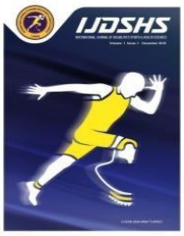

International Journal of
Disabilities Sports and Health Sciences
e-ISSN: 2645-9094

REVIEW ARTICLE

Field and Court-Based Tests Used in the Determination of Physical Performance in Tennis

Mekki ABDİOĞLU[1*], Hakkı MOR[2] and Ahmet MOR[3]

[1]Ankara University Institute of Health Sciences, Department of Sports Sciences, Ankara / Türkiye
[2]Ondokuz Mayıs University, Yaşar Doğu Faculty of Sports Sciences, Samsun / Türkiye
[3]Sinop University, Faculty of Sports Sciences, Sinop / Türkiye
[*]Corresponding Author: mekkiabdioglu@gmail.com

Abstract

Tennis matches were won based on factors like technique and strategy when wooden rackets were in use. But today, with the increase in technology, fiber carbon rackets, and advanced racket string are used in matches. This has increased the game structure of tennis to high-intensity levels. Players need to improve their physical capacity to perform at this level. Because tennis has shifted towards a branch where not only technical capacity is not enough, and strength, power, speed, and endurance are also at the forefront. Some performance tests are conducted to develop and monitor these motoric characteristics. Sport-specific technical skills and a high physical performance profile are the dominant factors in tennis. Conditioning test batteries help to analyze the performance levels of amateur and elite-level tennis players at different levels in the laboratory and on the court. In line with this view, some tennis-specific field tests have been developed in the literature. At the same time, these tests have been compared with laboratory tests and have validity and reliability. Thanks to these developed tests, it provides the opportunity to determine the performance profile of the individual at different times of the year and to adjust the individual training program individually according to these test results. Therefore, this review aims to describe and evaluate the different performance tests recommended and used by performance coaches, sports scientists, and organizations (national tennis federations).

Keywords
Tennis, Laboratory Tests, Field Tests, Performance

INTRODUCTION

Tennis is a popular sport played professionally and recreationally by large masses, followed by large audiences. The 2017 Australian Open men's final game, one of the four Grand Slam tournaments, was watched by 4.4 million people in Australia and 11 million in Europe. Professional tennis players participate in tournaments in different countries throughout the year. More than 500 international tournaments are annually scheduled on the professional tennis tournament calendar, including matches for men's and women's players, wheelchair players, and the national teams (Davis Cup, Fed Cup) (**Laursen & Jenkins, 2002**). The tournament season for professional tennis players approximately 10.5 months, with 64 tournaments in 31 different countries, and the off-season in tennis is almost nonexistent. The general game structure of tennis consists of short periods of moderate intensity, long periods, short periods of maximal or near maximal loads, sudden short accelerations-decelerations, repetitive overhead (spike, serve)

Received: 15 June 2023; Revised ;06 August 2023 ; **Accepted:** 23 November 2023; **Published:** 25 January 2024

How to cite this article: Abdioğlu, M., Mor, H., & Mor, A. (2024). Field and Court-Based Tests Used in The Determination of Physical Performance in Tennis. *Int J Disabil Sports Health Sci*;7(1):245-260. **https://doi.org/10.33438/ijdshs.1315076**

and basic hitting (forehand-backhand) movements, and rest periods determined by official rules (**Bernardi et al., 2002**).

Tennis is played over 3 or 5 sets on different courts such as hard, artificial grass, clay, and grass. The players' match tactic in tennis influences the rally's duration (continuous return shots after the serve). The average rally time in a match can be more than 15 seconds for strong back-line (baseliner) players and less than 5 seconds for net players (serve-volley) (**Bernardi et al., 2002**). Tennis is a high-intensity, fast-paced sport (**Kovacs, 2007**). The peak speed of the racket during a serve was recorded to be between 100-116 km/h, while the speed of the ball was recorded to be between 134-250 km/h (**Bernardi et al., 2002; Fernandez-Fernandez et al., 2006**). During a tennis match, players engage in high-intensity rallies that typically last for a short duration of 4-10 seconds. Tennis has short recovery intervals (20 s) at the end of each point (**Laursen & Jenkins, 2002; Smekal et al., 2001a; Smekal et al., 2001b**). Tennis matches typically last longer than an hour and, in rare instances, even more than five hours (e.g., the 2012 Australian Open men's final match lasted 5 hours 53 minutes). Generally, the average match duration is 1.5 hours (**Kovacs, 2007**), while ball retention rates range from 20 to 30 percent (**Fernandez-Fernandez et al., 2006; Mendez- Villanueva et al., 2007**).

A combination of continuous and intermittent loading characterizes tennis. Players cover approximately 3 meters for each stroke and 8–12 meters on average for each point. A match consists of approximately 1000 strokes, and competitors run an average of 3 kilometers. On average, competitors strike the tennis ball 2-3 times per point, and the ball changes direction 4 times per rally (**Fernandez-Fernandez et al., 2006**). Players typically engage in 300-500 high-intensity runs during a three-set tennis match. The average rally duration per point is 5 to 7 seconds, and ten percent of strokes are made within the 2.5 to 4.5 meters area. **(Mendez-Villanueva et al., 2007**). Accordingly, a study reported that skill accounted for 45 percent, game tactics for 20 percent, and physical capacity for 35 percent (**Nader, 2006)**. Serving and volley series, running to react to a stroke from the cross-court, hours of matches with high intensity, powerful explosive moves, or strenuous training sessions are essential elements of optimal tennis performance, and a high endurance capacity is required to perform these moves repetitively. Hence, the excessive physical demands of modern tennis require tennis players to have a high level of aerobic and anaerobic fitness (**Roetert & Ellenbecker, 2007**).

Traditionally, three different energy systems are utilized in tennis. 70% of the energy used during high-intensity competitions comes from the anaerobic system, 20% from the glycolytic system, and 10% from the aerobic system **(Ikeda et al., 2007**). Due to the physiological needs of tennis, movements are performed at a high level of intensity; consequently, the ATP-CP system is predominantly employed, and then this depleted energy store is rapidly replenished **(Ferrauti et al., 2011**). High intensity serves during a tennis match include sudden acceleration, deceleration and change of direction, and groundstrokes. In addition to the anaerobic energy system, the well-developed aerobic energy system allows the player to recover faster during these high-intensity movements and, thus, to perform the moves as demanded **(König et al., 2001**). Anaerobic power is the work done per unit of time using the ATP-CP energy store. The fact that the players reach 90% of their maximal HR values for 2.5-3 hours during the competitions and that all strokes are made with explosive power indicates how important anaerobic power is. (**David Bishop et al., 2011; Kilit et al., 2018**). One study has shown that females who play tennis have a lower aerobic capacity than men **(Kovacs, 2006**).

During a tennis match, players must hit their serves within 20 seconds. Considering that the playing time in a rally for one point is approximately 8–10 s, the rest/load ratio is determined as 8/24 = 1/3, and energy is generated by the anaerobic lactic pathway during 2-3 minutes of high-intensity activities (like in long rallies). **Kovacs** (**2007**) supportively reported that approximately 20% of the total playing time is supplied by the oxidative pathway, while the ATP-CP supplies 80%.

In some studies, heart rate (HR), blood lactic acid (LA) and MaxVO$_2$ were measured to determine the performance status of tennis players (**Baquet et al., 2002; Buchheit & Laursen, 2013; Sperlich et al., 2011**). Accordingly, in a tennis match, the mean HR ranged between 70% and 80% of maximal HR, whereas during high-intensity rallies, these values were between 90% and 100%. Also, MaxVO$_2$ was reported at approximately 50% to 60% in moderate-intensity rallies, while $MaxVO_2$ was reported above 80% during high-intensity rallies (**Harrison et al., 2015**). Performing tennis competitions on different surfaces, at different intensities and durations, causes athletes' LA accumulation fluctuations (**Fernandez-Fernandez et al., 2007; Fernandez-Fernandez et al., 2009**). However, LA values remain low during the match, and average LA values are between 1.7 and 3.8 mmol/L, which is more than 8 mmol/L in some elite players. (**Fernandez-Fernandez et al., 2007**).

Modern tennis has evolved into a physically demanding sport characterized by powerful groundstrokes and explosive serve speeds. Motor skills, including strength, power, agility, speed, mental alertness, and a highly developed neuromuscular coordination ability, have also been linked to tennis performance (**Girard & Millet, 2009; Ulbricht et al., 2016**). In long-lasting matches, fatigue leads players to make more mistakes in the final set (**Girard et al., 2008**).

Aerobic capacity is usually defined as the maximum amount of oxygen the body can utilize during intense exercise. $MaxVO_2$ was found between 57 and 65 $ml/kg^{-1}/min^{-1}$ in tennis players who are at the top of the world rankings **(Banzer et al., 2008; Smekal et al., 2001a**). Surprisingly, the aggressive players who play continuous serve-and-volley have lower $MaxVO_2$ values than the baseliners.

Green et al. (**2003**) reported that the $MaxVO_2$ value of an elite tennis player should be more than 50 $ml/kg^{-1}/min^{-1}$. In tests conducted on the court, the $MaxVO_2$ was found to be between 44-60 $ml/kg^{-1}/min^{-1}$ (**Fargeas-Gluck & Léger, 2012; Ferrauti et al., 2011**). In another study, it was suggested that the aerobic capacity of professional tennis players was 55-65 $ml/min^{-1}/kg^{-1}$, and the players typically competed in an average of 40 tournaments per year (**Banzer et al., 2008**). The $MaxVO_2$ values of tennis players were measured using both field and laboratory tests. MaxVO2 was found to be 41-49 $ml/kg^{-1}/min^{-1}$ in female and 54-66 $ml/kg^{-1}/min^{-1}$ in male **(König et al., 2001**).

Heart Rate is a practical method used to determine the intensity of exercise. There is an increase in both $MaxVO_2$ and HR in tennis matches (**Bernardi et al., 2002**). During or after a high-effort rally, HR reaches its maximum, and this value drops after a 90-second rest during players' field changes. In elite tennis players, depending on the intensity of the play, the maximum HR can increase up to 80-85% (**Fernandez-Fernandez et al., 2009**).

A study determined the average HR values of trained players aged 20-30 during the match as 140-160 beats per minute (bpm). However, HR was found to be 190-200 bpm during prolonged rallies due to high-intensity strokes (**Bergeron et al., 1991**). Another method used to determine the performance status of the players is the measurement of lactic acid. In a study, the LA level was measured as 3-4 mmol/L in trained tennis players during a singles match **(König et al., 2001**). However, during long and fast rallies, the lactate level can be as high as 6 mmol/L. Additionally, lactate level can be influenced by various factors such as the athlete's physical condition, the type of tournament, the number of sets (3 to 5 sets), the duration of the match, and the type of court surface (clay, grass, or hard court) (**König et al., 2001**).

Selecting appropriate tests is crucial to assess tennis players' performance based on the sport's specific requirements. Developing test batteries allows trainers to analyze players' athletic profiles and assess their training programs' efficacy. Therefore, the aim of this review was to define and evaluate the field-based and court tests used in tennis to determine the performance of tennis players.

MATERIALS AND METHODS

Initially, only tennis-specific field tests were selected as the criteria for selecting the tests. Tests associated with intermittent sports, such as tennis, were then selected. Although laboratory tests are also used in tennis, these tests were not described in detail in this study. In addition, some basic tests for each sport (such as strength and power) were also included in this study. Articles published before March 2023 were identified using Google Scholar (**http://scholar.google.com.tr/**) (**http://scholar.google.com.tr**/) and Pubmed (**http://www.ncbi.nlm.nih.gov/pubmed**) search engines. The keywords used in the search were "tennis" and "test" with words such as field tests, performance, speed, change of direction, aerobic, anaerobic, and strength. Reference lists of included studies, official publications of the International Tennis

Federation (ITF) and national tennis federations were also reviewed.

RESULTS

Laboratory and Field Tests Used in Testing Biomotor Characteristics in Tennis

Tennis is a sport with a complex interaction of various motoric characteristics (such as strength and agility), metabolic pathways (such as aerobic and anaerobic), and a high level of skill, which is a prerequisite for successful performance. In order to target these characteristics and maximize individual improvements, training efficiency and training should be defined according to a specific workload, the most important limiting performance factors, and individual technical and physical needs (**Fernandez-Fernandez et al., 2009**). For this reason, performance tests should be carried out to determine the condition of the players. These tests might give coaches more information about the player's physical performance. Short and long-term training programs are then adjusted in a general and individual way, and objective feedback is provided to motivate coaches and players to work better. One of the essential prerequisites in the structure of long-term athlete development is the regular physical performance assessment. In this process, the tests to be performed in determining the performance should be determined according to the player's needs. For speed and change of direction tests in tennis, 10 m, 20 m, Illinois test T-test and 5-0-5 are used in general tests, while the Sideward movement test, Shuttle sprint, Reactive agility, and Spider test are used in tennis-specific tests. For strength and power, general tests, Countermovement jump, squat jump, and dynamometer isokinetic tests are used, while medicine ball throw (overhead, forehand, backhand), medicine ball throw shot put tests are used in tennis-specific tests. Aerobic and anaerobic general tests, treadmill test, wingate test, repeat ability test, yo-yo IR1, and shuttle run tests are used, while in tennis-specific tests, smekal ball machine test, specific incremental test, Loughborough intermittent tennis test and test to exhaustion specific to tennis tests are used.

The specific criteria of validity, reliability, and objectivity of all tests to be used in the performance assessment should also be taken into account. In addition, laboratory or field-based tests can be selected, and these tests can be planned as crucial elements in creating the athlete profile and measuring training adaptation and the efficiency of the training program (**Hoff, 2005**).

In the context of individual sports, laboratory tests are commonly employed to evaluate key performance indicators. However, field-based methods may prove more advantageous, as laboratory tests are constrained in their ability to comprehensively assess an athlete's energy system, muscle group, and overall performance. Therefore, field-based tests are more suitable for measuring the demands of sports with complex playing patterns, such as tennis. Field tests allow a large number of participants to be tested simultaneously. Therefore, it is also easier to use by coaches and researchers (**Kovacs, 2006**).

The development and application of physical tests in tennis must be integrated into a complex scientific approach that can be used to design a long-term, sport-specific, and individual training optimization model. The first key step in this model is the knowledge of the workload profile during competition, which can be defined by combining the athlete's movement patterns with physiological demands (HR, LA, MaxVO$_2$). Therefore, data obtained during tennis matches can be used as external criteria for developing tennis-specific tests and designing specific training programs.

Laboratory Tests in Tennis

Aerobic and Anaerobic Capacity

Treadmill tests are commonly conducted in laboratory measurements. The assessment of aerobic capacity in the treadmill test involves the implementation of various test protocols that gradually increase the workload. Treadmill tests are common methods employed to assess an individual's aerobic capacity. Typically, these assessments are conducted at a pace of 8 to 10 km/min. The tests start at a fast pace and progressively increase until the point of exhaustion is reached by the athletes **(Brechbuhl et al., 2018; Fernandez-Fernandez et al., 2009; Kilit et al., 2018**).

In a study, a treadmill test and a tennis-specific test, the Specific Incremental test, were designed to determine the aerobic capacity of tennis players (**Girard et al., 2006**). 9 elite tennis players participated in the study. As a result of the study, the MaxVO$_2$ values of the participants were determined as 58.9 ± 5.3 (ml·kg^{-1} ·min^{-1}) in the treadmill and 63.8 ± 5.7 (ml·kg^{-1} ·min^{-1}) in the field test.

The higher oxygen consumption in the field test allowed the field test to be designed intermittently and thus allowed the participants to recover. In another study, the treadmill test values of 12 recreational players participating in the test were determined as 58.3 ± 4.3 (ml·kg^{-1} ·min^{-1}), while the participants' tennis-specific ball machine test values were 52.4 ± 3.7 (ml·kg^{-1} ·min^{-1}) (**Smekal et al., 2000**). Striking the ball from the opposite direction in this specific test resulted in premature exhaustion for the tennis players.

As in most sports, the 30 s Wingate test is used in tennis (**Tanner & Gore, 2012**). Although it is known that short-term exercise tests are insufficient to consume anaerobic energy stores, the Wingate test, which is a basic anaerobic test, is frequently used (**Buchheit & Rabbani, 2014**). The study conducted on elite female tennis players utilized the Wingate test to assess their anaerobic power status; however, a weak correlation was reported between maximum power and player rankings (**Ziemann et al., 2011**). Therefore, more specific tests need to be developed for tennis players.

Maximum Strength and Isokinetic Strength

Different isometric tests are used to determine the maximum voluntary muscle contraction (MVMC). These tests are usually carried out with the help of dynamometers (such as back-leg, shoulder, and hand grip dynamometer) or fixed resistance machines (bench press or squat) for different muscle groups (**Kelln et al., 2008**). However, in a study, the reliability of these tests was questioned due to the weak correlation between isometric test results and dynamic performance test results (**Murphy & Wilson, 1997**). To assess the difference between the dominant and non-dominant arm in tennis players, hand grip dynamometer measurement is widely used because of its practicality and low cost (**Ducher et al., 2005**). The hand dynamometer test results used in tennis players are presented in Table 2 according to different age groups.

Table 1. Laboratory test in tennis

Studies	Population	Level of Participants	Subject Age (y)	Aerobic Tests	MaxVO$_2$ (ml·kg^{-1} ·min^{-1})	HR (max·min^{-1})	LA (mmol/L)
Smekal et al. (**2000**)	12 M	Recreational	26.4 ± 5.2	Treadmill	58.3 ± 4.3	193.0 ± 10	12.5 ± 1.3
Girard et al. (**2016**)	9 M	Regional	16.0 ± 1.6		58.9 ± 5.3	194.1 ± 7.7	
Kilit and Arslan (**2016**)	14 M	Professional	23.0 ± 1.9		54.9 ± 2.2	195.1 ± 1.4	

HR: heart rate, LA: lactic acid.

Strength can be evaluated using various test equipment (free weights or fixed resistance machines). Traditionally, different test protocols (based on 1-3-5-10 repetition maximum (RM) for bench-press or squat) have been used to measure maximum strength (Brown and Weir, 2001). Free-weights can frequently be regarded as the most accurate way to determine sport-specific functional strength, as the athlete has a greater range of motion (ROM). However, such procedures may not be easy to control; because athletes need to be experts in the form of movement and be able to lift maximum loads. The purpose of testing maximum strength is that an increase in maximum strength is usually associated with an increase in relative strength and, consequently, an improvement in strength capabilities (Cronin and Henderson, 2004). In a study of female tennis players, although there was a moderate correlation between the speed of the ball in the service, forehand and backhand strokes, and the 1-RM military press (overhead) value, there was a weak correlation in the bench press (**Kraemer et al., 2003**).

The 1RM isotonic strength measurement of large cohorts has disadvantages, such as the long duration of the test and the risk of injury to the participants. For this reason, it has been suggested to use single sets in which 1RM values are estimated based on the number of repetitions performed with submaximal weight (5 repetitions with 80% of estimated 1-RM) (**Reynolds et al., 2006**). Isotonic tests are rarely used in tennis. Only normative values are obtained by tests conductedby a few national tennis federations (**Fernandez-Fernandez et al., 2014**).

Isokinetic measurements, typically using open kinetic chain exercises used to measure strength and power output at constant angular velocity throughout the movement, are used extensively in the assessments of sports injuries and in the rehabilitation field. Isokinetic tests were also employed in tennis studies. However, most of these tests were implemented to evaluate the status of the training techniques rather than the performance prediction, and several studies found different correlations on performance **(Cohen et al., 1994; Mont et al., 1994)**. The high incidence of overuse shoulder injuries in elite junior tennis players often results in the high repetitive stresses inherent in the game and muscle imbalances in the humeral rotators.

In a study, concentric glenohumeral joint internal and external rotation forces were measured to develop a bilateral descriptive profile of the players. A total of one hundred and forty-seven elite young players aged between 12 and 21 participated in this research and were tested bilaterally with 90° abduction with Cybex isokinetic dynamometer. Research results showed specific adaptations in shoulder strength and described a relative muscle imbalance between the inner and outer rotators in the dominant arm of elite young tennis players (**Ellenbecker & Roetert**, **2003**). Another study aimed to create population- and age-specific descriptive profiles of concentric isokinetic knee extension and flexion strength in elite young tennis players. In addition, it was investigated whether there were bilateral differences between the extremities and in age ranges (**Ellenbecker et al., 2007**). 103 male and 53 female tennis players aged 11-21 participated in the study. Bilateral concentric knee extension and flexion strength were tested isokinetically at 180 and 300 °/ s on a Cybex 6000 isokinetic dynamometer using a standard bilateral test protocol. There was no significant bilaterally significant difference between the dominant (racquet side) lower extremity and the contralateral non-dominant side in knee extension and flexion strength normalized to body weight or hamstring quadriceps strength ratios in male and female subjects. Male subjects aged 11-15 and 16-21 years showed significant increases (p= 0.001) in knee extension and flexion strength. Female subjects showed no significant change in normalized knee extension or flexion strength in their age range. Population and age-specific isokinetic descriptive data obtained from elite tennis players can guide the development and monitoring of performance improvement and rehabilitation programs for elite tennis players.

Table 2. Hand grip dynamometer tests

Study	Population	Level of Participants	Subject Age (y)	Grip Strength (kg)	
Ulbrricht et al. (2013)	24 M	Regional	11.48 ± 0.34	Dominant arm	24.17 ± 3.42
	26 M		13.05 ± 0.46		28.62 ± 5.56
	28 M		14.97 ± 0.46		42.96 ± 7.31
	17 F		11.46 ± 0.30		23.24 ± 4.10
	28 F		12.87 ± 0.51		29.00 ± 5.53
	24 F		14.89 ± 0.47		35.25 ± 4.37

In a study conducted in tennis, a positive correlation was found between isokinetic strength values and the speed ($km\cdot h^{-1}$) of strokes (spike, serve, forehand, and backhand) in tennis **(Perry et al., 2004)**. In accordance with this, several studies have shown that elite junior players' trunk rotation and flexion strength are highly correlated with forehand and backhand medicine ball throw performance (**Ellenbecker and Roetert, 2004; Roetert et al., 1996**). **Signorile et al.** (**2005**) reported a minimal association between the leg, shoulder, and wrist strength and serve speed in their research. Most functional movements demonstrate angular velocities that exceed the limits of isokinetic dynamometers (**Signorile et al., 2005**). Consequently, the measurements obtained using such dynamometers fail to accurately represent the functional range of motion essential for tennis players.

Therefore, other strength measurements (for instance, the test with medicine ball throws for the core area) should be included in testing procedures for tennis players. Also, these technologies (isokinetic equipment) are difficult and expensive to implement, making it challenging to implement tests.

Reactive Agility Test

The test was designed in a Y shape to determine the players' agility. With the help of the light timing system (Fusion Sports, Coopers Plains, Australia), players' reaction times are recorded (**Cooke et al., 2011**). After a 10 m run, whichever light comes on from the photocells, the players move in that direction. Another test is the Planned and reactive agility test applied by **Cooke et al**. (**2011**) on tennis players. In the test, which is 3 m between the starting point and the photocell, and there are 3 doors side by side, one of the doors randomly turns on, and the player passes through the lighted photocell door and then returns to the starting point. In a study by Cook et al. (2011) on female tennis players, planned agility was 7.7 s (Z score: 0.23); reactive agility was 8.35 s, (Z score: 1.26); reaction time was determined as 0.65 s (Z score: 1.35).

Field Tests Used in Tennis

Aerobic and Anaerobic Capacity

Treadmill test protocols made in the laboratory using an audible signal were adapted to field conditions to create field tests, allowing more than one participant to participate (**Ferrauti et al., 2011**). Field tests are more practical than laboratory tests because field tests do not require any equipment. These field tests include protocols such as the Cooper 12 min run/walk test, the Montréal track test, the Shuttle run test or the Vam-eval test. The protocols differ in these tests, but the main objective of the tests is to calculate the MaxVO$_2$ levels of the athletes by indirect methods **(Chtara et al., 2005; Uger and Boucher, 1980**). However, these tests failed to reflect the intermittent nature of racquet sports as they require a continuous running performance. Considering the demands of interval sports, it was questioned whether these tests could meet the demands of tennis. This question led to the development of more accurate and reliable intermittent sport-specific tests such as the Yo-Yo Intermittent Recovery (Yo-Yo IR) and the 30-15 Intermittent Fitness Test (30–15 IFT) (**Spencer et al., 2005**). The Yo-Yo IR test consists of a 2×20 m shuttle run at increasing speeds with a 10 s active recovery period (controlled by audio signals). Level 1 (Yo-Yo IR1) starts at a lower speed (stage 1, 10 km·hr^{-1}; final stage (15th), 19 km·hour^{-1}) and the test continues gradually with an increasing workload. Tests measuring aerobic capacity in tennis and their results are presented in Table 3.

Table 3. Aerobic tests in tennis

Study	Population	Level of Participants	Subject Age (y)		Aerobic Tests	MaxVO2 (ml·kg^{-1}·min^{-1})	HR (max·min^{-1})
Ferrauti et al. (2011)	14 M	International	24.0 ± 5	Aerobic specific tests	HTTT	60.4 ± 5.3	198 ± 7
Smekal et al. (2000)	12 M	Recreational	26.4 ± 5.2		SBMT	52.4 ± 3.7	192 ± 9
Fargeas-Gluck et al. (2012)	5 M 5 F	Regional	12.9 ± 0.3		Navten test	54.2 ± 5.9	202 ± 6.1
Girard et al. (2006)	9 M	Elite	16.0 ± 1.6		SIT	63.8 ± 5.7	190 ± 5.2
Srihirun et al. (2014)	20 M	College	16.6 ± 0.6		LITT	44.0 ± 6.40	
Brechbuhl et al. (2018)	8 M 19 F	International	16.8 ± 0.9	General aerobic tests	TEST	55.2 ± 5.5	199 ± 6.3
Kilit and Arslan (2016)	14 M	International	23.0 ± 1.9		YO-YO IR1	55.1 ± 0.9	196.4 ± 1.9
Fargeas-Gluck et al. (2012)	5 M 5 F	Regional	12.9 ± 0.3		Shuttle run	54.9 ± 6.0	208 ± 9.5

HTTT: hit-turn tennis test; SBMT: Smekal ball machine test; SIT: Spesific incremental test; LITT: Loughborough intermittent tennis test; TEST: Test to exhaustion specific to tennis.

The 30–15 Intermittent Fitness Test (IFT) consists of a 40m shuttle run for 30 seconds at a certain speed with 15 seconds of active recovery at the end of each stage. The first 30 s phase of the run starts at 8 km/h^{-1} and increases at 0.5 km/h with each stage. The test is done on a flat area of 40 m, and the midpoint of the area is marked and 3 m areas are determined on both sides of this marked area. Then the field is divided into 3 sections (A-B-C). Before starting the test, participants stand ready at point A. Then, with the start beep, the participants run toward points B and C. At the 2nd beep, the participants should be approximately passing through the area of point B and at the 3rd beep, the participants must be on point C or in a 3 m space. After completing this step, participants hear a different beep. After this beep, the participants enter the recovery period of 15 seconds and slowly move towards the first 3 meters area in their running direction (at points A, B or C).

During the rest period, the athletes wait until the 15 s time expires in the 3 m area, and after 15 s, the athletes start running from the 3 m area where they stand to their running direction. The test ends when the athlete stops running or fails to reach 3 m areas 3 times in a row simultaneously with the beep. Since the final running speed measured with this test is reliable and accurate in regulating the training intensity of the athletes, this protocol is widely used in intermittent sports branches (**Buchheit & Rabbani, 2014**). However, these tests were not appropriate for the playing structure of tennis as they could not be performed on the tennis court. In addition, these tests did not reflect the active muscle groups and running distance aspects frequently used in tennis (**Tanner and Gore, 2012**). Therefore, researchers studying this situation tried to develop more specific protocols. In this regard, different protocols have been published in recent years with acceptable accuracy under standardized conditions. **Weber & Hollmann** (**1984**) were the first to describe an on-court exercise test with an increased workload to assess aerobic power in tennis players.

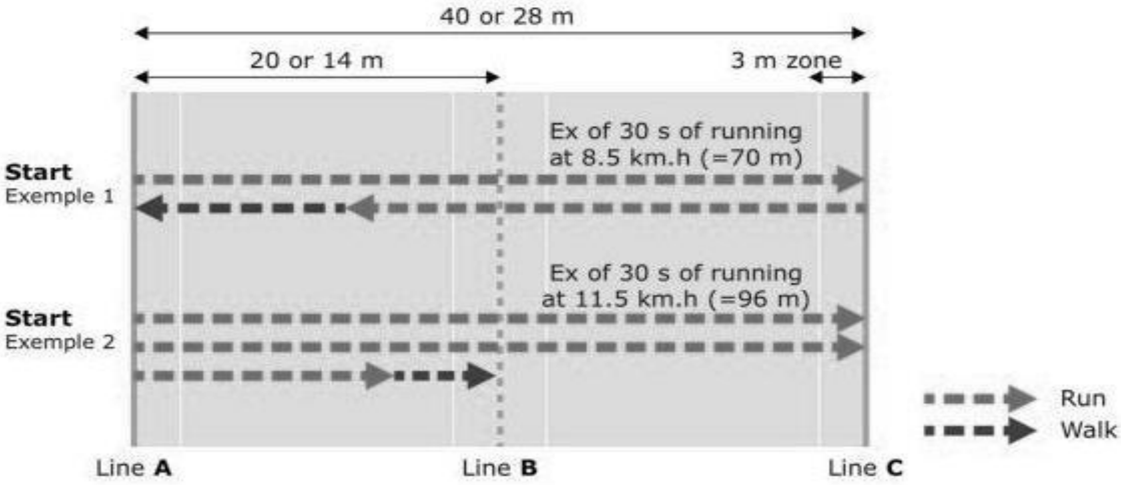

Figure 1. The 30–15 Intermittent Fitness Test (IFT)

This test was designed with a ball machine on the tennis court. The ball machine throws the ball to the right and left at certain intervals (Figure 2). Athletes had to perform both side step and cross-foot crossings in a predetermined order (for example, ball speed, flight height, and landing points) as a requirement of the game structure of tennis (**Weber & Hollmann, 1984**). This initial approach was based on some methodological distinctions. It also required the use of a ball machine to test. Subsequently, several more test protocols were developed that evaluated various physiological and skill performance criteria similar to this test (ball thrower, measurement of the velocity of strokes with radar) (**Cooke & Davey, 2005**). In addition, the primary test criteria (rhythm, direction and speed of ball feed) and athlete movements (strokes, running details) took much work to standardize. Thus, they could not be used routinely, making it difficult for reliable and valid comparisons among tennis players.

For this reason, the Hit-TurnTennis Test (HTTT) and Girard Test (GT), which can be easily performed on the court without requiring any expensive equipment, can be applied **(Ferrauti et al., 2011; Girard et al., 2006**). Both protocols were tested with acoustic feedback with an increased workload protocol with tennis-specific footwork. With these tests, tennis players' endurance profiles can be easily determined. The HTTT and GT phases each have an average duration of 40–50 s, with 10–20 s rest intervals with some protocol variation.

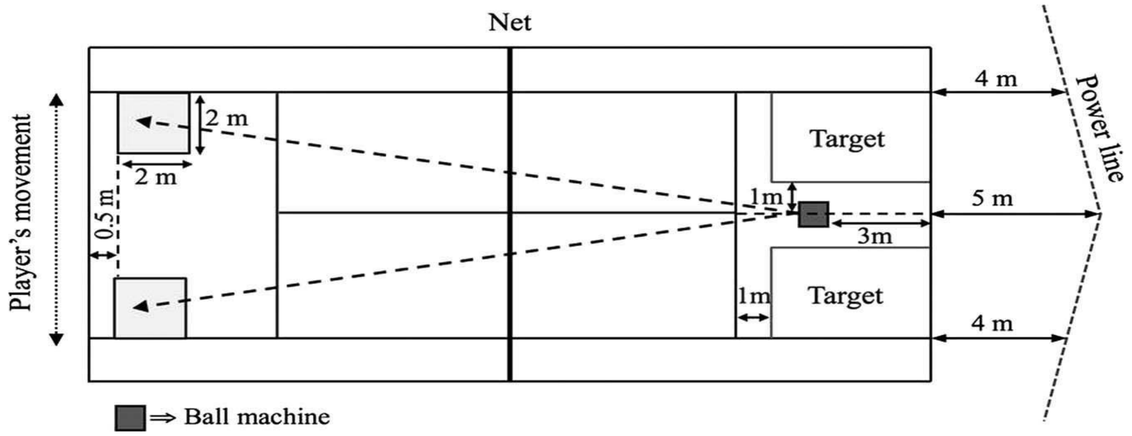

Figure 2. Schematic setting for the specific endurance field test.

In the Girard Test, the running direction, movement technique, and striking position are more consistent and somewhat uncertain than in the HTTT. This test protocol is more appropriate for the game pattern of tennis but makes the preparation and application of the test difficult. In both cases, it should be emphasized that acceleration quality is far from reality, and there are individual differences. Upper extremity exercises have been shown to contribute significantly to overall energy demand in tennis, so these exercises should be incorporated into the training plan (**Fernandez-Fernandez et al., 2014**). **Fernandez et al.** (**2014**), in their study on German athletes, defined the HTTT test stages as 13-19.4 in males aged 12-18, as a result of the in-court aerobic capacity test (HTTT), and determined that these values were between 12-16.8 in females in the same age group. To measure the anaerobic capacity of tennis players, step-running can be utilized or the anaerobic capacity of an individual can be determined by measuring the LA ratio in the blood after running a certain distance (80 m, 100 m or 200 m) at maximum speed (**Bleicher et al., 1998; Spriet et al., 2000**). However, for anaerobic tests, a more specific approach, the repeated sprint ability (RSA) test is also used. Repeated sprints can also be performed in the laboratory with a bicycle ergometer.

In addition, repeated sprints in the field (6-10 consecutive repetitions, lasting 5-6 seconds or running in the range of 20-40 m and having short rest intervals) can also be applied using different protocols (**David Bishop et al., 2011; Spencer et al., 2005**). Few studies have been published on the different protocols and normative values of RSA tests used in tennis. In tennis, RSA has been primarily implemented as a training protocol. The results of several studies carried out are presented in Table 4. Tennis Australia (governing body in Australia) recommended a protocol with a 10x20 m and 20-second rest interval (two performance points, sprint time in seconds, and percent reduction score) as the RSA test. A more specific tennis protocol was used in a study, including 10x~ 20 m shuttle sprints (Fernandez-Fernandez et al., 2012). However, besides the applicability of the RSA test, some aspects need to be underlined. Athletes frequently develop strategies related to increased speed throughout the test and may not exert maximum effort. In addition, since the total score is more reliable than the sprint time reduction scores, it is challenging to determine the score selection for performance (**Spencer et al., 2005**). Also, Increasing sprint time was associated with the best sprint time (**Buchheit, 2012**). A simple 20m sprint can be more practical and less challenging for athletes; however, more research is needed to clarify this issue.

Table 4. Repeated sprint ability tests

Study	Population	Level of Participants	Subject Age (y)	RSA$_{\text{best}}$ (s)	RSA$_{\text{tt}}$ (s)	S$_{\text{dec}}$ (%)
Brechbuhl et al. (2018)	10 M	Elite	24.8 ± 5.1	3.27 (3.18-3.36)	33.8 (32.8-34.89)	3.6 (2.4-4.8)
Fernandez et al. (2012)	12 M	National	21.2 ± 6 5.1	5.2 6 ± 0.1		3.1 6 ± 0.1

Power

The vertical jump (countermovement jump, squat jump) test, used to determine leg strength in many sports, is frequently used in tennis **(Bencke et al., 2002; Yaprak, 2020**). For practicality, these tests are also often done in the field using contact mats to obtain key measurements such as ground contact time and flight time.

Table 5. Jumping tests

Studies	Population	Level of Participants	Subject Age (y)	CMJ (cm)	SJ (cm)
Kraemer et al. (2003)	47 M	Elite	12.48 ± 22	30.65 ± 3.59	26.82 ± 2.86
	45 F		12.43 ± 30	29.61 ± 3.76	25.50 ± 3.27
Bencke et al. (2002)	12 M	Elite	11.9 ± 12.7	26.0 ± 21-36	25.5 (19-29)
Ulbricht et al. (2016)	24 M	Regional	11.48 ± 0.34	29.89 ± 5.04	
	26 M		13.05 ± 0.46	32.77 ± 3.43	
	28 M		14.97 ± 0.46	36.92 ± 2.82	
	17 F		11.46 ± 0.30	27.99 ± 2.93	
	28 F		12.87 ± 0.51	30.11 ± 3.78	
	24 F		14.89 ± 0.47	31.76 ± 4.34	
Girard and Millet (2009)	12 M	Club	13.6 ± 1.4	32.9 ± 13.10	34.09 ± 7.99
Ayala et al. (2016)	12 M	International	16.8 ± 0.3	42.7 ± 3.3	
Kilit and Arslan (2018)	14 M	Professional	23.0 ± 1.9	44.7 ± 2.7	42.1 ± 1.8
Yaprak (2020)	5 M 5F	Regional	19.50±0.84	40.03±2,5	

RSA: Repeated sprint ability

A study observed a high correlation between jump strength, which generates explosive power, and tennis players' 10-20 m sprint times (**Reid and Schneiker, 2008**). In other studies, the correlation between the jump test results and sprint times of 10–30 m in intermittent sports was found to be high **(Baker and Nance, 1999; Wisløff et al., 2004**). Regarding upper body strength, the medicine ball throwing (overhead, forehand, and backhand throws) test, which has a high validity reliability, is recommended for tennis players (**Dobos et al., 2021**).

This is because, in these tests, the force is produced from the lower body to the upper body, as in tennis strokes (**Roetert and Kovacs, 2019**). Studies have revealed a high correlation between medicine ball throwing, isokinetic trunk rotation, and service speed measurements **(Ellenbecker & Roetert, 2004; Ikeda et al., 2007; Sánchez-Pay et al., 2021**). Therefore, vertical jump tests and medicine ball throws have been part of the regular testing of tennis players in different national tennis associations. In their study, Fernandez et al. (2014) reported that the CMJ values of players in the U18 age group were between 40.1-42 cm in males and 31-35.4 cm in females.

Table 6. Medicine ball throw tests

Study	Population	Level of Participants	Subject Age (y)	MB OH (m)	MB FH (m)	MB BH (m)	MBT SP (m)
Ulbricht (2016)	24 M	Regional	11.48 ± 0.34	5.73 ± 97.82	7.34 ± 95.03	7.07 ± 88.94	
	26 M		13.05 ± 0.46	7.14 ± 31.98	9.39 ± 9.21	8.90 ± 154.2	
	28 M		14.97 ± 0.46	9.76 ± 132.8	12.54 ± .41	12.10 ± .22	
	17 F		11.46 ± 0.30	5.25 ± 59.41	6.88 ± 98.33	6.52 ± 88.69	
	28 F		12.87 ± 0.51	6.68 ± 108.54	8.68 ± 10.84	8.361 ± 06.91	
	24 F		14.89 ± 0.47	7.59 ± 105.67	9.87 ± 12.97	9.42 ± 111.82	
Dobos et al. (2020)	40 F	National and international	U16	8.84 ± 1.90			
	40 M		U16	9.35 ± 2.14			
	40 F		U18	10.74 ± 1.61			
	40 M		U18	14.50 ± 2.41			
Sánchez-Pay et al. (2021)	8 M	National	19.66 ± 1.63	9.11 ± 2.35			12.19 ± 3.03
	7 M	International		11.24 ± 2.14			12 ± 1.14

MB OH: medicine ball over head; MB FH: medicine ball forehand; MB BH: medicine ball backhand; MBT SP: medicine ball throwshot put

Sprint (5 m, 10 m, and 20 m)

The 20m sprint test, created with timing doors with 5m and 10m intervals, is frequently used to measure linear acceleration and speed due to its easy repetition. The first 5m door measures acceleration, while the 10-15m doors test speed. Although the 5 and 10 m distance runs are more appropriate for the game pattern of tennis, the 20 m sprint test provides more information about the athletes. The half-court area of the tennis court is 12 meters on average and there is an area of 5 meters between the baseline and the backcourt. Therefore, using the 20 m test, more details are obtained about the athlete's acceleration and speed. The 20 m sprint test is typically included in the tests conducted by national federations (**Ulbricht et al., 2016**). In the study of Fernandez et al. (2014), the speed values of U14 athletes were found to be 1.85-1.97 s for 10m and 3.34-3.47 s for 20 meters, while these values for women were 1.91-1.99 s for 10m and 3.38-3.50 s for 20m.

Ability to Change Direction

The most valid tests used in interval sports, such as tennis, are the 5–0–5 and Illinois agility tests (**Daniel Bishop and Middleton, 2013; Ulbricht et al., 2016**). Both tests showed a positive correlation with acceleration measurements (Stewart et al., 2014). The hexagon est is another commonly used test to measure the change of direction in tennis. In this test, participants are required to jump from the middle of a hexagon drawn on the floor to each side and then back to the center (Beekhuizen et al., 2009). Although this test is considered to be reliable, there is no scientific information about its relationship with other change of direction tests in addition to general speed measurements. Because tennis is a biomechanically and kinematically complex sport, only a few studies have analyzed the components of speed and change of direction in tennis players. Recently, the change of direction test has been modified by adding a visual signal in the direction to move (**Gamble, 2013**). **Cooke et al.** (**2011**) designed a test to determine participants' reactive agility, using an electronic timing system to respond to a visual stimulus. In this test protocol, the athlete waits on a contact mat at the bottom line of the field, and there are 3 doors with visual signals in front of the athlete (**Cooke et al., 2011**).

Table 7. Speed tests

Study	Population	Level of Participants	Subject Age (y)	10 m (s)	20 m (s)
Ulbrricht et al. (2016)	24 M	Regional	11.48 ± 0.34	2.00 ± 0.08	3.52 ± 0.19
	26 M		13.05 ± 0.46	1.95 ± 0.08	3.45 ± 0.13
	28 M		14.97 ± 0.46	1.85 ± 0.07	3.22 ± 0.12
	17 F		11.46 ± 0.30	2.02 ± 0.06	3.60 ± 0.11
	28 F		12.87 ± 0.51	1.99 ± 0.08	3.50 ± 0.14
	24 F		14.89 ± 0.47	1.93 ± 0.09	3.38 ± 0.15
Kilit and Arslan (206)	14 M	Professional	23.0 ± 1.9	1.8 ± 0.2	3.1 ± 0.2
Girard and Millet (2009)	12 M	Club	13.6 ± 1.4	2.02 ± 0.14	3.55 ± 0.27
Ayala et al. (2016)	20 M	International	16.8 ± 0.3		2.99 ± 0.10
Kilit and Arslan (2018)	26 M	National	13.5 ± 0.2	1.93 ± 0.05	3.39 ± 0.06

This contact mat is a switch to turn on the light on a random door. At which door the visual signal lights up, the athlete is expected to react quickly towards that door and then return to the contact mat where it first starts. In this way, the test is done in 3 times. In the trials, the best score is recorded, and the reactive agility performance of the athlete is determined.

Table 8. Change of diretion test

Study	Population	Level of Participants	Subject Age (y)	Change of Direction	Outcomes (s)
Huggins (2017)	10 M	Elite	15.1 ± 2.6	Spider (s)	16.04 ± 1.42
Kramer et al. (2016)	42 M	Elite	U 14	Spider (s)	17.31 ± 0.57
	41 M		U 15		17.11 ± 0.57
	31 M		U 16		16.39 ± 0.64
Bishop and Middleton (2013)	25 M	College	20.25 ± 1.28	Illinois test (s)	16.66 ± 0.60
Yaprak (2020)	5 F 5 M	Regional	19.50 ± 0.84	Illinois test (s	17.37 ± 0.12
Kilit et al. (2019)	26 M	National	13.5 ± 0.2	T-test (s)	11.21 ± 0.32
Fernandez-Fernandez et al. (2014)	16 M	Club	12.9 ± 0.4	5-0-5	2.71 ± 0.16
Chicote et al. (2016)	14 M 6 F	National	17.75 ± 1.7	Sideward movement (s)	6.53 ± 0.40

s: second, M: male, F: female.

Conclusion

The use of periodic fitness tests in tennis can result in the developing of a personalized database. These values are especially effective in monitoring the physical conditions of young players and preparing individualized training programs. Coaches have to decide on the most appropriate tests to analyze the performance status of their players in a sport- specific approach. In this way, they can determine the physical capacities of the players. Moreover, coaches allocate more time to tennis training and ensure that physical training programs are more efficient. This strategy is crucial for athletes because tennis includes a tournament schedule that lasts approximately 10.5 months throughout the year, and tennis players cannot find enough time for conditioning training. Regular physical tests on tennis players, especially youth tennis players, make redesigning the conditioning programs and following their individual development easier. Thanks to the test protocols mentioned above and the norm values obtained, tennis coaches can identify the strengths and weaknesses of their players' physical capacities. Using the data obtained, it could be possible to make personalized training programs for the players and review them together with retests, helping to ensure a longer-term and stable development.

Conflict of interest

The authors declare no conflict of interest. In addition, no financial support was received.

Author Contributions

Study Design: MA, AM and HM; Data Collection: MA and AM; Data Interpretation: MA and AM; Manuscript Preparation: MA, AM and HM; Final review and editing: AM and HM; Literature Search: MA, AM, and HM. All authors have read and agreed to the published version of the manuscript.

REFERENCES

Baker, D., & Nance, S. (1999). The relation between running speed and measures of strength and power in professional rugby league players. *The Journal of Strength & Conditioning Research, 13*(3), 230-235. [**CrossRef**]

Banzer, W., Thiel, C., Rosenhagen, A., & Vogt, L. (2008). Tennis ranking related to exercise capacity. *British journal of sports medicine, 42*(2), 152-154. [**PubMed**]

Baquet, G., Berthoin, S., Dupont, G., Blondel, N., Fabre, C., & Van Praagh, E. (2002). Effects of high intensity intermittent training on peak V˙ O2 in prepubertal children. *International journal of sports medicine, 23*(06), 439-444. [**PubMed**]

Beekhuizen, K. S., Davis, M. D., Kolber, M. J., & Cheng, M.S.S. (2009). Test-retest reliability and minimal detectable change of the hexagon agility test. *The Journal of Strength & Conditioning Research, 23*(7), 2167-2171. [**PubMed**]

Bencke, J., Damsgaard, R., Joergensen, K., and Klausen, K. (2002). Eighteen month development of anaerobic performanc.

Bergeron, M. F., Maresh, C., Kraemer, W., Abraham, A., Conroy, B., & Gabaree, C. (1991). Tennis: a physiological profile during match play. *International journal of sports medicine, 12*(05), 474-479. [**PubMed**]

Bernardi, M., De Vito, G., Falvo, M., Marino, S., & Montellanico, F. (2002). Cardiorespiratory adjustment in middle-level tennis players: are long term cardiovascular adjustments possible? In *Science and racket sports II* (pp. 38-44): Taylor & Francis. [**CrossRef**]

Bishop, D., Girard, O., & Mendez-Villanueva, A. (2011). Repeated-sprint ability—part II: recommendations for training. *Sports medicine, 41*, 741-756. [**PubMed**]

Bishop, D., & Middleton, G. (2013). Effects of static stretching following a dynamic warm-up on speed, agility and power. Journal of Human Sport and Exercise, 8(2):391-400. [**CrossRef**]

Bleicher, A., Mader, A., & Mester, J. (1998). Zur interpretation von laktatleistungskurven-experimentelle ergebnisse mit computergestuetzten nachberechnungen. *Spectrum der Sportwissenschaften, 10*(1), 92-104. [**CrossRef**]

Brechbuhl, C., Girard, O., Millet, G.P., & Schmitt, L. (2018). Differences within Elite Female Tennis Players during an Incremental Field Test. *Medicine and science in sports and exercise, 50*(12), 2465-2473. [**PubMed**]

Brown, L.E., & Weir, J.P. (2001). ASEP procedures recommendation I: accurate assessment of muscular strength and power. *Journal of Exercise Physiology Online, 4*(3). [**CrossRef**]

Buchheit, M. (2012). Repeated-sprint performance in team sport players: associations with measures of aerobic fitness, metabolic control and locomotor function. *International journal of sports medicine, 33*(03), 230-239. [**PubMed**]

Buchheit, M., & Laursen, P.B. (2013). High-intensity interval training, solutions to the programming puzzle: Part I: cardiopulmonary emphasis. *Sports medicine, 43*(5), 313-338. [**PubMed**]

Buchheit, M., & Rabbani, A. (2014). The 30–15 intermittent fitness test versus the yo-yo intermittent recovery test level 1: relationship and sensitivity to training. *International journal of sports physiology and performance, 9*(3), 522-524. [**PubMed**]

Chtara, M., Chamari, K., Chaouachi, M., Chaouachi, A., Koubaa, D., Feki, Y., & Amri, M. (2005). Effects of intra-session concurrent endurance and strength training sequence on aerobic performance and capacity. *British journal of sports medicine, 39*(8), 555-560. [**PubMed**]

Cohen, D.B., Mont, M. A., Campbell, K. R., Vogelstein, B. N., & Loewy, J. W. (1994). Upper extremity physical factors affecting tennis serve velocity. *The American Journal of Sports Medicine, 22*(6), 746-750. [**PubMed**]

Cooke, K., & Davey, P.R. (2005). Tennis ball diameter: the effect on performance and the concurrent physiological responses. *Journal of sports sciences*, *23*(1), 31-39. [**CrossRef**]

Cooke, K., Quinn, A., & Sibte, N. (2011). Testing speed and agility in elite tennis players. *Strength & Conditioning Journal*, *33*(4), 69-72. [**PubMed**]

Cronin, J.B., & Henderson, M.E. (2004). Maximal strength and power assessment in novice weight trainers. *The Journal of Strength & Conditioning Research, 18*(1), 48-52. [**CrossRef**]

Dobos, K., Novak, D., & Barbaros, P. (2021). Neuromuscular fitness is associated with success in sport for elite female, but not male tennis players. *International Journal of Environmental Research and Public Health, 18*(12), 6512. [**PubMed**]

Ducher, G., Courteix, D., Meme, S., Magni, C., Viala, J., & Benhamou, C. (2005). Bone geometry in response to long-term tennis playing and its relationship with muscle volume: a quantitative magnetic resonance imaging study in tennis players. *Bone, 37*(4), 457-466. [**PubMed**]

Ellenbecker, & Roetert, E. (2003). Age specific isokinetic glenohumeral internal and external rotation strength in elite junior tennis players. *Journal of science and medicine in sport*, *6*(1), 63-70. [**PubMed**]

Ellenbecker, Roetert, E.P., Sueyoshi, T., & Riewald, S. (2007). A descriptive profile of age-specific knee extension flexion strength in elite junior tennis players. *British journal of sports medicine, 41*(11), 728-732. [**PubMed**]

Ellenbecker, & Roetert, P. (2004). An Isokinetic Profile of Trunk Rotation Strength in Elite Tennis Players. *Medicine & Science in Sports & Exercise, 195*(9131/04), 1959. [**PubMed**]

Fargeas-Gluck, M.A., & Léger, L.A. (2012). Comparison of two aerobic field tests in young tennis players. *The Journal of Strength & Conditioning Research, 26*(11), 3036-3042. [**PubMed**]

Fernandez-Fernandez, J., Mendez-Villanueva, A., Fernandez-Garcia, B., & Terrados, N. (2007). Match activity and physiological responses during a junior female singles tennis tournament. *British journal of sports medicine*, *41*(11), 711-716. [**PubMed**]

Fernandez-Fernandez, J., Mendez-Villanueva, A., & Pluim, B. (2006). Intensity of tennis match play. *British journal of sports medicine, 40*(5), 387-391. [**PubMed**]

Fernandez-Fernandez, J., Sanz-Rivas, D., & Mendez-Villanueva, A. (2009). A review of the activity profile and physiological demands of tennis match play. *Strength & Conditioning Journal, 31*(4), 15-26. [**CrossRef**]

Fernandez-Fernandez, J., Ulbricht, A., & Ferrauti, A. (2014). Fitness testing of tennis players: how valuable is it? *British journal of sports medicine, 48*(1), i22-i31. [**PubMed**]

Fernandez-Fernandez, J., Zimek, R., Wiewelhove, T., & Ferrauti, A. (2012). High-intensity interval training vs. repeated-sprint training in tennis. *The Journal of Strength & Conditioning Research, 26*(1), 53-62. [**PubMed**]

Ferrauti, A., Kinner, V., & Fernandez-Fernandez, J. (2011). The Hit & Turn Tennis Test: An acoustically controlled endurance test for tennis players. *Journal of sports sciences, 29*(5), 485-494. [**CrossRef**]

Gamble, P. (2013). *Strength and conditioning for team sports: sport-specific physical preparation for high performance*: Routledge.

Girard, O., Chevalier, R., Leveque, F., Micallef, J.-P., & Millet, G. (2006). Specific incremental field test for aerobic fitness in tennis. *British journal of sports medicine, 40*(9), 791-796. [**PubMed**]

Girard, O., Lattier, G., Maffiuletti, N.A., Micallef, J.P., & Millet, G.P. (2008). Neuromuscular fatigue during a prolonged intermittent exercise: Application to tennis. *Journal of Electromyography and Kinesiology, 18*(6), 1038-1046. [**PubMed**]

Girard, O., & Millet, G.P. (2009). Physical determinants of tennis performance in competitive teenage players. *The Journal of Strength & Conditioning Research*, *23*(6), 1867-1872. [**PubMed**]

Harrison, C., Kinugasa, T., Gill, N., & Kilding, A. (2015). Aerobic fitness for young athletes: combining game-based and high-intensity interval training. *International journal of sports medicine*, *94*(11), 929-934. [**PubMed**]

Hoff, J. (2005). Training and testing physical capacities for elite soccer players. *Journal of sports sciences*, *23*(6), 573-582. [**PubMed**]

Ikeda, Y., Kijima, K., Kawabata, K., Fuchimoto, T., & Ito, A. (2007). Relationship between side medicine-ball throw performance and physical ability for male and female athletes. *European Journal of Applied Physiology*, *99*, 47-55. [**PubMed**]

Kelln, B. M., McKeon, P. O., Gontkof, L. M., & Hertel, J. (2008). Hand-held dynamometry: reliability of lower extremity muscle testing in healthy, physically active, young adults. *Journal of sport rehabilitation*, *17*(2), 160-170. [**PubMed**]

Kilit, B., Arslan, E., & Soylu, Y. (2018). Time-motion characteristics, notational analysis and physiological demands of tennis match play: A review. *Acta Kinesiologica*, *12*(2), 5-12. [**CrossRef**]

Kovacs, M. (2006). Applied physiology of tennis performance. *British journal of sports medicine*, *40*(5), 381-386. [**PubMed**]

Kovacs, M. (2007). Tennis physiology. *Sports medicine*, *37*(3), 189-198. [**PubMed**]

König, D., Huonker, M., Schmid, A., Halle, M., Berg, A., & Keul, J. (2001). Cardiovascular, metabolic, and hormonal parameters in professional tennis players. *Medicine and science in sports and exercise*, *33*(4), 654-658. [**PubMed**]

Kraemer, W. J., Hakkinen, K., Triplett-McBride, N. T., Fry, A. C., Koziris, L. P., Ratamess, N. A., & Newton, R. U. (2003). Physiological changes with periodized resistance training in women tennis players. *Medicine and science in sports and exercise*, *35*(1), 157-168. [**PubMed**]

Laursen, P. B., & Jenkins, D. G. (2002). The scientific basis for high-intensity interval training. *Sports medicine*, *32*(1), 53-73. [**PubMed**]

Mendez-Villanueva, A., Fernandez-Fernandez, J., & Bishop, D. (2007). Exercise-induced homeostatic perturbations provoked by singles tennis match play with reference to development of fatigue. *British journal of sports medicine*, *41*(11), 717-722. [**PubMed**]

Mont, M. A., Cohen, D. B., Campbell, K. R., Gravare, K., & Mathur, S. K. (1994). Isokinetic concentric versus eccentric training of shoulder rotators with functional evaluation of performance enhancement in elite tennis players. *The American Journal of Sports Medicine*, *22*(4), 513-517. [**PubMed**]

Murphy, A. J., & Wilson, G. J. (1997). The ability of tests of muscular function to reflect training-induced changes in performance. *Journal of sports sciences*, *15*(2), 191-200. [**PubMed**]

Nader, G.A. (2006). Concurrent strength and endurance training: from molecules to man. *Medicine and science in sports and exercise*, *38*(11), 1965. [**PubMed**]

Perry, A.C., Wang, X., Feldman, B.B., Ruth, T., & Signorile, J. (2004). Can laboratory-based tennis profiles predict field tests of tennis performance? *The Journal of Strength & Conditioning Research*, *18*(1), 136-143. [**PubMed**]

Reid, M., & Schneiker, K. (2008). Strength and conditioning in tennis: current research and practice. *Journal of science and medicine in sport*, *11*(3), 248-256. [**PubMed**]

Reynolds, J.M., Gordon, T.J., & Robergs, R.A. (2006). Prediction of one repetition maximum strength from multiple repetition maximum testing and anthropometry. *The Journal of Strength & Conditioning Research*, *20*(3), 584-592. [**CrossRef**]

Roetert, P., & Ellenbecker, T. S. (2007). *Complete conditioning for tennis*: Human Kinetics.

Roetert, P., & Kovacs, M. (2019). *Tennis anatomy*: Human Kinetics.

Roetert, P., McCormick, T. J., Brown, S. W., and Ellenbecker, T. S. (1996). Relationship between isokinetic and functional trunk strength in elite junior tennis players. *Isokinetics and Exercise Science*, *6*(1), 15-20. [**CrossRef**]

Sánchez-Pay, A., Ramón-Llin, J., Martínez-Gallego, R., Sanz-Rivas, D., Sánchez-Alcaraz, B. J., & Frutos, S. (2021). Fitness testing in tennis: Influence of anthropometric characteristics, physical performance, and functional test on serve velocity in professional players. *PLoS One, 16*(11), e0259497. [**PubMed**]

Signorile, J. F., Sandler, D. J., Smith, W. N., Stoutenberg, M., & Perry, A. C. (2005). Correlation analyses and regression modeling between isokinetic testing and on-court performance in competitive adolescent tennis players. *The Journal of Strength & Conditioning Research, 19*(3), 519-526. [**PubMed**]

Smekal, G., Pokan, R., Von Duvillard, S., Baron, R., Tschan, H., & Bachl, N. (2000). Comparison of laboratory and on-court endurance testing in tennis. *International journal of sports medicine, 21*(04), 242-249. [**PubMed**]

Smekal, G., Von Duvıllard, S., Rıhacek, C., Pokan, R., Hofmann, P., Baron, R., & Bachl, N. (2001a). A physiological profile of tennis match play. *Medicine & Science in Sports & Exercise, 33*(6), 999-1005. [**CrossRef**]

Smekal, G., Von Duvıllard, S. P., Rıhacek, C., Pokan, R., Hofmann, P., Baron, R., & Bachl, N. (2001b). A physiological profile of tennis match play. *Medicine & Science in Sports & Exercise, 33*(6), 999-1005. [**PubMed**]

Spencer, M., Bishop, D., Dawson, B., & Goodman, C. (2005). Physiological and metabolic responses of repeated-sprint activities: specific to field-based team sports. *Sports medicine, 35*, 1025-1044. [**PubMed**]

Sperlich, B., De Marées, M., Koehler, K., Linville, J., Holmberg, H.-C., & Mester, J. (2011). Effects of 5 weeks of high-intensity interval training vs. volume training in 14-year-old soccer players. *The Journal of Strength & Conditioning Research, 25*(5), 1271-1278. [**PubMed**]

Spriet, L.L., Howlett, R.A., & Heigenhauser, G.J. (2000). An enzymatic approach to lactate production in human skeletal muscle during exercise. *Medicine and science in sports and exercise, 32*(4), 756-763. [**PubMed**]

Stewart, P. F., Turner, A. N., & Miller, S. C. (2014). Reliability, factorial validity, and interrelationships of five commonly used change of direction speed tests. *Scandinavian journal of medicine & science in sports, 24*(3), 500-506. [**PubMed**]

Tanner, R., & Gore, C. (2012). *Physiological tests for elite athletes*: Human kinetics.

Uger, L., & Boucher, R. (1980). An indirect continuous running multistage field test: the Universite de Montreal track test. *Can. J. Appl. Sport. Sci, 5*, 77-84. [**PubMed**]

Ulbricht, A., Fernandez-Fernandez, J., Mendez-Villanueva, A., & Ferrauti, A. (2016). Impact of fitness characteristics on tennis performance in elite junior tennis players. *The Journal of Strength & Conditioning Research, 30*(4), 989-998. [**PubMed**]

Weber, K., & Hollmann, W. (1984). Neue Methoden zur Diagnostik und Trainingssteuerung der tennisspezifischen Ausdauerleistungsfähigkeit. *Talentsuche und Talentförderung im Tennis*, 186-209.

Wisløff, U., Castagna, C., Helgerud, J., Jones, R., & Hoff, J. (2004). Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *British journal of sports medicine, 38*(3), 285-288. [**PubMed**]

Yaprak, Y. (2020). A Comparison of Anaerobic Performance of Sub-Elite Tennis and Badminton Players. *European Journal of Physical Education and Sport Science*. [**CrossRef**]

Ziemann, E., Sledziewska, E., Grzywacz, T., Gibson, A. L., & Wierzba, T. H. (2011). Body composition and physical capacity of elite adolescent female tennis players. *Georgian Medical News*(196-197), 19-27. [**PubMed**]