powerful movement patters. This will also help stability through the trunk which will help the player optimise and coordinate linear momentum, but more specifically, angular momentum during realisation of the strokes.

-Rubber bands or low weight balls are commonly used means to perform complimentary preventative exercises. The repetitive stress and load creates sport-specific imbalances that require preventative interventions, considered useful to reduce the risk of injury. This is of primary importance for the rotators of the shoulder where groundstrokes require strong concentric internal rotation to generate power and this causes a muscular imbalance. Strong external rotators are necessary not only to adequately stabilise the shoulder joints, but must also eccentrically contract to decelerate the arm after a serve or forehand, and therefore both are prone to injury.

-**Planning of Training**: There is very little evidence regarding which is the best structuring model of the tennis training. In a generic way, the training of force acquires greater relevance in periods away from competition. However, it is very important to maintain adequate levels during the long competition period maintaining stimuli throughout the season, especially rapid force.

-For the development of a complete cycle of strength, four phases have been proposed, each typically lasting 3-6 weeks. However, considering that a professional player realises on average 60-80 matches yearly, and that the competitive period lasts some 11 months of the year, it would only be possible to realise one complete cycle, the duration of this in the majority of cases, less than that proposed by the authors.

- Phase 1: (3-6 weeks) 3 sets x 8-12 reps (75% 1RM)
- Phase 2: (3-4 weeks) 3-4 sets x 6-10 reps (60-85% 1RM)
- Phase 3: (3-4 weeks) 2-5 sets of 4-8 reps (65-85% 1RM)
- Phase 4: (3-4 weeks) 2-4 sets of 3-6 reps (70-95% 1RM) and 30-50% 1RM

-The proportion of FDM is higher during the first two or three phases and will reduce as the tennis player approaches competitions. At the same time, explosive strength training with light loads and high speed of execution and the use of specific exercises will increase, intending to maintain some optimum levels of FDM. Along these lines, one should try to monitor the evolution of FDM throughout the season, so that when one approaches competition the only thing that will be necessary is to improve the capacity to apply force to lighter loads and achieve higher force values.

Rivilla-Garcia et al (2011). Relation between general throwing tests with a medicine ball and specific test to evaluate throwing velocity with and without opposition in handball.

-Ninety-four handball players of different competitive levels, age groups and playing positions were tested in four throws of progressive specificity.

a) throwing distance with a heavy medicine ball (THMB) – 3kg overhead throw with two hands

b) throwing distance with a light medicine ball (TLMB) – 0.8kg overarm throw with one hand

c) throwing velocity (VS) – 0.45kg handball throwing at the goal from at least 9 metres

d) throwing velocity with opponent (VO) – opponent is in goal

-The data indicated not very high correlations between the THMB and the other tests, especially with the VO. Correlation values for TLMB-VS were very high in general (r=0.904) and in all groups.

-By contrast, the correlation between the throwing tests (VS-VO) was not high (r=0.594-0.632). The difference in velocity attained in both types of throws (VS 23.58 +/- 2.64 m/s versus VO 22.05 +/- 2.55 m/s) in spite of involving the same performance technique, showed the direct influence exerted by the opposition of the goalkeeper on the velocity reached by the player.

-The authors concluded that the general test has limited utility for assessing specific throwing capacity; that the TLMB adequately predicts VS; and that opposition has a significant influence on specific throwing speed.

Talukdar et al (2015). The Role of Rotational Mobility and Power on Throwing Velocity

-The ability of players to consistently throw at high velocity, with accuracy, is considered to be a challenging task that can influence the outcome of a game. Improved force output and rate of force development in the appropriate muscles can result in increased velocity.

-The ability to rapidly produce force in the transverse plane can be considered important in a rotational reliant sport such as cricket. Sports that involve throwing motions can be considered rotational power sports because of the requirements of explosive movements in either the transverse or oblique planes.

-Eleven professional cricketers and ten under-19 club-level cricketers performed the following:

- cable chop and lift (half kneeling)- 15% bodyweight for chop and 12% for lift with metal bar
- seated and standing cricket ball throw (0.163kg)
- seated and standing side medicine ball throw- 2kg
- seated active thoracic range of motion (ROM) and hip rotation ROM

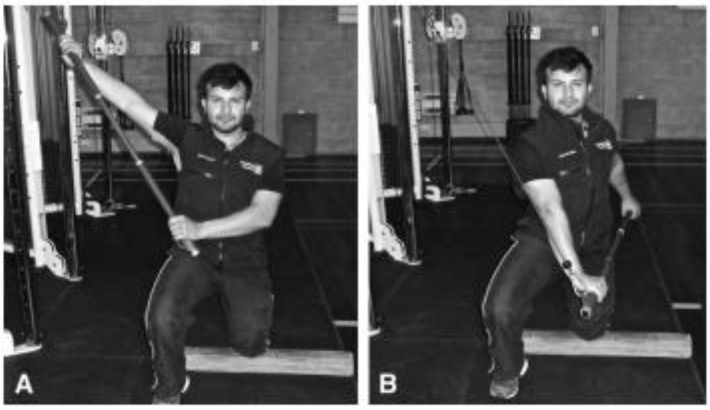


Figure 1. A) Chop start. B) Chop finish.

Figure 2. A) Lift start. B) Lift finish.

Figure 3. A) Side medicine ball start. B) Side medicine ball finish.

Figure 4. A) Hip internal rotation. B) Hip external rotation.

Figure 5. A) Thoracic rotation start. B) Thoracic rotation finish.

-Using a dowel resting across the chest thoracic mobility was measured using a goniometer. Similarly, a seated hip rotational assessment was conducted on a box with an inclinometer.

-Participants were divided into two groups (fast and slow) based on their standing cricket-ball throwing velocity.

-The seated and standing cricket ball throw on the dominant side was significantly different between fast and slow throwers (11.03 and 10.7 km/h, respectively).

-The standing side medicine ball throwing velocities (38.3 and 39.6 km/h) and the seated (33.0 and 31.6km/h) medicine ball throws were not significantly different between fast and slow throwers.

-Muscular performance measures such as bilateral thoracic rotation ROM, hip external ROM on the dominant side, and force and work required in the chop, were significantly different between fast and slow throwers.

-Faster throwers in this study displayed greater force (18.4%) and work (31.2%) outputs in the chop compared with the slower throwers; however, slower throwers showed significantly greater ROM in the thoracic (13.4-16.8%) and hip region (11.8%).

-It was concluded that greater ROM at proximal segments, such as hips and thoracic, may NOT increase throwing velocity in cricket as reduced ROM at proximal segments can be useful in transferring the momentum from the lower extremity in an explosive task such as throwing.

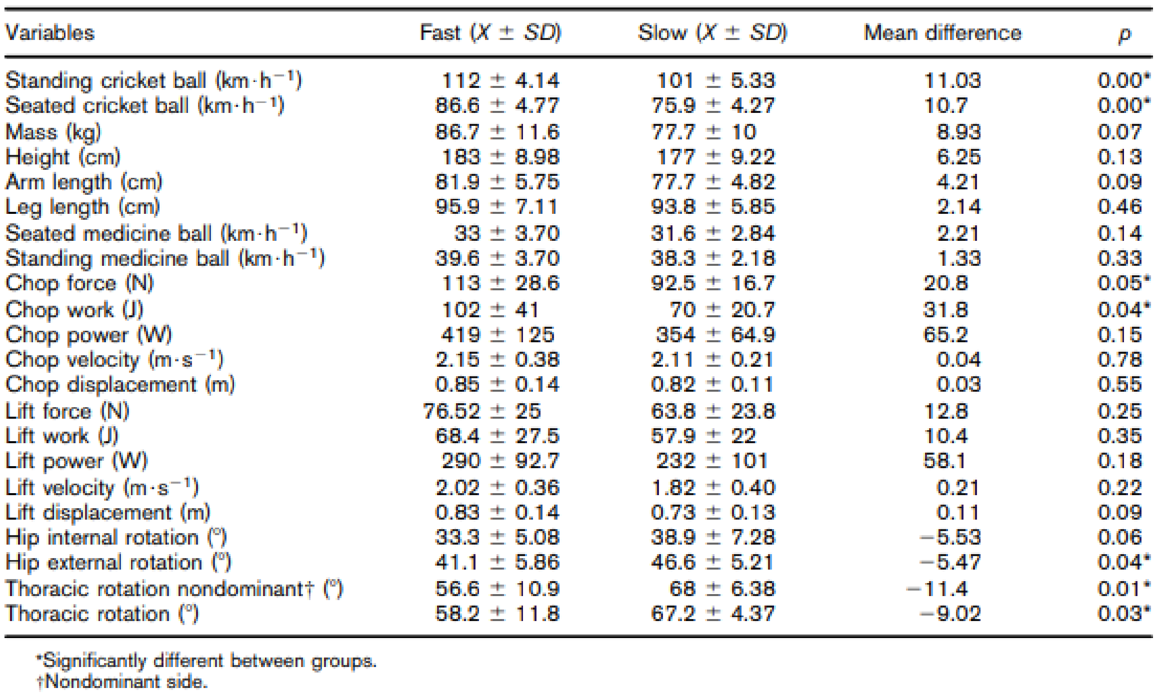


Table 1. Comparison of fast and slow throwers.

Variables	Fast (*X* ± *SD*)	Slow (*X* ± *SD*)	Mean difference	*p*
Standing cricket ball (km·h^{-1})	112 ± 4.14	101 ± 5.33	11.03	0.00*
Seated cricket ball (km·h^{-1})	86.6 ± 4.77	75.9 ± 4.27	10.7	0.00*
Mass (kg)	86.7 ± 11.6	77.7 ± 10	8.93	0.07
Height (cm)	183 ± 8.98	177 ± 9.22	6.25	0.13
Arm length (cm)	81.9 ± 5.75	77.7 ± 4.82	4.21	0.09
Leg length (cm)	95.9 ± 7.11	93.8 ± 5.85	2.14	0.46
Seated medicine ball (km·h^{-1})	33 ± 3.70	31.6 ± 2.84	2.21	0.14
Standing medicine ball (km·h^{-1})	39.6 ± 3.70	38.3 ± 2.18	1.33	0.33
Chop force (N)	113 ± 28.6	92.5 ± 16.7	20.8	0.05*
Chop work (J)	102 ± 41	70 ± 20.7	31.8	0.04*
Chop power (W)	419 ± 125	354 ± 64.9	65.2	0.15
Chop velocity (m·s^{-1})	2.15 ± 0.38	2.11 ± 0.21	0.04	0.78
Chop displacement (m)	0.85 ± 0.14	0.82 ± 0.11	0.03	0.55
Lift force (N)	76.52 ± 25	63.8 ± 23.8	12.8	0.25
Lift work (J)	68.4 ± 27.5	57.9 ± 22	10.4	0.35
Lift power (W)	290 ± 92.7	232 ± 101	58.1	0.18
Lift velocity (m·s^{-1})	2.02 ± 0.36	1.82 ± 0.40	0.21	0.22
Lift displacement (m)	0.83 ± 0.14	0.73 ± 0.13	0.11	0.09
Hip internal rotation (°)	33.3 ± 5.08	38.9 ± 7.28	−5.53	0.06
Hip external rotation (°)	41.1 ± 5.86	46.6 ± 5.21	−5.47	0.04*
Thoracic rotation nondominant† (°)	56.6 ± 10.9	68 ± 6.38	−11.4	0.01*
Thoracic rotation (°)	58.2 ± 11.8	67.2 ± 4.37	−9.02	0.03*

*Significantly different between groups.
†Nondominant side.

Special Focus on Core Stability and Core Strength from the Zemkova Research Group

Zemkova & Jelen (2013). Mean Velocity of Trunk Rotation Discriminates Athletes with Different Sport Related Demands

-Objective: The majority of core field tests assess muscular endurance. These tests are performed exclusively isometrically to task failure. Contrary to this, in the laboratory isometric and isokinetic dynamometers are used to assess core strength. However, these tests are not specific to the demands imposed by most sports. In addition, the external validity of these tests to sport-specific tasks is ambiguous.

-To avoid these drawbacks, one should evaluate the power and/or velocity of trunk movement in functional positions. However, it is unknown whether such testing distinguishes athletes with different demands on trunk rotation velocities. Therefore, the study compares mean velocity in acceleration phase of trunk rotation in athletes of different sports.

-Materials / Methods: Altogether 92 athletes (age 23.4 ± 4.1 years, height 178.1 ± 8.4 cm, weight 85.6 ± 15.7 kg) of different sports, i.e., karate, ice-hockey, tennis, golf, ballroom dancing, rock & roll dancing, judo, wrestling, canoeing, rowing, weightlifting, and bodybuilding performed 5 rotations of the trunk to each side in a seated position with barbell of 1 kg and 20 kg placed on the shoulders. The system FiTRO Torso Dynamometer was used to monitor basic biomechanical parameters involved in exercise. In this study, mean velocity in acceleration phase of trunk rotation was analysed.

-Results: Mean velocity in acceleration phase of trunk rotation with weight of 1 kg was significantly higher in tennis players than in golfers (422.4 ± 34.1 °/s and 368.1 ± 32.3 °/s, F = 7.196, p = 0.024, η2 = 0.392). However, its values did not differ significantly between these groups when weight of 20 kg was used (162.7 ± 20.1 °/s and 157.4 ± 19.8 °/s, p = 0.454). Significantly higher mean velocity in acceleration phase of trunk rotation in rock & roll dancers than in ballroom dancers was found with weight of 1 kg (501.3 ± 41.5 °/s and 321.0 ± 27.9 °/s, F = 18.916, p = 0.002, η2 = 0.624), as well as 20 kg (189.1 ± 24.5 °/s and 141.0 ± 17.5 °/s, F = 9.864, p = 0.009, η2 = 0.481).

-On the other hand, there were no significant differences in mean velocity in acceleration phase of trunk rotation between judoists and wrestlers with weight of 1 kg (466.5 ± 39.6 °/s and 455.9 ± 37.5°/s, p = 0.332) and 20 kg (184.3 ± 23.8 °/s and 179.0 ± 22.0 °/s, p = 0.457). Also, individual differences between athletes in mean velocity in acceleration phase of trunk rotation with weight of 1 kg and 20 kg were found, i.e. higher values in ice-hockey player than in karate competitor (7.8 % and 13.1 %, respectively), in canoeist than in rower (17.0 % and 26.7 %, respectively), and in weightlifter than in bodybuilder (21.7 % and 36.5 %, respectively).

-Conclusion: Mean velocity in acceleration phase of trunk rotation is a sensitive parameter able to identify group and individual differences. These differences may be attributed to specificity of training involving trunk movements of different velocities under different load conditions.

Zemkova et al (2015). Between-side differences in rotational power of trunk muscles in golfers and tennis players.

-Introduction / Aim: The asymmetric loading of trunk muscles in sports like golf or tennis may cause side-to-side imbalances in rotational muscle strength and endurance. Such imbalances may be compounded by the presence of low back pain (LBP) and related injuries. They comprise 15 to 34% of all golf injuries and 5 to 25% of all tennis injuries. Yet only few indicators of back pain were identified. For instance, golfers with LBP demonstrate significantly less endurance in the non-dominant direction (the follow-through of the golf swing) than the healthy group. If the left and right-side scores in the time which the subject can hold the side-lying position differ more than 5%, dysfunction exists. Conversely, maximal isometric strength and peak torque have shown no significant differences. Here we tested whether side-to-side differences exist in rotational power of trunk muscles in golfers and tennis players when compared to healthy fit controls.

-Materials and Methods: Groups of 19 golfers (age 23.5±3.4 years, height 177.8±7.1 cm, weight 84.6±9.9 kg), 22 tennis players (age 22.6±2.4 years, height 180.0±6.5 cm, weight 83.1±8.7 kg), and 42 control fit individuals (age 21.9±1.9 years, height 178.9±4.9 cm, weight 81.5±7.9 kg) performed 5 rotations of the trunk to each side in a seated position with a barbell of 20 kg placed on the shoulders. Basic biomechanical parameters involved in exercise were monitored using the FiTRO Torso Dynamometer.

-Results: Mean power in the acceleration phase of trunk rotation was significantly higher in the dominant than non-dominant side in golfers (156.4±26.3 vs. 137.8±23.6 W, p=0.036) as well as in tennis players (224.6±31.9 vs. 203.5±27.8 W, p=0.044). However, its values did not differ significantly between sides in their fit counterparts (126.5±21.9 vs. 118.6±17.7 W, p=0.127).

-Conclusion: Taking into account no significant side-to-side differences in muscle power in control fit individuals (6.2%) and its higher values in the dominant than non-dominant side in tennis players (9.4%) and golfers (11.9%), this parameter may be considered specific to asymmetric loading of trunk rotation. Presumably, this parameter might identify likelihood of LBP.

Zemkova et al (2018). Between-side differences in trunk rotational power in athletes trained in asymmetric sports

Background: The asymmetric loading of trunk muscles in sports like golf or tennis may cause side-to-side imbalances in rotational muscle strength and endurance. Such imbalances may be compounded by the presence of low back pain (LBP) and related injuries. However, trunk rotational power is a better predictor of athlete performance, and therefore its ability to reveal these asymmetries/dysbalances should be investigated.

-Objective: This study compares peak and mean values of power during trunk rotations on the dominant and non-dominant side in golfers, ice-hockey players, tennis players, and an age-matched control group of fit individuals.

-Methods: Groups of 17 golfers, 17 ice-hockey players, 21 tennis players, and 39 fit individuals performed standing trunk rotations to each side with a bar weight of 5.5, 10.5, 15.5, and 20 kg placed on the shoulders. Peak power and mean power in the acceleration phase of trunk rotations were measured using the FiTRO Torso Premium system.

-Results: Peak power and mean power in the acceleration phase of trunk rotations were significantly higher on the dominant (D) than non-dominant (ND) side at weights of 5.5 kg (14 and 14%), 10.5 kg (17 and 14%), 15.5 kg (16 and 15%), and 20 kg (16 and 16%) in ice-hockey players, at 5.5 kg (14 and 13%), 10.5 kg (17 and 14%), and 15.5 kg (15% - only peak power) in tennis players, and at 5.5 kg (17 and 18%) and 10.5 kg (19 and 17%) in golfers. However, their values did not differ significantly at these weights (< 10%) in the age-matched control group. The D/ND ratio was the highest in ice-hockey players (1.18, 1.19), followed by golfers (1.16, 1.17) and finally tennis players (1.12, 1.16).

-Conclusion: Taking into account significantly higher trunk rotational power on the dominant than the non-dominant side in golfers, tennis players and ice-hockey players at lower and/or higher weights and no significant side-to-side differences in a control group of fit individuals, this parameter may be considered specific to their asymmetric loading during trunk rotations. However, whether these asymmetries/dysbalances expressed by the D/ND ratio could also identify the likelihood of LBP, needs to be proven.

Zemkova et al (2017). A Novel Methods For Assessing Muscle Power During The Standing Cable Wood Chop Exercise.

-Most current field tests evaluate the endurance (trunk flexor and extensor endurance tests and lateral bridge test) rather than strength and power components of trunk muscles.

-Poor trunk endurance (and aberrant flexor/extensor ratios) correlate with lower back pain. However, rotational power is a better predictor of sport performance, and the strength and power components of trunk muscles may better mimic the demands imposed by sports.

-Core strength does have a significant effect on the athlete's ability to create and transfer forces to the extremities. It is obvious that the effective execution of the tennis stroke or golf swing not only requires rapid movement of the extremities but also substantial rotational power and/or velocity of the trunk muscles.

-Power increases from lower weights, reaches a peak, and then towards higher weights, decreases again. Such an optimal ''velocity'', that is, the one allowing the production of the greatest power, depends on the ratio of fast and slow twitch muscle fibres; thus it may be hardly changed with training. However, the optimal ''weight'' at which maximal power is achieved increases significantly after training.

-A group of 23 fit men performed:

a) maximal effort single repetitions of the standing cable wood chop exercises with weights increasing up to 1RM (to test maximal power).

b) a set of 20 repetitions at a previously established weight at which maximal power was achieved (to test endurance).

Mean power was analysed in all tests, so when they refer to maximal power they are referring to the maximal or highest value of mean power measured. 'Fit men' so not sport specialists.

Figure 1. Measurement of strength parameters during the standing cable wood chop exercise on a weight stack machine (A and B) using the FiTRO Dyne Premium system (C).

-Subjects were asked to grasp the handle with both hands. They rotated their body from the right (or the left) towards the opposite side until their hands reached the end position in front of their body. They were asked to keep their elbow close to their body. They were asked to perform repetitions with maximal effort in the concentric phase.

-Results showed that mean power during the standing cable wood chop exercise is a reliable parameter, and sensitive to be able to discriminate within-group differences in maximal power and endurance of core muscles.

-There were no significant differences in the mean power between the dominant and dominant sides of rotation with all weights used, or between the two testing sessions.

-The mean power at which 1RM was achieved showed substantial individual differences with 7 athletes at 67% 1RM (327.2+/-49.7 W), 11 at 75% 1RM (462.2+/- 57.4 W) and 5 at 83% 1RM (524.0 +/- 63.2 W). This corresponded to 40, 45 and 50kg, respectively.

-At these weights, there were also significant differences in mean power between the initial and final repetitions of the wood chop exercises (13.9%,10.2% and 13.8%, respectively).

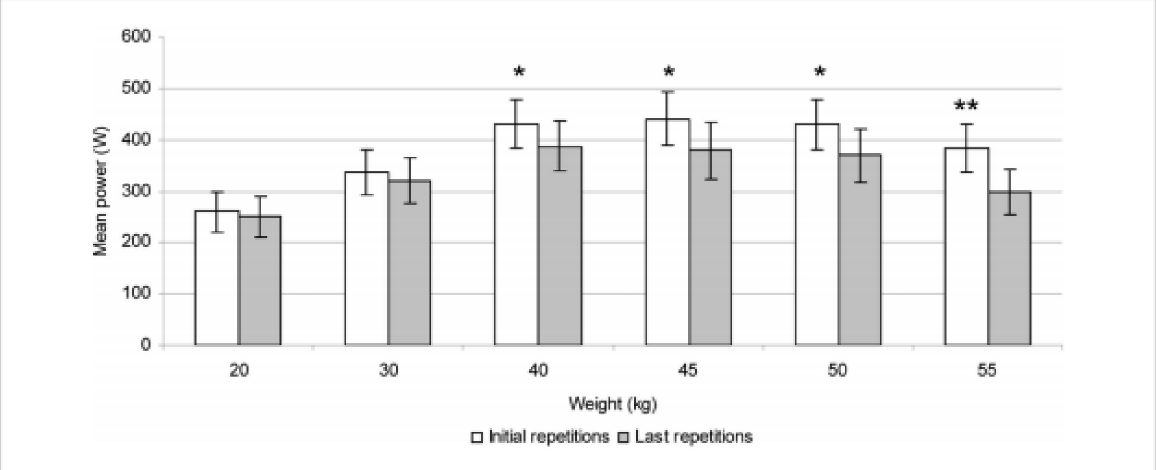


Figure 4. Maximal and minimal values of mean power during the standing cable wood chop exercise performed in a set of 20 repetitions with different weights.

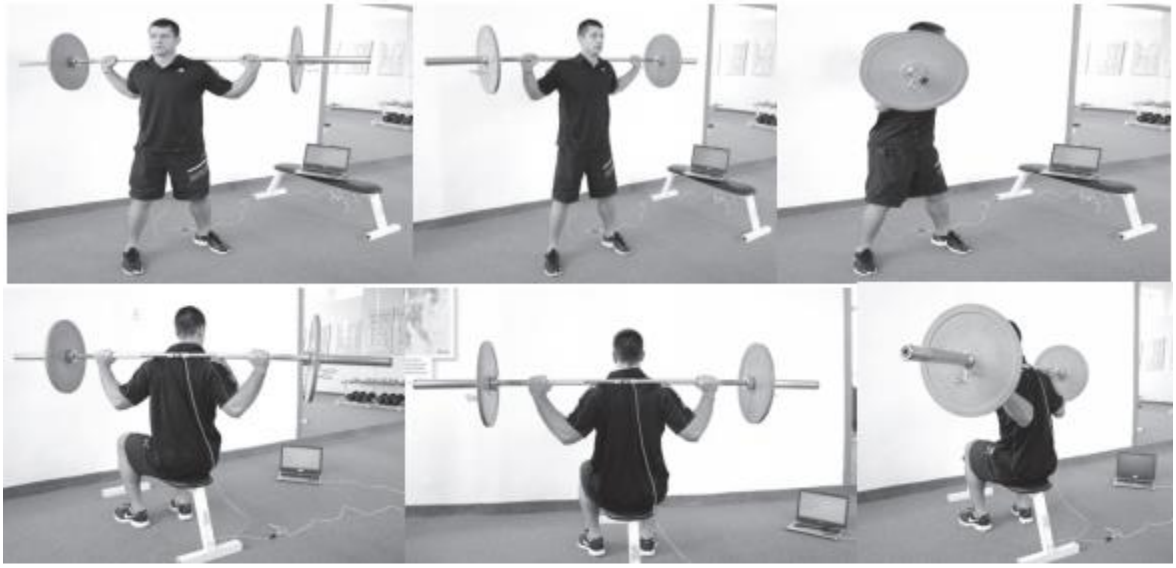
-When a weight of 50kg or more was used most athletes were not able to complete the entire set of 20 repetitions. Furthermore, when the weight was less than 40 kg, it was not able to discriminate between individuals with different levels of trunk endurance. Therefore, the weight at which maximum power was achieved should be thereafter used for the trunk endurance test.

Zemkova et al (2017). Muscle Power during Standing and Seated Trunk Rotations with Different Weights

-A oomputer-based system that can be directly connected to the weights stack machine may be considered to be a suitable and practical alternative for sport-specific and fitness orientated testing of trunk rotational power.

-However, some practitioners prefer free weights in their weight training workout routine. While machines are good for training of muscle strength they neglect key stabilisation components of the core. Using free weights is a way to 'functional' training that places greater demands on stabilising muscles. In addition, exercises with free weights allow performing a full range of trunk motion. Moreover, free-weight exercises are closer to many sports and daily activities.

-A group of 27 fit men completed four trials of trunk rotations in both standing and seated positions with a bar weight of 5.5, 10.5, 15.5 and 20kg placed on the shoulders.



-The FiTRO Torso Premium was used to monitor basic biomechanical parameters throughout the movement.

-Results showed significantly higher peak power during standing than seated trunk rotations at weights of 20kg (274.4+/-63.5 vs. 206.4+/-54.6W), 15.5kg (371.2+/-93.9 vs. 313.5+/-72.3W), and 10.5kg (336.9+/-77.8 vs. 286.3+/-66.0W) but not at 5.5kg (191.6+/-42.3 vs. 166.0+/-37.0W).

-Similarly, mean power in the acceleration phase of trunk rotations was significantly higher when performed in standing than seated positions at weights of 20kg (143.2+/-32.1 vs. 101.9 +/-23.7W), 15.5kg (185.1+/-42.3 vs. 150.4+/-6.5W), and 10.5kg (169.8+/-40.7 vs. 139.7+/-31.6W) but not at 5.5kg (107.4+/-29.4 vs. 86.5+/-21.1W).

-Low correlations between the power achieved during standing and seated trunk rotations with weights greater to or equal than 10.5kg suggests that these tests measure distinct qualities. This is because core muscles facilitate the movement of the trunk easier when the body is in an upright position.

-Taking these findings into account, measurement of the velocity of trunk rotations in a seated position with 1kg could lead to similar results as those obtained while standing.

-The higher values during standing trunk rotations may be ascribed to a greater range of trunk motion while standing compared to sitting, which allowed participants to accelerate the movement more forcefully at the beginning of rotation. As a result, there was a greater trunk rotational velocity and consequently also overall power output.

-Reduced range of motion of the hips and the thoracic spine, which allow the greatest rotation because of the orientation of the joints could contribute to lower movement velocity of the trunk and consequently influence ball velocity in throwing and striking sports.

-The force is transferred sequentially from the proximal segments, such as hips, toward the more distal segments, such as the shoulders and arms. Because of the kinetic linkage of the proximal to distal sequence in throwing, the rotational mobility may play an important role in production of trunk rotational power.

-In sports involving loaded trunk rotations, standing positions should be preferred when testing athlete's specific performance as opposed to currently used dynamometers allowing movement of the trunk in seated and fixed positions.

Zemkova et al (2018). Sport-related differences in trunk rotational power in standing and sitting positions.

-When comparing trunk rotational power at different weights while standing and sitting in athletes of various sports, the values were significantly higher in a standing compared to a sitting position with weights ≥ 10.5 kg in a group of athletes that are used to performing standing trunk rotational movements in their sports (boxers, hockey players, judo practitioners, karate practitioners, tennis players, and wrestlers).

-However, mean power in the acceleration phase of trunk rotations did not differ significantly during standing and seated trunk rotations in canoeists and kayakers at all weights used. In other words, there were no significant differences in the trunk rotational power between these groups of athletes when trunk rotations were performed in a standing position.

-When trunk rotations were performed in a sitting position, the values were significantly higher with weights ≥ 10.5 kg in athletes performing seated rather than standing trunk rotational movements in their sports.

-Although the respective angular displacement during trunk rotations showed a similar tendency, its values only moderately correlated with trunk rotational power in both the standing and sitting positions. This indicates that athletes were able to produce forceful movement, regardless of their range of trunk rotational motion.

-Greater trunk rotational power in either a standing or a seated position is undoubtedly due to the predominant exercise mode used during their training and competition. Therefore, the exercise that most closely replicates the upper/lower body rotation movements should be preferred in testing in order to assess sport-specific power.

Zemkova et al (2018). Trunk Rotational Velocity in Young and Older Adults: A Role of Trunk Angular Displacement

-This study investigated the relationship between peak and mean velocity during trunk rotations and respective angular displacements in young and older adults.

- Altogether 91 young and older subjects of both genders performed 5 rotations of the trunk to each side, in a seated position, with a barbell of 1kg and 20kg placed on their shoulders behind the neck.

--The FiTRO Torso Isoinertial Dynamometer was used to monitor basic biomechanical parameters throughout the movement.

-Peak velocity was significantly higher in young than older adults with both 1kg (699.1+/-90.5 s vs. 564.3+/-71.5 degrees/s) and 20kg (267.7+/-41.1 vs. 206.1+/-35.0 degrees/s).

-Similarly, mean velocity in the acceleration phase of trunk rotations was significantly higher in young than older adults with both of 1kg (420.2+/-62.7 vs. 342.4 +/-56.6 degrees/s), and 20kg (150.8+/-33.8 vs. 117.6+/-29.0 degrees/s).

-Trunk angular displacement was also significantly higher in young compared to older subjects with both 1kg (peak values 188.3 +/- 36.5 vs. 156.5+/-31.7 degrees; and mean values 104.5+/-25.4 vs. 88.5+/-21.9 degrees) and 20kg (peak values 166.2 +/- 27.2 vs. 132.6+/-24.6 degrees; and mean values 83.9+/-19.3 vs. 69.7+/-18.1 degrees).

-Peak and mean values of velocity correlated significantly with a range of trunk rotational motion at both at both weights used in young as well as older adults.

-These findings indicate that slower velocity of the trunk rotations is most likely due to a limited range of trunk rotational motion, which is more evident in older adults.

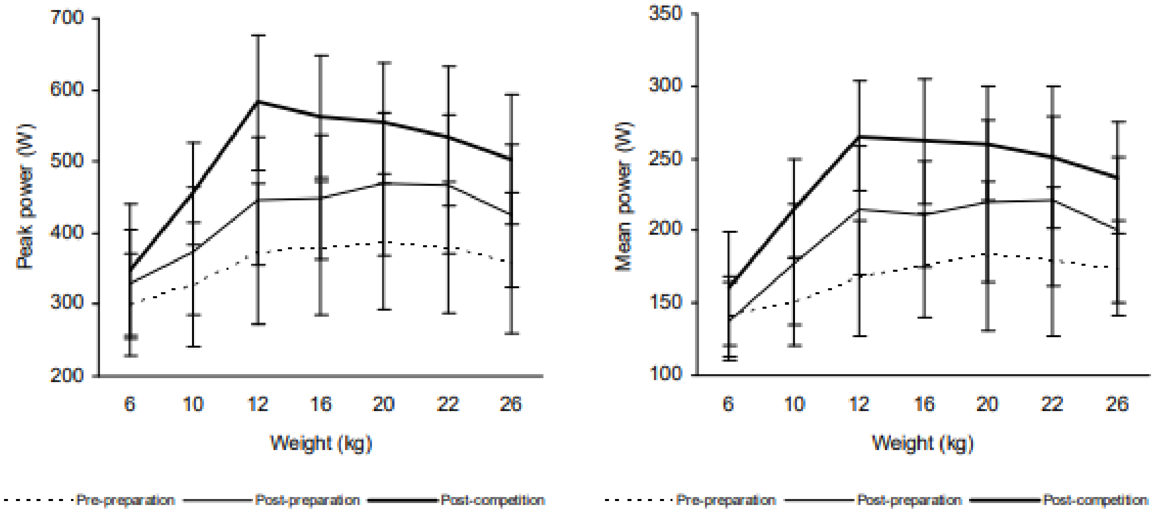
-It is speculated that due to the limited range of trunk motion, distal parts of the body could contribute more to the velocity of the movement (e.g. stroke, kick). This phenomenon was also observed in people with a lack of trunk muscle strength, who compensated for this by the recruitment of shoulder and arm muscles.

Poor & Zemkova (20018). The Effect of Training in the Preparatory and Competitive Periods of Trunk Rotational Power in Canoeists, Ice-Hockey Players and Tennis Players

-The subjects performed standing trunk rotations to each side with a barbell of different weights placed on the shoulders (6, 10, 12, 16, 20, 22 and 26kg) prior to and after 6 weeks of the preparatory and 6 weeks of the competitive period.

-It was hypothesised that the trunk rotational power would increase at higher weights after the preparatory period, whereas it would increase at lower weights after the competitive period.

-The results showed that mean power produced in the acceleration phase of trunk rotations increased significantly at weights from 10 to 26kg or 6 to 26kg after the preparatory and competitive periods respectively in tennis players**.**



(a) (b)

Figure 3. The peak power (a) and mean power produced during trunk rotations (b) at weights from 6 to 26 kg prior to and after 6 weeks of the preparatory period and 6 weeks of the competitive period in tennis players.

-The values obtained during trunk rotations with weights greater or equal to 12kg also increased significantly after the preparatory period in ice-hockey players, whereas there were no significant changes after the competitive period.

-Similarly, the mean power during trunk rotations with weights greater or equal to 10kg increased significantly only after the preparatory period in canoeists.

-Similar changes were observed for peak power.

-The highest values of mean power at 12kg corresponded to a velocity of 236.0 degrees/s. At 20kg this corresponded to a velocity of 186.8 degrees/s.

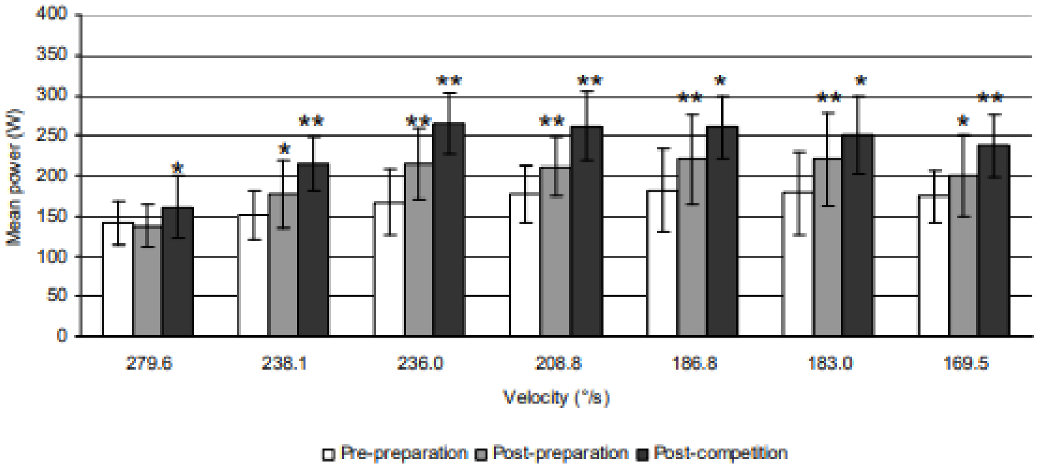


Figure 6. The mean power produced during trunk rotations at different velocities prior to and after 6 weeks of the preparatory period and 6 weeks of the competitive period in tennis players (* $p \leq 0.05$, ** $p \leq 0.01$).

-These findings support the hypothesis that trunk rotational power increases mainly at higher weights after the preparatory period. However, its values also increased significantly at all weights used after the competitive period in tennis players, whereas no significant changes were observed in ice-hockey players and canoeists.

Zemkova (2019). Reliability of a novel method assessing muscle power and velocity during seated trunk rotations

-Isometric and isokinetic dynamometers are mainly used for assessment of strength and endurance of core muscles. However, muscle power represents a more appropriate variable for evaluating of athlete performance that involve dynamic movements of the trunk.

-Introduction: This study estimated the test-retest reliability of trunk rotational power and velocity over a 1-week interval using the FiTRO Torso Isoinertial Dynamometer.

- Methods: A group of 32 physically active men performed 5 trunk rotations to each side while seated with a barbell of 1 kg or 20 kg placed on their shoulders. The construction of the testing system allowed the height of the seat to be adjusted for each individual with the lower limbs being fixed in place. The system monitors rotational movement of the barbell by means of a mechanically coupled precise angular velocity sensor.

-Results: Lower coefficients of variation for trunk rotational velocity rather than power indicate that the former represents a more reliable parameter and should be used for data analysis.

-Results showed that assessment of peak and mean velocity in the acceleration phase of trunk rotations with 1 kg provides reliable results (ICC = 0.94 and 0.92 respectively, SEM = 7.0% and 7.3% respectively). However, peak and mean values of velocity and power obtained during trunk rotations with a weight of 20 kg should be interpreted with caution (ICC < 0.80, SEM > 10%).

-Mean power produced in the acceleration phase of trunk rotations was 174.5+/-91.9 and 181.9+/-96.8W at 20kg, and mean velocity was 151.4+/-29.2 and 157.3+/-32.2 degrees/s

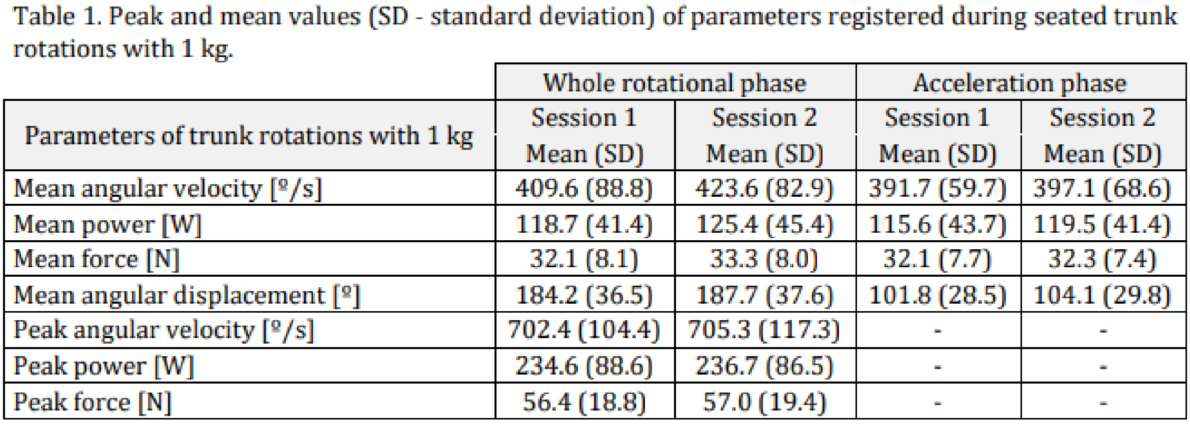


Table 1. Peak and mean values (SD - standard deviation) of parameters registered during seated trunk rotations with 1 kg.

Parameters of trunk rotations with 1 kg	Whole rotational phase		Acceleration phase	
	Session 1 Mean (SD)	Session 2 Mean (SD)	Session 1 Mean (SD)	Session 2 Mean (SD)
Mean angular velocity [º/s]	409.6 (88.8)	423.6 (82.9)	391.7 (59.7)	397.1 (68.6)
Mean power [W]	118.7 (41.4)	125.4 (45.4)	115.6 (43.7)	119.5 (41.4)
Mean force [N]	32.1 (8.1)	33.3 (8.0)	32.1 (7.7)	32.3 (7.4)
Mean angular displacement [º]	184.2 (36.5)	187.7 (37.6)	101.8 (28.5)	104.1 (29.8)
Peak angular velocity [º/s]	702.4 (104.4)	705.3 (117.3)	-	-
Peak power [W]	234.6 (88.6)	236.7 (86.5)	-	-
Peak force [N]	56.4 (18.8)	57.0 (19.4)	-	-

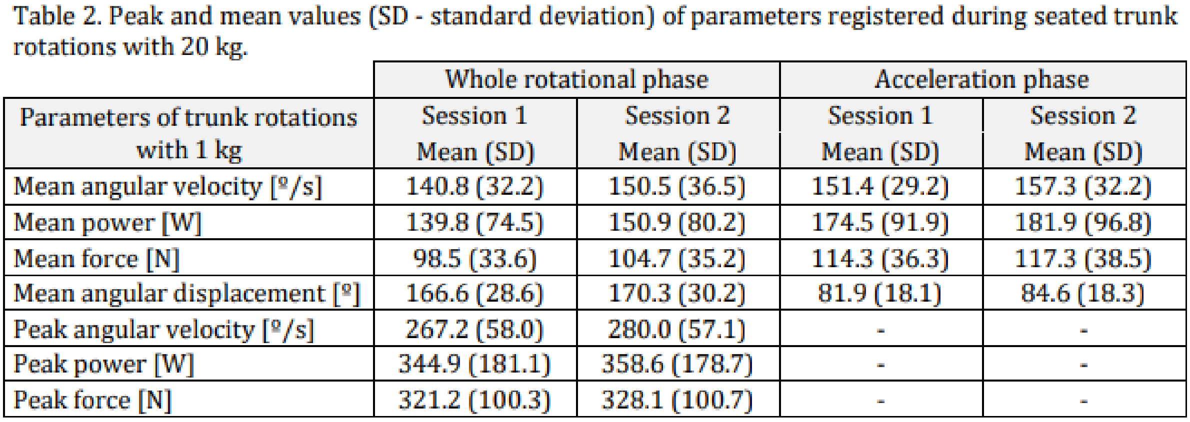


Table 2. Peak and mean values (SD - standard deviation) of parameters registered during seated trunk rotations with 20 kg.

Parameters of trunk rotations with 1 kg	Whole rotational phase		Acceleration phase	
	Session 1 Mean (SD)	Session 2 Mean (SD)	Session 1 Mean (SD)	Session 2 Mean (SD)
Mean angular velocity [º/s]	140.8 (32.2)	150.5 (36.5)	151.4 (29.2)	157.3 (32.2)
Mean power [W]	139.8 (74.5)	150.9 (80.2)	174.5 (91.9)	181.9 (96.8)
Mean force [N]	98.5 (33.6)	104.7 (35.2)	114.3 (36.3)	117.3 (38.5)
Mean angular displacement [º]	166.6 (28.6)	170.3 (30.2)	81.9 (18.1)	84.6 (18.3)
Peak angular velocity [º/s]	267.2 (58.0)	280.0 (57.1)	-	-
Peak power [W]	344.9 (181.1)	358.6 (178.7)	-	-
Peak force [N]	321.2 (100.3)	328.1 (100.7)	-	-

-Conclusions: Such an assessment of trunk rotational power and velocity can be used in practice, however with a limitation of performing trunk rotations in a seated position and using lower loads.

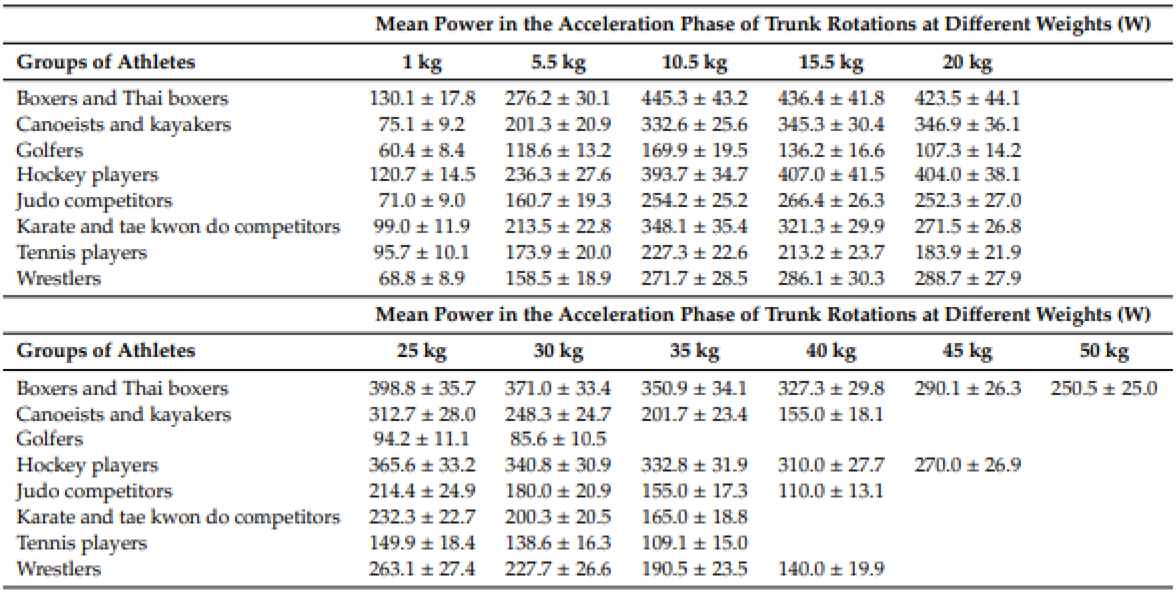
Zemkova et al (2020). Sport-Specific Differences in Power-Velocity-Force Profiling during Trunk Rotations at Different Loads

-Athletes of combat (n = 23), fighting (n = 39), ball (n = 52) and water sports (n = 19) with a mean age of 23.8 ± 1.5 years performed standing trunk rotations on each side with bars of different weights (from 1 kg up to 50 kg) placed on their shoulders

-Athletes were grouped by sport: combat sports (judo, wrestling), fighting sports (boxing, Thai boxing, karate, taekwondo), ball sports (golf, hockey, tennis) and water sports athletes (canoeing, kayaking).

-This study revealed that the highest power is produced by fighting sports athletes, followed by those of water, combat and ball sports, with the maximum achieved at 10.5, 20.0, 15.5 and 10.5 kg, respectively.

Table 2. Mean power in the acceleration phase of trunk rotations at different weights in groups of athletes of various sports (mean ± SD).



	Mean Power in the Acceleration Phase of Trunk Rotations at Different Weights (W)				
Groups of Athletes	**1 kg**	**5.5 kg**	**10.5 kg**	**15.5 kg**	**20 kg**
Boxers and Thai boxers	130.1 ± 17.8	276.2 ± 30.1	445.3 ± 43.2	436.4 ± 41.8	423.5 ± 44.1
Canoeists and kayakers	75.1 ± 9.2	201.3 ± 20.9	332.6 ± 25.6	345.3 ± 30.4	346.9 ± 36.1
Golfers	60.4 ± 8.4	118.6 ± 13.2	169.9 ± 19.5	136.2 ± 16.6	107.3 ± 14.2
Hockey players	120.7 ± 14.5	236.3 ± 27.6	393.7 ± 34.7	407.0 ± 41.5	404.0 ± 38.1
Judo competitors	71.0 ± 9.0	160.7 ± 19.3	254.2 ± 25.2	266.4 ± 26.3	252.3 ± 27.0
Karate and tae kwon do competitors	99.0 ± 11.9	213.5 ± 22.8	348.1 ± 35.4	321.3 ± 29.9	271.5 ± 26.8
Tennis players	95.7 ± 10.1	173.9 ± 20.0	227.3 ± 22.6	213.2 ± 23.7	183.9 ± 21.9
Wrestlers	68.8 ± 8.9	158.5 ± 18.9	271.7 ± 28.5	286.1 ± 30.3	288.7 ± 27.9

	Mean Power in the Acceleration Phase of Trunk Rotations at Different Weights (W)					
Groups of Athletes	**25 kg**	**30 kg**	**35 kg**	**40 kg**	**45 kg**	**50 kg**
Boxers and Thai boxers	398.8 ± 35.7	371.0 ± 33.4	350.9 ± 34.1	327.3 ± 29.8	290.1 ± 26.3	250.5 ± 25.0
Canoeists and kayakers	312.7 ± 28.0	248.3 ± 24.7	201.7 ± 23.4	155.0 ± 18.1		
Golfers	94.2 ± 11.1	85.6 ± 10.5				
Hockey players	365.6 ± 33.2	340.8 ± 30.9	332.8 ± 31.9	310.0 ± 27.7	270.0 ± 26.9	
Judo competitors	214.4 ± 24.9	180.0 ± 20.9	155.0 ± 17.3	110.0 ± 13.1		
Karate and tae kwon do competitors	232.3 ± 22.7	200.3 ± 20.5	165.0 ± 18.8			
Tennis players	149.9 ± 18.4	138.6 ± 16.3	109.1 ± 15.0			
Wrestlers	263.1 ± 27.4	227.7 ± 26.6	190.5 ± 23.5	140.0 ± 19.9		

-Additionally, angular velocity is the highest at lower weights in fighting sports athletes and at higher weights in water sports athletes. Alternatively, the highest force is achieved at higher velocities in fighting sports athletes and at lower velocities in water sports athletes.

-These findings indicate that power, velocity and force produced during trunk rotations are sensitive parameters able to discriminate between athletes with different demands on explosive strength and power of core muscles.

-While ball and fighting sports athletes who have to generate high force outputs in a short amount of time achieved the highest power at lower weights or at high velocities, water sports athletes who exert a high force against the water and those of combat sports who require high explosive strength of both the lower and upper body musculature to lift and throw the opponent were able to produce the highest power at higher weights.

[Daz comment: Question: what is the peak velocity for trunk rotation during a groundstroke? For example, we know in sprinting it is possible to work up to a speed of 12m/s which is why low speed activities such as jump squats and cleans (2m/s) and bodyweight jumps (3m/s) are so far away from that. Even bounding (5.9m/s) and speed bounding (8.2m/s) don't get there. Sled sprints with 16% bodyweight get to 8.2m/s also.

[Training Application: Training for Power- Joseph Coyne Power Development Aims with Elite Sprinters: For weaker athletes in General Prep- increase the weight at peak power. For strong athletes in Specific Prep & Comp, increase the peak power at the same weight and keep the same peak power at lower weights.]

Knudson & Blackwell (2000). Trunk Muscle Activation in Open Stance and Square Stance Tennis Forehands.

- Electromyography of the trunk muscles were compared between the open and square stance forehand drives of 14 collegiate tennis players.

- Biomechanical studies later confirmed the existence of two kinds of coordination in the forehand drive, the single unit and a multi-segment forehand.

- The lighter, larger headed, and more powerful composite rackets have helped fuel the trend of more players using open stance (OS) forehand stroke technique, rather than classic square stance (SS) technique.

- Tennis experts believe that the OS technique relies more on ballistic, angular momentum generated by the hips and trunk than the SS technique. This potential reliance on the trunk and arm action, at the expense of linear momentum from the lower extremities, is hypothesized to increase the risk of overuse injuries and contribute to strength imbalances.

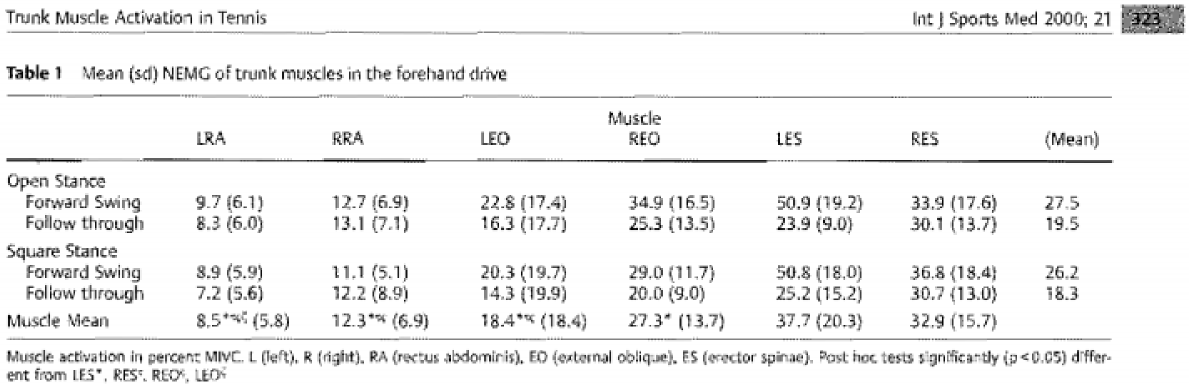
- Therapists treating tennis players report an increasing number of abdominal muscle strains that they attribute to greater use of the OS forehand technique. Tennis conditioning programs have tended to emphasize trunk muscle training and specifically trunk twist exercises.

- Surface EMG were bilaterally collected from the rectus abdominis (RA), external oblique (EO), and erector spinae (ES) in open and square stance forehand drives.

- The nonsignificant differences in muscle activation between stances did not support the belief of tennis experts that open stance forehands require greater trunk activation than square stance forehands.

- Mean NEMG of the ES were significantly ($p < 0.05$) larger than EO or RA, which was consistent with observations of tennis-specific strength imbalances and increasing incidence of low back injuries in tennis.

- Greater mean activation of the left ES (50.9%) in the forward stroke compared to the follow through (24.6%).



Trunk Muscle Activation in Tennis Int J Sports Med 2000; 21 323

Table 1 Mean (sd) NEMG of trunk muscles in the forehand drive

	LRA	RRA	LEO	Muscle REO	LES	RES	(Mean)
Open Stance							
Forward Swing	9.7 (6.1)	12.7 (6.9)	22.8 (17.4)	34.9 (16.5)	50.9 (19.2)	33.9 (17.6)	27.5
Follow through	8.3 (6.0)	13.1 (7.1)	16.3 (17.7)	25.3 (13.5)	23.9 (9.0)	30.1 (13.7)	19.5
Square Stance							
Forward Swing	8.9 (5.9)	11.1 (5.1)	20.3 (19.7)	29.0 (11.7)	50.8 (18.0)	36.8 (18.4)	26.2
Follow through	7.2 (5.6)	12.2 (8.9)	14.3 (19.9)	20.0 (9.0)	25.2 (15.2)	30.7 (13.0)	18.3
Muscle Mean	$8.5^{*\dagger\S\P}$ (5.8)	$12.3^{*\dagger\S}$ (6.9)	$18.4^{*\dagger\S}$ (18.4)	27.3^{*} (13.7)	37.7 (20.3)	32.9 (15.7)	

Muscle activation in percent MIVC. L (left), R (right), RA (rectus abdominis), EO (external oblique), ES (erector spinae). Post hoc tests significantly ($p < 0.05$) different from LES*, RES†, REO§, LEO¶

- There was a non-significant trend of greater activation of trunk muscles in the open stance (23.6±17.8%) compared to the square stance (22.1±18.1 %).

- The significantly larger mean NEMG of the forward swing (26.8 ± 20.2 %) compared to the follow through (18.9 ± 14.3 %) could be due to less muscle activation to slow the racket or the smaller EMG observed in primarily eccentric compared to concentric muscle actions (suggesting that none of the muscles studied were specifically activated at high levels of eccentric action to slow the motion of the trunk or racket).

- Mean LES activity was significantly larger than the mean activation of all the abdominal muscles studied. Peak values of NEMG of the ES muscles in the forehands approached and occasionally exceeded 100% MIVC. while peak values of the abdominal muscles were lower and did not exceed 100%.

- The significant differences in trunk flexor and extensor activation supports the contention that tennis-specific strength imbalances in the trunk could develop if supplemental conditioning exercises are not performed.

- This strong activation of the ES muscles in the forehand could also contribute to the clinical observations of increased incidence of low back injuries in tennis and the above average trunk extensor strength observed in tennis players.

- The EO is commonly observed as the primary agonist to axial rotation of the trunk to the contra lateral side. The present data supported this in the forehand drive since REO had a mean activation significantly (p < 0. OS) greater than the other abdominal muscles during the forward swing.

- Twisting abdominal exercises are likely to be an effective training modality for both styles of the tennis forehand drive.

- The data supported previous research on strength imbalances in tennis players because of marked ES activity. the importance of EO in axial rotation. and indicated that female players may require greater EO activity because of a less oblique fibre orientation of the EO.

Sogut (2016). The Relation Between Core Stability and Tennis-Related Performance Determinants

-Participants were competitive male (n= 14, age= 13.64 ± 1.65 years) and female (n= 15, age= 13.60 ± 1.72 years) junior tennis players.

-They were tested on core stability (sport-specific core stability test), maximal serve speed (sports radar), dynamic balance (star excursion balance test), agility (spider run test), upper body strength (forehand and backhand medicine ball throws), and lower body strength (standing long jump test).

-Core stability is defined in athletic settings as the optimum production, transfer and control of force from the centre of the body to the limbs, through stabilization of the position and motion of torso.

-Since both on-court movements and strokes in tennis depend mainly on eccentric and concentric muscle contraction performance measures were selected accordingly. Conversely, assessment of core stability requires muscular endurance and isometric contraction.

-Core Stability Test. Sport-specific core stability test (SCST) developed by Mackenzie was used to assess the core stability of the subjects. The SCST is a valid and reliable test for measuring core stability in athletes.

-The protocol involves maintaining a prone bridge position during the following stages:

1) holding the basic plank position for 60 s;
2) lifting the right arm off the ground and holding this position for 15 s;
3) returning the right arm to the ground and lifting the left arm off the ground for 15 s;
4) returning the left arm to the ground and lift the right leg off the ground for 15 s;
5) returning the right leg to the ground and lift the left leg off the ground for 15 s;
6) lifting both the left leg and the right arm from the ground and hold for 15 s;
7) returning the left leg and right arm to the ground, and lift both the right leg and the left arm off the ground for 15 s;
8) returning to the basic plank position for 30 s.

-The test was discarded when the subject was unable to hold the required position. The score is the length of time that the subject maintains the correct position. The test was repeated twice and the best score was recorded for the data analysis.

-Pearson’s correlation coefficient indicated no significant correlation between core stability and other variables in both genders.

-The study recommended to strength and conditioning coaches engaged with tennis players in these age groups better not to focus primarily on core stability training in order to enhance performances on the aforementioned parameters.

[The following section is a **BONUS section** featuring training approaches used in professional baseball pitching. While clearly the pitching action has limited transfer to the hitting action in tennis, it nevertheless highlights principles which could be applied to tennis strength & conditioning with the goal of improving racket velocity.]

Tread Athletics- Building the 95 MPH Body (Ebook)

Training Specificity - Baseball

-Power production is largely plane specific. This means that an athlete's ability to express power in one plane does not necessarily mean they will be able to express that power in another. For example, pitchers who can vertical jump off the charts will not necessarily be able to express a high degree of power in a lateral skater jump.

-Because pitching takes place in all three planes of motion, it is, therefore, sensible to train power movements in all of these. An athlete who only trains within one plane (i.e., only linear 'sagittal plane' movements) will be limiting his power potential.

-Furthermore, research on pitchers has shown that of the three planes, power movements performed in the sagittal plane have the lowest correlation to ball velocity.

-Unsurprisingly, the lateral jump, which occurs in the frontal plane and mimics the throwing stride, and the medicine ball scoop toss, which occurs in the transverse plane and mimics the violent torso rotation of pitching, were the best predictors of velocity in this particular study.

-This doesn't mean that training squats and deadlifts won't also increase lateral jump distance and/or velocity, or that an individual can't have good power output despite having never done multi-planar work.

-All this is to say that what may be a fantastic power training prescription for a sprinter, whose sport primarily exists in the sagittal plane, ends up being a sub-optimal prescription for pitchers, whose primary movement pattern incorporates all three planes of motion.

Frontal plane

-The frontal plane may indeed be the most important of the three planes, with the initial stride functioning to both generate and transfer force through the kinetic chain by initiating lateral momentum of the centre of mass towards the target. This lateral force is generated with the drive leg by producing force into the ground in the direction of the target, and the magnitude of this force is highly associated with ball velocity.

- The fact that increased momentum of the centre of mass is strongly correlated to high velocities intuitively makes sense; individuals can typically throw 3 to 6+ mph harder from a running start than from their pitching motion (the exception being individuals unfamiliar with proper crow-hop footwork). Other throwing sports have demonstrated the need for initiating momentum of the centre of mass towards the target in order to generate velocity as well, both in javelin throwers and in cricket bowlers. In both cases, higher run-up velocities were associated with longer strides, greater arm speed and increased throwing distance / ball velocity.

A Tri-Planer Approach

- While we still need a large strength base, incorporating heavy sagittal movements to build up the involved musculature, the majority of our more specific, power training should include all three planes. Here we break down why each plane is important, and sample exercises that are useful for developing power in these planes.

- Improving lateral power: Why do we need it? During the initial stride phase of the delivery, lateral power is necessary for producing large ground reaction forces with the drive leg into the pitching rubber.

- Alternating/band resisted lateral bounds
- Lateral sled drags
- Slide-board skaters

- Improving rotational power: Why do we need it? The throwing motion involves both properly sequenced hip rotation and torso rotation, in addition to the obvious shoulder external/internal rotation that is occurring. Training for strength and power in this plane is therefore useful for velocity.

- Med ball scoop toss
- Med ball Rotational Shot-put
- Tornado ball Wall slams
- Tight rotations

A note on Hip Rotation.

-Research suggests that speed of hip rotation is actually similar between low and high velocity pitchers. Don't force hip rotation. The timing of this hip rotation is the important factor – properly sequencing the hips ahead of the torso and upper half allows optimal energy transfer from the ground up, which ultimately translates into greater arm speed and ball exit velocity

QUESTION- Application to Tennis: is it worth spending time on sequencing with cable work with relatively slow contraction times if the whole forward swing motion is only 0.32 seconds, with the pelvis and trunk rotation being around 0.10 seconds later in the professionals versus high performance players, and being the difference which accounts for the greater lag and therefore higher racket horizontal velocity?

-Improving sagittal power: Why do we need it? There is a significant sagittal plane component in the throwing delivery in the final pull-down phase. Here, torso flexion and shoulder extension help to accelerate the ball towards the target.

- Med ball floor slams
- Med ball wall slams
- Sledgehammer tyre swings

Driving off the rubber

A common misconception is that "driving" off the rubber means dropping into a deep knee bend and then "pushing" with the quadriceps to move down the mound. This is one way to move quickly down the mound, but it generally becomes unusable kinetic energy and destroys proper sequencing of the delivery and hip/shoulder separation. Most high-level throwers instead keep a slight bend in the rear leg, and, while keeping the torso tall and "stacked" over that leg, engage the muscles in the lateral hip as well as the hamstrings to initiate forward motion.

Weighted Balls

Below is an extract from the Tread Athletics 4-Week-Intro-to-Weighted-Ball-Training programme. Click here to download your FREE copy.

''Everything has its place, in the right context and for the right guy.''

That's why most cues or drills exist and get passed on in the first place – they worked for somebody, at some point in time. The problem arises when coaches take it a dangerous step further: because it worked for one athlete or scenario, it's the way every athlete in every scenario should do things.

Through data collection and experience, certain trends will emerge as relatively constant principles but coaches must be just as careful to avoid assuming they have it figured out. I want you to read. I want you to think. I want you to understand why you're doing what you're doing, and I want you to test within your own mechanics and routines what works best for you.

Caveat - This guide is also not meant to be used as a rehab throwing program – which generally require significantly more individualization and oversight depending on the scope of the injury.

These are the principles, or essentials, that we've come to rely on in producing results with our athletes. Can some athletes get results by skipping a warm-up, not doing any drill work, having no progression and avoiding their arm care? Of course - but that doesn't mean it's the best course of action over time or when implemented at scale with dozens (or in Tread's case: thousands) of players. That said, here are the essentials, as I see it:

- A warm-up and activation phase
- Preparatory drill-work (generally utilizing backwards chaining)
- Catch play / long toss (with a partner)
- A recovery / arm care routine
- Uses progression, periodization and autoregulation principles

- When you understand the principles, you'll begin to understand why not all of our athletes utilize long toss or weighted balls. You'll see why not all of them throw plyos, and understand better why some of them have very minimal post-throwing recovery routines while others have more extensive ones.

Backward Chaining (Weighted Balls)

- This section could very easily be called "drill-work" or "mechanical patterning," but I decided to be as specific as possible in describing this approach to improving mechanics using drill work. This is meant as a place to focus on your mechanics.

- Backwards chaining is a motor learning technique, popularized in the baseball world (as far as I can tell) by Paul Nyman in the late 90's / early 2000's. The technique essentially acknowledges that changing complex motor patterns (like throwing a baseball) is difficult, but can be changed over time by deconstructing the movement into chunks (drills), and by working on those chunks from back to front, rather than front to back. In other words, backwards-chaining addresses the end of the throw first (i.e. torso rotation, ball release, follow through), and then adds in each preceding drill from there (leg lift, hand break, etc.).

- Now, there are arguments for forwards chaining as well – and I'll admit that a flawed first half of the throw can make it extremely difficult to finish properly, no matter how good you become at arm action drills. Nonetheless, I have found that, in general, backwards chaining is an effective concept.

- As far as how to do the following drills, you can either:

a) do them with soft weighted balls thrown into a wall

b) hard weighted baseballs thrown into a net, or

c) hard weighted balls thrown to a partner in catch play.

- As far as why weighted balls are beneficial for this drill work, the short answer is that slightly heavier balls provide very loud and substantial "proprioceptive" feedback to your arm about where it is in space, and helps smooth over inefficiencies in the patterns by increasing your awareness of any lags, pauses or inefficiencies. You'll be using slightly heavier balls than a baseball for most of this lower intensity drill-work.

- While heavier balls work well for improving the arm path at lower intensities, lighter balls work well for addressing raw arm speed and “whip” at higher intensities, once your arm path has improved.

-Stronger, slower twitch athletes often need to learn to relax and avoid muscling their arm into release, which is where underweight balls shine. You don’t want to go so heavy that you can’t flow and relax into the throw (we only use balls heavier than 1lb (450 grams) in very specific scenarios), and you don’t want to go so light that you lose any carryover to throwing a 5 oz. baseball (we don’t use anything under a 3 oz. ball either).

- For reference - the weight of a baseball is between 5 and 5.25 ounces (142 and 149 grams). In weighted ball programmes we will generally use 5 oz, 7 oz all the way up to a 1lb plyo ball.

- The following plyo balls are used in training: Blue ~1lb, Red ~7 oz, Yellow ~5 oz, Gray ~3.5 oz

- They are most useful for improving patterning – their biggest benefit is perhaps during sub maximal throwing and drill work. High intent throwing accounts for a relatively small piece of the progress our athletes make – maybe 2-3 miles per hour.

- More max effort throws won’t generally get you more velocity. Our high intensity phases usually <u>only have 15 or 20 high effort throws, twice per week</u>

- The further you get from a 5 oz. regulation ball, the harder time you’ll have with direct velocity carryover – while heavy balls work well for low effort patterning, all of our testing is in the 3 oz. to 7 oz. range. We don’t test 1lb or 2 lb balls, and 2 oz. balls are off the table as well

- Athletes must be on-ramped, have a strength base and be free of any red flag mechanical or movement issues before being put on a max effort-throwing program that includes weighted balls.

Arm Care

- Arm care exercises are necessary, but if we're limited to lighter "activation" and "stimulation" exercises pre-throwing, when do we do the real strengthening work? The way I see it, you've got two options:

1. Do 100% of your arm care work post throwing. This can work if you keep the volume down, but I don't like overly zealous post-throwing routines for the reasons above. Still, many athletes would rather knock it out while they're already warmed up and in throwing mode, so this makes it an appealing option.

2. Sprinkle your arm care work in during training sessions. Personally, this is what I do. Resting in between sets of squats? Alternate sets with posterior cuff work. Nothing to do after sets of rows? Go hit some serratus anterior work.

So what are the major components of a good arm care program? Here's what just about every pitcher could use more of:

1. Posterior cuff strength

- The teres minor, supraspinatus and infraspinatus all play a role in dynamic stability of the shoulder during overhead actions, and this is particularly important the harder you throw and stronger your accelerators get, as studies have shown that the ratio between isometric strength of the external rotators in relation to the internal rotators of the shoulder is a key predictor of injury. So strengthen that rotator cuff!

2. Lower trapezius recruitment / scapular posterior tilt

-The lower trap works in concert with the serratus anterior to help the scap tilt backwards and upwardly rotate.

Prone Y raises, face pulls and TRX Y raises are good examples of lower trap exercises. You'll notice they all take place at or above 90 degrees of shoulder abduction, in order to load the line of the lower trap fibres most effectively.

3. Scapular / cuff co-contraction and timing

-Can you coordinate and fire all of these muscles together and with proper timing as opposed to just isolating them in simple exercises? The job of these muscles is to stabilize the scapula against the ribcage and maintain position of the shoulder in the socket during dynamic overhead movement. The timing and coordination of these muscles matter – so most pitchers would do well to add in a general stabilization exercise like the shoulder tube, bodyblade, or partner rhythmic stabilizations.

-The latter is my favourite option, because it forces the cuff and scapular muscles to respond to an unpredictable external force. Plus, it’s far less fatiguing than the first two options because it’s more of a motor control exercise than a strength/endurance one.

4. Middle trapezius recruitment / scapular retraction

- Scap loading coined by Paul Nyman, is where the throwing scap is fully retracted with the thoracic spine extending as well to create a stretch through the chest and abdominals. This position occurs just prior to torso rotation, where the arm will be driven into violent layback – so the ability of the middle trap to help control the scapula in this shortened and retracted position is important.

-T raises, band pull-aparts and reverse flies all target the middle trap.

5. Serratus anterior recruitment / scapular upward rotation

-The serratus anterior stabilizes the scapula flush against the rib cage during overhead movement, which is important for providing a stable base for the throw to occur (a pitcher’s shoulder internally rotates at 7000-9000 degrees per second, making it the fastest movement in all of sports). Furthermore, the serratus anterior is involved in upwardly rotating, posteriorly tilting and protracting the scapula during the throw – all necessary actions for the scapula to be able to do in order for the shoulder to stay centered in the socket during the throw.

-Wall slides, scap push-ups, yoga push-ups and bear crawls all target this muscle effectively, among many others

Summary of Structural Factors

- It is generally accepted that most of the energy or force used to accelerate a tennis racket is transferred to the arm and racket from the larger muscle groups in the legs and trunk
- Leg drive utilizes ground reaction forces and is critical for linear to angular momentum transfer and the development of high racket speed. Energy from the leg is transferred as the hips open up first, followed by the shoulders.
- The main kinetic chain motions that create racket speed in the forehand are trunk rotation, horizontal shoulder adduction, and internal rotation.
- Strength training should focus on maintaining or improving the levels of USEFUL or APPLIED strength, increasing the power developed in the competitive skill.
- An eight-week training programme with overloads, medicine balls and elastic bands has positive effects on serve speed, as well as one- and two-arm medicine ball throwing capacity.
- Both handled medicine ball throws and over weighted racket training modalities improved tennis forehand drive performance, but it was suggested that the handled medicine ball throws may be incorporated into the preseason program preferably, while the overweight racket forehand drives may be included in the in-season program.
- In professional men's tennis one has observed a hitting frequency of 44 +/- 0.6 strokes per minute. This requires a high display of explosive strength both in the upper limbs to accelerate the racket, as well as in the lower body to transmit the final force to the arms by means of the kinetic chain.
- We must consider that game actions (groundstrokes) are performed an average of 270 times during a match, between 300 and 500 if it is the best of 5 sets.
- For comparison, the maximum force for a bench press is reached around 400ms, while the movement forward of the racket with a forehand lasts a little over 120ms.
- The ultimate goal of strength training is to improve your hitting speed in tennis to improve the useful force or specific expression of explosive force, and therefore improve the ability to apply more force in the time that the action lasts in the concentric acceleration of the racket towards the ball.
- A study showed that throwing a light medicine ball (TLMB) in one hand adequately predicts throwing velocity with a handball (VS).
- It was concluded that greater ROM at proximal segments, such as hips and thoracic, may NOT increase throwing velocity in cricket as reduced ROM at proximal segments can be useful in transferring the momentum from the lower extremity in an explosive task such as throwing.
- Mean power in the acceleration phase of trunk rotation in a seated position with a barbell of 20 kg placed on the shoulders was significantly higher in the dominant than non-dominant side in golfers (156.4±26.3 vs. 137.8±23.6 W, $p=0.036$) as well as in tennis players (224.6±31.9 vs. 203.5±27.8 W, $p=0.044$).

- There was a non-significant trend of greater activation of trunk muscles in the open stance (23.6±17.8%) compared to the square stance (22.1±18.1 %).
- Mean NEMG of the ES were significantly ($p < 0.05$) larger than EO or RA, which was consistent with observations of tennis-specific strength imbalances and increasing incidence of low back injuries in tennis
- Pearson’s correlation coefficient indicated no significant correlation between core stability and other variables in both genders. These tests included maximal serve speed (sports radar), dynamic balance (star excursion balance test), agility (spider run test), upper body strength (forehand and backhand medicine ball throws), and lower body strength (standing long jump test)
- Power production is largely plane specific. This means that an athlete’s ability to express power in one plane does not necessarily mean they will be able to express that power in another.

Mechanical Factors

Coordination

Tennis coaches and players are constantly striving to improve their strokes from a technical point of view hopping that one of the key factors of the game’s technique, which is *racquet speed,* will become greater, and therefore, will make the players’ “weapons” more effective.

To examine performance from the standpoints of efficiency and effectiveness seems extremely worthwhile. Performance models can be generated to study efficiency from the aspects of performing at a high level with less energy, so the athlete conserves more energy for later in the competition, or efficiency from the standpoint of performing with less stress on muscles or joints.

To improve the effectiveness of a performer, the biomechanist is concerned with how to *increase the force imparted to the ball* without causing injury to the performer, or how to better control specific aspects of movement for improved accuracy of stroke production.

When improving the effectiveness of performance, the biomechanist must be aware of the excessive stress that could be created by increased force. An increase in force production may contribute to increased stress about a joint, depending on how the constraints of that joint have been determined. (Groppel, 1986).

One other point to make is that we are not concerned with identification of various individualistic idiosyncrasies that one might see when examining groundstroke ‘technique.’ Obviously, to properly segregate idiosyncrasies or error symptoms from performance attributes, the researcher must have a good working knowledge of tennis. We are concerned with the body's linked system moves in synchronization to perform optimally.

Groppel, J (1986). The Biomechanics of Tennis: An Overview

In the 1960-1980s a lot of research was conducted on the forehand to better understand whether a stroke was caused by muscular effort in the upper limb or via ballistic action provided by the trunk. These authors concluded that the pectoralis major, anterior deltoid, and biceps brachii seemed to be the major contributors to arm acceleration in the forehand drive, while the latissimus dorsi and middle deltoid served as synergists.

Work in the 1970s brought us to the present day understanding of how the kinetic chain works- basically it seems that the upper limb in the forehand drive of a skilled performer receives a great deal of impetus from the hips and trunk in the linked system.

Although the upper limb contributes to the entire force of the stroke, its contribution seems to be much less than that of the hips and trunk. This seems logical, given the mass of the respective body segments, but it is important that the practitioner recognize this concept to realize that *the upper limb is as much a controlling mechanism of the racquet head* as it is a force-producing mechanism.

One handed Backhand (1HBH) vs. Forehand (FH)

The stroking mechanics between the forehand drive and the one-handed backhand drive are actually quite different (Groppel, 1984). As the body tums sideways to the net in preparation for the stroke, the limb that manoeuvres the racquet in the forehand drive is found to be on the side of the body opposite the net. This forces movement of the hips and trunk to assist in bringing the racquet head into the proper impact position. The opposite is true for the one-handed backhand drive. As the body tums sideways to the net, the limb that manoeuvres the racquet is found to be nearest the net or where the ball will be approaching. This means that although the hips and trunk play a large role in the one-handed backhand, they cannot be used as extensively as they are in the forehand drive. The more skilled a tennis player becomes at hitting a one-handed backhand, the more movement of the hips and trunk are seen prior to the impact point.

Kinetic chain

Groppel found that the one-handed backhand was basically a five-segment stroke, once the transfer of linear momentum had been accomplished by a step forward. It was found that, following this movement forward, the five body parts in action are the hips, trunk, upper arm, forearm, and hand and racquet, respectively. Groppel denoted that the action of three separate upper limb segments was distinct in analyzing the one-handed backhand of 18 highly skilled female competitors. From a mechanical standpoint, this may help the practitioner to understand problems of coordination in beginners learning a one-handed backhand drive—that a movement using five body parts may be difficult for a novice to leam. The same study found that once the step forward was completed for the two-handed backhand, the stroke is basically a two-segment body action. That is, the hips were observed to rotate and then the trunk and arms followed as one body part up to the impact point. Following impact, the action of the upper limbs and the trunk separated in the follow-through; but since this is a follow-through mechanism, Groppel felt that as it relates to the stroke itself, the key point is what happens up to and during impact. For the teacher of tennis, this may imply that the two-handed backhand is easier to leam at the initial stage of tennis instruction.

Reach differences

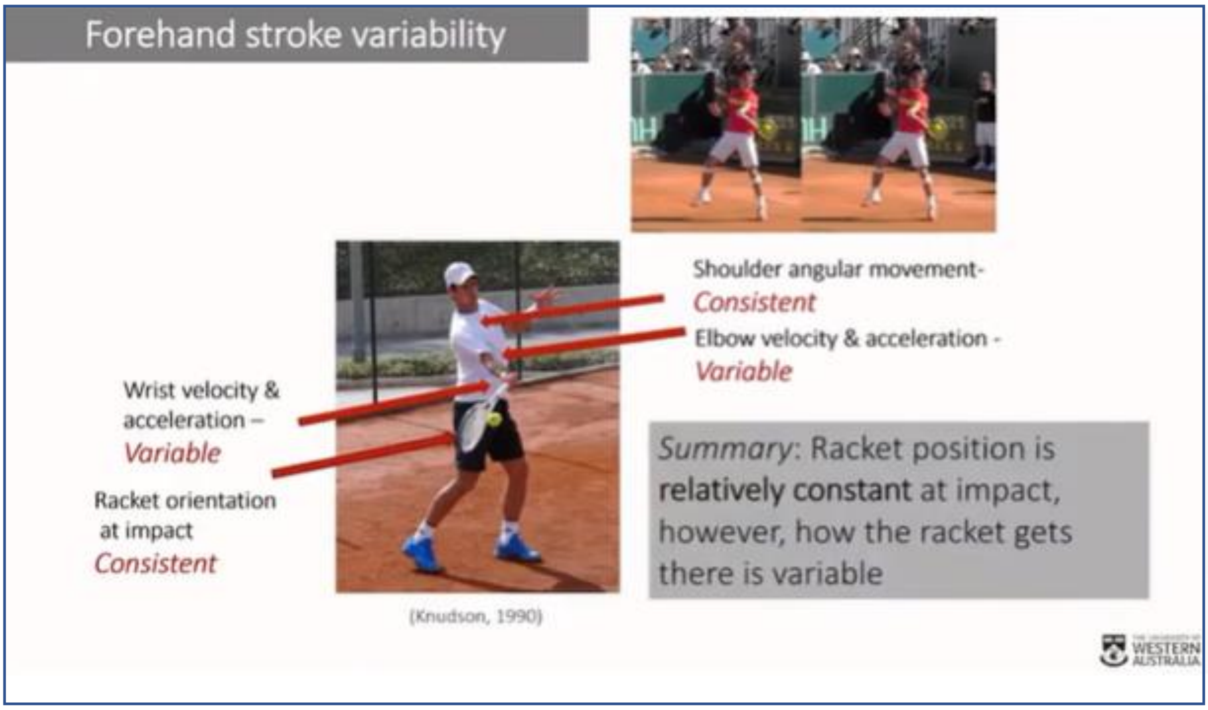
The one area the experts often criticize about the two-handed backhand is that of reach. It is claimed that the difference in reach is confounded by the fact that two limbs must be in contact with the racquet through the impact point. Groppel (1978) found that when the athlete is able to position his/her body comfortably relative to the point of impact, there is no statistical difference between the reach of the subjects. This has ramifications for the tennis instructor claiming differences in reach between the two striking pattems. Upon further inquiry, the expert instructor might point to a wide shot (one that a player must lunge for) and how that relates to performance with two hands on the racquet. Groppel (1984) disclaimed the fact that a two-handed backhand player could reach that shot, but also discussed the fact that even the one-handed backhand player cannot hit an offensive retum when lunging for a shot and usually must play a defensive shot. He claimed that the two-handed backhand player can leam a one-handed defensive manoeuvre to either lob the ball or hit it with underspin.

When trying to improve the velocity and control of a shot, most skilled players resort to heavy ball spin production (topspin).

Grips

Elliot found that as grip firmness increased, post-impact ball velocity increased. This implies that the firmness of grip may play a role in enhancing post-impact ball velocity. It should be noted, however, that the firmness of grip seems to be much more important for stroke control than for ball velocity; at the same time, sports medicine experts should also recognize that the firmer one's grip on the racquet handle, the greater the transmission of impact forces from the racquet into the hand. Therefore, instructors are cautioned about teaching strokes using very firm grips when playing tennis. In the beginning stages, the grip probably needs to be only as firm as will prevent the racquet from flying out of the hand due to the radial acceleration from the swing itself.

Knudson (1990). Intrasubject variability of Upper Extremity Angular Kinematics in the Tennis Forehand Drive.



Forehand stroke variability

Shoulder angular movement- *Consistent*

Elbow velocity & acceleration - *Variable*

Wrist velocity & acceleration – *Variable*

Racket orientation at impact *Consistent*

Summary: Racket position is **relatively constant** at impact, however, how the racket gets there is variable

(Knudson, 1990)

-Study based on two college tennis players, and the first eight strokes quantitively judged to be flat and down the centre of the court were analysed to calculate the variability of angular kinematics.

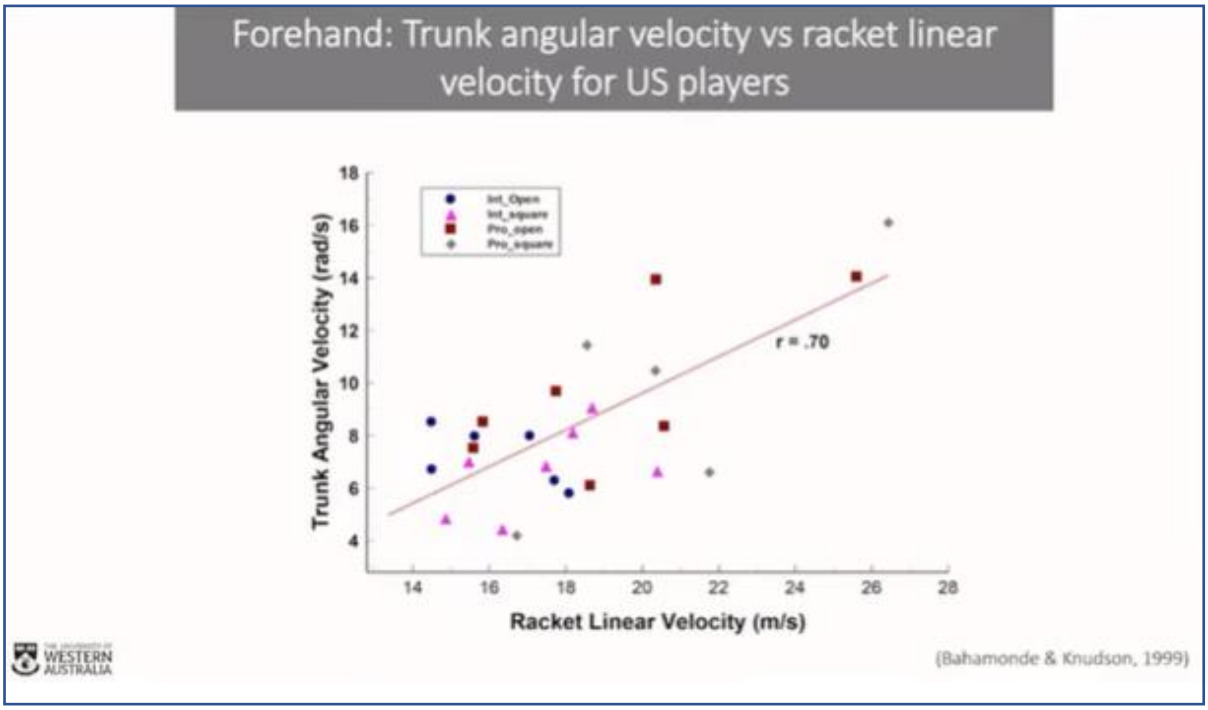
-Wrist and elbow angular POSITION data were quite consistent, with curve coefficients of variation (CV) less than 5.9%

-The consistent angular positions during the forward strokes did not result from highly consistent patterns of angular velocities or accelerations.

-For both the wrist and elbow joints, intrasubject variability increased for the angular VELOCITY (CV = 90.6%) and angular ACCELERATION (CV = 129.5%).

-There is a trend of increasing variability moving proximally.

Knudson & Bahamonde (1999). Trunk and racket kinematics at impact in the open and square stance tennis forehand.



Forehand: Trunk angular velocity vs racket linear velocity for US players

(Bahamonde & Knudson, 1999)

-Open stance forehands have been shown to have court coverage advantages, but may have several biomechanical disadvantages.

-Eleven tennis players (6 pros and 5 intermediates) performed three open and square stance forehand drives from behind the baseline, ranging in age from 21 to 62.

-The trial with the maximum ball velocity was selected for analysis.

-Professional subjects had a higher mean resultant velocity or racket at impact 21.7+/- 3.3 m/s than the intermediates 16.1 +/-2.5m/s

-Non-significant effects for stance or in the interaction of stance and skill on resultant velocity.

-There was a trend of the open stance creating LOWER velocities at impact (21.2 and 15.8 m/s) than the square stance (22.3 and 16.4 m/s).

-There were no significant main effects or interactions for the vertical path of the racket at impact. This did NOT support the hypothesis of a more elongated and less steep angle of racket motion at impact in the square stance technique.

-There was a significant effect of skill on trunk angular velocity at impact, but nonsignificant effects of stance or the interaction of stance and skill. The data did NOT support the hypothesis of a greater trunk angular velocity in open stance compared to the square stance forehand. In fact, there was a nonsignificant trend of higher trunk angular velocities at impact in square stance strokes (6.2 rads/s) compared to open stance strokes (5.0 rads/s).

-There was greater variability in trunk angular velocity curves (CVs = 42-47%) compared to racket resultant velocity curves (CV = 20-24%).

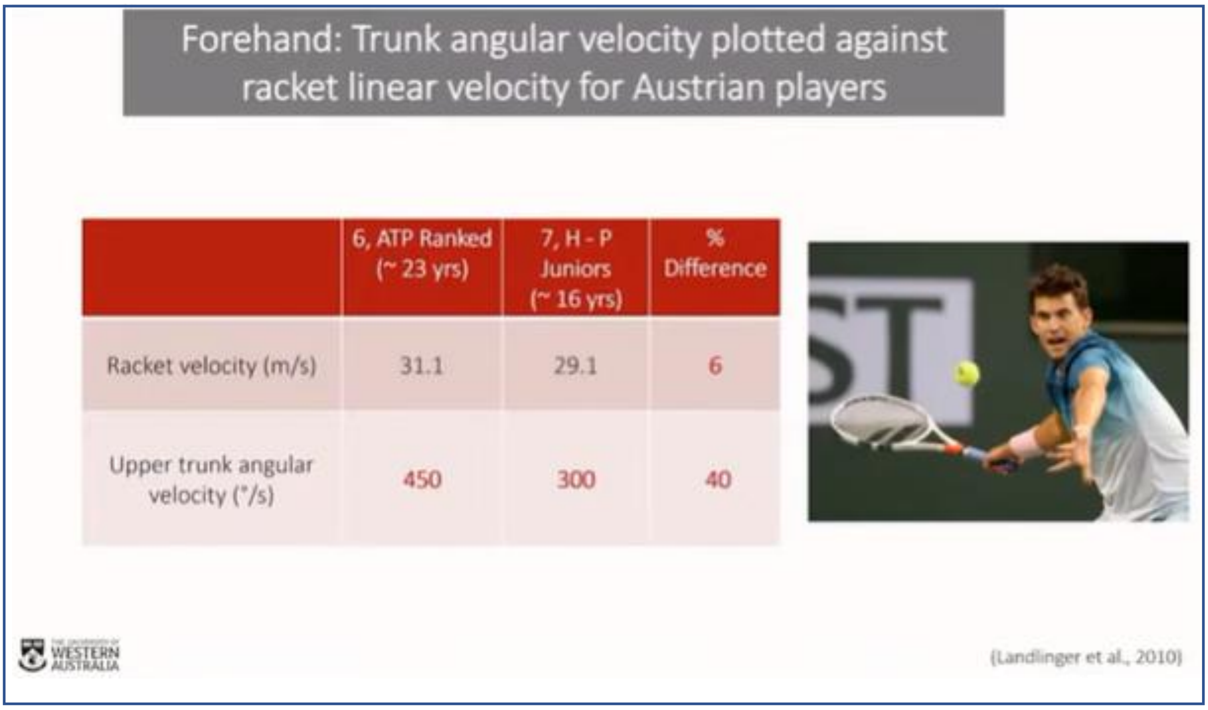
-Professional subjects had a significantly larger mean trunk angular velocity at impact (7.3+/-3.1 rad/s) compared to intermediate subjects (3.9+/-2.5 rads/s).

-There was consistent, but nonsignificant trends of greater angular velocity and racket resultant velocity at impact in the classic square stance technique compared to the open stance.

-This provided only tentative support to the view that the square stance forehand technique may have biomechanical advantages over the open stance technique in the tennis forehand.

-It was concluded that similarities between open and closed stance forehand techniques may be GREATER than the potential differences hypothesized by instructional experts

Landlinger et al (2010). Kinematic differences of elite and high-performance tennis players in the cross court and down the line forehand.



Forehand: Trunk angular velocity plotted against racket linear velocity for Austrian players

	6, ATP Ranked (~ 23 yrs)	7, H - P Juniors (~ 16 yrs)	% Difference
Racket velocity (m/s)	31.1	29.1	6
Upper trunk angular velocity (°/s)	450	300	40

(Landlinger et al., 2010)

-Significant differences (p<0.01) and large effect sizes were observed between elite and high-performance players in linear velocity of the shoulder (2.0 vs. 1.2 m/s), angular velocity of the pelvis (295 vs. 168 ◦/s), and angular velocity of the upper trunk (453 vs. 292 ◦/s) at impact.

- The elite group showed a tendency towards higher racquet velocities (31.1 vs 29.1 m/s) at impact (p <0.05).

- No significant differences were found in angular displacement of the racquet, hip alignment, or shoulder alignment at the completion of the backswing; nor did angular displacement vary significantly at impact.

-However, all players rotated their upper trunk well beyond their hips in order to pre-stretch the trunk rotators, creating a separation angle (elite vs. high performance: -22.9◦ +/- 7.7 vs. -26.9◦ +/- 9.9).

- Both groups rotated their hips significantly further in the down the line situation (resulting in a smaller separation angle due to the fact that shoulder alignment did not really change in the two different situations). Measures for racquet rotations were not significantly different (p<0.01), however, a large effect size was recorded.

- When playing the cross court shot, elite (-25.08) and high-performance (-29.28) players created significantly greater separation angles than when playing down the line (elite: -20.98, high performance: -24.58).

-The separation angle of the high-performance group was larger than in the elite group, although not significantly greater. This trend leads to the assumption that a greater separation angle is surely beneficial for pre-stretching the large trunk muscles, but does not guarantee an increased racquet speed.

- Although the distance over which racquet speed can be developed is critical in producing explosive strokes, elite players did not experience greater racquet rotation angles. Nevertheless, the high standard deviations for racquet rotation angles of both groups, next to similar findings in elbow flexion angles at the end of backswing, tell us that it is unrealistic to discuss a uniform backswing.

-The above stated variance of elbow and racquet orientation angles within the groups also brings terms like stroke and movement variability or differential learning, which are mainly based on the dynamical systems theory, into play. Lindinger and Benko (2007) pointed out that the key concept of modern coaching was lifelong differential learning and peripheral self-organizing patterns, rather than drill training and technical models. Not only the different anthropometrics of the athletes, but also the dynamic nature of tennis itself, has made it almost impossible to talk about an “identical” way of stroke production.

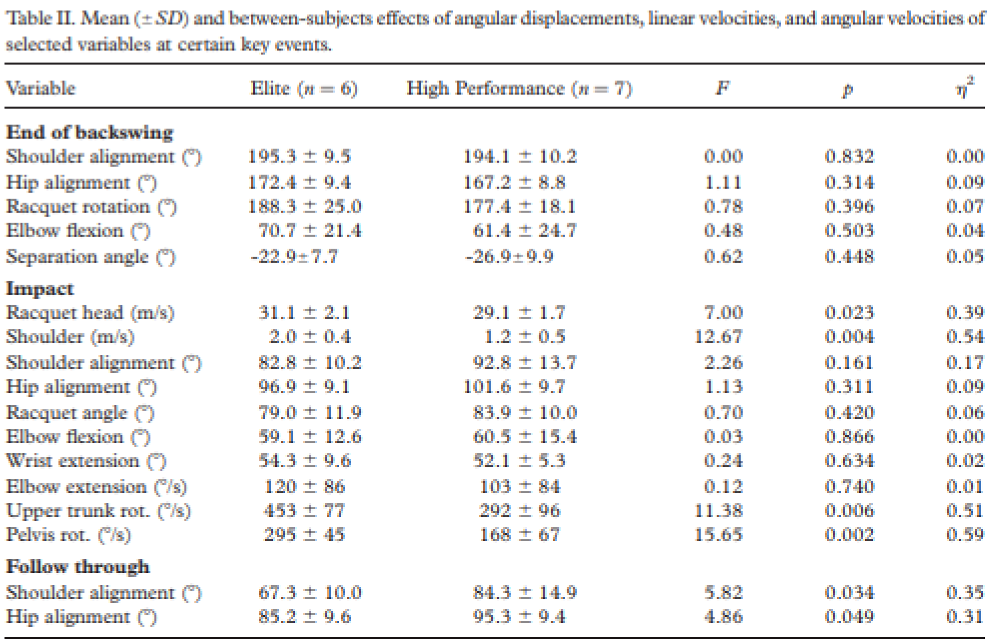


Table II. Mean (± *SD*) and between-subjects effects of angular displacements, linear velocities, and angular velocities of selected variables at certain key events.

Variable	Elite ($n = 6$)	High Performance ($n = 7$)	F	p	η^2
End of backswing					
Shoulder alignment (°)	195.3 ± 9.5	194.1 ± 10.2	0.00	0.832	0.00
Hip alignment (°)	172.4 ± 9.4	167.2 ± 8.8	1.11	0.314	0.09
Racquet rotation (°)	188.3 ± 25.0	177.4 ± 18.1	0.78	0.396	0.07
Elbow flexion (°)	70.7 ± 21.4	61.4 ± 24.7	0.48	0.503	0.04
Separation angle (°)	-22.9±7.7	-26.9±9.9	0.62	0.448	0.05
Impact					
Racquet head (m/s)	31.1 ± 2.1	29.1 ± 1.7	7.00	0.023	0.39
Shoulder (m/s)	2.0 ± 0.4	1.2 ± 0.5	12.67	0.004	0.54
Shoulder alignment (°)	82.8 ± 10.2	92.8 ± 13.7	2.26	0.161	0.17
Hip alignment (°)	96.9 ± 9.1	101.6 ± 9.7	1.13	0.311	0.09
Racquet angle (°)	79.0 ± 11.9	83.9 ± 10.0	0.70	0.420	0.06
Elbow flexion (°)	59.1 ± 12.6	60.5 ± 15.4	0.03	0.866	0.00
Wrist extension (°)	54.3 ± 9.6	52.1 ± 5.3	0.24	0.634	0.02
Elbow extension (°/s)	120 ± 86	103 ± 84	0.12	0.740	0.01
Upper trunk rot. (°/s)	453 ± 77	292 ± 96	11.38	0.006	0.51
Pelvis rot. (°/s)	295 ± 45	168 ± 67	15.65	0.002	0.59
Follow through					
Shoulder alignment (°)	67.3 ± 10.0	84.3 ± 14.9	5.82	0.034	0.35
Hip alignment (°)	85.2 ± 9.6	95.3 ± 9.4	4.86	0.049	0.31

-At impact, the hips, the shoulders, and the racquet of both groups were aligned significantly further in front when the ball was played cross court.

- Results confirm that players used the square stance significantly more often when playing the ball down the line.

- In addition to pre-stretching the shoulder muscles prior to the subsequent rotation, lower limb segment rotation and trunk rotation account for approximately 10% of the final racquet velocity.

-One should interpret this relatively low percentage with caution, however, since trunk rotation is probably the most crucial factor in the development of racquet speed. This assumption is supported by the significantly higher pelvis and upper trunk angular velocities of the elite players at impact in the present study.

-Since the shoulder is basically the end point of the trunk, trunk rotation influences the forward movement of the shoulder in a positive way, thereby increasing the speed of the racquet. It is stated that the forward speed of the racquet shoulder contributes about 10% to racquet speed at impact.

-Consequently, the elite’s significantly higher shoulder velocity underlines the obvious positive link of trunk rotation and linear velocity of the shoulder. Trunk rotation can also effect shoulder internal rotation due to the fact that internal rotators of the shoulder are pre-stretched through the preceding rotation of the trunk.

-Generally speaking, the follow through constantly varies because it depends on various factors like the grip, the type of shot played, and the tactical intention of the shot.

-The results show that the hips and shoulders of both groups were aligned further in front when the ball was played cross court. Nevertheless, the elite players must have rotated more “through” the shot since they demonstrated a tendency ($p < 0.05$) with large effects of smaller hip and shoulder alignment angles compared with the high-performance players at the end of the forward racquet movement.

(Assuming 0 is forward towards the net and 180 degrees is back towards the fence, so a smaller angle means they are closer to 0 facing the net)

-This might be a result of the higher angular velocity of the pelvis and the upper trunk at impact in the elite group. It is often seen in professional players that their back leg moves forward during the follow through when there is vigorous rotation of the hip and the trunk. Moreover, a high creation of linear momentum will also lead to this forward step, which helps on the one hand to slow down the fast actions of the body segments, and on the other hand helps to dissipate kinetic energy next to maintaining balance.

- From a technical perspective, results suggest that an increased angular velocity of the pelvis and the trunk at impact, next to a high horizontal velocity of the shoulder, is beneficial in terms of generating higher racquet speeds

Landlinger et al (2010). Key factors and timing patterns in the tennis forehand of different skill levels.

- Crespo and Higueras (2001) pointed out that the ability to hit the ball with immense power is a distinguishing feature of the modern game.

- One of the most important principles responsible for fast strokes is "the summation of speed principle."

- It simply states that the central segments that are closer to the body initiate a motion and provide a platform to produce maximum speed at the end of the distal segment. The proximal-to-distal sequencing pattern is the main characteristic of this principle.

- In tennis a greater maximum torso-pelvic separation angle increases torso rotation velocity and, consequentially, racquet and ball velocity. However, it has not been explicitly studied yet.

- Vicon motion analysis system recorded kinematic data of six ATP-professionals (elite) and seven high performance (HP) players when shots were played cross court and down the line.

- A ball machine controlled the pre-impact ball horizontal velocity (20 m·s-1) and trajectory.

- New tennis balls were projected down the line when participants had to play cross court and vice versa. Before testing, subjects were encouraged to hit the ball with the same velocity and action as they would in a match. They were instructed to hit two series of ten forehands cross court and down the line (4 x 10 strokes) to a target area (randomized order).

- Participants had a two-minute break after each series. To derive representative and accurate kinematics of the recorded forehand strokes, the six fastest cross court and down the line shots that landed in the target area were chosen for analysis. Therefore, a total of 12 strokes per subject were considered for analysis in this study.

- When the hips, the shoulders, or the racquet rotated backwards, such that they were perpendicular to the baseline, (e.g., at the beginning of the forward swing), a 180° angle was recorded).

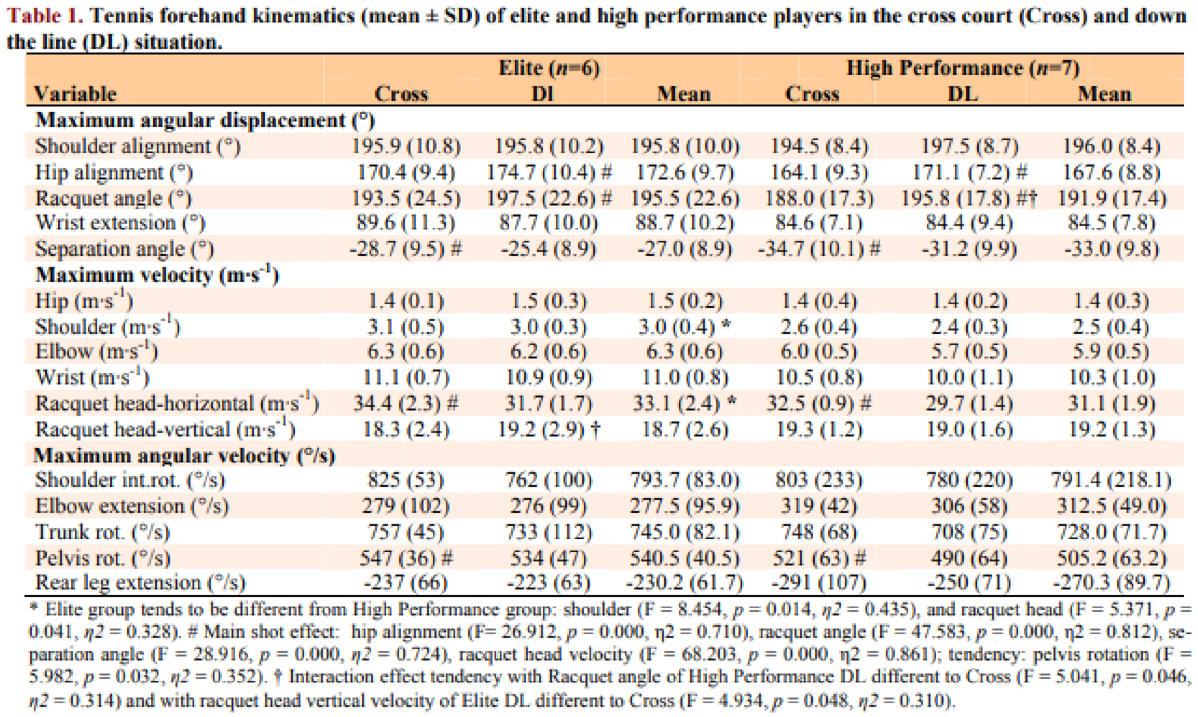


Table 1. **Tennis forehand kinematics (mean ± SD) of elite and high performance players in the cross court (Cross) and down the line (DL) situation.**

	Elite (n=6)			High Performance (n=7)		
Variable	**Cross**	**Dl**	**Mean**	**Cross**	**DL**	**Mean**
Maximum angular displacement (°)						
Shoulder alignment (°)	195.9 (10.8)	195.8 (10.2)	195.8 (10.0)	194.5 (8.4)	197.5 (8.7)	196.0 (8.4)
Hip alignment (°)	170.4 (9.4)	174.7 (10.4) #	172.6 (9.7)	164.1 (9.3)	171.1 (7.2) #	167.6 (8.8)
Racquet angle (°)	193.5 (24.5)	197.5 (22.6) #	195.5 (22.6)	188.0 (17.3)	195.8 (17.8) #†	191.9 (17.4)
Wrist extension (°)	89.6 (11.3)	87.7 (10.0)	88.7 (10.2)	84.6 (7.1)	84.4 (9.4)	84.5 (7.8)
Separation angle (°)	-28.7 (9.5) #	-25.4 (8.9)	-27.0 (8.9)	-34.7 (10.1) #	-31.2 (9.9)	-33.0 (9.8)
Maximum velocity (m·s^{-1})						
Hip (m·s^{-1})	1.4 (0.1)	1.5 (0.3)	1.5 (0.2)	1.4 (0.4)	1.4 (0.2)	1.4 (0.3)
Shoulder (m·s^{-1})	3.1 (0.5)	3.0 (0.3)	3.0 (0.4) *	2.6 (0.4)	2.4 (0.3)	2.5 (0.4)
Elbow (m·s^{-1})	6.3 (0.6)	6.2 (0.6)	6.3 (0.6)	6.0 (0.5)	5.7 (0.5)	5.9 (0.5)
Wrist (m·s^{-1})	11.1 (0.7)	10.9 (0.9)	11.0 (0.8)	10.5 (0.8)	10.0 (1.1)	10.3 (1.0)
Racquet head-horizontal (m·s^{-1})	34.4 (2.3) #	31.7 (1.7)	33.1 (2.4) *	32.5 (0.9) #	29.7 (1.4)	31.1 (1.9)
Racquet head-vertical (m·s^{-1})	18.3 (2.4)	19.2 (2.9) †	18.7 (2.6)	19.3 (1.2)	19.0 (1.6)	19.2 (1.3)
Maximum angular velocity (°/s)						
Shoulder int.rot. (°/s)	825 (53)	762 (100)	793.7 (83.0)	803 (233)	780 (220)	791.4 (218.1)
Elbow extension (°/s)	279 (102)	276 (99)	277.5 (95.9)	319 (42)	306 (58)	312.5 (49.0)
Trunk rot. (°/s)	757 (45)	733 (112)	745.0 (82.1)	748 (68)	708 (75)	728.0 (71.7)
Pelvis rot. (°/s)	547 (36) #	534 (47)	540.5 (40.5)	521 (63) #	490 (64)	505.2 (63.2)
Rear leg extension (°/s)	-237 (66)	-223 (63)	-230.2 (61.7)	-291 (107)	-250 (71)	-270.3 (89.7)

* Elite group tends to be different from High Performance group: shoulder (F = 8.454, $p = 0.014$, η2 = 0.435), and racquet head (F = 5.371, $p = 0.041$, η2 = 0.328). # Main shot effect: hip alignment (F= 26.912, $p = 0.000$, η2 = 0.710), racquet angle (F = 47.583, $p = 0.000$, η2 = 0.812), separation angle (F = 28.916, $p = 0.000$, η2 = 0.724), racquet head velocity (F = 68.203, $p = 0.000$, η2 = 0.861); tendency: pelvis rotation (F = 5.982, $p = 0.032$, η2 = 0.352). † Interaction effect tendency with Racquet angle of High Performance DL different to Cross (F = 5.041, $p = 0.046$, η2 = 0.314) and with racquet head vertical velocity of Elite DL different to Cross (F = 4.934, $p = 0.048$, η2 = 0.310).

- Timing of the maximum angles, linear and angular velocities was measured prior to and after impact. A total of twelve strokes per subject were analysed from the beginning to the end of horizontal racquet movement**.**

-Significant differences ($p < 0.01$) and large effect sizes were observed between elite and HP players in the timing of maximum pelvis (-0.075 ± 0.008 vs. -0.093 ± 0.012 s) and trunk angular velocities (-0.057 ± 0.004 vs. - 0.075 ± 0.011 s) before impact. [1 second = 1000 milliseconds. 0.075 to 0.093 is 20 milliseconds difference]

- The elite group showed a tendency ($p < 0.05$) towards higher peak horizontal shoulder (3.0 ± 0.4 vs. 2.5 ± 0.4 m·s-1) and racquet velocities (33.1 ± 2.4 vs. 31.1 ± 1.9 m·s-1) compared to the HP players.

- The later occurrence of maximum angular pelvis and trunk rotations were the main reasons for the tendency towards higher horizontal shoulder and racquet velocities in the elite group.

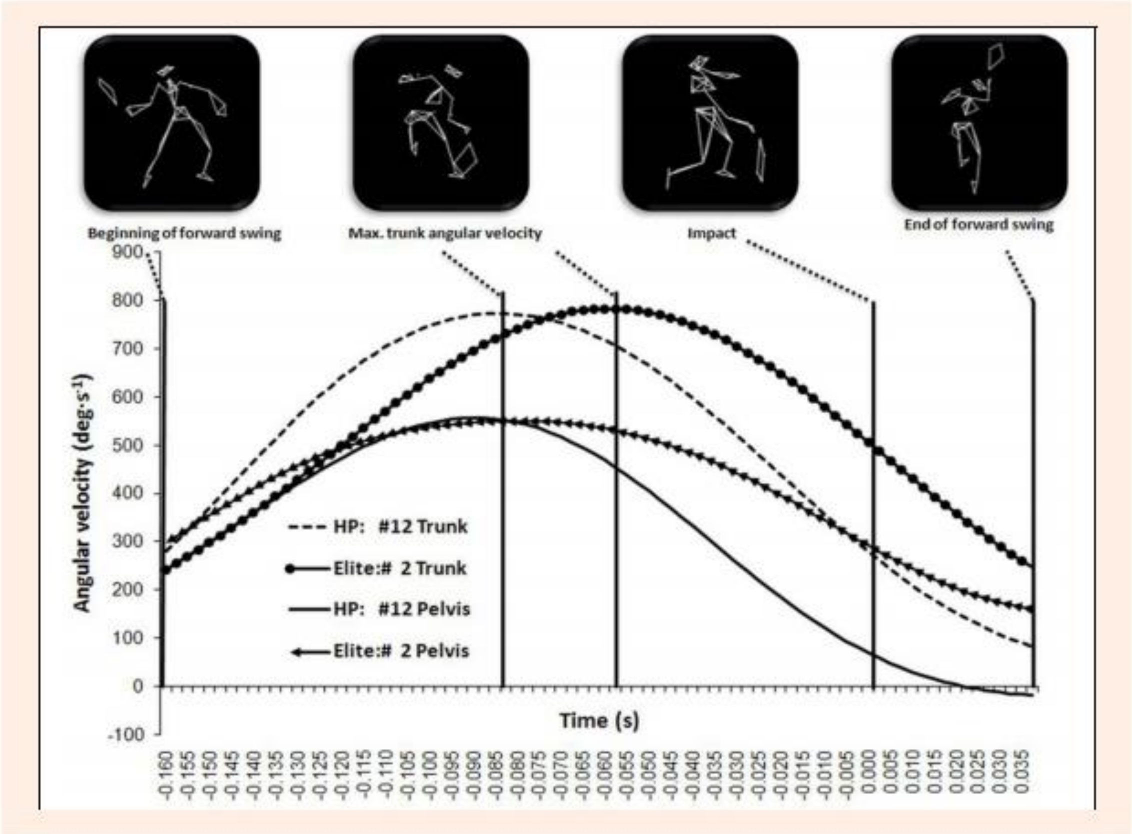


Figure 2. **A representative example of maximum pelvis and trunk angular velocities in a forehand cross court stroke of an elite (participant #2) and a high performance player (participant #12).**

- A greater rotation of the shoulders compared to the hips resulted in a greater negative separation angle.

- Mean forward swing time of the tennis forehand for the cross court and down the line situation did not vary between elite (0.324 ± 0.086 s) and high-performance players (0.326 ± 0.064 s).

- In the down the line situation, both groups rotated their hips and racquets further backwards ($p < 0.01$) but reduced their separation angle.

- Both groups showed higher values for horizontal racquet head velocity when hitting the cross court compared to the down the line situation ($p < 0.01$).

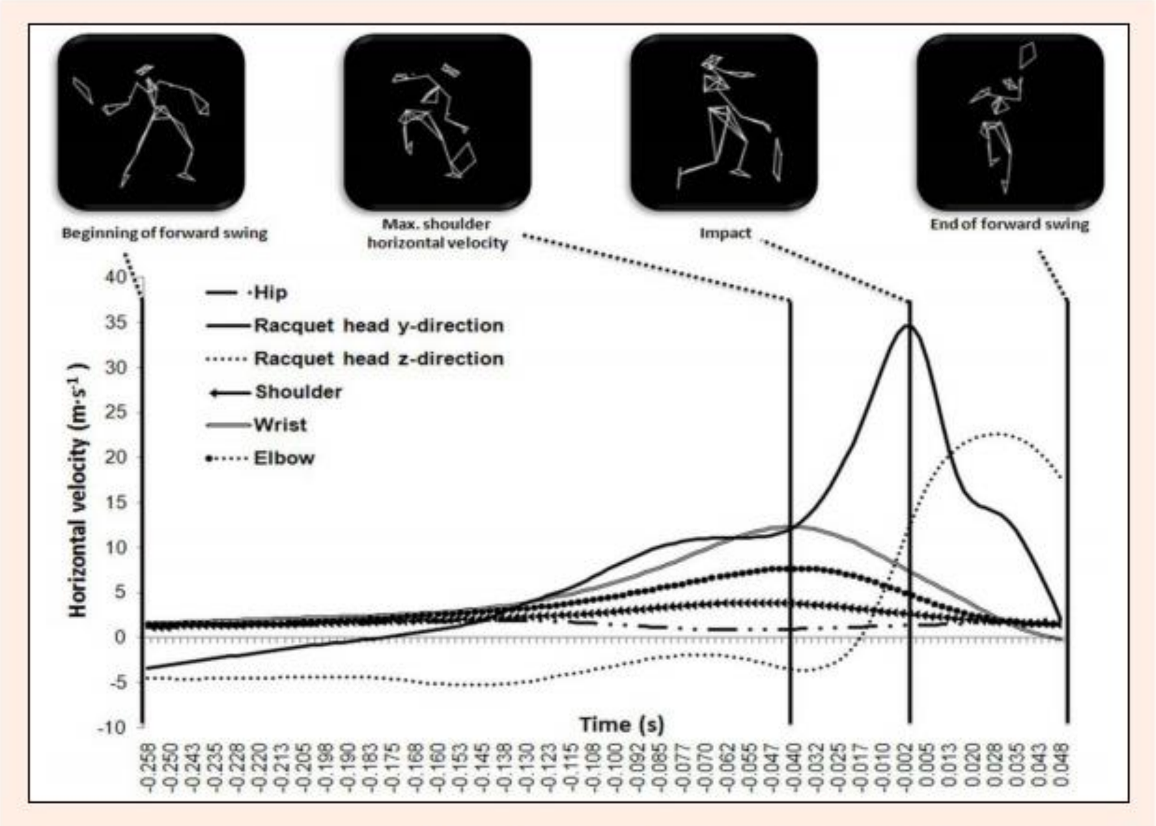


Figure 3. A representative proximal-to-distal sequencing pattern of maximum linear velocities (m·s^{-1}) in the tennis forehand of an elite player (personal best ATP ranking: 167).

- Elite and high-performance players tended to increase their pelvis rotation velocity in the cross- court situation ($p < 0.05$, η2 = 0.352.)

- All players demonstrated a complete proximal-to-distal sequence of peak linear velocities, and they reached their maximum internal rotation velocity of the shoulder after impact.

- Measures for maximum separation angle and shoulder alignments were comparable between groups.

- The magnitude of rotation for the racquet and the hips did not divide the elite from the high-performance players.

- Shortly after the end of the backswing, both groups reached their maximum displacement of the hips, followed by the shoulders. The timing of the maximum separation angle later in the stroke points out that the hips must have started the counter-clockwise rotation towards the ball earlier than the shoulders; therefore, probably increasing the pre-stretch on the trunk.

- The even later appearance of peak angular racquet rotation in the elite group demonstrates that the racquet tends to lag behind; thus, also pre-stretching the shoulder musculature which should enhance their capacity to generate more force.

- It seems that after vigorous hip and trunk rotation, both groups took advantage of their well-coordinated movements. There is a complete proximal-to-distal sequence of maximum joint linear velocities. The hip, shoulder, elbow, wrist, and the racquet reached their peak speeds in sequence, therefore confirming "the summation of speed principle."

- Due to the fact that maximum elbow and wrist velocities were comparable between the elite and the high-performance players, one can assume that the elite group's tendency towards higher shoulder velocities contributed to the obvious trend of increased horizontal racquet velocities in this group.

- Increased racquet speed for both groups when balls were played cross court instead of down the line. Cross court shot is safer (mainly due to the longer distance); thereby, giving a meaningful general reason why shots in the present study were played faster in the cross court situation.

-The elite players tended to increase their racquet velocity in the vertical direction when playing down the line. It seems that the elite players in this study imparted more topspin to the ball when hitting down the line; therefore, increasing the margin for error over the net.

- The rear leg drive is mainly responsible for the pelvis and the later trunk rotation in the tennis forehand.

- During the extension of the back leg, the rotational velocity of the pelvis in the elite group increased until it reached a maximum mean of about 541 deg·s-1, 0.075 seconds prior to ball contact. This timing of peak hip rotation velocity was exactly the same in a study of baseball batting (Welch, 1995).

- Nevertheless, the high-performance players reached their maximum pelvis angular velocity significantly earlier (-0.093 ± 0.012 s).

- The same results with respect to timing (Elite: -0.057 ± 0.004 vs. High performance: -0.075 ± 0.011 s) were found for the trunk rotational velocity, a parameter which has been found to strongly correlate with racquet velocity, regardless of skill level and the type of stance used in a previous study (Bahamonde and Knudson, 1998).

- The comparison of pelvis and trunk rotations gives a plausible explanation why the elite players tended to create greater horizontal racquet speeds. Even though maximum peak values of the pelvis and the trunk were similar between the two groups, their different timing patterns led to higher values in the elite group through impact.

- Due to its great mass, e.g., ~70% of body mass (Winter, 1990) and the positive influence of trunk rotation on horizontal shoulder velocity, it can be seen as the key feature of racquet speed generation in the present study.

- The pelvis and the trunk slowed down naturally. Consequently, there is no need to block certain segments.

- Both groups increased internal rotation of the shoulder very late in the swing, which was similar to findings in the serve (Elliott et al., 1995; Fleisig et al., 2003) and the forehand (Bahamonde and Knudson, 2003; Takahashi et al., 1996), but reached their peak values even after impact. These results demonstrate that both groups continued to increase the angular velocity of the shoulder through impact and shortly after. Although shoulder internal rotation can contribute up to 40% to the racquet speed at impact (Elliott et al., 1997), the peak values in our study must have been irrelevant in terms of racquet speed because of their occurrence after impact.

- Our findings suggest that for the improvement of the Tennis forehand - key factors forehand performance level, coaches and athletes should focus mainly on three things: proper 1) pelvis and 2) trunk rotation velocity and 3) their timing.

-A good rear leg drive will initiate pelvis rotation and, consequently, increase the separation angle, which will do its part in terms of storing elastic energy for subsequent rotations. In case of vigorous trunk angular velocity, the players will even step forward with their rear leg after impact. Overall, this can be a model for technique training in the tennis forehand.

- In terms of strength and conditioning, coaches should keep the principle of kinematic affinity between tennis groundstroke techniques and strength training exercises in mind. Therefore, they need to find exercises that mimic tennis specific movements and involve the coordination of body segments.

Seeley et al (2011). Tennis forehand kinematics change as post-impact ball speed is altered.

-Upper- and lower-extremity segments that contribute to racket head speed and corresponding post-impact forehand ball speed have been identified (Elliott et al., 1989; Elliott, 1995).

-For example, shoulder internal rotation has been identified as a key upper-extremity kinematic variable related to racket speed; shoulder internal rotation is responsible for 40% of the linear racket velocity in the forward direction and 54% of the linear racket velocity in the upward direction (Takahashi et al., 1996; Elliott et al., 1997).

-Consistent sequential movement patterns (joint angles and joint angular velocities) exist during the tennis forehand. For example, the rear knee and hip flex to angles of 52◦ and 41◦ at the end of backswing (Elliott & Marsh, 1989), while the trunk rotates 26◦ toward the side of the hitting arm (Takahashi et al., 1996). Next, an effective rear leg drive (knee and hip extension) initiates pelvis and trunk rotation toward the ball (Landlinger et al., 2010a). The forward motion of the racket is then further facilitated by coordinated upper-extremity motions that are generally believed to occur in a proximal to distal manner.

- However, kinematics should not be considered as causal mechanisms related to the kinetic origins of racket speed during the forehand groundstroke.

- In previous studies researchers have focused only on maximal effort strokes, yet a maximal effort forehand is not always representative of a competitive tennis environment.

- Tennis balls were fed to the subjects using a ball machine that was placed 4.0 m behind the net and 9.5 m in front of the subject. Each ball was ejected from the ball machine at an initial speed of 11 m/s.

- 12 highly skilled tennis players performed forehands at three different post-impact ball speeds: fast (42.7 +/- 3.8 m/s), medium (32.1 +/- 2.9 m/s), and slow (21.4 +/- 2.0 m/s).

-Several dominant-side peak joint angles (prior to ball impact) increased as post-impact ball speed increased from slow to fast: wrist extension (16%), trunk rotation (28%), hip flexion (38%), knee flexion (27%), and dorsiflexion (5%).

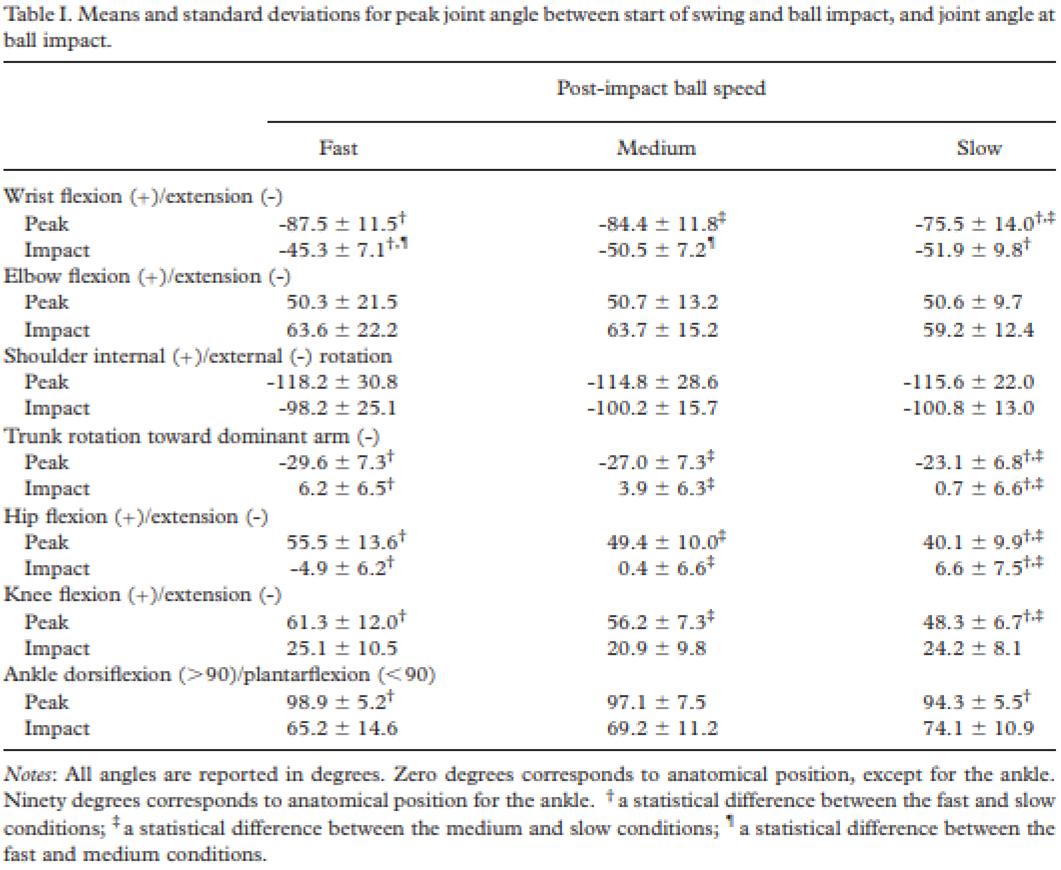


Table I. Means and standard deviations for peak joint angle between start of swing and ball impact, and joint angle at ball impact.

	Post-impact ball speed		
	Fast	Medium	Slow
Wrist flexion (+)/extension (-)			
Peak	-87.5 ± 11.5[†]	-84.4 ± 11.8[‡]	-75.5 ± 14.0[†,‡]
Impact	-45.3 ± 7.1[†,¶]	-50.5 ± 7.2[¶]	-51.9 ± 9.8[†]
Elbow flexion (+)/extension (-)			
Peak	50.3 ± 21.5	50.7 ± 13.2	50.6 ± 9.7
Impact	63.6 ± 22.2	63.7 ± 15.2	59.2 ± 12.4
Shoulder internal (+)/external (-) rotation			
Peak	-118.2 ± 30.8	-114.8 ± 28.6	-115.6 ± 22.0
Impact	-98.2 ± 25.1	-100.2 ± 15.7	-100.8 ± 13.0
Trunk rotation toward dominant arm (-)			
Peak	-29.6 ± 7.3[†]	-27.0 ± 7.3[‡]	-23.1 ± 6.8[†,‡]
Impact	6.2 ± 6.5[†]	3.9 ± 6.3[‡]	0.7 ± 6.6[†,‡]
Hip flexion (+)/extension (-)			
Peak	55.5 ± 13.6[†]	49.4 ± 10.0[‡]	40.1 ± 9.9[†,‡]
Impact	-4.9 ± 6.2[†]	0.4 ± 6.6[‡]	6.6 ± 7.5[†,‡]
Knee flexion (+)/extension (-)			
Peak	61.3 ± 12.0[†]	56.2 ± 7.3[‡]	48.3 ± 6.7[†,‡]
Impact	25.1 ± 10.5	20.9 ± 9.8	24.2 ± 8.1
Ankle dorsiflexion (>90)/plantarflexion (<90)			
Peak	98.9 ± 5.2[†]	97.1 ± 7.5	94.3 ± 5.5[†]
Impact	65.2 ± 14.6	69.2 ± 11.2	74.1 ± 10.9

Notes: All angles are reported in degrees. Zero degrees corresponds to anatomical position, except for the ankle. Ninety degrees corresponds to anatomical position for the ankle. [†] a statistical difference between the fast and slow conditions; [‡] a statistical difference between the medium and slow conditions; [¶] a statistical difference between the fast and medium conditions.

- All peak joint angles were significantly affected by post-impact ball speed, except external shoulder rotation and elbow flexion.

-Joint angle at impact- post-impact ball speed significantly affected three measures (Table I). Wrist extension was 10% less for the fast condition than for the medium condition ($p<0.007$; ES = 0.722). Trunk rotation for the medium condition was 82% greater than for the slow condition ($p< 0.001$; ES = 0.500). Hip flexion angle for the medium condition was 93% less than for the slow condition ($p< 0.001$; ES = 0.874).

- Dominant-side peak angular velocities increased as ball speed increased from slow to fast: peak wrist flexion (118%), elbow flexion (176%), trunk rotation (99%), hip extension (143%), knee extension (56%), and plantarflexion (87%).

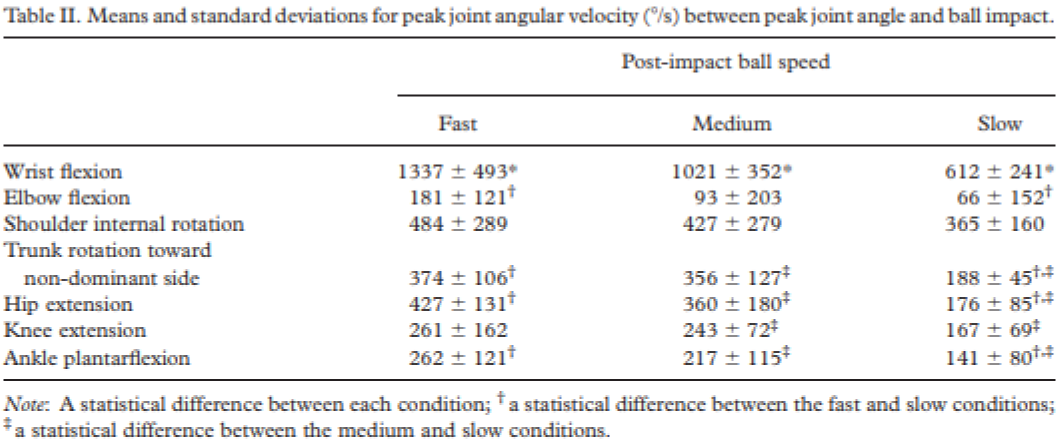


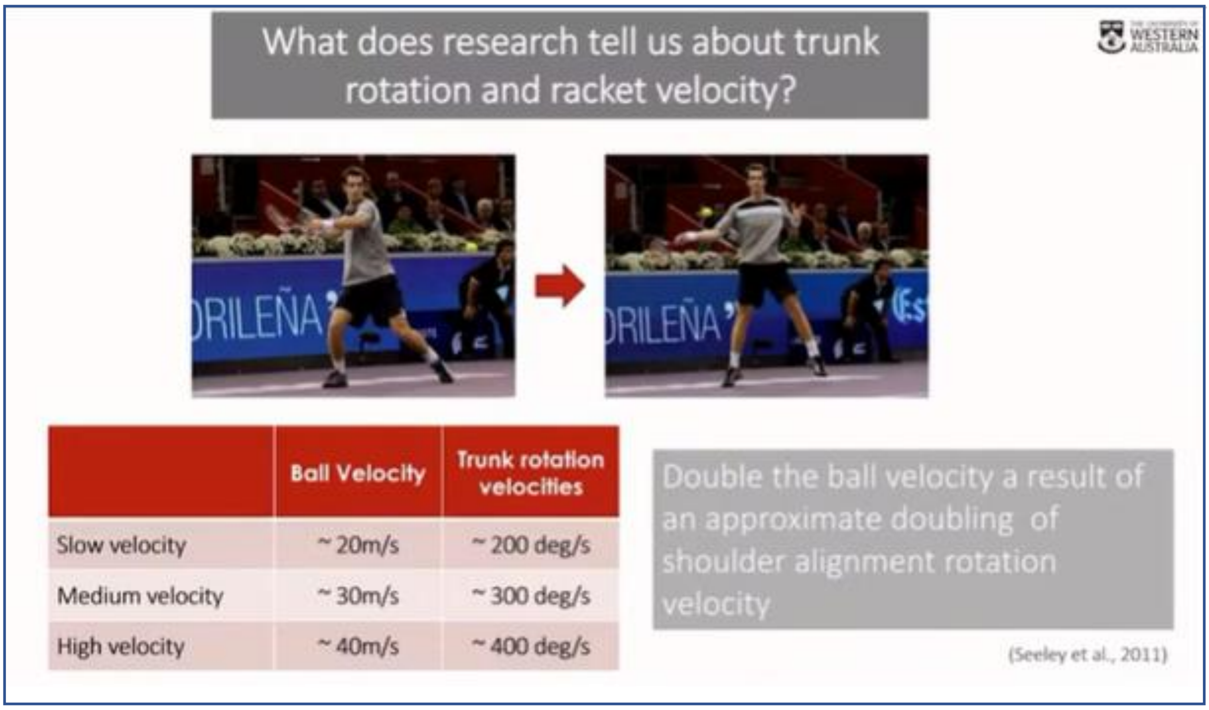
Table II. Means and standard deviations for peak joint angular velocity (°/s) between peak joint angle and ball impact.

	Post-impact ball speed		
	Fast	Medium	Slow
Wrist flexion	1337 ± 493*	1021 ± 352*	612 ± 241*
Elbow flexion	181 ± 121†	93 ± 203	66 ± 152†
Shoulder internal rotation	484 ± 289	427 ± 279	365 ± 160
Trunk rotation toward non-dominant side	374 ± 106†	356 ± 127‡	188 ± 45†,‡
Hip extension	427 ± 131†	360 ± 180‡	176 ± 85†,‡
Knee extension	261 ± 162	243 ± 72‡	167 ± 69‡
Ankle plantarflexion	262 ± 121†	217 ± 115‡	141 ± 80†,‡

Note: A statistical difference between each condition; † a statistical difference between the fast and slow conditions; ‡ a statistical difference between the medium and slow conditions.

-Similar to joint angles, most peak angular velocities increased as post-impact ball speed increased; peak shoulder internal rotation did not.

-The only peak joint angular velocity that increased as ball speed changed from medium to fast was wrist flexion; 31% greater.



What does research tell us about trunk rotation and racket velocity?

	Ball Velocity	Trunk rotation velocities
Slow velocity	~ 20m/s	~ 200 deg/s
Medium velocity	~ 30m/s	~ 300 deg/s
High velocity	~ 40m/s	~ 400 deg/s

Double the ball velocity a result of an approximate doubling of shoulder alignment rotation velocity

(Seeley et al., 2011)

-Bruce Elliot comment: Juniors on the other hand are using their upper limb segments and shoulder internal rotation/wrist to get the racket speed (getting more velocity out of the arm) rather than using their trunk- which is a better way to consistently maintain velocity. With juniors using the arm strategy, you would expect the velocities to drop off over a match.

- At ball impact, only wrist and trunk angular velocities were significantly affected by post-impact ball speed.

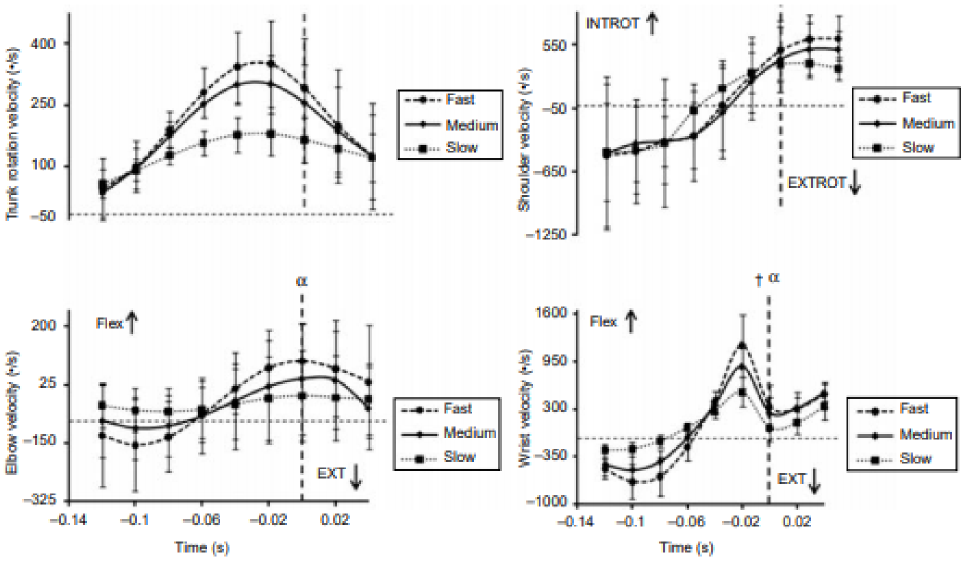


Figure 3. Means and standard deviations for upper-extremity angular velocities at various times of the tennis forehand, relative to ball impact (vertical dashed line). * Indicates a significant difference between each condition. ‡

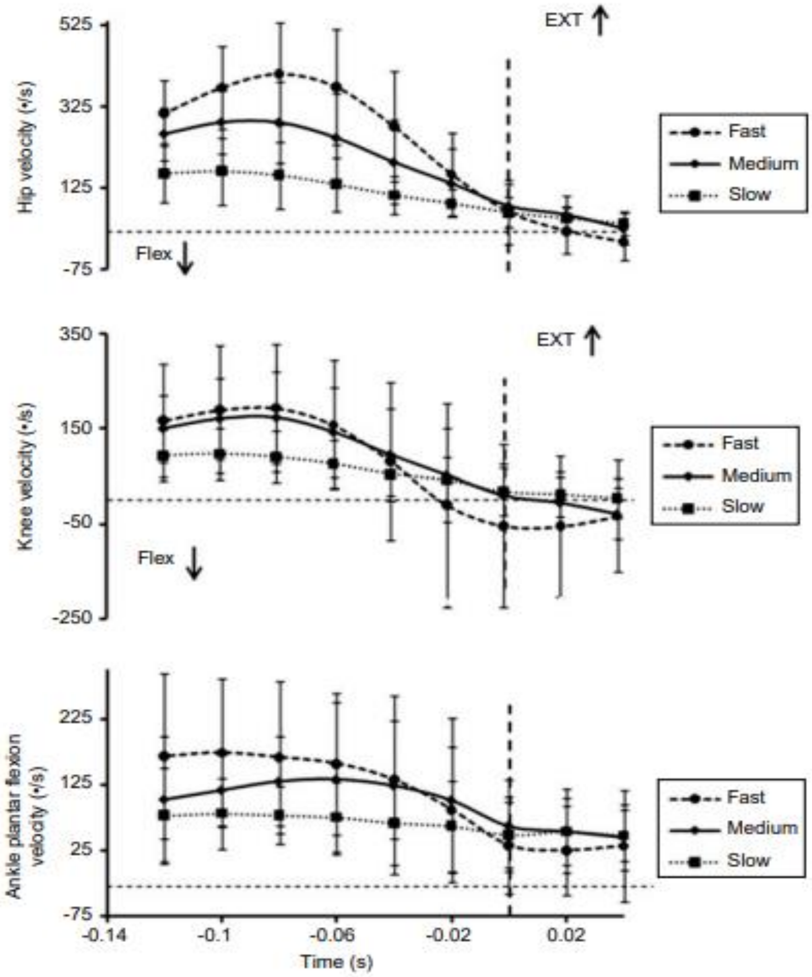


Figure 4. Means and standard deviations for lower-extremity angular velocities at various times of the tennis forehand, relative to ball impact (vertical dashed line). * Indicates a significant difference between each condition. ‡ Indicates a difference between the fast and medium conditions. † Indicates a difference between the fast and slow conditions. α Indicates a difference between the medium and slow conditions.

- Wrist flexion velocity for the slow condition was 82% less ($p<0.004$; ES = 1.055) than for the medium condition. Trunk rotation velocity for the slow condition was 35% less ($p<0.001$; ES = 1.203) than for the medium condition.

-In summary, peak joint angle and joint angle at impact were significantly influenced by ball speed for all racket-side joints, except the elbow and shoulder. Peak angular velocity was generally affected by ball speed, with the exception of the shoulder and knee joints. Conversely, angular velocity at impact was usually not affected by ball speed; only the wrist and trunk were significantly altered.

-Increased peak joint angle, prior to ball impact (as the player lowers the whole-body centre of mass during the backswing), likely contributes to post-impact ball speed. In speculation, increased peak joint angle may increase elastic potential energy stored in musculotendon units during the stretch-shortening cycle, work output, and performance.

-It is especially important for the large abdominal muscles being stretched during trunk rotation. The observed increase for trunk angle, as post-impact ball speed increased, suggests an increased separation between the hips and shoulders, and increased eccentric activation of certain abdominal muscles.

-It should be emphasized, however, that mechanical energy gained from the stretch-shortening cycle depends on countermovement amplitude and coordination, not simply the production of large joint angles.

-Segmental coordination during the forward motion influences the utilization of the stored elastic energy that may be used to accelerate the arm and racket head forward.

-Upper-extremity coordination did appear to differ slightly with changes in post-impact ball speed. This coordination change was manifest primarily in the timing differences between the trunk and upper arm: internal humeral rotation appeared to occur later (closer to impact) for the medium and fast conditions than for the slow condition. (Figure 3).

-Generally, peak joint angular velocities increased disproportionally more than peak joint angles (Table II). This implies that muscular strength may be more important than range of motion; i.e. an athlete’s ability to accelerate the racket forward is more important to post-impact ball speed than maximizing joint angle at the completion of backswing.

-In contradiction to our second hypothesis, post-impact ball speed did not significantly affect peak shoulder external rotation angle and internal rotation velocity. This is difficult to explain. Perhaps this consistency for humeral kinematics is related to the relative importance of this variable to forehand success. It is possible that shoulder internal rotation is so vital to forehand success that it remained more consistent than other joint motions.

-Another plausible explanation for this consistency may be related to the duration over which peak joint angular velocity was considered (from the beginning of the swing to ball impact). In hindsight, we noticed that many of our subjects exhibited greater internal rotation velocity after ball impact (Figure 3).

-Although the transfer of kinetic energy cannot be inferred from kinematics alone, the sequential nature of the angular velocity peaks (Figures 3 and 4) support the kinetic chain idea (lower-extremity angular velocities peaked before upper-extremity angular velocities, and proximal-segment angular velocities peaked before distal-segment angular velocities).

-Elliott et al. (1989, 1997) showed that the legs and trunk are responsible for approximately 10% of final racket head velocity. Specifically, the knee has been identified as being an especially important contributor to racket head velocity at ball impact (Girard et al., 2007; Nesbit et al., 2008; Reid et al., 2008). The present data suggest that the hip and ankle muscles are also important to forehand ball speed.

Summary of Mechanical Factors

- The limb that manoeuvres the racquet in the forehand drive is found to be on the side of the body opposite the net. This forces movement of the hips and trunk to assist in bringing the racquet head into the proper impact position.
- For the one-handed BH, as the body tums sideways to the net, the limb that manoeuvres the racquet is found to be nearest the net or where the ball will be approaching. This means that although the hips and trunk play a large role in the one-handed backhand, they cannot be used as extensively as they are in the forehand drive
- Groppel found that the one-handed backhand was basically a five-segment stroke, once the transfer of linear momentum had been accomplished by a step forward. This compares to a two-segment stroke for the two-handed backhand.
- The consistent angular positions during the forward strokes did not result from highly consistent patterns of angular velocities or accelerations.
- Professional subjects had a higher mean resultant velocity or racket at impact 21.7+/-3.3 m/s than the intermediates 16.1 +/-2.5m/s.
- Professional subjects had a significantly larger mean trunk angular velocity at impact (7.3+/-3.1 rad/s) compared to intermediate subjects (3.9+/-2.5 rads/s).
- Significant differences ($p<0.01$) and large effect sizes were observed between elite and high-performance players in linear velocity of the shoulder (2.0 vs. 1.2 m/s), angular velocity of the pelvis (295 vs. 168 ◦/s), and angular velocity of the upper trunk (453 vs. 292 ◦/s) at impact.
- The elite group showed a tendency towards higher racquet velocities (31.1 vs 29.1 m/s) at impact ($p <0.05$).
- The separation angle of the high-performance group was larger than in the elite group, although not significantly greater. This trend leads to the assumption that a greater separation angle is surely beneficial for pre-stretching the large trunk muscles, but does not guarantee an increased racquet speed.
- Consequently, the elite's significantly higher shoulder velocity underlines the obvious positive link of trunk rotation and linear velocity of the shoulder.
- Significant differences ($p < 0.01$) and large effect sizes were observed between elite and HP players in the timing of maximum pelvis (-0.075 ± 0.008 vs. -0.093 ± 0.012 s) and trunk angular velocities (-0.057 ± 0.004 vs. - 0.075 ± 0.011 s) before impact
- The later occurrence of maximum angular pelvis and trunk rotations were the main reasons for the tendency towards higher horizontal shoulder and racquet velocities in the elite group
- Mean forward swing time of the tennis forehand for the cross court and down the line situation did not vary between elite (0.324 ± 0.086 s) and high-performance players (0.326 ± 0.064 s).
- Shortly after the end of the backswing, both groups reached their maximum displacement of the hips, followed by the shoulders. The timing of the maximum separation angle later in the stroke points out that the hips must have started the counter-clockwise rotation towards the ball earlier than the shoulders; therefore, probably increasing the pre-stretch on the trunk.

- The rear leg drive is mainly responsible for the pelvis and the later trunk rotation in the tennis forehand
- In terms of strength and conditioning, coaches should keep the principle of kinematic affinity between tennis groundstroke techniques and strength training exercises in mind. Therefore, they need to find exercises that mimic tennis specific movements and involve the coordination of body segments.
- The observed increase for trunk angle, as post-impact ball speed increased, suggests an increased separation between the hips and shoulders, and increased eccentric activation of certain abdominal muscles.

Practical Implications

Anthropometric factors

From a strength & conditioning point of view a coach needs to know what ‘world class’ looks like. As you were able to see, the height of professional tennis players is all over the place. There are successful players who measure 211 cm and others who measure 170 cm.

Height is an important matter in tennis. Shorter players generally tend to move better, but taller players can serve faster and hit better angles. While players at the ends of the spectrum will excel in one aspect but fail in another, players with an optimal height (e.g., between 185 – 190 cm for men) can usually excel at both.

Structural factors

It is generally accepted that most of the energy or force used to accelerate a tennis racket is transferred to the arm and racket from the larger muscle groups in the legs and trunk.

The ultimate goal of strength training is to improve your hitting speed in tennis to improve the useful force or specific expression of explosive force, and therefore improve the ability to apply more force in the time that the action lasts in the concentric acceleration of the racket towards the ball.

Mechanical factors

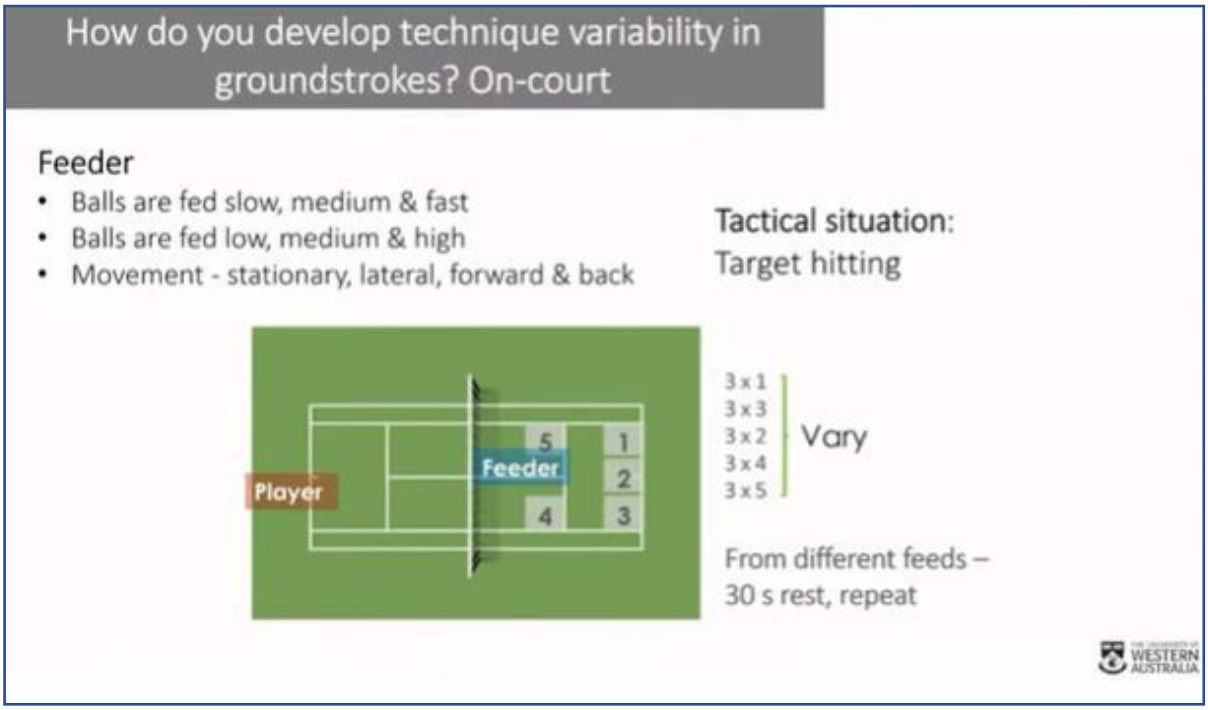
Professional players have a higher racket velocity than non- professional players. Research has shown that this is due to a higher trunk and shoulder velocity, and the timing of those velocities.

Groundstrokes- Technical Variability

-The previously stated variance of elbow and racquet orientation angles within the groups also brings terms like stroke and movement variability or differential learning, which are mainly based on the dynamical systems theory, into play.

-Lindinger and Benko (2007) pointed out that the key concept of modern coaching was lifelong differential learning and peripheral self-organizing patterns, rather than drill training and technical models. Not only the different anthropometrics of the athletes, but also the dynamic nature of tennis itself, has made it almost impossible to talk about an “identical” way of stroke production.

To this end it is advised to develop technique variability. This should not be limited to the confines of technical work on the court with the tennis coach, but the same principles could be applied with the strength & conditioning coach, and the use of medicine ball work, and other related modalities.



How do you develop technique variability in groundstrokes? On-court

Feeder
- Balls are fed slow, medium & fast
- Balls are fed low, medium & high
- Movement - stationary, lateral, forward & back

Tactical situation:
Target hitting

3 x 1
3 x 3
3 x 2
3 x 4
3 x 5
Vary

From different feeds – 30 s rest, repeat

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