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Articles

Is clay court the best tennis surface? A narrative review

¿Es la cancha de arcilla la mejor superficie en el tenis? Una revisión narrativa

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Abstract

This paper aims to demonstrate that clay courts are likely the most suitable playing surfaces in terms of muscle contraction, efficiency and the reduction of risk factors associated with the viscoelastic and frictional properties of the surfaces themselves. The style of play, with more or less frequent accelerations, decelerations and changes of direction, the duration of the match and the frequent tournaments on different playing surfaces can be additional risk factors. In fact, it has been shown that muscles are sensitive to surface stiffness and that frequent playing on different surfaces can be associated with lower limb injuries. Furthermore the busy calendar of ATP (Association of Tennis Professionals) and WTA (Women's Tennis Association) is stigmatised because it is characterized by the sudden transition from hard to clay and/or clay to grass without the necessary gradualness, thus preventing proper motor adaptation. The aims of this work emerge from literature and from a biomechanical-theoretical analysis of the loads that result in the musculoskeletal system by human and playing surface interaction.

Keywords: *Tennis surfaces, clay court, hard court, grass court, injuries.*

Resumen

Este artículo tiene como objetivo demostrar que las canchas de arcilla son probablemente las superficies de juego más adecuadas en términos de contracción muscular, eficiencia y reducción de factores de riesgo asociados con las propiedades viscoelásticas y de fricción de las propias superficies. El estilo de juego, las aceleraciones, las desaceleraciones, los cambios de dirección más o menos frecuentes, la duración del partido y los torneos frecuentes en diferentes superficies de juego pueden ser factores de riesgo adicionales. De hecho, se ha demostrado que los músculos son sensibles a la rigidez de la superficie y que jugar frecuentemente en distintas superficies puede estar asociado con lesiones en las extremidades inferiores. Además, se critica el calendario saturado de la ATP (Asociación de Tenistas Profesionales) y la WTA (Asociación de Tenis Femenino), ya que se caracteriza por incluir transiciones abruptas de superficies duras a arcilla o de arcilla a césped sin la gradualidad necesaria, lo que impide una adaptación motriz adecuada. Los objetivos de este trabajo surgen tanto de la literatura como de un análisis teórico-biomecánico de las cargas que se generan en el sistema musculoesquelético por la interacción entre el ser humano y la superficie de juego.

Palabras clave: *superficies de tenis, cancha de arcilla, cancha dura, cancha de césped, lesiones.*

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Introduction

In tennis, a fundamental role, both for performance and for the possible onset of pathologies or injuries, is played by the components characterizing the game (Allen et al., 2019). The development and production of innovative playing equipment and surfaces, which in theory can be more performing, do not always guarantee the expected results in terms of quality of performance (Lakotos et al., 2024) and safety of practitioners. If, at the highest levels, problems often arise due to the intensity and frequency of performances (Moreno-Pérez et al., 2021), at an amateur level one of the main causes of injuries, due to technological peculiarities, lies in the lack of awareness of how much the shoe and the surface mediate the transfer of loads between man and the surrounding environment. Any modification of these components involves the redistribution of mechanical stresses on the biological system, with effects that are difficult to predict without the necessary knowledge of its potential and limits. In fact, even if we assume that manufacturer provides an accurate description of the mechanical properties of the tool, we cannot forget the individuality of the human being (anthropometric differences, muscular conformation and biological response to stimuli). It follows that we need a more in-depth knowledge of both components (man and tool) to obtain the best coupling according to the chosen final objective.

Various research has shown how, during a tennis match, the game can be altered by various factors intrinsic to the sport, such as the type of surfaces (clay, hard, grass), gender, different tactical behaviours (the big server, serve and volleyer, all-court player, attacking baseliner, solid baseline, counter puncher) and thermal stress (Kramer et al., 2017; Morante & Brotherhood, 2008; Hornery et al., 2007; O'Donoghue & Ingram, 2001; Smekal et al., 2001). All these variables can influence the match as well as the individual physiological conditions.

As to the playing surface, some studies have analysed how the type of surface influences the bounce of the tennis ball and, consequently, its speed and the game characteristics (Groppel & Roetert, 1992). Slower surfaces, such as clay, are characterized by greater friction. This friction results in a moderate bounce of the ball: this event allows the player to have more time to prepare to hit compared to when he tries his hand on hard surfaces (Haake et al., 2003).

As a consequence, an important factor emerges: competing on different playing surfaces involves an adaptation of the movements with important kinetic changes that produce different stress patterns on the lower limbs joints. This evidence is well known in training practice: the players' muscles should be trained in such a way as to generate optimal forces during the different levels of movement considering the playing surface (Verstegen, 2003).

A further parameter to consider is the lactate concentration. It has been shown that it is not significantly different between clay and hard courts (Girard & Millet, 2004). The slight discrepancies are probably a result of differences in the characteristics of the subjects (number, playing ability, age, height and body mass).

In tennis, fatigue can be related to prolonged effort or high physical intensity (Hornery et al., 2007). The mentioned authors made a series of comparisons on players playing tennis on different surfaces and came out with the following consideration: tennis matches played on clay are physically more demanding than those played on fast courts. From here, it can easily be deduced that tiredness induced by more intense physical effort can hinder performance. This suggests the need for more accurate methods for monitoring training intensity during tennis practice.

Two methods to measure tennis court speed: CPI and CPR

The International Tennis Federation (ITF) distinguishes four key properties of a tennis court surface (Capel-Davies et al., 2015):

- *Friction*, i.e. the resistance encountered by an object sliding on a surface. In this context it is the tangential force encountered by the tennis ball or by the player's shoes in the relative motion with respect to the surface of a tennis court. It is defined by the coefficient of friction (COF), corresponding to the ratio between the tangential force and the force normal to the surface. A surface with greater roughness has a higher COF, which results in a greater deceleration of the horizontal speed of the ball, consequently making the play on the surface perceived as slower. The effect of friction on the shoes is to reduce their sliding possibility, increasing the braking force.
- *Energy dispersion*, referring to the tennis ball during the impact on the surface, is measured through the coefficient of restitution (COR), i.e. the ratio between the vertical speed of the ball after the bounce and that before impact. COR is an indicator of how efficiently an impact restitutes the kinetic energy to the ball, and depends on the characteristics of both materials in contact. A surface with a higher COR is generally perceived as slower, as the ball will reach a greater height after impact, thus allowing an increase in the time available to reach the ball.
- *Topography and dimensions*, i.e. surface uniformity, size and slope.
- *Consistency*, i.e. the uniformity of surface properties across the entire playing area and their stability over time.

There are two different methods for classifying the speed of a tennis court: Court Pace Index (CPI) and Court Pace Rating (CPR). The CPI, which is a measure deriving from the data collected by "Hawk-Eye" through a triangulation camera system, shows the performance of the fields in real matches and consists of an average of multiple kinematic variables calculated over the seven days in which an ATP tournament is played. The CPR, on the other hand, measures the effect of the interaction between the surface and the tennis ball and is calculated with a test that uses a ball-shooting machine and a complex piece of equipment, known as Sestée.

Officially, the ITF regulates the criteria and procedures for classifying playing surfaces by dividing them, through the CPR, into five categories: slow, medium-slow, medium, medium-fast, fast (Table 1).

Table 1
Classification of playing surfaces according to the CPR

Type of surface	CPR
Slow	≤29
Medium-slow	30-34
Medium	35-39
Medium-fast	40-44
Fast	≥45

The measurement of CPR, through the Sestée, is regulated by the ITF itself and requires careful and precise calibration of the instrument. Mathematically, the CPR is a function of both the coefficient of friction (COF) and the coefficient of restitution (COR), according to the formula:

$$CPR = 100 \cdot (1 - COF) + 150 \cdot (0.81 - COR)$$

The first term [100·(1-COF)] is the Surface Pace Rating (SPR) i.e. the measurement system that was adopted before the definition of CPR itself. The second term [150·(0.81-COR)], referred as K, represents the individual perception factor of the tennis player in relation to a given surface. The first term is a function of the COF and inversely proportional to it (it increases as the COF itself decreases). The calculation of the COF is done in the laboratory and is often linked to the use of complex equipment (Cross, 2010). A fast surface has a higher SPR (lower COF) than a slow surface (Cross, 2010; Cross, 2003; Cross & Lindsey, 2019; Martin & Prioux, 2014). The second term (K) includes the number 0.81 (average restitution coefficient for all types of surfaces) and the number 150, which represents the rhythm perception constant. It is determined through empirical research and calibration processes that aim to match CPR to players' perceptions of playing speed on different surfaces. CPR is the result of a balance between objective measurements of the physical properties of the courts, such as COF and COR (Table 2), and the subjective assessments of the players on the perception of the speed of the court (Cross, 2010).

Table 2
Summary table of CPR, COF and COR values of clay, hard and grass tennis courts

Type of tennis courts	CPR	COF	COR
Clay	23	>0.71	0.86
Hard	35-39	0.56-0.70	0.79-0.84
Grass	46*	<0.55	0.77*

* According to Miller (2006) and Brody (2003).

Choosing a value of 150 ensures that the CPR formula accurately reflects the gaming experience, considering how the physical characteristics of the surface influence the human perception of game speed.

The COR measurement is obtained by comparing the bounce and fall heights of a sphere, as occurs in the normal drop test (Haron & Ismail, 2012). Furthermore, a methodology has recently emerged that aims to use a low-cost portable apparatus (Colombo et al., 2016; Espinosa et al., 2016).

In summary, playing surfaces - clay, hard, grass - are strongly differentiated in terms of CPR. On clay, the ball's horizontal advancement speed is slowed down, and bounces are facilitated, which favour prolonged rallies. Unlike grass which, having a high CPR, penalizes the vertical bounce speed, keeping the ball closer to the ground. Finally, the concrete surfaces, which have a variable CPR and are halfway between clay and grass, provide a moderate playing speed and a higher rebound, when compared with the typical surfaces of Church Road (Wimbledon) and all those in preparation for the third slam of the year.

Playing surfaces and injuries

Moving on now to consider the athlete's interaction with the ground, a first aspect concerns the ability of the ground itself and the athlete's muscular system to absorb fall energy. If we consider the impact of a rigid body on a yielding surface, we will find two important differences compared to what happens with a rigid surface. In the first case, the phenomenon develops with greater surface deformations and the contact force has a lower peak value and longer duration. In the second case, simplifying, we can state that if the surface is rigid, the impact is more rapid and violent.

The effects of the foot-ground impact on the "human system" also depend on the "global rigidity" of the biological system, i.e. on its instantaneous mechanical characteristics. These characteristics are determined by the combined contribution of the passive components (bones, ligaments, etc.), the active ones (muscles) and the segmental and joint kinematics. The subject is able to vary - within certain limits - his “global stiffness” in order to control and, if necessary, reduce the loads to be supported. The strategy adopted is to modify the level of contraction of the muscles involved and to use adequate motor strategies (see controlled flexion of the knees in order to absorb the impact of a downward jump).

Tennis could be played on more or less soft ground and the amount of energy dissipated by the ground itself affects the energy demand on the muscular system. A soft ground, if truly elastic, returns a large part of the energy absorbed, helping to reduce the consumption of metabolic energy. Even rigid (non-deformable) ground produces the same effect, as it does not absorb energy. Otherwise, an inelastic surface - such as clay - absorbs a large part of the deformation energy, dissipating it into heat. As previously reported, different properties of the surface do not affect the global physiological parameters like lactate, while muscle intervention is strongly affected by them. As regards aspects of muscle physiology, it is known that a concentric contraction, preceded by an eccentric contraction, is associated with a reduction in metabolic energy consumption. The esploitation of this mechanism is partly connected to the elastic characteristics of the court. In fact, if we assume that the ground and the athlete (who, for simplicity, we will call ’the muscle’) can be schematised as a system of two springs in series, the total energy L absorbed during the impact is given by the sum of the energy absorbed by the ground (L_g) and that absorbed by the muscle (L_m):

$$L = L_g + L_m \quad (1)$$

For ideal springs, $F=k\Delta x$ (k is the stiffness and Δx is the deformation).

The accumulated elastic energy for a given deformation is $Le= \int F\,dx = \int k\,\Delta x\,dx = (1/2)k\,(\Delta x)^2$

With reference to equation (1) we have

$$L_g=(1/2)\,k_g\,(\Delta x_g)^2 \text{ and } L_m= (1/2)\,k_m\,(\Delta x_m)^2$$

Where k_g, Δx_g, k_m, Δx_m are, respectively, stiffness and deformation of the two springs.

In this model, consisting of two springs in series, the force F acting on each spring is the same; it is therefore possible to obtain the deformation of each component:

$$\Delta x_g=F/k_g$$

$$\Delta x_m=F/k_m$$

This means that the stiffer spring (higher k) will experience smaller deformations than the more compliant spring. The work absorbed as a function of force is expressed as follows:

$$L=(1/2)\,k\,(\Delta x)^2 = (1/2)\,k\,(F/k)^2 =(1/2)\,F^2/k$$

It follows that the stiffer spring (high k), which undergoes smaller deformations, will absorb less energy than the more compliant one. During the execution of a certain gesture, when the athlete lands on a very soft surface(small k_g), that surface will deform considerably, absorbing more energy than when the athlete lands on a rigid surface.

For a given amount of total energy absorption, if the energy absorbed by the ground increases, the energy absorbed by the muscular system will decrease.

In this situation (yielding surface), the muscle’s ability to store elastic energy, and then release it to support the contraction, is certainly penalized. If, however, the playing surface is rigid (large k_g), the muscle can absorb a considerable amount of elastic energy and then return it to the benefit of its mechanical performance.

However, it should be considered that the notable difference between the deformation of the ground and of the muscular system Δx_m (for Δx_m we can consider the vertical position change of the center of gravity of the athlete with respect to the ground during the impact) leads us to believe that the k_g is considerably greater than k_m and therefore the energy absorbed by the ground during landing from a jump is very small compared to that absorbed by the muscular system, at least for the playing fields usually used.

Therefore, the difference between various playing fields will have little influence on the energy demand from the muscular system (significant effects could be observed only if, for example, extremely deformable terrains were considered). Different considerations apply regarding the aspect of horizontal sliding. Epidemiological studies indicate strong correlations between the number of micro events during the play and the type of terrain. Players accustomed to surfaces that allow controlled sliding (clay) - where, for the same impulse, the longer braking time implies the achievement of lower maximum forces - are affected by significantly fewer painful situations or injuries compared to those who play tennis on hard surfaces, such as concrete or asphalt (Nigg & Yeadon, 1987; Dragoo & Braun, 2010). This statement is also confirmed in an even more recent study which refers precisely to surfaces that allowed for controlled sliding: the injury rate on clay courts is lower than that on hard courts, which is believed to be due to lower friction (Starbuck et al., 2015). These findings have a clear biomechanical justifications if we consider that, for example, the horizontal component of the Ground

Reaction Force (GRF), in some shots, is three times higher on hard surfaces than on common clay courts (Tiegermann, 1984).

Ground Reaction Force (GRF) is one of the main external forces that act on the human body in contact with the earth's surface. Since this force balances the body weight and the inertia forces of the center of gravity, it is directly related to the movement performed (Chow et al., 1999). It is also an important component for estimating the internal forces that act on the musculoskeletal system. GRF is measured with dynamometric platforms, made up of a rigid plane of rectangular or square shape, usually supported in four points by force sensors assembled in load cells. The load cells are constrained to a rigid support base, which is in turn constrained to the ground (Van Gheluwe & Hebbelinck, 1986).

Synthetic surfaces, due to the high COF, amplify the critical issues imposed by the starting, stopping and changing direction phases. Taking the same braking as an example, where the tennis player (of mass m) reaches the ball with a given speed (V_0) and slides on the surface, the initial momentum ($Q = mv_0$) will be dampened by the friction force which will act throughout braking time. This force is transmitted to the musculoskeletal-tendinous system and, the greater the friction force, the greater the load applied to the musculoskeletal-tendinous system.

To reduce the momentum to 0, the friction force F must act for a time Δt determined by the following equation:

$$\Delta Q = m(v_o - 0) = \int_0^{\Delta t} F dt \quad (2)$$

In fact, for a decelerating mass, $F = mdv/dt$ for which $mdv = Fdt$ (dt is the time differential, i.e. an infinitesimal time variation). By integrating this equation over time we obtain equation (2). If we assume that the force F is constant over time, the integral of (2) leads to:

$$\Delta Q = m\Delta v = F\Delta t$$

It can therefore be argued that an increase in friction force corresponds to a reduction of the momentum in a shorter time. In fact, the same change of momentum can be obtained by applying a greater force for a short period or a smaller force for a longer time. Increased grip strength (short time) leads to a consequent increase in the loads on the biological system. It is therefore useful to refer to the study by Strauss (2006), who focused on two mechanical properties: stiffness and deflection. First of all, stiffness means the ability of a body to oppose the elastic deformation caused by an applied force. In the elastic field for small deformations, the deformation is proportional to the applied stress (Hook's law). The coefficient of proportionality is Young's modulus, which measures the resistance of materials to elastic deformation for states of simple tensile or compressive stress. Its unit of measurement is the Pascal (Pa = Newton / m^2). Young's modulus is usually reported in MegaPascals (MPa) for polymers or in GigaPascals (GPa) for stronger materials such as metals. The term deflection, however, refers to the deformation that a body undergoes when subjected to a force. It can be expressed directly, both with the value of ΔL in mm, and with the ratio between deformation and initial length L_0, which is called the strain $\varepsilon = \Delta L / L_0$).

Well, it is highlighted that the grass surface is less rigid than the clay one and even less rigid than the artificial surfaces (Strauss, 2006). The high rigidity of synthetic surfaces can be correlated, together with the damping component, to considerable impact forces. This characteristic, associated with the high friction coefficient, is compatible with the greater occurrence of accidents. The clay-grass comparison is more complex. Clay court appears stiffer than grass, but we are not aware of precise data on damping. It is therefore difficult to hypothesize comparisons between the impact forces that can develop on the two terrains. Furthermore, the strong dependence of the physical and mechanical characteristics on environmental conditions also makes it difficult to speculate on the friction coefficient.

Natural grass courts present further and different variables in relation to environmental and climatic factors, such as the influence of humidity on the aforementioned friction coefficient. The dynamic or sliding friction coefficient on dry grass is 0.40-0.50, while on wet grass - a widespread condition in gloomy London, home of the renowned Wimbledon tournament - the value is around 0.30-0.40. This is an extremely interesting figure, especially when compared to that relating to ice (0.15) and concrete (0.60). The potential lack of adhesion, therefore, depends (also) on the state of the turf (in addition to unfavorable weather conditions, we remember the wear and the presence of light patches due to some plant disease), and is configured as a risk factor for the tennis player's foot-ankle structure.

Synthetic grass fields are essentially divided into two categories: those which have an infill of a specially developed polymer between the blades (of grass) and those that use simple shredded tires. Both solutions present the problem of accentuated heating due to increased solar radiation.

In particular, the aforementioned phenomenon is more accentuated for carpets with a filling based on shredded tires, which can be associated with the emission of volatile organic compounds (VOCs) and unpleasant odors.

Compared to synthetic grass, the surface temperature is lower on natural fields, reasonably thanks to the natural evaporation of the water always present in the ground in such quantities as to allow the life cycle of the grass. This condition cannot be successfully applied to a synthetic carpet since the quantity of water that can accumulate, without making it impracticable, is reduced, thus making the evaporation effect short-lived. Thermal variations probably also influence the overall friction coefficient of the surface. In fact, it must be remembered that polymers, with an increase in temperature, are characterized by the transition from a glassy-rubber phase to the so-called “glass transition temperature”. This step implies a change in the mechanical properties (greater deformability/lesser stiffness and increase in energy dissipated/lesser energy returned by the soil). It is conceivable how - leaving aside the aspects linked to the ball/ground interaction - the surface temperatures detectable in a synthetic grass covering can significantly modify the grip of the shoe and, consequently, motor patterns and stability of the body (Lisi, 2016).

At this point, a further consideration is necessary. Professional tennis tournaments take place in numerous locations around the world and on different surfaces. It is not unusual for players to be forced to change playing fields in the space of one or two weeks, moving, for example, from clay court of Roland Garros, and other European tournaments, to grass courts like those of Queen’s and the German Halle. These sudden changes, due to an increasingly busy competitive calendar, and the impossibility of adapting to this or that specific surface in such a short time, translate into a greater predisposition to traumatic injuries to the lower limbs. In fact, playing frequently on different surfaces can be associated with injuries to the lower limbs (Hutchinson et al., 1995; Safran et al., 1999; Alexander et al., 2022). More specifically, players who played on multiple surfaces had a higher prevalence of those overuse injuries, compared to those who played primarily on one court surface (Alexander et al., 2022). A key role in this respect is played by the foot.

Foot presents a very rich proprioception afferent to the central nervous system (CNS) capable of implementing automatic motor reflexes calibrated on the basis of previous experiences. Therefore, if by taking a jump the subject’s brain unconsciously “predicts” a certain resistance of the ground, the nervous system automatically “pre-loads” those muscles and tendons (agonists and antagonists) best suited to the need, and with a tension adequate to the task. Obviously, if the aforementioned prediction turns out to be incorrect (see, for example, a grassy layer that is too soft), the agonist/antagonist balance become unbalanced with the consequence that the load ends up weighing on an unstable ankle. In this case sprains, ligament injuries and fractures are likely to occur (Lisi, 2016).

Amateur player does not seem to suffer much from superficial changes (Saal, 1996). As for clay, it is not particularly harmful as it absorbs blows better, cushions and requires a sliding step (Saal, 1996). while “composite” fields would transfer greater loads to the lower limbs and spine. As for grass, we know their shock absorption characteristics, but some authors consider them even worse than composite court (Saal, 1996). In this regard, it has been found that, compared to sports on clay and hard courts, trunk injuries are more common on grass courts (Kryger et al., 2015).

From the results of a study (von Salis-Soglio, 1979) it emerged that a small group (15 subjects) of expert players experienced pain in the back and in the lower limbs during the practice of tennis on hard surfaces. This painful symptomatology, however, was generally modest, if not completely absent, when the same players carried out their professional activity on clay courts.

Empirically gleaned information from Gieck (1979), along with his personal experiences with degenerative disc disease, indicates that softer surfaces, such as grass or clay, reduce the impact on the musculoskeletal system compared to hard surfaces, such as asphalt and concrete (Gieck, 1979).

Regardless of the playing surface, it must be evidenced the significant influence on the ball speed due to the change of material, rigidity, size and weight of the rackets.

Graphite rackets allow the player to transfer a higher momentum to the ball in comparison with those produced by wooden made rackets. Furthermore the first group allow to impact more spin to the ball (Miller & Cross, 2003). Graphite rackets are lighter and stiffer with a potential advantage for the player but the, as a whole, the game speed has dramatically increased on all the surfaces. Despite a scientific comparison is not available, it is reasonable to speculate that a stronger biomechanical body stress can be associated to the evolution of the rackets mainly due to speed and strategy of play.

Reflections and conclusions

Based on what has been explained so far, is it still preferable to practice the sport of tennis on a “soft”, slow surface, such as the very common red clay? The answer seems to be yes, also because, from the results of research conducted on professional male tennis players, it can be seen that hard courts are characterized by a significant higher incidence of injuries compared to clay courts (Bastholt, 2000). It can be seen how, among the four different surfaces examined, the rate of lower limbs injuries on hard surfaces is higher than on clay (Alexander et al., 2022). On the other hand, if most tournaments in Europe are played on clay, tennis courts in America and the rest of the world are made of hard material (Table 3).

Table 3
Different court surfaces in the four most important tournaments in tennis (Grand Slam)

Grand Slam tournament	Type of court surfaces
Australian Open	Plexicushion Prestige hard courts
Roland Garros	Clay courts
Wimbledon	Grass courts
US Open	DecoTurf hard courts

Some author's investigation (O'Donoghue & Liddle, 1998; O'Donoghue & Ingram, 2001) focusing on side aspects of the mechanical properties of the surface, have shown how competition on clay can be an indirect cause of injuries due to the duration of the match itself and only partly attributable to the surface. On grass, where the matches have a shorter duration and the tennis player frequently uses descents to the net immediately after the serve ("serve and volley"), the different types of movement are likely to cause damage of varying degrees and intensity, but in this case referable more to the style of play than to the characteristics of the surface (O'Donoghue & Liddle, 1998; O'Donoghue & Ingram, 2001).

On turf, probably following muscle fatigue, the fibers most involved in a certain type of physical-motor activity become more difficult to recruit, so movement control is progressively less automatic and efficient. This exposes the player to the possibility of sudden and very violent contractions.

In the second case, the typical "serve & volley" techinique, involving continuous accelerations and stops, increase the risk of acute associated injuries (meniscus, ligaments), especially in those tennis players who do not have perfect control of the stability of the ankle, mainly on the coronal plane.

Compared with the other court surfaces, there was a higher prevalence of lower limb overuse injuries when playing on hard court (Pluim et al., 2018).

It is interesting, however, to table the results of the studies (Table 4) analyzed in the systematic review of Alexander et al. (2022).

Authors cited above (Alexander et al., 2022) recall how it has been established in the literature that compared to clay courts, hard courts are significantly more foreseeable, having higher grasp, higher hardness, and difficulty to slide on (Starbuck et al., 2015). High loading has been linked to hardcourts, especially on the lateral parts of the foot (Damm et al., 2014). Ankle inversion injuries have previously been linked to high degrees of inversion (Kristianslund et al., 2011).

Table 4
Summarises the percentage of the incidence of injuries in surfaces as reported in five different studies (Alexander et al., 2022)

Study	Incidence Rate	Surface the injury been reported
1	Total of 700 injuries occurred at a rate of 20.7%	Grass courts (throughout the competition season, switching between surfaces)
2	50% to 65% for men 60% and 70% for women	Hard, clay and grass courts
3	Less than 50%	Clay and grass courts
4	Men and women are respectively – 80%	Clay and hard courts
5	57% of the injured players	Clay and hard courts

In tennis, it is worth remembering that the potentially riskiest movements are the lateral movements in which the player stops abruptly to hit the ball.

In this particular situation the soles of the shoes can act as a lever pin, forcing the foot into supination and sometimes causing a trauma. A surface with high friction is more critical than clay: the latter, in fact, allowing a certain degree of sliding, leaves the player sufficient time to actively control the movement. This assertion is scientifically supported by the values of the maximum rotation moment, measured with a dynamometric platform in 12 subjects who wore different shoes. The result obtained appears extremely interesting: the variability of the maximum moment found on the different surfaces is much greater (approximately 100%) compared to that found between the different shoes (Nigg, 1978).

The latter data suggest that the mechanical properties of the surface produce greater variations in joint load compared to footwear. It can therefore be stated that, regardless of the type of footwear, it is the playing field that determines the stresses imposed on the musculoskeletal system (Lisi, 2016). Among other things, another difference between clay and concrete is a greater angle of inversion of the ankle during stance (Damm et al., 2013). The results showed that hard courts required treatment for injuries much more frequently than clay courts during matches (Damm et al., 2013).

We agree with some authors (Alexander et al., 2022) who underline that trunk injuries (more frequent than on clay or concrete surfaces) are attributable to the fact playing on the quicker surface of grass, with a smaller ball bounce and shorter point length, may significantly affect patterns of injury because there is a potential risk of injury when moving from clay to grass.

We have already had the opportunity to remember how the transition from clay to grass occurs in a very short time, without the necessary gradualness (Lisi, 2016). Suffice it to say that, in ATP and WTA 2024 calendar (Table 5 & Table 6), Roland Garros starts at the end of May and ends at the beginning of June (May 26 - June 9), while the first grass tournaments start the day after the Paris tournament. In the 2024 tennis season, the situation became even more complicated as the Olympic Games took place (Paris, 26 July - 11 August) and, for some of the strongest tennis players, the 6 Kings Slam, a tennis exhibition tournament which took place in Riyadh (Saudi Arabia, 16-19 October).

Table 5
The busy calendar of GS* and ATP tournaments limited to the May-July 2024 period

Start date	ATP Tournament	Location and surface
May 26	**Roland Garros**	**Paris, clay**
June 10	Libéma Open	s-Hertogenbosch, grass
June 10	Boss Open	Stuttgart, grass
June 17	Terra Wortman Open	Halle, grass
June 17	Cinch Championships	London, grass
June 23	Mallorca Championships	Mallorca, grass
June 24	Rothesay International	Eastbourne, grass
July 1	**Wimbledon**	**Great Britain, grass**
July 15	Hamburg European Open	Hamburg, clay
July 15	Nordea Open	Bastad, clay
July 15	EFG Swiss Open	Gstaad, clay
July 15	Infosys Hall of Fame Open	Newport, grass
July 22	Atlanta Open	Atlanta, hard
July 22	Generali Open	Kitzbuhel, clay
July 22	Plava Laguna	Umag, clay
July 26	**Olympic Games**	**Paris, clay**
July 29	Citi Open	Washington, hard

* GS: Grand Slam

Table 6
The busy calendar of GS* and WTA tournaments limited to the May-July 2024 period

Start date	WTA Tournament	Location and surface
May 26	**Roland Garros**	**Paris, clay**
June 10	Libéma Open	s-Hertogenbosch, grass
June 10	Rothesay Open	Nottingham, grass
June 10	BBVAOpen	Valencia, clay
June 17	Rothesay Classic	Birmingham, grass
June 17	ecotrans Ladies Open	Berlin, grass
June 17	Veneto Open	Gaiba, clay
June 23	Bad Homburg Open	Bad Homburg, grass
June 24	Rothesay International	Eastbourne, grass
July 1	**Wimbledon**	**Great Britain, grass**
July 8	Nordea Open, Bastad	Bastad, clay
July 8	Grand Est Open 88	Contrexeville, clay
July 15	Ladies Open	Palermo, clay
July 15	Hungarian Grand Prix	Budapest, clay
July 21	Livesport Prague Open	Prague, clay
July 21	Unicredit Iasi Open	Iasi, clay
July 22	Polish Open	Warsaw, hard
July 26	**Olympic Games**	**Paris, clay**
July 29	Mubadala City DC Open	Washington, hard

* GS: Grand Slam

We once again reiterate the opportunity to modify the ATP and WTA calendar in consideration also of the recent complaints of the protagonists of the tour. During the Cincinnati 2024 tournament, one of the strongest WTA tennis players asked for a reduction in the tennis calendar in an interview with Sky Sports (Dimon, 2024). During the seventh edition of the Laver Cup (Berlin, September 20-22), a four-time Grand Slam singles winner has criticised the congested ATP tennis calendar (Fonseca, 2024).

Conflict of interests

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AUTHORS' CONTRIBUTIONS

Conceptualization: Rodolfo Lisi. Data curation: Rodolfo Lisi, Carlo Albino Frigo, Renato Rodano. Formal analysis: Carlo Albino Frigo, Renato Rodano. Investigation: Rodolfo Lisi, Federico Colombo, Renato Rodano. Methodology: Rodolfo Lisi, Renato Rodano, Carlo Albino Frigo. Project administration: Rodolfo Lisi. Supervision: Renato Rodano, Carlo Albino Frigo. Writing- original draft: Rodolfo Lisi, Renato Rodano. Writing- review & editing: Renato Rodano, Carlo Albino Frigo.

STATEMENT ABOUT THE USE OF AI

In this scientific work, generative artificial intelligence (AI) has not been used and Rodolfo Lisi, as the first author of the paper, takes full responsibility for its content, claims, and references.

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Tennis Doubles development: Two historical snapshots show enormous tactical changes at the professional level over 20 years

El desarrollo de los dobles: dos momentos históricos muestran enormes cambios tácticos a nivel profesional a lo largo de 20 años

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Abstract

We aimed to compare tactical characteristics in professional men´s tennis doubles by notational analysis of two historical samples of matches collected at least 20 years apart. Samples were taken either between 1985 and 1990 ($D<_{1990}$: 57 matches, 9.305 points, 34.428 strokes) or in 2011 ($D>_{2010}$: 8 matches, 1.002 points, 4.297 strokes) during official ATP tournaments. Players were internationally ATP Ranking ($D<_{1990}$: 76 ± 89; $D>_{2010}$: 102 ± 91) and all matches were played on clay courts following ITF rules. Notational analysis was done by tagging video recordings following the same self-programmed notation software model. Absolute and percentage numbers of stroke rates, winners, and errors as well as specific tactics for services (e. g. Serve & Volley), returns (e. g. Chip & Charge), volleys and groundstrokes (e. g. positioning) were analysed. Coding was done by two experienced tennis coaches. Interrater reliability was calculated by Cohen's Kappa and items with r < 0.9 were excluded. Differences between $D<_{1990}$ and $D>_{2010}$ were calculated by independent t-tests. Significance level was set at p<0.05. Rally length (3.7±0.3 vs. 4.2±0.5 strokes per point, p<0.001) increased significantly from $D<_{1990}$ to $D>_{2010}$. The percentage of serves (32.5±3.9 vs. 23.8±3.5 %) and volleys (25.1±4.0 vs. 17.3±5.7 %) decreased while the percentage of groundstrokes increased over time (8.8±3.6 vs. 26.9±7.0 %) (p<0.001). Serve & Volley application was reduced to one third in $D>_{2010}$ (98.7±2.0 % vs 33.9±33.4 %) with a high individual variation. Positioning of Returns (more often behind the baseline) and volleys (shorter distance to the net) changed in D>2010 (p<0.001). Tactical characteristics in men´s tennis doubles completely changed within a time frame of 20 years mainly attributed to a decreased Serve & Volley application from most but not from all double players. The current variability in technical and tactical demands must be considered by individualized coaching guidelines.

Keywords: *History and development, notational analysis, ATP doubles, Serve & Volley tactics.*

Resumen

El objetivo de este estudio fue comparar las características tácticas de dobles de tenis masculinos profesionales a través de un análisis notacional de dos muestras históricas de partidos recolectadas con al menos 20 años de diferencia. Las muestras fueron tomadas entre 1985 y 1990 ($D<_{1990}$: 57 partidos, 9305 puntos, 34 428 golpes) o en 2011 ($D>_{2010}$: 8 partidos, 1002 puntos, 4297 golpes) durante torneos ATP oficiales. Los jugadores fueron ranqueados

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internacionalmente por la ATP ($D<_{1990}$: 76 ± 89; D>2010: 102 ± 91) y todos los partidos fueron jugados en canchas de arcilla según las reglas de la ITF. El análisis notacional fue realizado etiquetando grabaciones de video siguiendo el mismo modelo de software de notación autoprogramado. Se analizaron las cifras absolutas y porcentuales de las tasas de golpes, los ganadores, los errores y las tácticas específicas en los saques (e. g. saque y volea), las devoluciones (e. g. *chip and charge*), las voleas y los golpes de fondo (e. g. posicionamiento). La codificación fue hecha por dos entrenadores de tenis experimentados. La fiabilidad interevaluador se calculó mediante el coeficiente Kappa de Cohen y los elementos con r < 0,9 fueron excluidos. Las diferencias entre $D<_{1990}$ y $D>_{2010}$ fueron calculadas con pruebas t independientes. El nivel de significancia se fijó en p<0,05. La duración del peloteo (3,7±0,3 vs. 4,2±0,5 golpes por punto, p<0,001) aumentó significativamente de $D<_{1990}$ a $D>_{2010}$. El porcentaje de saques (32,5±3,9 vs. 23,8±3,5 %) y de voleas (25,1±4,0 vs. 17,3±5,7 %) disminuyó, mientras que el porcentaje de golpes de fondo aumentó con el tiempo (8,8±3,6 vs. 26,9±7,0 %) (p<0,001). La aplicación del saque y volea se redujo a un tercio en $D>_{2010}$ (98,7±2,0 % vs 33,9±33,4 %) con una alta variación individual. El posicionamiento en las devoluciones (más frecuentemente detrás de la línea de fondo) y las voleas (menor distancia a la red) cambió en $D>_{2010}$ (p<0,001). Las características tácticas en los dobles de tenis masculinos cambiaron completamente en un periodo de 20 años, y se le atribuye principalmente a la disminución en la implementación del saque y volea por parte de la mayoría, pero no todos los jugadores de dobles. La variabilidad actual en las demandas técnicas y tácticas debe ser considerada en guias de entrenamiento individuales.

Palabras clave: *historia y desarrollo, análisis notacional, dobles ATP, tácticas de saque y volea.*

INTRODUCTION

Tennis doubles represent a special attraction for spectators as well as players. Almost all professional tournaments organised by the Association of Tennis Professionals [ATP] and the International Tennis Federation [ITF] include doubles draws (Martinez-Gallego et al., 2021c; Borderias et al., 2024; ATP, 2024; ITF, 2024). Changes in team competition formats (e. g. Davis Cup and ATP Cup) increase the importance of doubles while making doubles play the deciding point (Martinez-Gallego et al., 2021a). Interestingly, due to the specific skill demands in tennis singles and doubles an increasing number of tennis players on ATP tour are specializing on doubles or mixed doubles competition which comes along with a negative correlation between doubles and singles ATP ranking (r=-0.5, February 2025) and only 15 from the top 100 doubles ranked players are ranked beyond the top 1,000 in ATP singles ranking (https://live-tennis.eu).

Due to the rules and regulations, the doubles game has several differences compared to singles. Doubles are played in pairs, which implies a decision-making during the game between the players (Borderias et al., 2024). Players not only have to watch the ball but also their partners and opponents, demanding a higher perceptual skill compared to singles (Carboch et al., 2014; Carboch & Kocib, 2015). The court dimensions include added alleys, but the space per player is smaller, affecting movement, positioning, physiological demands, timing, and training. Communication between players is crucial, as it can determine the outcome of a match and is essential during and between points (Lausic et al., 2009; Kocib et al., 2020; Martinez-Gallego et al., 2021b). Nowadays, the scoring system at the international level differs from singles, featuring the best of two tie-break sets and a match tie-break, along with the no-ad rule. In contrast, Grand Slam doubles matches are played in a best-of-three tiebreak sets format with advantage sets, like singles (Pollard & Pollard, 2010; Borderias et al., 2024).

Although tennis doubles hold considerable importance in professional tennis, studies on this subject are limited. Research on doubles has primary focused on match structure (Martinez-Gallego et al., 2020), communication (Lausic et al., 2009), scoring systems (Pollard & Pollard, 2010), time characteristics (Martinez-Gallego et al., 2021), and technical facts like serve efficiency between male and female athletes (Carboch & Kocib, 2015), and volley positions (Martinez-Gallego et al., 2021a). Only one article by Black & Van de Braam (2012) outlined changes in the modern double's tactics over the years due to increased ball velocities, which impact the net game. However, none of the studies used notational match analysis to quantify this evolution. Therefore, we compared tactical characteristics in professional men´s tennis doubles in two samples of matches collected at least 20 years apart using the same self-programmed notational analysis software. We hypothesized fundamental game structural changes relevant for training prescription.

MATERIALS AND METHODS

Sample and participants

Historical data from notational analysis in men's tennis doubles taken during ATP Tournaments between 1985 and 1990 ($D_{<1990}$: 57 matches, 9.305 points, 34.428 strokes) are compared with more current data from 2011 ($D_{>2010}$: 8 matches, 1.002 points, 4.297 strokes) (Table 1).

The $D_{<1990}$ sample includes observations taken during World Team Cup 1985, 1986, 1989, and 1990, which was the men's team championship of the Association of Tennis Professionals (ATP) annually held in Düsseldorf (Germany), as well as data taken during the French Open ATP Grand Slam Tournaments 1985 and 1986 in Paris (France). The $D_{>2010}$ sample was taken during the World Team Cup 2011 in Düsseldorf (Germany).

All matches were played on clay courts following the same rules of the International Tennis Federation (www.itftennis.com). Matches were played to the best of 3 sets (full 3rd set, no match tie-break). Since the tennis matches were open to the public, no consent forms were obtained from the players in either study. All players were internationally registered in the ATP Doubles Ranking ($D_{<1990}$: 76 ± 89; $D>_{2010}$: 102 ± 91) (Table 1).

Table 1
Overview about sample sizes and player characteristics

Sample & participants	D<1990	D>2010
Matches (n)	57	8
Players (n)	111	20
Age (yrs)	24.9±3.9	28.7±3.7
ATP Doubles Ranking	76.1±89.2	102.6±90.9
Points	9305	1002
Strokes	34428	4297
Serves (1st & 2nd)	11189	1339
Returns	8194	998
Ground Strokes	3030	1141
Volleys	8641	752
Half Volleys	861	143
Smashs	1308	140
Lobs	1205	131

Procedures

Video recording and tagging

Matches were recorded using a digital video camera with a wide-angle lens, positioned at an elevated camera angle at the front of the court. From these video files, the matches were analysed, allowing for the reproduction of all match-deciding strokes and game actions in a randomly delayed sequence. Observation and tagging were conducted by two experienced tennis coaches and tournament players.

Observation model and definitions

The observation model was developed and programmed in MS-DOS language as a specific observation software for tennis doubles called *"TENDO"* (Ferrauti, 1992). The model was primarily focused on recording individual actions and consists of seven hierarchical observation levels: 1. player, 2. stroke technique, 3. Serve position & stroke hand (e. g. Forehand, Backhand), 4. Serve spin, return position & volley action, 5. Serve direction, stroke spin & volley position, 6. stroke direction and serve follow-up (like serve & volley) and 7. stroke effectiveness (Figure 1).

Definition of the observation levels:

1. **Player:** the two players of one double are player A or B.
2. **Stroke technique:** First and second serve, return of serve, volley, half volley, smash, groundstrokes, lob according to the general accepted definitions (Roetert & Groppel, 2001).
3. **Serve position & stroke hand:** serves from deuce or ad-court side and forehand or backhand strokes, respectively (Roetert & Groppel, 2001).
4. **Serve spin, return position & volley action:** in serves only two variants (flat serve or spin serve) were differentiated. Regarding stroke position the field was divided into several zones in length and width (Figure 2). In volleys we differentiated two stroke actions (moving volley or standing volley).
5. **Serve direction, stroke spin & volley position:** serve direction was differentiated into three variants (left, body, right) from the server's perspective. Regarding stroke spin it was differed between topspin and slice (Roetert & Groppel, 2001).
6. **Stroke direction & serve follow-up:** for the assignment of "cross", "middle" and "longline", the ball flight was evaluated in relation to the position of the opponents (Figure 2). For the server, a distinction was made as to whether a net attack followed.
7. **Stroke effectiveness:** a distinction is made between "point" (the ball hits in the opponent's court in accordance with the rules, and no further stroke action by the opponent can be observed), "error" (the ball hits in the net or outside the court), or "neutral" (at least one further stroke movement by the opponent's double can be observed).
8. **Additional items:** Later, after finishing the software, special tactical features such as "Australian Formation" and "Chip & Charge" were added und needed to be recorded separately using the paper and pencil method.

Data analysis and statistics

Data entry to the observation program *"Tendo"* was performed using the numeric keypad. For each point, three to seven entries were required in a predetermined sequence (Figure 1). The list of entry codes (e. g. 1,1,2,2,1,1,1) was processed by the software but could also be exported to other statistics programs. Interrater reliability was calculated between two tennis coaches (processing two sets from two randomly chosen matches) according to Cohen's Kappa and reached values between 0.94 and 1.0, which represent a good reliability (Cohen, 1968; Table 2).

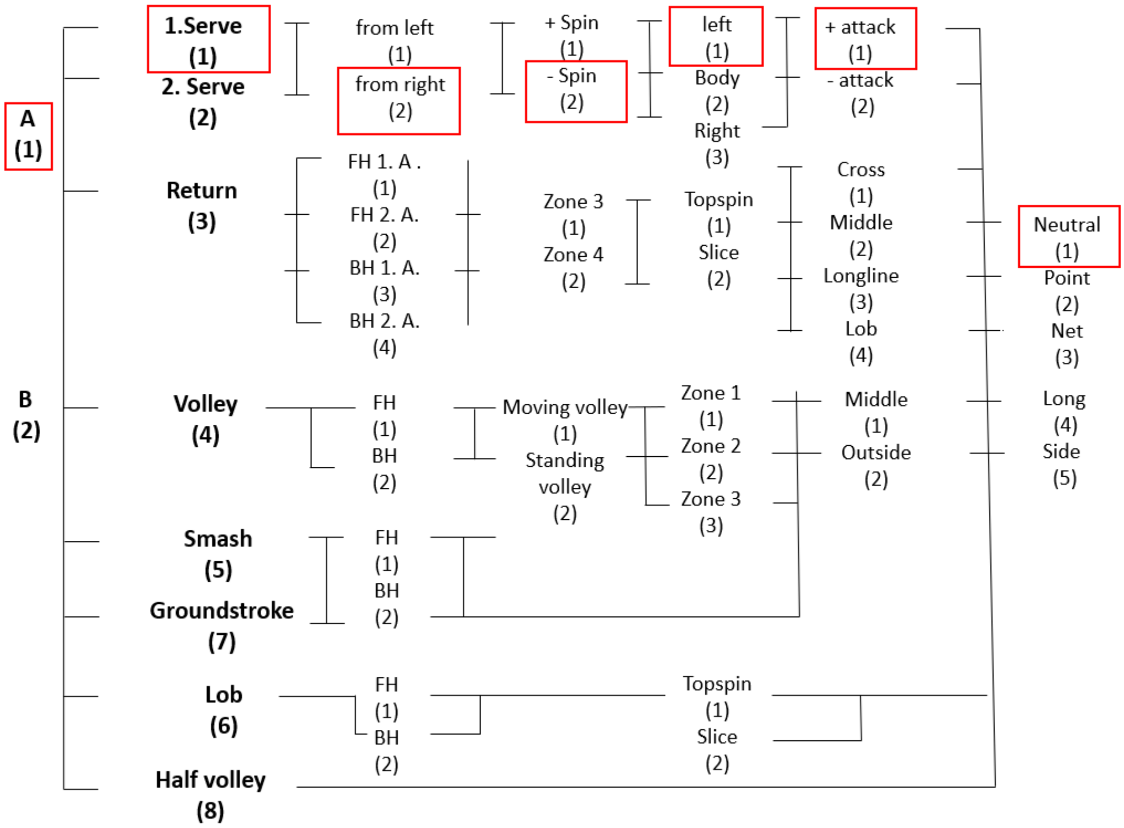

Figure 1

Sequence and structure of observation levels and items programmed in the software *"TENDO"* (Ferrauti, 1992). A coding example is highlighted in colour. Code 1-1-2-2-1-1-1 means a flat and wide 1st serve of player A from the deuce court side, followed by a net approach.

Note: in addition to this online evaluation, special tactical features such as "Australian Formation" and "Chip & Charge" were recorded separately using the paper and pencil method).

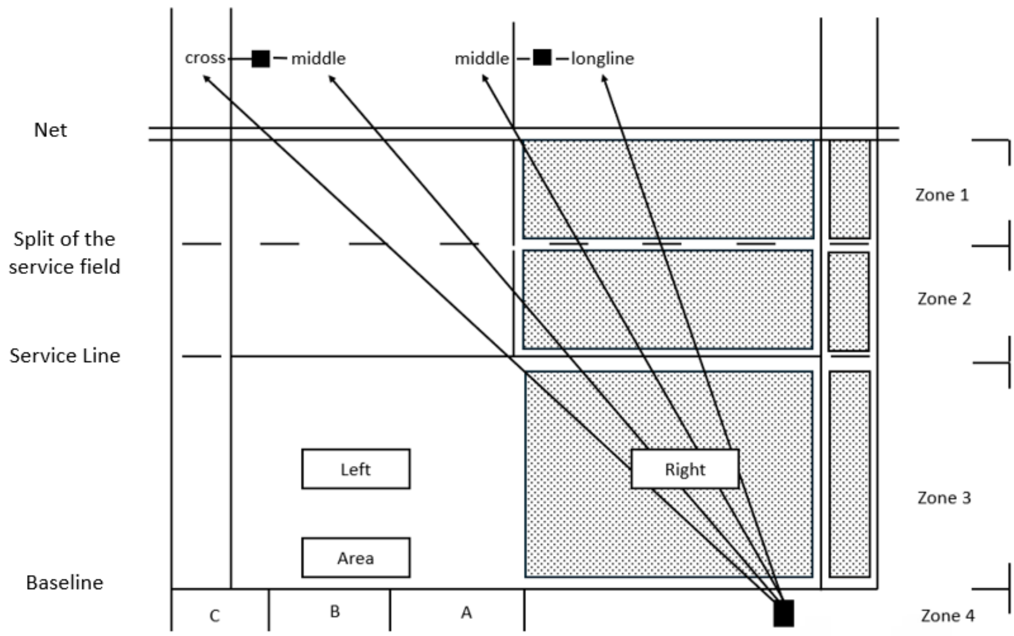

Figure 2

Definition of zones in length and width on the double field as well as stroke direction evaluation guidelines for cross, middle, or long line strokes.

The raw data from each double pair (both players combined) and for each match were first calculated into percentage data per double pair and per match based on the absolute total numbers of observations per match. From the resulting 114 percentage data sets in $D<_{1990}$ and the 16 data sets in $D>_{2010}$, respectively, we the calculated means ± standard deviations (SD).

An independent t-test was used to compare the percentage mean values between $D<_{1990}$ and $D>_{2010}$. The Shapiro-Wilk test was used to test for normal distribution. T-Tests were conducted using an online t-test calculator (GraphPad, 2024). Significance level was set at p<0.05.

Table 2
Interrater Kappa values of selected items.

Items	Interrater Reliability (Kappa)
Player	1.00
Stroke technique	0.99
Serve position	0.98
Serve direction	0.98
Serve & Volley	0.99
Forehand or backhand	1.00
Stroke position	0.96
Stroke direction	0.94
Moving or Standing Volley	0.96
Volley position	0.98

RESULTS

Stroke Pattern: Rally length (3.7 ± 0.3 vs. 4.2 ± 0.5 strokes per point, p<.001) increased significantly between $D<_{1990}$ and $D>_{2010}$. The mean percentage of serves (32.5 ± 3.9 vs. 23.8 ± 3.5 %, p<.001) and volleys (25.1 ± 4.0 vs. 17.3 ± 5.7 %, p<.001) decreased, while the mean percentage of groundstrokes substantially increased (8.8 ± 3.6 vs. 26.9 ± 7.0 %, p<.001) between $D<_{1990}$ and $D>_{2010}$. Additionally, more half volleys were played in $D>_{2010}$ compared to D<1990 (3.3 ± 1.3 vs. 2.5 ± 1.2 %, p = 0.015) (Figure 3).

Service: In $D<_{1990}$, almost every point beginning after 1st and 2nd serve was started by Serve & Volley (98.7 ± 2.0 %), while this was reduced to one third (33.9 ± 33.4 %, p<.001) with a high variation between players (Table 3). Meanwhile, I-formation and Australian formation percentage increased significantly from $D<_{1990}$ (3.5 ± 3.2 %) to $D>_{2010}$ (8.9 ± 9.0 %, p<.001). Serve direction remained constant with around two thirds of the serves played at the opponent's backhand (64.9 ± 9.6 vs. 67.3 ± 8.6 %, p = 0.345). Additionally, the positioning of the serve partner remained relatively consistent over the years (Table 3 and Figure 4).

Return: In earlier times, significantly more returns were played from Zone 3 before the baseline inside of court (58.9 ± 13.2 vs. 27.7 ± 7.4, p<.001*) and more often the return was combined with a net attack called "Chip & Charge" (30.4 ± 17.7 % vs. 6.8 ± 6.0, p<.001) (Table 3). Also, the return partner´s position was more offensive in $D<_{1990}$. Return partners were positioned in 80 % of first serve points in offensive Zones 1 or 2 compared to 16,5 % in $D>_{2010}$. The starting position was more offensive before second serves in both groups, but the difference remained (Figure 4).

Volley: More recently, a strikingly higher number of volleys were played from a close distance to the net in Zone 1 (42.9 ± 10.9 %, p<.001) ensuring a high hitting point (84.0 ± 4.7), while in earlier times volleys were mainly played from Zone 2 (76.0 ± 13.1, p<.001) with a lower hitting point (Table 3 and Figure 4). Volleys are played almost equally while moving forward or from a standing position (p = 0.548) (Table 3).

Table 3
Percentage of selected technical-tactical features (means ± standard deviations) of the stroke techniques serve, return and volley observed in professional men's doubles in $D<_{1990}$ and $D>_{2010}$.

Technical-tactical features		$D_{<1990}$	$D_{>2010}$	p-Value
Serve (%)	Serve & Volley	98.7 ± 2.0	33.9 ± 33.4	<.001*
	I-Formation/ Australian formation	3.5 ± 3.2	8.9 ± 9.0	<.001*
	FH	35.1 ± 9.6	32.7 ± 8.6	0.345
	BH	64.9 ± 9.6	67.3 ± 8.6	0.345
Return (%)	Chip & Charge	30.4 ± 17.7	6.8 ± 6.0	<.001*
	cross	54.5 ± 12.2	58.0 ± 15.0	0.297
	middle	31.6 ± 11.7	19.6 ± 12.9	<.001*
	longline	10.3 ± 5.0	15.0 ± 3.6	<.001*
	Lob	3.7 ± 3.7	7.7 ± 7.8	<.001*
	Zone 3	58.9 ± 13.2	27.7 ± 7.4	<.001*
Volley (%)	High	57.3 ± 5.0	84.0 ± 4.7	<.001*
	Low	42.7 ± 5.0	16.0 ± 4.7	<.001*
	Standing	47.2 ± 10.3	45.6 ± 6.6	0.548
	Moving	52.8 ± 10.3	54.4 ± 6.6	0.548
	Zone 1	76.0 ± 13.1	42.9 ± 10.9	<.001*
	Zone 2	58.9 ± 13.2	49.9 ± 10.9	<.001*
	Zone 3	11.5 ± 9.6	7.3 ± 5.5	0.090

DISCUSSION

This is the first study on professional level men's doubles in tennis quantifying tactical characteristics and their historical development over a period of more than 20 years. The data presented indicate a significant shift in the fundamental playing structure of tennis doubles and in multiple technical and tactical details. The main differences between earlier and more recent doubles characteristics consists in a lower but individually inhomogeneous frequency of the serve & volley strategy from the server, a move of the service partner closer to the net (because he is no longer responsible for securing the back field) and, a more defensive position of the return players,

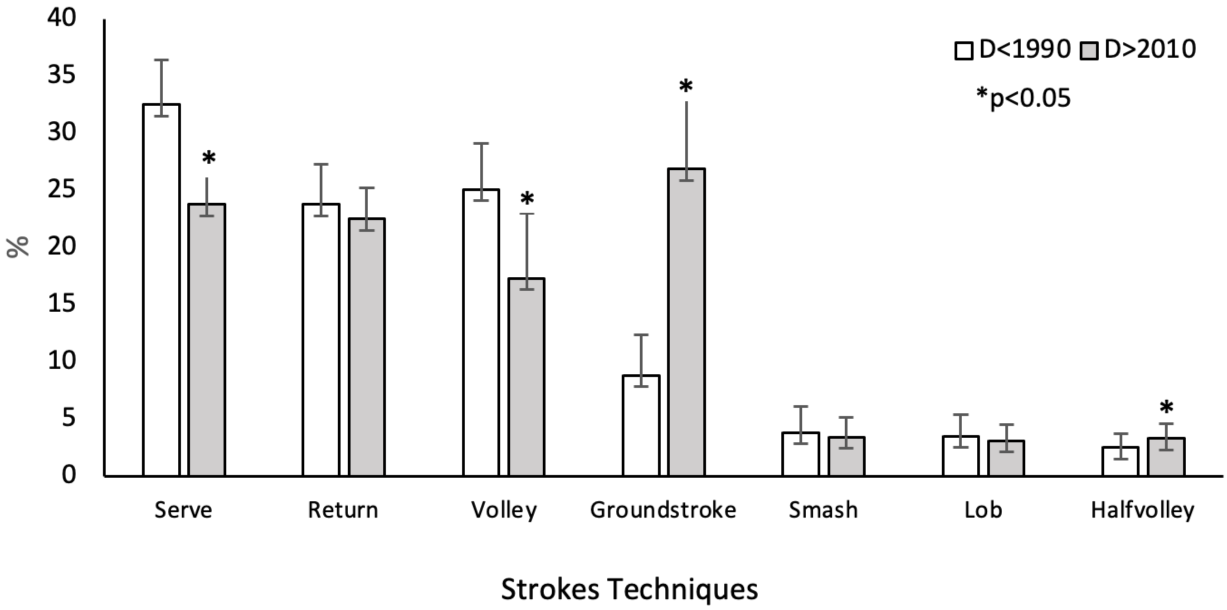

Figure 3
Percentage of the different stroke techniques (means and standard deviations) in professional men´s doubles in D<$_{1990}$ and D>$_{2010}$.

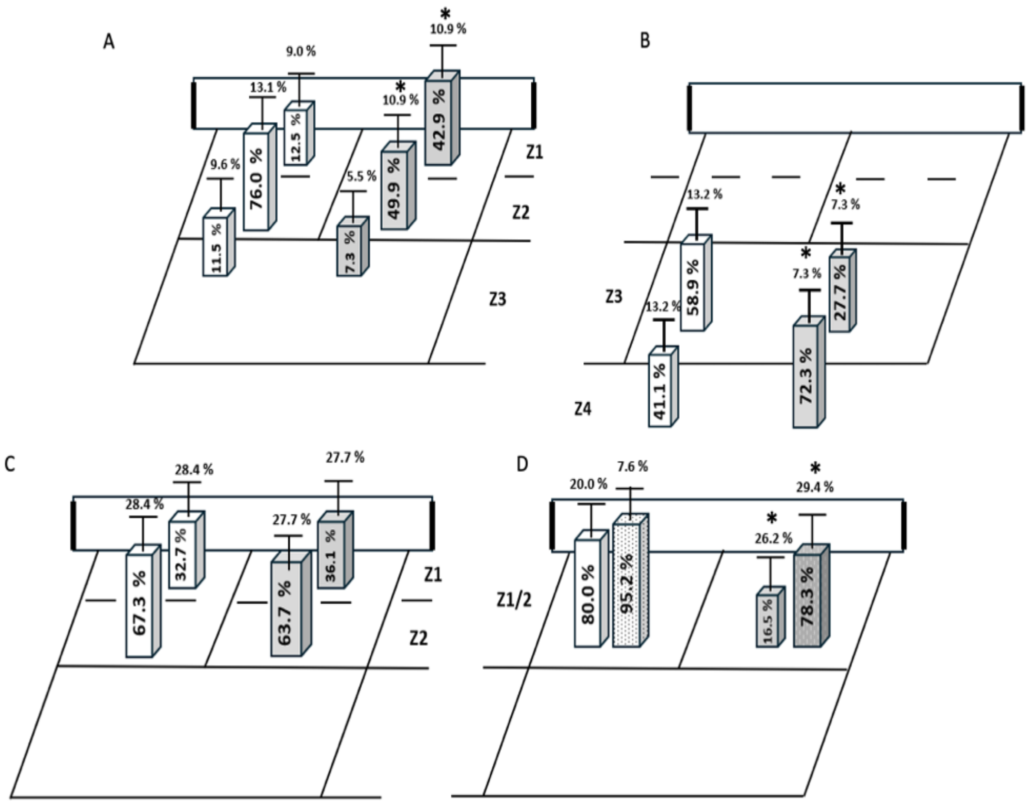

Figure 4
Percentage rate of different on court positions for volleys (A), returns (B), serve partner (C), and return partner (D) in D<$_{1990}$ (white bars) and D>$_{2010}$ (grey bars). In Figure D, the dotted bars indicate the return partner position awaiting a 2nd serve.

both, regarding return player position as well as return partner. These changes are coming along with an increase in stroke rate and importance of the baseline ground strokes while reducing net play, and consequently an extension of the rally duration (Figure 3 and Table 3). This striking development is even more remarkable since no major rule changes during the last decades and no significant change in the players anthropometrics have taken place. Since the social relevance and the prize money structure in doubles remain lower than in singles, these aspects also seem to have no impact.

The reasons for the observed changes can only be speculated and they are very likely diverse. Previous studies showed that the velocity of both, serves and groundstrokes significantly increased over the past decades (Fernandez-Fernandez et al., 2010), whereas the proportion of specialized Serve & Volley players in singles declined. There is a lot of evidence that the quality (power and precision) of the baseline groundstrokes has improved to such an extent that attacking the net in both, singles, and doubles is rarely successful (Black & Van de Braam, 2012; Martinez-Gallego et al., 2021c). It can be hypothesized that an improved physical performance and athletic of the players, as well an innovative racket technology are the main underlying explanatory factors. Apart from that, a change in teaching and learning philosophy of coaches and some well accepted ITF programmes promoting an earlier starting age in children's tennis (e. g. "Play and Stay" as well as "Tennis 10s") may also play a role (https://www.itftennis.com). Due to the shorter stature and arm span of very young players, the net play is neglected in training and competition. Therefore, older players did not experience sufficient learning opportunities for developing the necessary skills to cover the entire court adequately (Schmidhofer et al., 2014). As a result, servers usually remain at the baseline after second serves, and only occasionally approach the net following first serves.

Generally, the dimensions of the playing field in doubles are in favour of a joint offensive at the net because of the reduced responsibility on half a doubles court (5.49m/player in doubles vs. 8.23m/player in singles). This may lead to a few doubles pairs still favouring a net attack strategy. Assuming that Serve & Volley is a key indicator for the basic strategy in doubles, one can observe extreme heterogeneity in the more recent sample (Table 4). It can be distinguished between doubles pairs that almost never or very rarely play Serve & Volley (n=9), those that use it about half of the points (n=3) and those that almost always play it, even following a 2nd serve (n=3) (Table. 4). Usually, but not always, the rate is higher after a 1st serve. Some individuals tend to attack more often after the 2nd serve, possibly because it allows more time to get to the net (e. g. Chela/Monaco, ARG). The table also shows a high consistency between multiple observations of a double pair (e.g. Petzschner/Kas, GER), like a fingerprint.

Table 4
Serve & Volley rate of different doubles pairs from sample D>2010. Lopez and Granollers (ESP) were the winners of the ATP World Tour Finals 2012. Granollers was ranked Number 1 on ATP Doubles ranking in 2024.

Serve & Volley rate (%)	1st serve	2nd serve
Lindstedt/Aspelin	100.0	100.0
Petzschner/Mayen	98.0	70.4
Isner/Fish	80.0	68.8
Petzschner/Kas	62.5	52.2
Petzschner/Kas	58.1	40.7
Zimonkic/Tipsarevic	54.5	52.0
Gonzales/Monaco	24.4	50.0
Chela/Monaco	2.7	46.7
Isner/Querrey	27.8	17.6
Gonzalez/Monaco	28.6	12.0
Golubejew/Kukuschkin	13.9	0.0
Tursuznov/Andreev	10.8	4.2
Golubjew/Kukuschkin	2.4	0.0
Tipsarevic/Troicki	2.9	0.0
Tursunov/Andreev	0.0	0.0
Lopez/Granollers*	0.0	0.0

The Serve & Volley application does not seem to be a performance-differentiating feature compared to earlier times. For example, it is noticeable that one of the most successful pairs in our analysis and Champion at the ATP World Tour Doubles Finals (López/Granollers, ESP) did not complete a single attack. These tremendous variations bring uncertainty among coaches which strategies should be taught and applied. The decision is probably a balancing act between having a good serve and stable volleys as well as above-average height (speaks for Serve & Volley strategy) or by possessing exceptionally good groundstrokes, high speed and mobility and smaller body size (speaks for baseline strategy). Since both strategies can be successful, perfecting the chosen style seems to be more important by regularly participating in doubles tournaments with an experienced partner. While in $D<_{1990}$ the singles and doubles ranking were correlated quite well (r=0.5), in recent doubles we found even negative correlations and only 15 players of the TOP 100 ATP doubles ranking are positioned beyond the TOP 1000 in ATP singles ranking. This indicates nowadays an increasing specialization in doubles competition.

Staying at the baseline after serve influences the return strategy. In $D<_{1990}$, doubles specialists returned almost exclusively from a position inside of court (Zone 3) to put the advancing server under time pressure (Figure 4). In more recent doubles, returns after the first serve are more often executed from a position behind the baseline. This change in return strategy might also be related to the faster serve velocity. Due to the greater distance from the net, the Chip & Charge strategy is now used in less than 10% of cases (Table 3). Also, the returner's partner is increasingly positioned further back during the first serve (Figure 4), meaning that the returning pair often defends from the baseline during the rally. In contrast, when the game starts with a second serve, the returning pair often adopts an offensive position. Since in these cases the server more often remains on the baseline, the classic, diagonally offset pattern of one net player and one baseline player leads to crossing to the opposite side, either by agreement or spontaneously, depending on the game situation. In addition, the I-formation or Australian formation are now more frequently used as variants (Black & Van de Braam, 2012; Kocib et al., 2020). In contrast, the basic structure in $D<_{1990}$ consisted of two net-players (serving pair) facing either one to two players at the baseline or two opposing net players (returning pair).

Both, the altered serving and returning strategy led to changes in the characteristics of the volleys. Previous volley demands in $D<_{1990}$ involved a lower contact point and a longer stroke distance to the net (Table 3, Figure 4). In contrast, current hitting positions are located closer to the net with a higher hitting point and mainly from a standing position. This is because players nowadays are less likely to bridge the gap from the baseline to the net during rallies and less often play the Serve & Volley strategy. The technical execution of the volleys has therefore changed completely. In contrast to the earlier, more guided movement under less time pressure, a volley with short movements and an extreme angle from a position very close to the net dominates today.

It must be emphasized that the study suffers from important limitations. The major one refers to the difference in the sample sizes ($D<_{1990}$ n=57 matches; $D>_{2010}$ n=8 matches). Furthermore, current data is missing because $D>_{2010}$ is already partially outdate. Finally, players from $D>_{2010}$ were lower ranked on ATP doubles ranking (Table 1). In total these limitations might potentially influence the results of the study and emphasises the importance of careful interpretation. On the other hand, the quantitative differences shown are so clear and highly significant that we see a relevant gain in knowledge despite the limitations mentioned. Even if a comparison to actual current data is unfortunately missing, the data shows the possible extent of historical changes in racket sports.

CONCLUSIONS

The results of this study indicate a historical shift in doubles tactics. While Serve & Volley was the main hallmark of competitive doubles 30 years ago, the frequency of net attacks by the server has decreased significantly in most double pairs. This change comes along with a backwards shifted return position, a decreased amount of net play, a volley position closer to the net, and a higher percentage of groundstrokes from the baseline. These changes are frequently leading to a diagonally shifted one up, one back players position during the rallies and more sideways shifts and side switches between partners. In contrast to the rather uniform game structure of the past, today's doubles pairs have very different basic strategies. It is a particular challenge for coaches to develop and train a strategy that is tailored to the individual player or doubles pair. This is even more important as an increasing number of players are concentrating only on the doubles competition and are not taking part in singles tournaments as well.

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Sliding benchmarks might prevent de-selection of talented badminton players

Los criterios de referencia variables podrían evitar la deselección de jugadores de bádminton talentosos

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Abstract

Despite potential advantages of talent identification practices, the degree of bias in decision-making due to relative age and maturity timing remains a concern. To investigate the impact of relative age and maturity on selection processes, and to examine the possible influence of an intervention aimed at minimizing the impact of relative age and maturity biases, thirty-three boys (M_{age} = 12.43y ± 0.36y) invited to compete for Badminton Malaysia, completed three anthropometrical measures, eight physical performance assessments, and five motor coordination tests. These players were tracked throughout their career to determine pathway progression (i.e., dropout or continuation) and their level of success (i.e., season-end rankings). With regards to the relative age of athletes and the initial selection to the U13 team, findings revealed that younger and less mature players were disadvantaged, since their morphology, physical fitness, and motor capacities were less developed than their peers. A sliding benchmark intervention was applied, where raw scores were adjusted. Although, the dropout rate from the U13 team was high (24/33 players, 73%), 6 of 9 remaining players of the national team achieved exceptional results, which were evident six years later. As a result of the sliding benchmark intervention, two relatively younger, late maturers with superior motor competence scores, were selected to the elite sport school. Without this intervention, both players might never have won the BWF Junior World Championships. This paper examines the pathway of these competitive badminton athletes and discusses the potential value of applying a sliding benchmark intervention in competitive sport selection settings.

Keywords: *Talent identification, athlete selection, talent selection, relative age, maturity.*

Resumen

A pesar de las posibles ventajas de las prácticas de identificación de talento, el grado de sesgo en la toma de decisiones debido a la edad relativa y el momento de madurez sigue siendo motivo de preocupación. Para investigar el impacto de la edad relativa y la madurez en los procesos de selección, y examinar la posible influencia

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de una intervención destinada a minimizar el impacto de los sesgos de edad relativa y madurez, treinta y tres jóvenes (edad promedio = 12,43a ± 0,36a) invitados a competir para Bádminton Malasia completaron tres medidas antropométricas, ocho evaluaciones de rendimiento físico y cinco pruebas de coordinación motora. Se realizó un seguimiento a estos jugadores a lo largo de su carrera para determinar la progresión de su trayectoria (i.e, abandono o continuación) y su nivel de éxito (i.e, clasificación al final de la temporada). En lo que respecta a la edad relativa de los atletas y la selección inicial para el equipo sub-13, los resultados revelaron que los jugadores más jóvenes y menos maduros se encontraban en desventaja, ya que su morfología, condición física y capacidades motoras estaban menos desarrolladas que las de sus compañeros. Se aplicó una intervención de puntos de referencia variables, en la que se ajustaron las puntuaciones brutas. Aunque la tasa de abandono del equipo sub-13 fue elevada (24/33 jugadores, 73 %), 6 de los 9 jugadores que permanecieron en la selección nacional obtuvieron resultados excepcionales, que se hicieron evidentes seis años después. Como resultado de la intervención con puntos de referencia variables, dos jugadores relativamente más jóvenes y de maduración tardía, con puntuaciones superiores en competencia motora, fueron seleccionados para la escuela deportiva de élite. Sin esta intervención, es posible que ninguno de los dos jugadores hubiera ganado el Campeonato Mundial Sub-21. Este artículo examina la trayectoria de estos atletas de bádminton de competición y analiza el valor potencial de aplicar una intervención con puntos de referencia variables en entornos de selección deportiva de competición.

Palabras clave: *Identificación de talento, selección de atletas, selección de talentos, edad relativa, madurez.*

INTRODUCTION

Talent identification and selection have long been of great interest to coaches, researchers, communities, and governments. Talent identification (TID) is the process of finding the most talented individuals within a specific domain in a homogeneous talented population, a process, at least in theory, that should play a major role in sport (Pion et al., 2015). Similarly, talent selection (TS) is the process of making decisions on which athletes continue to progress in each system, and which ones are removed from the system. As international competition across many sports has improved and intensified, there has been a growing importance on identifying and selecting athletes at younger and younger ages who might be capable of top performance (Williams & Reilly, 2000).

Despite being an integral part of the selection process for elite-level athletes, TID programs remain a controversial topic in research. On the one hand, sports scientists advise against early TID due to its potential in leading to burnout and sport withdrawal (Güllich et al., 2023). On the other hand, some researchers argue that early investments are necessary to nurture athletes years before they reach peak performance (Hohmann, 2009; Pion et al., 2015; Woods et al., 2016; Lemoyne et al., 2022). Numerous studies (Matthys et al., 2011; Pion et al., 2015; Norjali et al., 2017; Robertson et al., 2022; Hohmann & Siener, 2021; Chapelle et al., 2023) have convincingly demonstrated that the identification of certain characteristics in young children can provide a strong foundation for identifying those most likely to excel at the international competition level. Many countries have adopted TID and talent development (the process of nurturing an athlete to help them flourish) programs in sport to increase their success on the global stage (Balyi et al., 2013; Gulbin et al., 2014). Some specific studies have generated valuable data that outlines the factors distinguishing athletes across various levels, providing a scientific basis for talent development programs (Faber et al., 2014), as well as the underlying performance characteristics that relate to international success (Robertson et al., 2018). While this area of study is important and helpful for athlete selection and development approaches, the evidence to date, is that there is much room for improvement.

One of the major concerns with the identification process for athlete selection, is the degree of bias that informs decision-making due to the athletes' relative age and maturity timing. In this sense, the highest ranked players are often those who are born earlier in the year and/or are early maturers, at least in some sports like football and badminton (Sweeney et al, 2023). With earlier born children outperforming their later-born peers (Jakobsson et al, 2021), biological maturity status and timing have large implications for (de)selection decisions (Hill et al, 2023). In the context of badminton, for example, this system affects all de-selected players, since they will not have the chance to further develop at the highest level. Furthermore, relative age and maturity may remain a delayed risk of dropout for the selected players. In the end, the risk to de-select all the tested players is extremely large and costly.

In addition, despite the widespread use of TID programs by sports organizations, there is no clear set of variables that consistently predicts future success (Johnston et al., 2018). Many existing models overemphasize early identification rather than focusing on the long-term development of potentially talented athletes (Abbott et al., 2005). This imbalance may lead to suboptimal outcomes and missed opportunities to support athletes with latent potential. To enhance the development of athletes, well-founded decisions are critical, especially given the substantial financial investments in elite sports. Reliable benchmarks and a valid selection process are essential to optimize these investments and to identify individuals with the highest potential for long-term success.

A clear understanding of key priorities is needed to develop long-term plans for young athletes, rather than pushing them towards early success at the risk of burnout or attrition in sports. Importantly, many characteristics and skills can change through training, maturation, or good coaching. The criteria for elite performance appear to be idiosyncratic and may make up for deficiencies in a specific area and with strengths in another (i.e., compensation) (Simonton, 1999). Striking the right balance between broad-based development and targeted investments remains one of the core challenges in the field of TID. Ultimately, the effectiveness of TID programs depends on the implementation of reliable benchmarks that can accurately assess potential over time.

There are multiple strategies for determining reliable benchmarks, however on sucuh tool is the SportKompas. Characterised by a generic approach of anthropometric, physical, and motor competence measurements, the SporKompas has been recognized for being a helpful tool for determining benchmarks for a wide variety of sports (Pion, 2024). It offers possibilities to better understand the potential underlying performance characteristics of a given sport and allows for the tracking of young athletes across their developmental pathway. When comparing athlete data with benchmarks for heterogeneous populations, generic tests can be applied for the detection of the superior 'movers' in schools. When comparing an athlete's testing results with sport-specific benchmarks, this approach can help with the identification of superiorly performing athletes in clubs and sports associations.

Despite the SportKompas' potential benefits, there are limitations to establishing benchmarks. The common practice of placing children into age groups for sport will still acutely benefit those who are more developed physically, emotionally, and cognitively. Those born later in the year appear to be at a disadvantage because they are less developed than their peers (Malina et al., 2015; Cumming et al., 2017; Pion, 2024). Furthermore, it is difficult to copy a champion's profile. Collecting data from champions and drawing causal conclusions comes with limitations.

One such strategy to minimize the impact of those limitations, is to apply a 'sliding benchmark' approach to selection. To minimize the impact of an athlete's chronological and biological age-related, a sliding benchmark approach can be used to control for maturity and chronological age. For example, two 12-year-old boys can differ by nearly an entire year based on when their birthdays are relative to a cut-off date for selection. The difference of one year is a significant advantage requiring recalculation to the appropriate proportions. Moreover, the difference in biological age (maturity) also results in a physical advantage. The sliding benchmarks method can be compared to an equaliser to adjust music output; it is possible to slide the raw test scores along the benchmarks of both the age group and the maturity group to obtain adjusted scores for chronological and biological age. To compute these sliding benchmarks, the dataset must be recalculated for the younger and older players in the cohort as well as for the less mature players and the more mature players.

To date, however, there is no known study that empirically investigates a sliding benchmark approach within a high-performance sport context. To address this, the present study aims to critically examine the impact of a sliding benchmark approach in neutralising performance advantages and disadvantages due to relative age and maturity status. Specifically, the study explores the possibility of applying the sliding benchmark approach to a selected group of elite young badminton players. The research question is twofold, 1) is it possible to successfully draft 12-year-old late mature boys, born later in the year when applying sliding benchmarks? 2) what is the predictive value when looking years ahead?

MATERIALS AND METHODS

Participants

Every year Badminton Association of Malaysia (BAM) invites up to 60 of the best U13 players based on their competition ranking to participate in various test sessions. From these sessions a minimum of six girls and six boys are selected as feeders for the national squads at the national elite sports centre. The selection aims to improve the development of the most talented players, based on the assumption that early selection increases their chance to win medals at the major international tournaments and Olympic Games. A cross-sectional study was carried out with the 33 highest ranked U13 badminton boys in Malaysia (age range 11.87y – 13.19y). The badminton test battery applied as an entry test for the elite sport school in Flanders and which is related to the generic test of SportKompas (Pion et al., 2015; Robertson et al., 2022), has been conducted likewise to select the high potentials for further development in the elite sport school in Malaysia. All data were recorded in a de-identified data set. It should be indicated that the sample in this study is small (n=33), but it was replicated at the suggestion of the BWF because of its much higher quality than the sample tested in Flanders (n=189).

Measurements

The badminton test battery presented in this study was discussed at the 6th World Congress of Racket Sport

Science in Bangkok, Thailand in 2018. The participants started with the measurement of body height after which they moved on to the next station and completed three other anthropometrical tests, eight physical performance tests, and five motor coordination tests. All tests were examined on the same day by a team of eight experienced examiners who were trained to administer this generic test battery. Instruction and demonstration were standardised according to the test guidelines (see below for detailed explanation). The athletes performed all tests barefoot except the sprints, the counter movement jump, and the endurance shuttle run test, which were all performed with running shoes.

Anthropometry: Height (H) and sitting height (SH) (0.1 cm, Harpenden, portable Stadiometer, Holtain, UK) and body weight (BW) (0.1 kg, Tanita, BC-420SMA) were assessed according to previously described procedures (Lohmann et al., 1988) and manufacturer guidelines. Also, the height of the parents was collected to calculate the % of predicted adult height (Khamis & Roche, 1994). Using percentage of predicted adult stature, which is an estimate of maturing timing, it is possible to group athletes into maturity categories (Khamis & Roche, 1994; Cumming et al., 2017).

Physical Performance: Flexibility was assessed by the sit-and-reach test of the Eurofit test battery with an accuracy of 0.5 cm and 15 cm at the level of the feet (Council of Europe, 1988). Explosive leg power was measured with the standing broad jump of the Eurofit test battery with an accuracy of 1 cm (Council of Europe, 1988), and the counter-movement jump (CMJ) (0.1 cm) using Optojump, requiring the gymnasts to jump as high as possible from an upright position with the hands on the hips (Microgate, Bolzano, Italy), counting the highest of 3 jumps (Cometti & Cometti, 2007). Speed was evaluated by two maximal sprints of 30 meters with split time measured at five meters. The recovery time between each sprint was set at two minutes. The fastest time for the 5m sprint and 30m sprint was used for analysis (Matthys et al., 2011) The sprint tests were recorded with MicroGate Racetime2 chronometry and Polifemo Light photocells at an accuracy of 0.001s (MicroGate, Italy). The 10x5m shuttle run (SR) test (Council of Europe, 1988) was used to measure speed and agility. The time it took the athletes to run 5 times back and forth (equalling ten 5m sprints) as quickly as possible between two lines 5 meters apart, 10 times in a row, reflected their speed and agility. Upper body strength was determined by the performance of curl-ups according to the BOT2 procedures (Bruininks & Bruininks, 2016), requiring the athletes to execute as many repetitions as possible in 30 seconds. The beep test (endurance shuttle run), with the final 30 seconds that persisted (0.5 min), was used for evaluating the endurance of the participants (Council of Europe, 1988).

Motor Coordination: The assessment of motor coordination consisted of five test items 1) in the balance beam test; participants had to walk 3 times backwards along balance beams of decreasing width (6 cm; 4.5 cm and 3 cm respectively) (Kiphard & Schilling, 2007). 2) For the jumping sideways test; participants had to jump sideways with both feet over a wooden slat as fast as possible (2 x 15 s), with the final score being the sum of the number of jumps over the two trials (Kiphard & Schilling, 2007). 3) For the moving sideways test, participants had to move sideways on wooden platforms (2 x 20 s), summing the number of relocations over two trials (Kiphard & Schilling, 2007). 4) In the eye hand coordination test, children needed to throw a tennis ball at a rectangle target (height 137 cm, width 152.5 cm; positioned at 1 m from the ground) on a flat wall at 1 m distance with one hand and to catch the ball correctly with the other hand as many times as possible in 30 s. The best number of correct catches of two attempts was recorded as raw outcome score (Faber et al, 2014). 5) Finally, the overhead-throwing test with a badminton shuttle, also from the SportKompas, either was used to evaluate over- arm throwing competency (Mohamed et al., 2009). The goal of this test was to throw the shuttle as far and accurately (straight forward) as possible, holding the shuttle between thumb and index finger. Throwing a shuttle requires less strength than throwing coordination. The summed throwing distance of 5 trials was recorded in cm. (Mohamed et al., 2009).

Data Collection

To calculate the sliding benchmarks and to adjust the (dis)advantages for relative age and maturity, the athletes were subdivided in 3 relative age groups and 3 maturity groups. Using percentage of predicted adult stature at the time of observation (PAH) it is possible to group athletes into maturity categories (Khamis & Roche, 1994; Malina et al., 2015; Cumming et al., 2017). Relative age: 1) Players < 12.20y (n=10) 2) players aged between 12.20y and 12.60y (n=16) and 3) players aged > 12.60y (n=7). Maturity: 1) Players with PAH < 85% (n=11) 2) players with PAH between 85% and 89% (n=13) and 3) players with PAH > 89% (n=9).

Data were collected on October 10th, 2018. All players were tested under similar indoor conditions. Total testing time for all players was approximately two hours. Test leaders were physical education students instructed and trained to the same extent by an expert.

Statistical Analysis

Data was analysed using SPSS for Windows 25.0. Basic descriptive indicators (mean and standard deviation) were calculated for all variables. The raw scores were converted to normalized quotient scores i.e., ((z-score*15) +100) to better understand the advantages and disadvantages for each variable and to calculate the overall scores for physical and motor performance. The Kolmogorov Smirnov test revealed that some of the variables i.e., body height; shuttle run; sit-ups; plate tapping; endurance shuttle run; moving sideways and throwing shuttles, were not normally distributed ($p<0.05$). Consequently, the non-parametric Kruskal-Wallis Test was used to compare all test results across the three relative age groups and the three maturity groups. The standing broad jump and the eye-hand coordination test showed significant differences among the three relative age groups, while for stature, weight and standing broad jump significant differences were found between the three maturity groups. Subsequently all normalised scores were summed for physical and motor performance. All scores from physical performance tests were summed and divided by the number of physical performance tests (n=9) and for the overall motor performance score the sum of all motor quotient scores were summed and divided by the number of motor performance tests (n=5).

RESULTS

Basic descriptive statistics (Table 1) were used to benchmark the 12-year-old boys (n=33)

The individual results based on age-group benchmarks for physical (x-axis) and motor performance (y-axis) were plotted in the theoretical selection model proposed by Baker et al. (2018). The figure visually represents which players can be selected (Figure 1).

Players n° 1; 2; 3; 4 and 20 are categorized as obvious talented with above-average performance; players n° 5; 6 and 10 are high potentials that meet performance standards.

Unfortunately, RAE and maturity distort the results in Figure 1, since relatively younger players are disadvantaged by the age group benchmarks (Table 2).

When sliding the sum scores according to the relative age and maturity status (%PAH), the advantages and disadvantages become more visible, and the selection looks different (Figure 3).

Six years after the selection process, it was checked which players are still part of the national team. 9 players out of 33 are still competing for BAM.

DISCUSSION

This study sought to explore the value in using sliding benchmarking to help neutralise the advantages and disadvantages that certain athletes have due to relative age and maturity status (Pion, 2024). Performance benchmarks from the badminton test battery related to the SportKompas are an objective approach to selecting high potentials and to support coaches' decisions, albeit that the age group benchmarks are biased for relative age and maturity (Table 1). The relative younger boys (< 12.20y) are overall 3% smaller, and the relative older boys (> 12.60y) are 2% taller compared to the measurements for the complete cohort. Late mature boys (PAH <85%) are 5% smaller, and early mature boys (PAH > 89%) are 8% taller. Using these benchmarks within this age group, is making the mistake of comparing apples to oranges. When comparing Figures 2 and 4, it appears that the late mature (red dots) shift to the left, and the early mature (green dots) to the right. Comparing within the age group without considering RAE and PAH clearly shows why 12-year-old late-maturing boys, born later in the year can hardly be selected for the Malaysian U13 Badminton Organisation (Figure 2). When applying the sliding benchmarks approach, the selection probability increases (Figure 4).

Our findings revealed that relative age and maturity distort the selection process. In this study the coaches made a preliminary selection of U13 players (n=33) and the sport scientists used the data of the badminton test battery to support their decision for a final selection of nine players each. Shifting the benchmarks reveals advantages and disadvantages. Figure 3 shows what the disadvantage for late-maturing boys (PAH<85) and the advantage for precocious boys (PAH>89), combined with an estimate of the disadvantage for relatively younger boys (>12.20y) and the advantage for relatively older boys (>12.60y) looks like.

Younger and less mature players are being overlooked during the selection procedure, since their morphology, physical fitness and motor capacities are less developed than their peers (Cumming et al., 2017; Mann et al., 2017). Talent identification takes place at a certain moment in time and so far, the objective measurements refer to age group benchmarks. It is important to highlight the distinction between identification and development of high potential athletes.

For decades, RAE and maturity have a huge impact on 'here and now' assessments of young athletes for identification and selection purposes (Barnsley, 2025). In any case, one must consider adjustments for RAE and maturity whether to selection contains objective or subjective criteria? This is one of the first studies to show that it is possible and feasible to adjust strategies by using sliding benchmarks. In this respect, the article is also a model for many other sports. Although it is important to acknowledge some limitations of this study. Firstly, the sample size was small. This is mainly because the larger population of elite badminton players is relatively small, and the authors feel lucky enough to take part in the selection process of a very successful cohort of players. To provide context on the size of the sample, in 2018, 33 players were screened. The dropout rate of 73% is high (24/33 players). On the other hand, the 9 remaining players who are still members of the national team achieve exceptional results and became national U21

Table 1
Descriptive benchmarks for 12-year-old badminton players (boys), related to RAE and PAH

Benchmark	Age group 12y old boys (n= 33)	Age < 12.2(n=10)	12.2 > Age > 12.6 (n=16)	Age > 12.6 (n=7)	%PAH < 85 (n=11)	85 > %PAH > 89 (n=13)	%PAH > 89 (n= 9)
Age (y.)	12.43 ± 0.36	12.03 ± .12	12.44 ± 0.13	13.00 ± 0.24	12.24 ± 0.28	12.45 ± 0.33	12.58 ± 0.42
%PAH (%)	86.9 ± 3.3	84.8 ± 2.2	87.9 ± 2.9	87.7 ± 4.4	83.5 ± 1.3	86.8 ± 1.1	91.2 ± 1.3
Height (cm)	151.8 ± 9.3	146.5 ± 5.3	155.0 ± 8.7	155.1 ± 15.0	144.2 ± 5.2	150.4 ± 3.9	163.2 ± 7.6
Weight (kg)	43.6 ± 8.0	40.0 ± 6.6	46.2 ± 8.5	45.1 ± 10.0	37.3 ± 4.8	41.7 ± 3.8	54.0 ± 5.1
12.6	32 ± 6	31 ± 7	33 ± 6	33 ± 4	31 ± 5	32 ± 5	35 ± 6
Sprint 5m (s)	1.191 ± .079	1.213 ± .060	1.164 ± 0.022	1.221 ± .090	1.221 ± .061	1.195 ± .080	1.149 ± .074
Sprint 30m (s)	5.019 ± 0.291	5.117 ± 0.223	5.004 ± 0.356	4.914 ± 0.350	5.131 ± .240	5.032 ± .0.248	4.863 ± 0.355
Shuttle run 10x5m (s)	19.063 ± .1.020	19.320 ± .0.685	19.089 ± 1.109	18.636 ± .1.156	19.195 ± .0.725	19.268 ± .1.022	18.607 ± .1.260
Counter movement jump (cm)	43.1 ± 6.8	39.5 ± 5.4	43.9 ± 7.5	46.2 ± 5.4	40.2 ± 4.5	42.7 ± 5.5	47.0 ± 9.0
Standing broad jump (cm)	180 ± 23	169 ± 17	178 ± 23	200 ± 20	168 ± 14	178 ± 19	197 ± 29
Curl ups (N/30s)	33 ± 9	36 ± 8	29 ± 8	38 ± 9	33 ± 9	33 ± 10	33 ± 7
Plate tapping (s)	12.2 ± 2.4	12.8 ± 2.1	12.4 ± 2.4	9.5 ± 0.3	12.1 ± 2.5	12.7 ± 2.4	11.4 ± 2.1
Endurance shuttle run (min)	9 ± 2	9 ± 2	9 ± 1	9 ± 2	9 ± 1	10 ± 2	9 ± 2
Balance beam KTK	56 ± 9	58 ± 8	53 ± 11	62 ± 10	59 ± 8	54 ± 11	57 ± 12
Jumping sideways KTK	88 ± 18	94 ± 20	81 ± 17	97 ± 9	91 ± 13	88 ± 20	86 ± 20
Moving sideways KTK	38 ± 12	34 ± 6	37 ± 11	49 ± 16	35 ± 3	42 ± 12	38 ± 18
Eye-hand coordination (Faber)	53 ± 11	49 ± 8	51 ± 12	62 ± 5	52 ± 8	54 ± 14	51 ± 11
Throwing shuttles	37 ± 2	36 ± 2	37 ± 2	40 ± 5	37 ± 2	37 ± 2	38 ± 3

Figure 1
Individual scores for physical performance and motor performance based on age group benchmarks for 12-year-old boys (badminton), plotted in the theoretical selection model according with Baker et al. (2018).

Table 2
Overall scores for physical (PQ) and motor (MQ) tests related to RAE and PAH

Age group 12y old boys (n= 33)	Age < 12.2(n=10)	12.2 > Age > 12.6 (n=16)	Age > 12.6 (n=7)	%PAH < 85 (n=11)	85 > %PAH > 89 (n=13)	%PAH > 89 (n= 9)
PQ = 100.0 ± 8.0	PQ = 96.4 ± 7.2	PQ = 99.7 ± 8.1	PQ = 106.0 ± 5.8	PQ = 96.6 ± 6.6	PQ = 99.4 ± 5.9	PQ = 105 ± 10.1
MQ = 100.0 ± 8.7	MQ = 98.3 ± 5.4	MQ = 96.9 ± 8.5	MQ = 109.6 ± 7.2	MQ = 99.7 ± 5.0	MQ = 99.9 ± 88	MQ = 100.7 ± 12.3

Quotient score = (100 + (15* Z-score)).

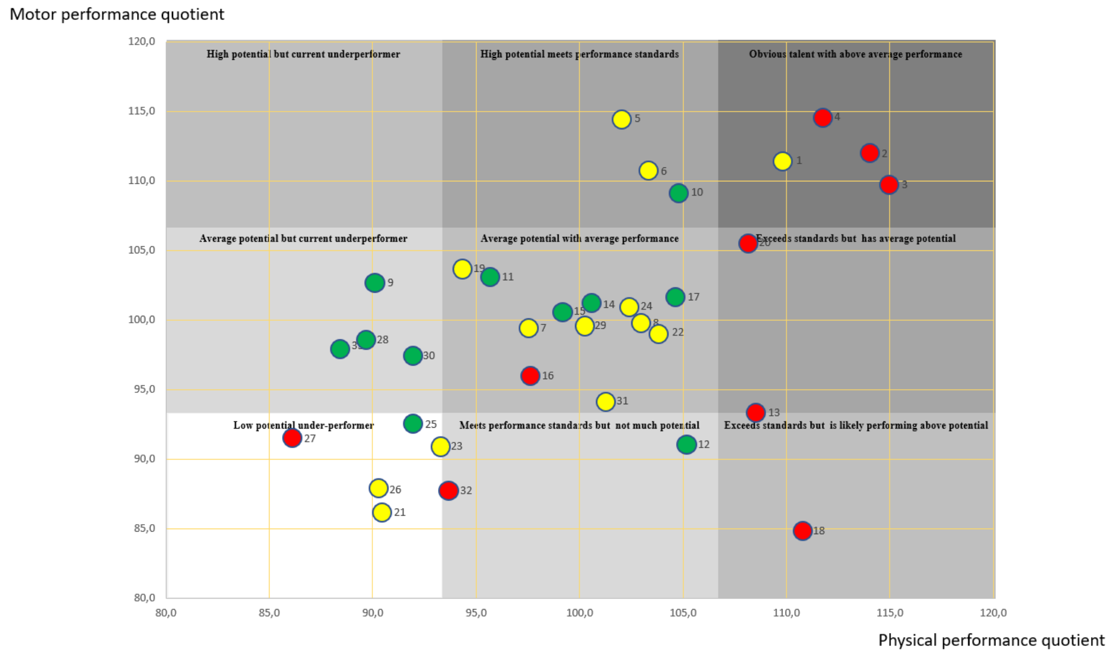

Figure 2
Individual scores for physical performance and motor performance based on age group benchmarks for 12-year-old boys (badminton), plotted in the theoretical selection model of Baker et al. (2018). Red dots PAH >89; green dots PAH <85, yellow dots 85> PAH <89.

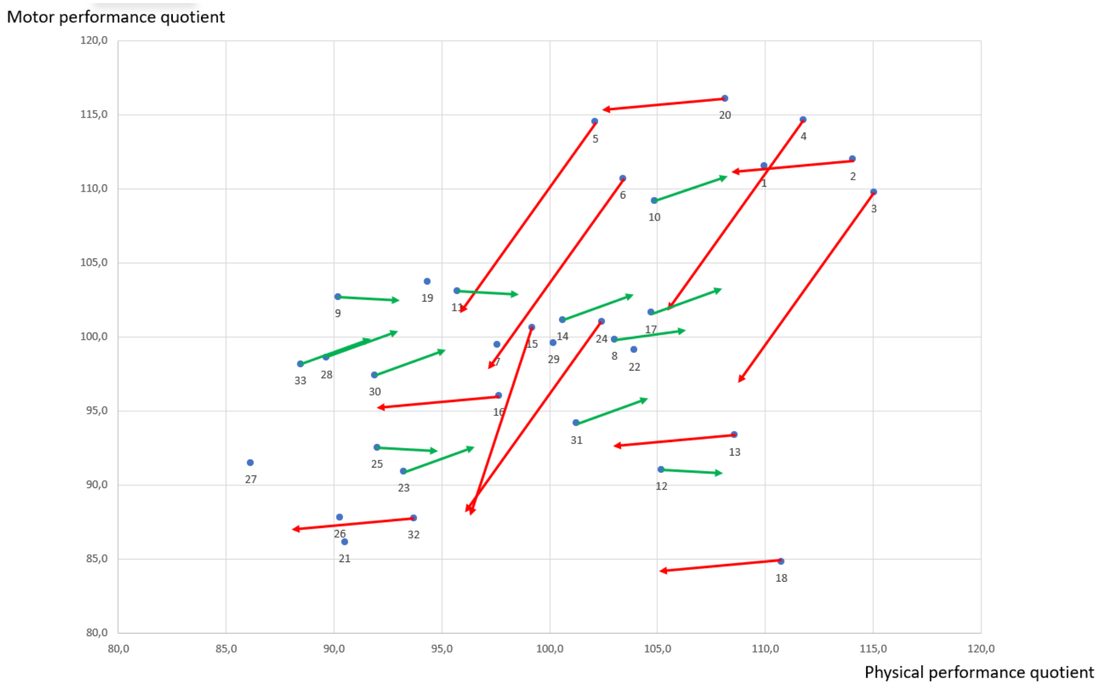

Figure 3
Sliding benchmark approach for 12-year-old boys (badminton).

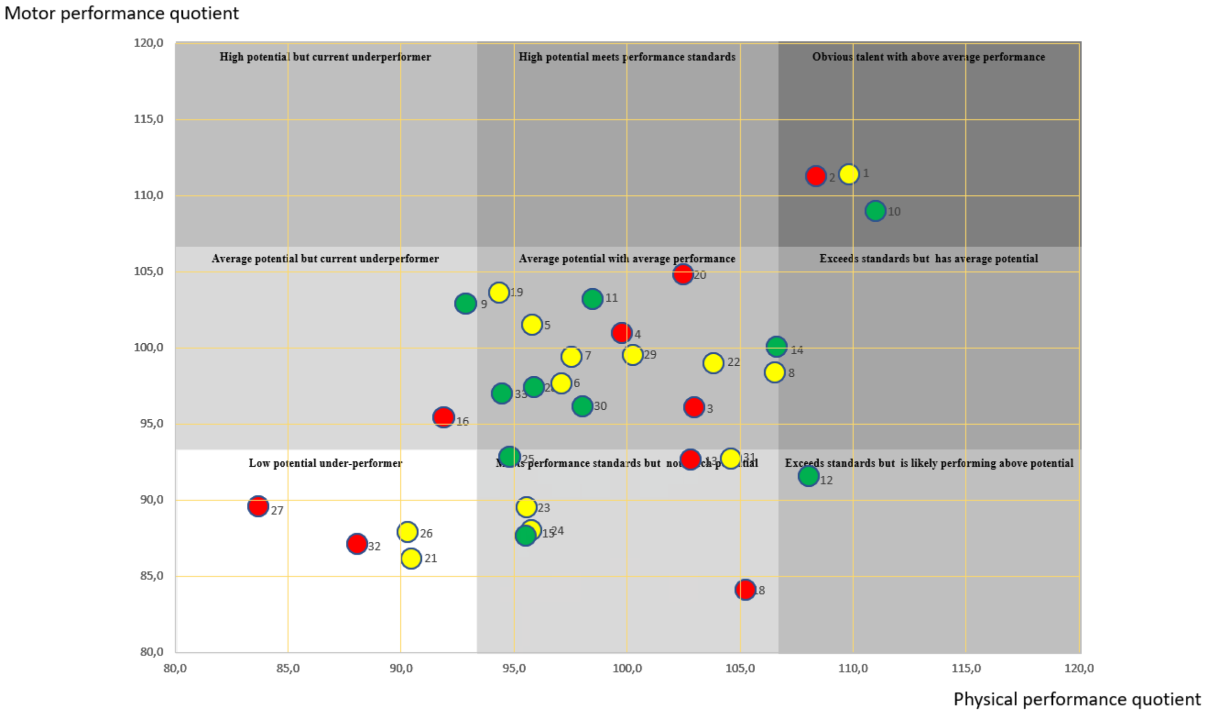

Figure 4
Individual scores for physical performance and motor performance adjusted with the sliding benchmarks for 12-year-old boys (badminton), plotted in the theoretical selection model Baker et al. (2018). Red dots PAH >89; green dots PAH <85, yellow dots 85> PAH <89.

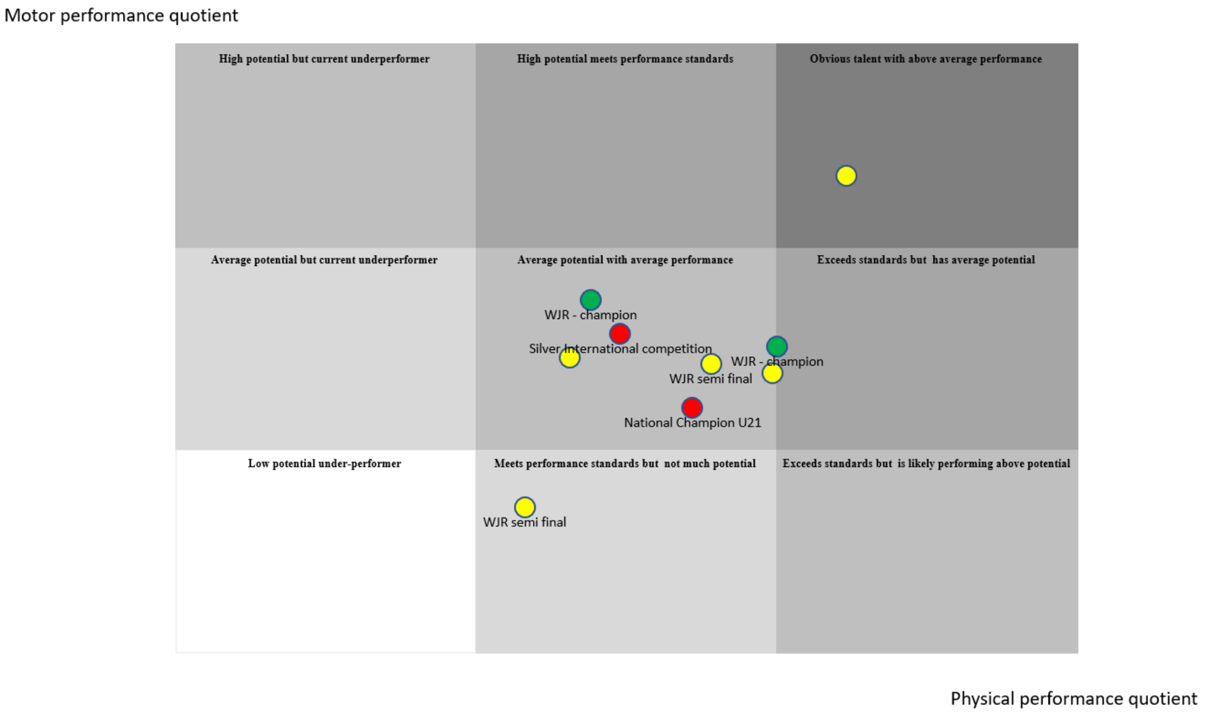

Figure 5
Active players after a 6-year development period. plotted in the theoretical selection model Baker et al. (2018). Red dots PAH >89; green dots PAH <85, yellow dots 85> PAH <89.

champions, international match silver, 2 BWF junior World Champions and 2 semi-finalists at the junior World Championships (Figure 5). The decision to include two late mature players with average physical scores but superior motor competence during the badminton draft in 2018 was successful. Without the sliding benchmark intervention, they would never have been selected. These players benefited from a specific development in the elite sport school and became junior world champions six years later.

Second, the sum scores for the physical and motor performance test were not weighed. With the data of a small sample, it is difficult to build accurate prediction models, but in the future, it will be possible with the big data collected during the talent identification sessions. Nevertheless, the benchmarks for age groups and especially during the growth spurt are biased and therefore the results should be equalised. A coach can equalise the (dis)advantage due to relative age and maturity in the same way as equalising the sound of the radio with a bit more bass or treble. To be able to make good predictions in the future, it is important to collect data year after year and to keep adjusting the benchmarks.

Morphology, physical fitness, and motor competence are much more common to measure than social and psychological characteristics. In this badminton identification tool only morphology, physical fitness and motor competence are included. In a holistic approach, also the technical, social, and psychological development should be considered to assess the potential of youth athletes (Faber et al., 2016; Nijenhuis et al., 2024; Schoof et al., 2024; Teunissen et al., 2024).

Coaches' decisions on talent selection in sport can be approached from two angles. On the one hand, a more objective approach is possible, in which coaches apply a multi-faceted formula for scoring as a means of predicting their future success. On the other hand, a subjective approach is possible, also known as the coach's eye, in which these professionals select or de-select athletes based on their personal observations and impressions (Bar-Eli et al., 2024). Both approaches are often seen as complementary. Selecting talented players is often a matter of feeling and expertise. Although, in the future, accurate prediction models, based on a combination of observations and performance tests can be applied to support the selection of the next cohorts.

CONCLUSIONS

The practical implications of this cross-sectional study conducted in a small sample of 12-year-old boys (n=33) shows that if relative age and maturity are not considered, talented players who are disadvantaged by this may be excluded early in their sport. Given athlete selection largely depends on the practical and scientific background of sport professionals, coaches may want to consider age group benchmarks, which can be made more objective by using accurate benchmarks related to chronological and biological age. This is the first known study that revealed that implementing sliding benchmarks can help to reduce the risk of de-selection of talented badminton players.

AUTHORS' CONTRIBUTIONS

Conceptualization: Johan Pion. Data curation: Johan Pion, Mohd Rozilee Wazir Norjali Wazir, Pieter Vansteenkiste. Formal analysis: Johan Pion, Mohd Rozilee Wazir Norjali Wazir. Funding acquisition: Tengku-Fadilah Kamalden. Investigation and Resources: Johan Pion, Mohd Rozilee Wazir Norjali Wazir, Tengku-Fadilah Kamalden. Methodology: Johan Pion. Project administration: Mohd Rozilee Wazir Norjali Wazir, Tengku-Fadilah Kamalden. Software: Johan Pion, Pieter Vansteenkiste. Supervision: Johan Pion. Validation: Irene Faber, Kathryn Johnston, Matthieu Lenoir. Visualization: Johan Pion, Pieter Vansteenkiste. Writing – original draft: Johan Pion. Writing – review & editing: Mohd Rozilee Wazir Norjali Wazir, Irene Faber , Kathryn Johnston , Pieter Vansteenkiste, Matthieu Lenoir, Tengku-Fadilah Kamalden.

STATEMENT ABOUT THE USE OF AI

In this article the authors did not use Artifical Inteligence tools.

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Article

Lower limb landing mechanics of scissor-kick jumps in elite badminton players

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Abstract

Scissor-kick jumps are frequently employed by elite badminton players when performing forehand jump strokes from the rear court forehand side. The joint loads experienced during the landing phase may contribute to the high number of lower limb injuries, yet our understanding of these loads is limited. This exploratory study comprehensively evaluates the lower limb joint mechanics during scissor-kick jump landings in elite male badminton players. Ten Danish national male players performed three variations of the scissor-kick jump in a biomechanical laboratory: submaximal jumps from a static position, maximal jumps from a static position, and jumps with game-like backward chassé steps. We recorded the landing 3-dimensional joint kinematics and kinetics of the racket-leg using a 10-camera motion capture system and a force platform. Our analysis using statistical parametric mapping one-way repeated measures ANOVA revealed no significant differences in the hip, knee, and ankle joint angles, moments, and power waveforms during the landing phase across the three jump variations. Indicating that elite male badminton players landing mechanics are not altered by increased jump height or the inclusion of preceding game-like footwork. We observed that the triceps surae muscles absorb 41% of the total eccentric joint work during the landing phase, indicating their crucial role in managing landing impacts. Additionally, the initial landing phase is characterized by high external knee and hip extensor and adductor moments. These findings highlight the importance of incorporating exercises targeting the triceps surae muscles and Achilles tendons in badminton-specific training programs to prepare players for the high eccentric loads during scissor-kick jump landings. The high hip, knee and ankle joint loads identified in this study may contribute to the high incidence of lower limb injuries in elite badminton.

Keywords: *Forehand stroke, jump height, footwork, joint loading.*

Resumen

Los saltos con patada de tijera son frecuentemente usados por los jugadores de bádminton de élite cuando realizan golpes de derecha en salto desde la parte trasera de la cancha. Las cargas articulares que se producen durante la fase de aterrizaje pueden contribuir al elevado número de lesiones en las extremidades inferiores, pero nuestro conocimiento sobre estas cargas es limitado. Este estudio exploratorio evalúa de forma exhaustiva

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la mecánica articular de las extremidades inferiores durante los aterrizajes de saltos con patada de tijera en jugadores de bádminton de élite. Diez jugadores daneses de la selección nacional masculina realizaron tres variaciones del salto con patada de tijera en un laboratorio biomecánico: saltos submáximos desde una posición estática, saltos máximos desde una posición estática y saltos con pasos *chassé* hacia atrás similares a los del juego. Registramos la cinemática y la cinética tridimensionales de la articulación de la pierna de la raqueta durante el aterrizaje utilizando un sistema de captura de movimiento de 10 cámaras y una plataforma de fuerza. Nuestro análisis, realizado mediante un mapa paramétrico estadístico y un ANOVA unidireccional de medidas repetidas, no reveló diferencias significativas en los ángulos, los momentos y las ondas de potencia de las articulaciones de la cadera, la rodilla y el tobillo durante la fase de aterrizaje en las tres variaciones de salto. Esto indica que la mecánica de aterrizaje de los jugadores de bádminton de élite no se ve alterada por el aumento de la altura del salto o la inclusión de pasos similares a los del juego. Observamos que los músculos tríceps surales absorben el 41 % del trabajo excéntrico total de las articulaciones durante la fase de aterrizaje, lo que indica su papel crucial en la gestión de los impactos del aterrizaje. Además, la fase inicial de aterrizaje se caracteriza por altos momentos externos de extensión y aducción de la rodilla y la cadera. Estos hallazgos resaltan la importancia de incorporar ejercicios dirigidos a los músculos tríceps surales y los tendones de Aquiles en los programas de entrenamiento específicos para el bádminton, con el fin de preparar a los jugadores para las altas cargas excéntricas durante los aterrizajes de saltos con patada de tijera. Las altas cargas en las articulaciones de la cadera, la rodilla y el tobillo identificadas en este estudio pueden contribuir a la alta incidencia de lesiones en las extremidades inferiores en el bádminton de élite.

Palabras clave: *golpe de derecha, altura del salto, juego de pies, carga articular.*

INTRODUCTION

Badminton players perform a range of badminton-specific movements, including jumps, lunges, sidestepping and changes in direction to reach the shuttlecock (Cabello Manrique & González-Badillo, 2003; Phomsoupha & Laffaye, 2015). The repetitive high-intensity actions do however place high demands on the players' lower limbs. In fact, a recent study by Nagano et al. (2020) revealed that adolescent female badminton players perform 7.72 actions with trunk accelerations above 4g per minute during games, (Nagano et al., 2020). Generating body accelerations at this level is likely an important contributor in the high incidence of lower limb injuries, particularly the knee and ankle joints, are prevalent among elite and recreational badminton players (Goh et al., 2013; Miyake et al., 2016; Reeves et al., 2015).

The high loads experienced during single-leg landings, following forehand and overhead jump strokes, have been associated with increased risk of anterior cruciate ligament injuries (Kaldau et al., 2024; Kimura et al., 2010, 2012) and Achilles tendon ruptures (Fahlström et al., 1998; Kaalund et al., 1989), and may in general contribute to the high incidence of lower limb injuries in badminton (Goh et al., 2013; Miyake et al., 2016; Reeves et al., 2015). Thus, existing biomechanical literature have focus on differences in lower limb landing mechanics between genders (Hu et al., 2023; Zhang et al., 2023; Zhao & Gu, 2019), and playing level (Kaldau et al., 2022; Nedergaard et al., 2022; Zhao & Li, 2019). Whereas the impact of jump intensity levels and inclusion of pre-jump footwork are not represented in the existing literature, despite its potential influence on lower limb mechanics and injuries.

The scissor-kick jump (SKJ) is a frequently utilised technique among badminton players when returning the shuttlecock from the rear-court forehand side (Kaldau et al., 2022), but also a frequent ACL injury situation (Kaldau et al., 2024). The SKJ involves a backward jump with a 180 degrees body rotation along the player's longitudinal axis, resulting in the characteristic crossing of the legs in mid-air. The in-air rotation allows players to generate more power in their stroke and the ability to swiftly push off the ground and return to the court's center (Brahms, 2014). We have recently demonstrated that recreational badminton players can reduce Achilles tendon forces by 25% when employing the SKJ technique during forehand jump strokes (Kaldau et al., 2022) and that the knee joint loads, during the initial contact phase of SKJs with submaximal intensity, are similar between elite and recreational male badminton players (Nedergaard et al., 2022). Nevertheless, despite its frequent use in elite badminton, a comprehensive understanding of the lower limb joint loads experienced during the initial landing phase after a SKJ, and the impact of jump intensity and match-like footwork remains limited.

In this exploratory study, we aimed to evaluate the lower limb joint landing mechanics that elite badminton players experience following SKJs. Considering the dynamic nature of badminton, where players constantly adjust their movement patterns, such as altering jump height or footwork to reach the shuttlecock, we specifically aimed to explore how increased jump intensity and inclusion of chasse steps prior to the SKJ alter lower-limb landing mechanics.

MATERIALS AND METHODS

Participants

Ten elite male badminton players (age: 28.2 ± 7.6 yr., height: 180.5 ± 48.6 cm, mass: 72.4 ± 6.6 kg), all competing at the highest level in Denmark, volunteered to participate in this study. All players were injury-free 6 months prior to testing and had no history of severe lower limb injuries. The study was approved by the local ethics committee (VD-2019-40) and written consent was obtained prior to testing for all players.

Experimental Protocol

After a 15-minute standardized warm-up routine, including an individual number of SKJ_s, players were instructed to complete three variations of the SKJ: 1) a set of submaximal SKJs (SKJ_{SubMax}) initiated from a fixed static start position in front of the force platform, corresponding to 50% of the players' leg length (measured from the anterior superior iliac spine to the medial malleolus); 2) another set of SKJ_s as described above, but with the instruction to jump as high as possible (SKJ_{max}) to simulate a jump-smash; 3) a set of SKJ_s following three backward chasse-steps (SKJ_{chasse}), simulating the frequent match situation where players move backward toward the rear court as part of the SKJ sequence. For all SKJ variations, players were instructed to accelerate forward immediately upon on landing and reach a target placed 3 meter in front of the force platform (Figure 1).

Due to the limited floor-to-ceiling height in the biomechanical laboratory, players were instructed to perform the SKJs without a racket. To facilitate a natural upper-body movement, players were instructed to hit a target with their normal racket-hand. The target was placed approximately 30 cm above their standing reach height. The players completed an individual series of SKJs until five successful trials were obtained for each condition (hitting the target and landing with their none-racket leg within the force platform). To avoid fatigue, time between trials was kept at minimum 45 seconds.

Data Collection

The SKJ_s and subsequent landing phases were captured at 200 Hz with an 8-camera Vicon motion capture system (T40 cameras, Vicon Motion Systems Ltd, Oxford, UK), with simultaneous recording of landing ground reaction forces (GRF) of the non-racket leg at 1000Hz (OR-6-7, AMTI, Massachusetts, USA). Lower limb kinematics were computed from a modified Helen Hayes marker set including 24 retroreflective markers (Bencke et al., 2013). Kinematic marker trajectory data were filtered using a Woltering cubic spline filter (Woltring, 1986), with a predicted mean square error of 10 mm, whilst GRF data were filtered using a zero-lag fourth order low-pass Butterworth filter at 50 Hz cutoff.

Subsequently, hip, knee and ankle joint kinematics and kinetics (external joint moments and instantaneous net joint power) in the sagittal, frontal, and transverse planes were calculated for the participant's non-racket leg using inverse dynamics in Vicon plug-in-gait software (Nexus 2.9, Vicon Motion Systems Ltd, Oxford, UK). Only joint kinematics and kinetics from the landing phase were analysed in this study. Touchdown and take off were identified when the vertical GRF exceeded and subsequently fell below a 10 N threshold, respectively. Net positive and negative joint work for each joint was calculated by integrating the positive and negative portions of the instantaneous joint power curves,

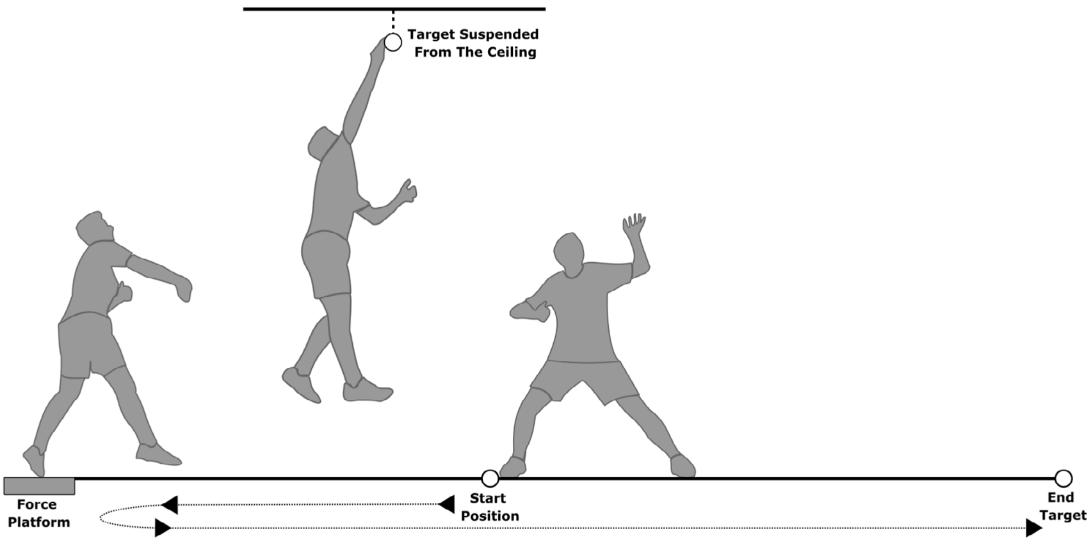

Figure 1
Illustration of the laboratory setup. For both the SKJ_{SubMax} and SKJ_{max} conditions, players' starting position was in front of the force platform, at a distance equal to 50% of their leg length. Individual start positions were employed for the $SKJ_{chassé}$ condition. During the SKJ, players were instructed to hit a ceiling-suspended target with their racket arm to promote natural upper-body movement. Immediately upon landing, players ran forward to reach a target positioned 3 meters from the force platform.

respectively, with respect to time. The total amount of positive and negative lower limb joint work produced by the non-racket leg during the landing phase was subsequently calculated as the sum of the individual joint's (hip, knee, and ankle) work. Finally, jump height and average forward velocity ($V_{Forward}$) upon landing were calculated as described in Kaldau et al. (2022).

Statistical analysis

The average of five trials was calculated for each participant and used for the statistical analysis and all kinetic data were normalised to the players' body mass. A one-way repeated measures ANOVA (α = 0.05) was used to compare jump height, contact time, $V_{Forward}$ and joint work between the three SKJs variations in SPSS (version 22.0, SPSS Inc. Chicago, IL, USA). In cases of significance, a Bonferroni corrected post-hoc test (α = 0.0167) was performed for pairwise comparisons.

Furthermore, one-dimensional statistical parametric mapping (SPM) (Friston et al., 2007; Pataky, 2012) one-way repeated measures ANOVA was computed using open-source SPM1D software (v0.4, www.spm1d.org, (Pataky, 2012)) in Matlab (version R2019a, The MathWorks, Inc., Natick, MA, USA) to compare joint moment and power waveforms for the landing phases. In cases with significant main effects, post-hoc testing using a one-sample SPM t-test, with a Bonferroni adjustment (α = 0.0167), was used to compare waveforms between the individual SKJs

RESULTS

The repeated measures ANOVA revealed that jump height was significantly different between the three SKJ variations ($F_{(1.253,\ 11.273)}$ = 35.401, $p < 0.001$). Post-hoc analysis showed that jump height was significantly higher for SKJ_{Max} (48.6 ± 7.2 cm) compared to both SKJ_{SubMax} (30.6 ± 9.8 cm, $p < 0.001$) and $SKJ_{Chassé}$ (33.9 ± 8.5 cm, p = 0.001). Furthermore, contact time for the landing phase was significantly different between SKJ variations ($F_{(1.899,\ 17.088)}$ = 8.543, p = 0.003), with post-hoc analysis showing that the SKJ_{Max} (389 ± 56 ms) had significantly longer contact time than the SKJChassé (342 ± 42 ms, p = 0.012) but not the SKJ_{SubMax} (368 ± 48 ms, p = 0.086). There was no significant difference in $V_{Forward}$ (p = 0.639) between the three SKJ variations (SKJ_{SubMax}: 4.85 ± 0.46 ms; SKJ_{Max}: 4.93 ± 0.37 ms; $SKJ_{Chassé}$: 4.98 ± 0.40 ms).

Only minor differences were observed in the joint angles and moments across the three SKJ variations (Figure 2). In general, the SKJ_{Max} and $SKJ_{Chassé}$ variations displayed greater hip and knee joint moments in the frontal and transverse plane, and greater plantar flexor moments compared to the SKJ_{SubMax}. Nevertheless, the one-way repeated-measures SPM ANOVA found no significant difference in hip, knee, ankle joint angles and moments between the three SKJ variations.

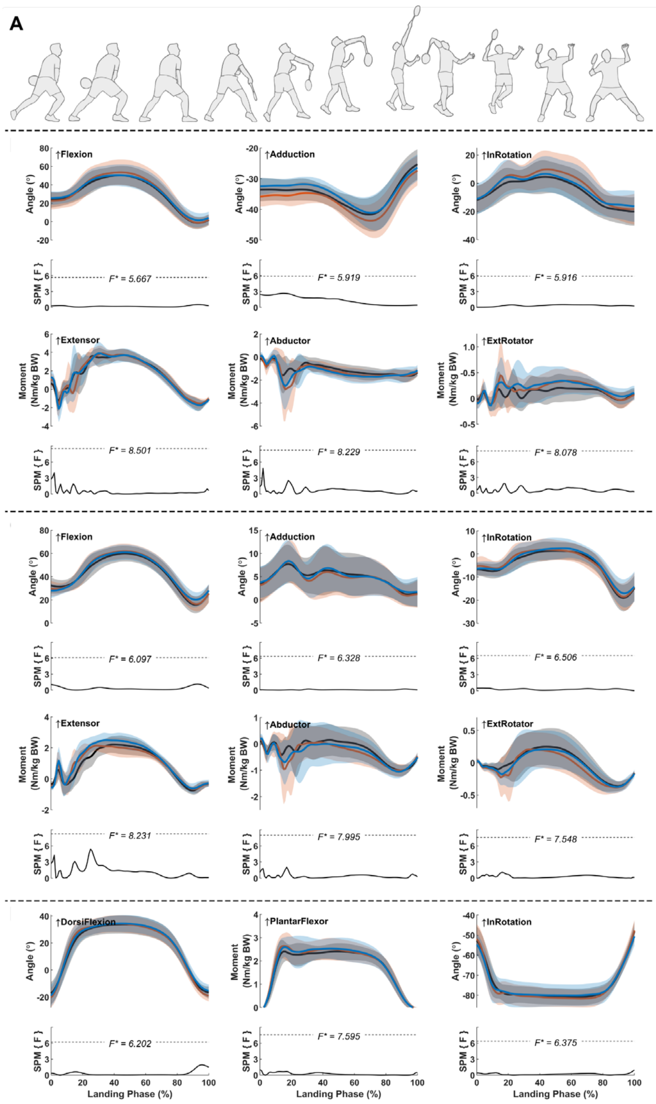

Figure 2
(A) Silhouette representation of the SKJ movement, with the sequence of movements shown from right to left, starting with the jump phase and transitioning to the landing phase. (B) Mean ± SD clouds for hip joint angles and moments across all planes. (C) Mean ± SD clouds for knee joint angles and moments across all planes. (D) Mean ± SD clouds for sagittal ankle joint angles, moments, and foot progression angles. The average waveform plots, displaying only the landing phase, include three SKJ variations: SKJ_{SubMax} (black line), SKJ_{Max} (orange line), and $SKJ_{Chassé}$ (blue line). Below the waveform plots, Statistical Parametric Mapping (SPM{F}) results from the one-way repeated measures ANOVA are shown. Significant main effects between SKJ variations are indicated where the F-curve (grey line) exceeds the critical threshold (horizontal dashed line). All curves are normalized to the landing phase (%).

The total amount of joint work absorbed by the non-racket leg was significantly affected by SKJ variations ($F_{(1.796,\ 16.167)}$ = 4.493, p = 0.031), but without any significant differences at a post-hoc level (Figure 3). The percentage of joint work absorbed at the knee was significantly affected by SKJ variations (F($_{1.915,\ 17.239)}$ = 7.895, p = 0.004). More specifically, the post-hoc analysis revealed that the work absorbed by the knee was significantly higher for the SKJ_{Max} (30.8 ± 5.3%) compared to the SKJ_{SubMax} (27.1 ± 3.7%, p = 0.011). Similarly, the percentages of joint work generated by the knee during the push-off phase were significantly different between SKJ variations ($F_{(1.966,\ 17.694)}$ = 7.444, p = 0.005). More specific, the post-hoc analysis revealed that the work generated by the knee was significantly higher for the SKJ_{Max} (23.0 ± 3.5%) compared to the $SKJ_{Chassé}$ (19.9 ± 4.3%, p = 0.017).

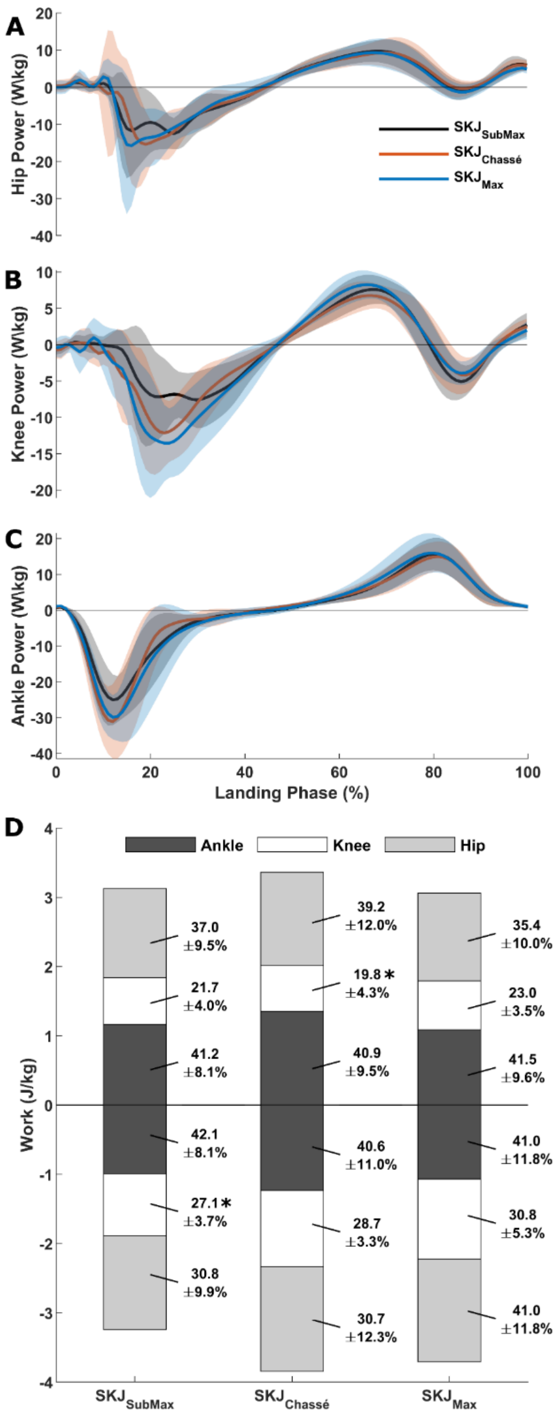

Figure 3
Mean ± SD clouds for the hip (A), knee (B), ankle (C) joint power for the landing phase (normalized to 100%) of the three SKJ variations. D) Average positive and negative joint work (absolute and percentage) for the three SKJ variations. * Indicates that the joint work is significantly different from the SKJ_{SubMax} (P < 0.0167).

DISCUSSION

In the present study we demonstrate that elite male badminton players exhibit great ankle plantar flexor moments together with large hip and knee extensor and adductor moments during landings following SKJs. Particularly the triceps surae muscles are exposed to high eccentric loads accounting for ~41% of the total joint work absorbed by the non-racket leg during the landing phase. Finally, our results illustrate that landing mechanics (joint moments, powers and work) of elite badminton players is largely unaffected by SKJ intensity or the inclusion of backward chassé steps.

Only the percentage of eccentric joint work absorbed at the knee, and concentric joint work generated at the knee significantly differed between SKJ variations in the presented study. The increased jump height in the SKJ_{Max} resulted in higher peak knee eccentric power (Figure 2B) compared to SKJ_{SubMax}, which is in line with previous studies that showed increased landing impacts and eccentric knee joint work with increased drop height (Ali et al., 2014). The greatest differences in concentric knee joint power (Figure 2B) were observed between the SKJ_{Max} and $SKJ_{Chassé}$ which in turn can explain the significant difference observed in the concentric knee joint work between these two. Previously, it has been shown that single-leg horizontal jumps for distance significantly increased the percentage of eccentric work at the knee, compared to vertical jumps with maximal effort (Kotsifaki et al., 2021). Nevertheless, the inclusion of the horizontal chassé footwork component prior to the SKJ in the presented study did not alter the elite players landing mechanics, most likely because all SKJ variations included a horizontal component with the players jumping horizontally onto the force plate. The lack of differences between SKJ variations observed in the present study demonstrate that minor alterations in jump strategies do not alter landing mechanics in elite male badminton players.

The lower limb landing mechanics observed for the SKJ in the present study generally resemble those previously described for single-leg landings following overhead strokes (Hung et al., 2020; Kimura et al., 2012; Zhao & Gu, 2019). In short, the peak plantar flexor moments of the SKJ were within the range of those previously presented for overhead backhand strokes in male badminton players (Hung et al., 2020; Zhao & Gu, 2019). However, the knee and hip extensor moments observed in the present study were higher than those previously reported for male badminton players during single-leg landings following overhead strokes. (Hung et al., 2020; Zhao & Gu, 2019), likely because all players in the present study competed at the highest level in Denmark. The peak external knee abduction moments, a well-known risk factor for anterior cruciate ligament injury during single-leg landing in badminton (Kimura et al., 2010), observed in the present study exceed those previously reported during overhead strokes for female players (0.42 + 0.26 Nm/kg)

(Kimura et al., 2012) and for a mixed group of male and females players (0.89 ± 0.46 Nm/kg/m) (Hu et al., 2022). This indicates the importance of strong and active knee adductors to counteract the high external knee abduction moment (Zebis et al., 2022). Nevertheless, the current literature on single leg landing mechanics in badminton lacks sufficient data on joint moments in the frontal and transverse planes. Hence, we strongly encourage researchers to incorporate the non-sagittal kinetics when exploring the loading demands of other badminton specific jump landings and their association with injury risk.

This study was conducted on 10 elite male badminton players; thus, the findings may not be generalizable to female or non-elite players. Previous research has identified gender differences in single-leg landings following a backhand overhead stroke from the rear-court. For instance, female badminton players show smaller ankle, knee, and hip flexion angles, and higher ground reaction forces during landing (Zhao & Gu, 2019). They also display lower leg and knee stiffness, indicating reduced dynamic stability (Zhang et al., 2023), and different lower-limb neuromuscular control strategies during the pre-landing phase (Hu et al., 2023). Similar differences may for the rear-court forehand SKJ examined in this study, which potentially could explain the higher incidence of ACL injuries reported among female players on the rear-court forehand side compared to males (Kaldau et al., 2024). Further research is needed to determine whether the differences in peak eccentric and concentric knee joint power observed across SKJ conditions here are gender specific.

A limitation with this study is that the players performed the SKJs without a racket and shuttlecock, due to the limited laboratory floor-to-ceiling height. Furthermore, we acknowledge that landing mechanics differ between shadow and actual hitting actions (Hung et al., 2020). Nevertheless, since all the players included in this study were familiar with the SKJ movement, we strongly believe the players were able to reproduce the movement pattern from practice/games. Another limitation with our study design and the joint mechanics presented is that ground reaction forces only was measured for the non-racket leg, though players had double support in the last part of the SKJ landing. We did however focus on joint kinetics of the non-racket leg in this study because it indisputably is exposed to the highest loads during the SKJ landing. Moreover, the non-racket leg is generally more exposed to severe injuries (e.g. knee injuries) during jump landings than the racket leg in badminton (Kaldau et al., 2024; Kimura et al., 2010).

The landing mechanics of the SKJ described in the present study is similar to that previously observed during side-cutting (Bencke et al., 2013). This highlights the importance of simultaneous muscle activation of the hip extensor, adductors, and external rotators to counteract the high loads forcing the hip into internal rotation and abduction. Also, knee extensor activation is necessary for absorbing impact forces and stabilizing the knee. Additionally, activation of the knee adductors (i.e., the medial hamstrings) before landing is crucial to counteract the high external knee abduction moment during the initial landing phase. These musculoskeletal loads may contribute to the high knee injuries rates in badminton players (Goh et al., 2013; Miyake et al., 2016; Reeves et al., 2015). Similarly, our findings highlight the significant workload undertaken by the plantar flexors, which may contribute to the high incidence of Achilles tendon injuries in badminton. Previously, we demonstrated that novice players experience greater Achilles tendon forces, which can be significantly reduced by adopting the SKJ landing technique used by elite players (Kaldau et al., 2022). This highlights the importance of proper landing mechanics in mitigating stress on both the Achilles tendon and the knee (Kaldau et al., 2022; Kimura et al., 2010). In recreational players with lower fitness levels, the high plantar flexor and Achilles tendon loads during intense movements impose a relatively greater strain, even with correct technique. Hence, coaches should consider moderating the intensity of such actions to prevent overuse injuries. Additionally, the high horizontal landing velocity of the SKJ challenges knee and ankle joint stability, especially in less fit or skilled players. This supports recommendations for a progressive increase in exercise intensity during badminton-specific jump skill development, such as the SKJ, alongside target strengthening of the stabilizing musculature around the knee and ankle.

Whilst the direct association between SKJ landing mechanics and lower limb injury incidence in elite badminton remains unknown, physiotherapists and strength and conditioning coaches can benefit from the information on lower limb muscle/joint loads found in this study when designing injury prevention programs for elite badminton players. Ultimately, contributing to the overall goal by reducing the high incidence of lower limb injuries in competitive badminton.

Conclusions

In conclusion, we found that the triceps surae muscles absorb 41% of the total joint work in the non-racket leg during the landing phase of SKJs. This highlights the importance of strong triceps surae muscles and Achilles tendons, which should be a focus in badminton-specific training programs to help players tolerate the high eccentric loads of forehand SKJ landings. The high joint moments in the knee and hip's sagittal and frontal planes also emphasize the need for strong hip and knee extensors and adductors to improve knee joint stability. Finally, aside from minor changes in knee joint work, our results show that neither jump height nor the inclusion of preceding footwork altered the SKJ landing mechanics of elite male badminton players.

DISCLOSURE STATEMENT

The authors declare that there are no conflicts of interest.

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CONTRIBUTIONS

Niels Jensby Nedergaard, Niels Christian Kaldau, Per Hölmich and Jesper Bencke conceptualised and designed the study. Niels Jensby Nedergaard and Niels Christian Kaldau collected the data. Niels Jensby Nedergaard and Jesper Bencke analysed and interpreted the data. Niels Jensby Nedergaard drafted the manuscript. All authors critically revised the manuscript and approved the final version.

AI USE STATEMENT

AI tools (ChatGPT) were used for proofreading to identify grammatical errors. All suggestions from the AI tools were critically reviewed by the first author.

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Tournament Design in Doubles Pickleball

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Abstract

This paper considers a common tournament design in doubles pickleball where N players compete across n matches. The research question involves the assignment of partners and opponents over the n matches. It is demonstrated that a particular design for the practical tournament corresponding to N = 16 and n = 5 has the desirable property that each player will either compete with or against every other player exactly once. Commentary is provided for other choices of *N* and *n*.

Keywords: *Mutually orthogonal Latin squares, orthogonal arrays, resolvable balanced incomplete block designs, scheduling, sports analytics.*

Resumen

Este artículo analiza un diseño común de torneos de dobles de *pickleball* en los que N jugadores compiten en n partidos. La pregunta de investigación involucra la asignación de compañeros y oponentes en los n partidos. Se demuestra que un diseño concreto para un torneo práctico con N = 16 y n = 5 tiene la propiedad deseable de que cada jugador competirá con o contra cada uno de los demás jugadores exactamente una vez. Se ofrecen comentarios sobre otras opciones de N y n..

Palabras clave: *cuadrados latinos mutuamente ortogonales, arreglos ortogonales, diseños de bloques incompletos equilibrados resolubles, programación, analítica deportiva.*

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INTRODUCTION

The sport of pickleball is booming. According to USA Pickleball (https://usapickleball.org/ about-us/organizational-docs/pickleball-annual-growth-report/) 4,000 US pickleball court locations were added in 2024, bringing the total to 15,910 courts nationwide. In terms of participation, the Sports & Fitness Industry Association (2024) deemed pickleball the fastest-growing sport in America for the third consecutive year. Academics are attempting to understand the pickleball phenomenon from a health perspective, leading to several recent papers including Cerezuela et al. (2023), Stroesser et al. (2024) and Casper et al. (2023).

Despite the popularity of pickleball, there has been limited analytics research that has been published on the sport. Gill & Swartz (2019) consider the impact of strong and weak links on success in doubles pickleball. In the analysis, it is determined that pickleball is a strong link game where success is based more on the quality of the stronger partner. Emond et al. (2024) study pickleball projectile motion and concluded that playing into a moderate wind is preferable than playing with the wind. Steyn et al. (2025) propose optimal speeds for executing the third shot drop. Notably, Swartz (2024) looks at various questions of pickleball strategy where some of the recommendations break with established tradition.

In this paper, we add to the pickleball analytics literature by considering tournament design (Devriesere et al., 2025). In particular, we are interested in a popular recreational doubles tournament sometimes known as a "random draw tournament" or a "scramble" or a "luck of the draw tournament". Henceforth, for brevity, we refer to this type of tournament as a scramble. In this format, we have N players where typically N is divisible by 4; this enables all players to play at the same time given that there are enough available pickleball courts. Further, we let n be the number of *rounds* which is the number of matches in which each player participates. In this more social type of tournament (where players do not have fixed partners), for each round, a player is assigned a partner and two opponents. The focus of research on this paper is the assignment of partners and opponents.

A "low-tech" solution to the assignment problem involves randomly drawing names in each round (Kang et al., 2008). This approach has the disadvantage that a player can end up playing with someone or against someone frequently. Obviously, frequent pairings with a weak partner is a disadvantage. By borrowing from the literature on experimental design (Street & Street, 1986), we attempt to minimize the occurrences of frequent partners and opponents. We note that the internet provides several resources to carry out assignments including the method of random draws. These include the website Plan 2 Play (https://app.plan2play.com/tournaments/roundRobin.php) and the website Pickle- heads (https://www.pickleheads.com/round-robin-simulator?format=popcorn). However, neither of these sites provide draws that have the optimality properties proposed by the methods in this paper.

The topic of draws falls generally under the umbrella of "scheduling". Scheduling has a prominent role in sport and has been influential in major sports including soccer (Goossens & Spieksma, 2009), Major League Baseball (Trick, 2009, as it is shown by IMA UMN, 2014), and even fringe sports such as highland dance (Swartz, 2007). However, the problem considered in this paper has a structure that differs from the traditional scheduling problem.

In Section 2, we provide some background material on the theory used to construct the proposed designs for the scramble tournament. The material relies on resolvable balanced incomplete block designs (Hanani, 1974). This section is more technical and is not essential reading. However, the material may be useful to readers who wish to develop designs for combinations (N, n) that are not discussed in this manuscript. In Section 3, we outline the methods and procedures that convert the theory from Section 2 into the context of scramble tournaments in pickleball. In Section 4, we provide the explicit and practical designs that can be utilized for scramble pickleball tournaments, and we explain the optimality of the designs. The designs are "ready to use" and do not require any expertise. Some concluding remarks are given in Section 5.

ASSOCIATED THEORY

The theory used in designing scramble pickleball tournaments is that of resolvable balanced incomplete block designs. We refer to Street & Street (1986) for a general reading on combinatorial designs. Our discussion is expository.

Suppose that N treatments are to be compared in a scientific or technological investigation, and the experiments are to be run in b blocks of size k ($k < N$) due to heterogeneity of experimental material. This scenario gives rise to an incomplete block design because each block can accommodate only a subset of k treatments out of all the N treatments. An incomplete block design is said to be balanced if every pair of treatments occurs in the same number of blocks. The following is the simplest balanced incomplete block design:

$$(1, 2), (3, 4); (1, 3), (2, 4); (1, 4), (2, 3).$$

This design has N = 4 treatments, labeled as 1, 2, 3 and 4. It has b = 6 blocks, each containing k = 2 treatments. We see that every pair of treatments occurs in exactly one block. This design has another appealing property that the six blocks are divided into *n* = 3 groups, delineated by semicolons, such that the two blocks within each group contain all the treatments exactly once. Such a balanced incomplete block design is said to be resolvable.

The following is a resolvable balanced incomplete block design for *N* = 9 treatments with *b* = 12 blocks of size *k* = 3:

(1, 2, 3), (4, 5, 6), (7, 8, 9); (1, 4, 7), (2, 5, 8), (3, 6, 9);

(1, 6, 8), (2, 4, 9), (3, 5, 7); (1, 5, 9), (2, 6, 7), (3, 4, 8).

In this design, each pair of treatments occurs in exactly one block. The design is resolved into *n* = 4 groups of three blocks with each group containing all the nine treatments.

Next, we give a resolvable balanced incomplete block design for *N* = 16 treatments with *b* = 20 blocks of size *k* = 4, with each pair of treatments occurring in exactly one block. The design is resolvable because it has *n* = 5 groups of blocks with each group containing all the 16 treatments.

(1, 2, 3, 4), (5, 6, 7, 8), (9, 10, 11, 12), (13, 14, 15, 16);

(1, 5, 9, 13), (2, 6, 10, 14), (3, 7, 11, 15), (4, 8, 12, 16);

(1, 6, 11, 16), (2, 5, 12, 15), (3, 8, 9, 14), (4, 7, 10, 13);

(1, 7, 12, 14), (2, 8, 11, 13), (3, 5, 10, 16), (4, 6, 9, 15);

(1, 8, 10, 15), (2, 7, 9, 16), (3, 6, 12, 13), (4, 5, 11, 14).

From one resolvable balanced incomplete block design, one can obtain other resolvable balanced incomplete block designs by repeatedly using all the blocks. For example, from the design for *N* = 4 with *b* = 6 blocks, one obtains another resolvable balanced incomplete block design for *N* = 4 with *b* = 12:

(1, 2), (3, 4); (1, 3), (2, 4); (1, 4), (2, 3); (1, 2), (3, 4); (1, 3), (2, 4); (1, 4), (2, 3).

In this design, each pair of treatment occurs in exactly two blocks.

METHODS AND PROCEDURES

When designing scramble doubles pickleball tournaments with N players, resolvable balanced incomplete block designs with block size k = 4 are relevant. In this case, one identifies the N treatments with the N players. Then each block contains four players, which can be divided into two teams of two players each. Suppose that the design is resolvable into n groups. Then every group of blocks can be used as one round of matches.

We consider the two attractive cases of N = 16 and N = 28 players participating in a scramble tournament. These cases are attractive since they are common tournament sizes. Also, these cases yield desirable results in terms of minimizing repetition amongst playing partners.

For the case of N = 16 participants and n = 5 rounds, we obtain a resolvable balanced incomplete block design. The design corresponds to the case of 20 blocks according to the theory outlined in Section 2. We also obtain related designs for alternative numbers of rounds.

For the case of N = 28 participants and n = 9 rounds, we obtain a resolvable balanced incomplete block design. The design corresponds to the case of 63 blocks according to the theory outlined in Section 2. We also obtain related designs for alternative numbers of rounds.

In the pickleball scramble context (i.e. k = 4), resolvable balanced incomplete block designs are also available for N = 40 participants according to Mathon & Rosa (1990). With N = 40, a balanced incomplete block design is available for b = 130 and k = 4, which is resolvable into n = 13 groups of 10 blocks each. However, this tournament is likely too large for practical purposes.

Resolvable balanced incomplete block designs do not always exist. For example, for N = 20 and 24, it is not possible to find a resolvable balanced incomplete block design with k = 4 such that every pair of treatments occurs in exactly one block. In such situations, we may consider resolvable incomplete block designs that are as balanced as possible.

RESULTS

There are an infinite number of combinations of *N* (number of players) and *n* number of rounds that can be considered in the pickleball scramble context. However, we restrict attention to values of N and n that are reasonable from a planning perspective and provide attractive results.

N = 16 Players

According to the theory of Section 2, N = 16 is a special number which yields attractive results for various values of n. From a practical perspective, N = 16 demands the availability of four courts if all N = 16 players play simultaneously. Many pickleball venues have at least four courts. We think of N = 16 as an ideal number. For N << 16, it is not much of a tournament with so few participants. With N >> 16, scramble tournaments can become unwieldy, e.g. higher chance of dropouts amongst competitors, more courts required for simultaneous play, etc.

We begin with the ideal number of rounds, n = 5. From a planning perspective, a doubles pickleball match to 11 points may take roughly 20 minutes (including match breaks). Therefore, a scramble tournament with n = 5 rounds may take approximately 5(20) = 100 minutes. When medal rounds are added in, this may be the ideal length for a tournament. The number of rounds n = 5 is also highly attractive from the optimality result that each player will play exactly once with every other player (either as a partner or as an opponent). Table 1 provides an optimal draw for the case N = 16 and n = 5. Here, the players are randomly numbered 1-16.

Table 1
The proposed assignment of partners and opponents in the case of (N = 16, n = 5).

Round	Team 1		Team 2	
1	1	2	3	4
1	5	6	7	8
1	9	10	11	12
1	13	14	15	16
2	1	5	9	13
2	2	6	10	14
2	3	7	11	15
2	4	8	12	16
3	1	6	11	16
3	2	5	12	15
3	3	8	9	14
3	4	7	10	13
4	1	7	12	14
4	2	8	11	13
4	3	5	10	16
4	4	6	9	15
5	1	8	10	15
5	2	7	9	16
5	3	6	12	13
5	4	5	11	14

At the Country Roads Pickleball Club in Yuma, Arizona, scramble tournaments typically consist of N = 16 players with n = 6 rounds. With n = 6 rounds, it is impossible for each participant to play exactly once with every other player (either as a partner or as an opponent). In this case, we suggest that the tournament organizers use Table 1 for the first five rounds. At the end of round 5, each player's total points can be tallied (i.e. number of points scored in all five matches). Then, for the sixth round, we propose matching the 1st and 2nd ranked players versus the 15th and 16th ranked players, the 3rd and 4th ranked players versus the 13th and 14th ranked players, the 5th and 6th ranked players versus the 11th and 12th ranked players, and the 7th and 8th ranked players versus the 9th and 10th ranked players. This would give the more deserving players (those doing better in rounds 1-5) a better opportunity to advance to the medal rounds.

When N = 16 and n = 7, 8, 9, then it is possible to have each competitor play with every other player (either as a partner or an opponent) at most twice. We do not find these designs desirable and do not list them here. We believe that a tournament organizer ought to consider either (N = 16, n = 5) or (N = 16, n = 6) described previously.

When N = 16 and n = 10, we are beginning to push reasonable time limits for a social tournament as this would require approximately 10(20) = 200 minutes of play prior to the medal rounds. However, from an optimality perspective, this is an appealing case as there exists a design where each player meets all other players exactly twice.

A simple way of obtaining the design for (N = 16, n = 10) involves using Table 1 for rounds 1-5. Then, repeat Table 1 for rounds 6-10 but make the following modification: when a row lists players x1, x2, x3, x4, change this to x1, x3, x2, x4. This method will cause the same four players to play twice together. For example, players 1, 2, 3, and 4 will play together in rounds 1 and 6. However, on the second meeting, each player will have a different partner. An alternative scheme is to re-randomize the players, meaning that another randomization is performed to label the 16 players as players 1-16 for rounds 6-10.

N = 28 Players

The case N = 28 may be considered nearly an upper bound for the number of viable players in a scramble tournament that yields "nice" results. Perhaps a tournament with N = 28 players would be appropriate over two days.

As mentioned in Section 2, a resolvable incomplete block design can be constructed for N = 28 and k = 4 so that every pair of treatments occurs in exactly one block. This design is resolvable into 9 groups of 7 blocks each. We can use this design to organize a scramble doubles tournament for N = 28 players over n = 9 rounds of play. All players participate in all 9 rounds. In any one round, the 28 players are divided into 7 sets of four players, and for each set, two teams can then be formed to play against each other. The design guarantees that each player meets every other player (either as a partner or as an opponent) exactly once. If fewer than nine rounds are considered because of the time constraints, the design guarantees that each player meets every other player at most once. Table 2 provides the recommended design.

While the theoretical construction of the design in Table 2 was established previously in the design literature - see for example Street and Street (1986, Chapter 3), the fully displayed design in the ready-to-use format as given in Table 2 appears to be new. The actual construction of this design is no simple matter to most design practitioners as it involves the use of difference sets and Galois fields. The R packages bibd and crossdes are useful for finding small balanced incomplete block designs but have failed to generate a balanced incomplete block design for N = 28 treatments with b = 7 × 9 = 63 blocks of size k = 4, the required set of parameters under consideration.

DISCUSSION

Scramble pickleball tournaments are popular formats that are both social and competitive. In such tournaments, it is desirable that a player does not have frequent repeated partners and opponents. The methods in this paper provide partner and opponent assignments that minimize frequent pairings.

There are many practical issues that are relevant when organizing a scramble tournament in doubles pickleball. How many courts are available? How many competitors are interested in participating? What is the desirable length, in time, for the tournament? To what degree are repetitive assignments of partners and opponents to be tolerated? These issues are interconnected. For example, it may not be possible to host an appealing tournament for all choices of *N* (the number of competitors) and *n* (the number of rounds of play). For this reason, compromises may need to be considered. In this paper, from all perspectives, an appealing tournament schedule is given for the case (*N* = 16, *n* = 5) and presented in Table 1. In addition, Table 2 provides a highly appealing tournament schedule for the case (*N* = 28, *n* = 9). These schedules are ready-to-go and can be immediately adapted by organizers. Suggested modifications to these schedules are also suggested for alternative values of *n*.

Our methods do not differentiate between a pair of players who are either partners or opponents. It seems desirable that if player A and player B must participate together in two rounds, then in one round they should be partners and in the other round, they should be opponents. Taking this into consideration is a topic of future research.

The “perfect” solutions as given by resolvable balanced incomplete block designs are available for *N* = 16, *N* = 28 and *N* = 40 players. For other practically important values of *N* = 20, 24, 32 and 36, it is impossible to find a design such that every player meets all the other players exactly once as the corresponding resolvable balanced incomplete block designs do not exist. Useful designs for these situations can be derived from resolvable incomplete block designs that are nearly balanced. This is another interesting topic for future research.

AUTHORS’ CONTRIBUTIONS

In this research, Boxin Tang’s primary roles concerned the formal analysis, methodology, the use of software and writing. Tim Swartz’s primary roles concerned conceptualization, methodology, and writing.

Table 2
The proposed assignment of partners and opponents in the case of (N = 28, n = 9).

Round	Team 1		Team 2		Round	Team 1		Team 2		Round	Team 1		Team 2	
1	9	3	16	14	2	10	4	14	15	3	8	2	15	16
1	18	12	25	23	2	19	13	23	24	3	17	11	24	25
1	27	21	7	5	2	28	22	5	6	3	26	20	6	7
1	8	19	4	11	2	9	17	2	12	3	10	18	3	13
1	17	28	13	20	2	18	26	11	21	3	19	27	12	22
1	26	10	22	2	2	27	8	20	3	3	28	9	21	4
1	6	15	24	1	2	7	16	25	1	3	5	14	23	1
4	3	6	19	17	5	4	7	17	18	6	2	5	18	19
4	12	15	28	26	5	13	16	26	27	6	11	14	27	28
4	21	24	10	8	5	22	25	8	9	6	20	23	9	10
4	2	13	7	14	5	3	11	5	15	6	4	12	6	16
4	11	22	16	23	5	12	20	14	24	6	13	21	15	25
4	20	4	25	5	5	21	2	23	6	6	22	3	24	7
4	9	18	27	1	5	10	19	28	1	6	8	17	26	1
7	6	9	13	11	8	7	10	11	12	9	5	8	12	13
7	15	18	22	20	8	16	19	20	21	9	14	17	21	22
7	24	27	4	2	8	25	28	2	3	9	23	26	3	4
7	5	16	10	17	8	6	14	8	18	9	7	15	9	19
7	14	25	19	26	8	15	23	17	27	9	16	24	18	28
7	23	7	28	8	8	24	5	26	9	9	25	6	27	10
7	3	12	21	1	8	4	13	22	1	9	2	11	20	1

STATEMENT ABOUT THE USE OF AI

AI was not used in this investigation.

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Quantifying and Predicting Momentum in Tennis Match via Machine Learning Approach

Cuantificación y predicción del momentum en partidos de tenis mediante un enfoque de aprendizaje automático

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Abstract

This study aims to identify and analyze momentum shifts in tennis, developing a data-driven model to quantify and predict these shifts and assess their influence on match outcomes. Using data from 6 tournaments, including 564 matches and over 135,000 points, this study constructed a momentum calculation model integrating 14 weighted match factors such as point progression, server advantage, and player ranking differences. The model incorporates adjustments for set discontinuities and initial momentum based on player rankings to enhance predictive accuracy. Following data processing and validation, a Kappa consistency test was performed on the 2023 Wimbledon Championship data, yielding a high alignment with actual outcomes (Kappa = 0.96). Using a Gradient Boosting Decision Tree (GBDT) regression model, the study achieved a high accuracy in predicting momentum shifts, identifying key variables such as serve advantage and score gaps as primary indicators of performance dynamics. This model further revealed that players' momentum tends to stabilize at critical points, such as 40:30, while fluctuating more at disadvantageous scores. These findings highlight the model's utility for pre-match analysis, enabling detailed insights into opponents' tactical patterns and psychological responses under varying score conditions. Overall, this momentum model provides valuable applications for enhancing player preparation and in-game strategic adjustments, offering coaches and players a quantifiable tool to interpret and influence match outcomes.

Keywords: *Result prediction, gradient boosting decision tree, sports performance analysis.*

Resumen

El objetivo de este estudio es identificar y analizar los cambios de *momentum* en el tenis, desarrollando un modelo basado en datos para cuantificar y predecir estos cambios y evaluar su influencia en los resultados de los partidos. A partir de datos de 6 torneos, que incluyen 564 partidos y más de 135 000 puntos, este estudio construyó un modelo de cálculo del *momentum* que integra 14 factores ponderados del partido, como la progresión de los puntos, la ventaja del servidor y las diferencias en la clasificación de los jugadores. El modelo incorpora ajustes para las discontinuidades de los sets y el *momentum* inicial basado en la clasificación de los jugadores para mejorar la precisión de la predicción. Tras el procesamiento y la validación de los datos, se realizó una prueba de concordancia Kappa con los datos del Campeonato de Wimbledon de 2023, la cual arrojó una alta coincidencia con los resultados reales (Kappa = 0,96). Utilizando un modelo de regresión con árboles de decisión potenciados por gradiente (GBDT), el estudio logró una alta precisión en la predicción de los cambios de *momentum* e identificó

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variables clave como la ventaja en el servicio y las diferencias en el marcador como indicadores principales de la dinámica del rendimiento. Este modelo reveló además que el *momentum* de los jugadores tiende a estabilizarse en puntos críticos, como el 40:30, mientras que fluctúa más en puntuaciones desfavorables. Estos hallazgos resaltan la utilidad del modelo para el análisis previo al partido, ya que permite obtener información detallada sobre los patrones tácticos y las respuestas psicológicas de los oponentes en condiciones de puntuación variables. En general, este modelo de *momentum* ofrece aplicaciones valiosas para mejorar la preparación de los jugadores y los ajustes estratégicos durante el partido, proporcionando a los entrenadores y a los jugadores una herramienta cuantificable para interpretar e influir en los resultados de los partidos.

Palabras clave: *predicción de resultados, árboles de decisión potenciados por gradiente, análisis del rendimiento deportivo.*

Introduction

With the integration of big data analytics into the sports industry, sports performance data collection and analysis have achieved unprecedented depth and precision, gaining widespread attention across professional, media, and fan communities. In recent years, metrics like win probability have become increasingly prominent in sports broadcasting (Duen & Peker, 2024), providing audiences with real-time insights into each player's likelihood of success and enhancing the viewing experience. Tennis stands out due to its dynamic tactical shifts and intense point-to-point momentum changes, making it a rich subject for performance analysis. A prime example is the 2023 Wimbledon Men's Singles Final, where 20-year-old Spanish star Carlos Alcaraz defeated 36-year-old legend Novak Djokovic. The match saw dramatic swings in momentum—from Djokovic's dominance in the first set to Alcaraz's pivotal tiebreak win in the second, and then a series of momentum shifts that led to Alcaraz's victory. Such dynamic shifts sparked widespread discussions about the concept of "momentum" in sports. However, while momentum is often described as "strength or force gained by motion or by a series of events" (Merriam-Webster, 2024), accurately measuring and analyzing it remains a challenge for both academic and sports communities. Therefore, defining momentum, identifying the factors influencing match flow, and predicting its impact on match outcomes are essential areas of performance analysis research in tennis (Sampaio et al., 2024). Relevant findings would hold significant value when informing coaches to refine tactical strategies and enabling players to better adapt to real-time changes during matches.

Research on tennis covers a wide range of areas, including player skill and tactics analysis, match outcome factors, match prediction, and sports betting. The focus on player performance has garnered significant attention, with extensive studies exploring pre-match predictions and post-match analyses (Bayram et al., 2021). However, the necessity and significance of real-time momentum analysis during matches remain underexplored, likely due to the complexities and dynamic nature of capturing momentum shifts as they unfold. This gap highlights the need for a deeper understanding of how momentum influences the flow and outcome of matches, which could offer valuable insights for both players and coaches (Tognini & Perciavalle, 2022).

Defining momentum is challenging. Some scholars view it as a psychological state, reflecting a player's confidence and drive during a match, while others consider it a technical and tactical advantage (Ahola & Dotson, 2014, Zheng Cao, 2011). On the other hand, tennis data provider defines it as "an exponentially weighted moving average of the leverage gained by a player" (Manuel, 2022). Dietl and Nesseler (2017) argue that players benefit from momentum as long as they control the match; once they lose control, their chance of winning subsequent sets diminishes significantly. Despite these differing perspectives, momentum clearly influences match outcomes. Real-time momentum analysis, however, demands large-scale, detailed match data alongside sophisticated data acquisition and processing tools to manage and analyze this information in real-time.

Quantifying and measuring momentum pose further challenges. Traditionally, momentum has been assessed based on score and performance sequences. For instance, Moss investigates whether the outcomes of service games were significantly associated with the outcomes of the receiving and next serving games that followed (Moss & O'Donoghue, 2015). However, with advancements in data analytics, more studies are employing big data and statistical models to quantify momentum shifts, capturing the dynamics and trends within matches for a more precise analysis of game flow. Zhong introduced a composite model integrating a Logistic Regression Model and a LASSO-based Sparse ARMAX Model to predict momentum shifts and guide strategic decisions during games (Zhong et al., 2024). Ahmed (2014) analyzed the relationship between a binomial probability distribution and the process of match play in tennis and constructed a probability model for two players of predictable abilities. Momentum analysis has also been explored across various sports, particularly in football and basketball. Noel et al. (2024) developed a data pipeline and indicated that momentum should be studied more from a feature/performance indicator point-of-view and less from the view of the dependence of sequential outcomes in the future. Mingjia Qiu (2024) designed a quantitative framework to accurately identify momentum in basketball games, and explored the role of momentum in games. Notably, Ötting et al. (2023) investigated the potential occurrence of momentum shifts in the dynamics of football matches.

However, despite these advancements, existing literature lacks comprehensive approaches for real-time momentum analysis, particularly in tennis. Studies are often limited to retrospective analyses or are constrained by simplified models that overlook the complexity of in-game factors. Additionally, they tend to neglect situational variables, such as player condition, court type, and environmental factors which significantly influence momentum shifts in live matches (Wang & Lin, 2005; Martínez-Gallego et al., 2013). These gaps highlight the necessity for more advanced, adaptable models capable of analyzing and predicting momentum in real time, accommodating the multifaceted influences inherent in tennis matches.

Therefore, this study aims to develop a comprehensive model to quantify and predict momentum shifts in professional tennis matches using a machine learning approach. We hypothesize that the proposed momentum model, integrating player performance indicators and point-by-point dynamics, can effectively identify momentum shifts and predict match outcomes with high accuracy. The model is designed to offer both theoretical and practical value by enhancing our understanding of momentum as a quantifiable variable and providing actionable insights for tactical decision-making in competitive tennis.

Methodology

Sample and Data

The data from the study included detailed point-by-point data of 564 men's singles main draw matches during 2021-2023 U.S. Open and Wimbledon tournaments provided by Jeff Sackmann (2024) via Tennis Abstract (www.tennisabstract.com). In total, there were 135,110 points played by 211 individual players.

Procedures and Statistical Analysis

Initially, missing value and outlier were detected to ensure data quality. For instance, missing values in the serve speed (mph) were treated as null speeds when calculating each match's average serve speed, thereby maintaining the completeness and accuracy of dataset. Subsequently, cleaned point-by-point data were used to extract relevant indicators for analyzing player performance. The data processing workflow is illustrated in Figure 1.

Based on the existing literature and information in the raw data, summary statistics of 12 indicators were extracted to represent player's match performance. Additionally, a ranking gap was included as opposition effect factor on performance (see Table 1).

Research Framework

The study first developed a comprehensive research framework to capture, analyze, and predict momentum

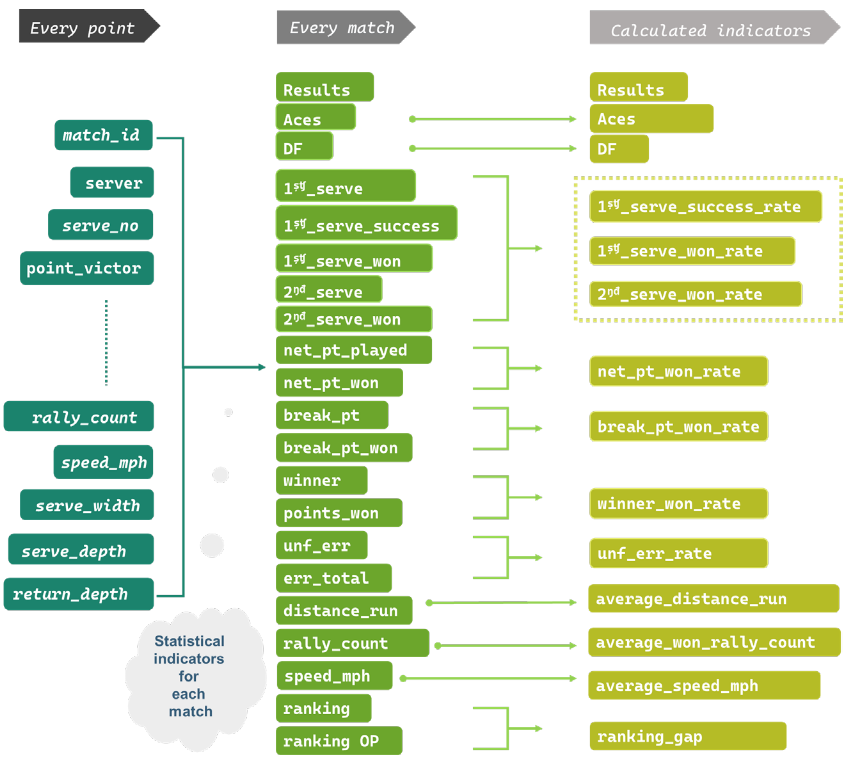

Figure 1. Performance indicator screening flow chart

Table 1
Indicators Explanation Table

Index	Definition
Results	The match outcome, indicating whether the player1 won or play2 won
Aces	The total number of serves that landed in the service box and were untouched by the opponent
DF	The total number of consecutive faults during serve attempts, resulting in the loss of a point
1st_serve_success_rate	The proportion of successful first serves relative to the number of serves
1st_serve_won_rate	The proportion of points won on successful first serves
2nd_serve_won_rate	The proportion of points won on second serves
net_pt_won_rate	The proportion of points won at the net relative to net points played
break_pt_won_rate	The proportion of break points successfully won by the player
winner_won_rate	The proportion of points won by hitting winners (shots not touched by the opponent)
unf_err_rate	The proportion of unforced errors committed relative to the total number of errors
average_distance_run	The average distance covered per point during the match
average_won_rally_count	The average number of strokes in rallies won by the player
average_speed_mph	The average speed of all serves during the match
ranking_gap	The difference between the player's ranking and the opponent's ranking

in tennis matches. Figure 2 provides an overview of the framework, detailing the key stages of the research process, from data preparation to model application. The process began with the extraction of key performance indicators, followed by the establishment of a mathematical model to quantify momentum. To validate the model, a consistency check was performed by comparing the player with the higher momentum at the end of each set to the actual match outcome. This validation step assessed the model's alignment with actual results. Subsequently, a predictive model was developed using a Gradient Boosting Decision Tree (GBDT) regression approach. This model analyzed turning points within tennis matches, identifying areas where momentum shifts significantly impact player performance. The predictive model's accuracy and interpretability were further evaluated to generate actionable tactical insights. These insights can be applied across various contexts, including pre-match analysis, in-match tactical adjustments, and post-match reviews to optimize training and performance.

Tennis Momentum Model

In the modeling stage, the research transformed the weights into additive changes according to the different indicators with different impact weights.

The study combines this with the fact that research will use the ranking as an initialization momentum. The initialization of momentum scores in equations (1) to (3) is grounded in the use of ATP rankings, which serve as a proxy for pre-match strength and reputation, an approach that has been utilized in prior research to set player baseline states (Pham & Bufi, 2023). First, we will use the variable $M_i(t)$ (the momentum of player i (the i^{th} player)at time t (the t^{th} time point)), represents the change in momentum of player i with time, $M_1(t)$ represents the change in momentum of player 1 with respect to time t, $M2(t)$ represents the change in momentum of player 2 with respect to time t, p_1 (p_i is the rank of player i)denotes the ranking of player 1, denotes the ranking of player 2. Thus, study can get the initialized momentum score, as shown in equations (1), (2), and (3):

$$M_1(0) = \alpha p_1 \qquad (1)$$

$$M_2(0) = \alpha p_2 \qquad (2)$$

$$M_i(0) = \alpha p_i \qquad (3)$$

Equation (4) defines momentum as a recursive function over time, drawing on basic principles of temporal state propagation found in time-series models such as AR and ARMA. The additive momentum increments in equation (5) are inspired by feature-based performance scoring systems common in sports analytics (Ma, 2024), where different actions (e.g., ace, break_point, point_won) contribute unequally to performance trends. As study traverse each time point t in the race, the momentum variable is updated according to equation (4):

$$M_i(t) = M_i(t\text{-}1)+\Delta M_i(t) \qquad (4)$$

Whenever a player wins a point, his performance status is expected to improve and therefore his momentum should be elevated. Such increase is represented by an increment, as shown in equation (5). For instance, if the player wins a point, his momentum increases by a fixed value d_j(j is the j^{th} scoring item, and is the scoring points for scoring item); Similarly, when player breaks serve successfully or hits an ace, this brings a lot of momentum, so his momentum should have a different increase. Our study can represent this increase using other increments, which research will set to d_2, d_3 respectively.

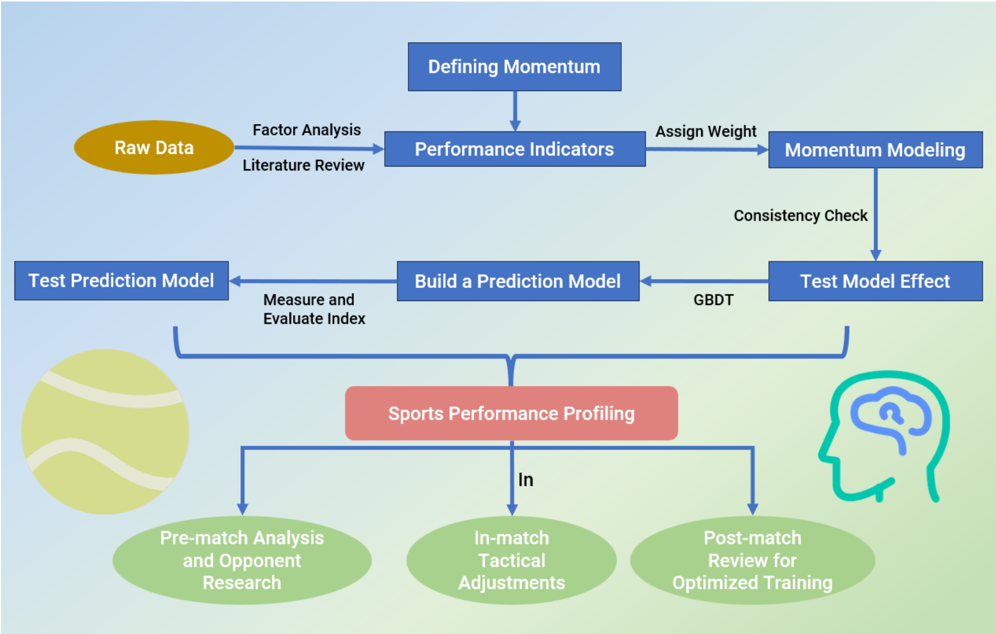

Figure 2. The Structure of the Research Framework for Tennis Match Momentum Analysis

$$\Delta M_i(t)=\Sigma_{(j=1)}^{n} d_j \quad (5)$$

Furthermore, it was also assumed that the outcome of the previous game impacts the current game (Klaassen & Magnus, 2001). To reflect this, an initial momentum value is recalculated at the beginning of each game. This recalculation incorporates the player's ranking and the weighted momentum value from the last point of the previous game, as shown in equation (6). Equation (6) introduces an inter-game adjustment mechanism based on weighted memory of previous performance, reflecting concepts from state transition models and psychological momentum theories (Ma, 2024), with the addition of a tunable weight β to model state carry-over. To balance the relationship between game and reflect players' state adjustments, experiments determined the optimal weighting coefficient $\beta=0.2$. The equation for the initial momentum of each game is:

$$M_i(t) = \alpha p_i + \beta M_i(t\text{-}1)\text{+}s \quad (6)$$

At this point, the study established a mathematical model that captures the flow of the situation as the game progresses. The model is represented by equation (7):

$$\begin{cases} M_i(0) = \alpha p_i,\ t = 0 \\ M_i(t) = \alpha p_i + \beta M_i(t\text{-}1)\text{+}s, t>0 \text{ and server change} \\ M_i(t) = M_i(t\text{-}1) + \Delta M_i(t), t>0 \text{ and server not change} \end{cases} \quad (7)$$

After getting the mathematical model of momentum, our study used python code to write the model and made the visualization of the data, taking $d_1=1$, $d_2=1, d_3=1, s=1$, Here, in order to show more intuitively the tendency of the players' momentum change when the match is in progress, this study introduced a concept of momentum difference, which is obtained by subtracting the momentum of player1 and player2, and at the same time.

To validate the model, a Kappa consistency test was conducted (Cohen, 1960). Momentum data from the 31 matches of the 2023 Wimbledon tournament were extracted and processed into a binary classification: values greater than 0 indicate that Player 1 had, while values less than 0 indicate that Player 2. Our research then calculated the match outcome for each point based on the momentum and filtered the results to obtain set-level outcomes. A Kappa coefficient model was established to compare these results with the actual set outcomes (game_winner), conducting a Kappa consistency test to assess alignment.

The Kappa coefficient was utilized to assess the agreement between predicted results derived from the model and actual outcomes from the raw data. As a widely recognized metric for measuring correlation between categorical data, the Kappa coefficient was appropriate for this binary classification task. This method provided a robust measure of the model's consistency and alignment with real-world results. According to the widely accepted Kappa coefficient interpretation standard proposed by Cohen (1960), a Kappa value below 0 indicates no agreement, 0–0.20 indicates slight agreement, 0.21–0.40 indicates fair agreement, 0.41–0.60 indicates moderate agreement, 0.61–0.80 indicates substantial agreement, and values above 0.81 indicate almost perfect agreement.

The Kappa value of 0.96 achieved in this study thus demonstrates an almost perfect alignment between the predicted and actual outcomes, validating the reliability of the proposed model.

Momentum Prediction Model

The study also aimed to predict critical factors influencing match dynamics. Building on the concept of momentum differential, a threshold of 0 was set to identify “swings” or turning points within matches. The GBDT regression model was trained on the data to predict these momentum swings, and feature importance was analyzed to determine the key predictors of momentum shifts. Several configurations of the GBDT model were tested to optimize performance. The final model parameters are presented in Table 2. Then, the feature importance is determined by calculating the contribution of each feature to the splits across all decision trees.

Table 2
Main Parameters

Parameter Name	Parameter Value	Parameter Name	Parameter Value
Data Split	0.7	Min Samples Leaf	1
Number of Base Learners	100	Min Weight Samples Leaf	0
Learning Rate	0.1	Max Tree Depth	4
Min Samples Split	5	Max Leaf Nodes	30

To evaluate the effectiveness and generalization ability of the proposed momentum prediction model, several alternative machine learning algorithms were tested alongside GBDT. These included LightGBM, XGBoost, and K-Nearest Neighbors (KNN). All models were trained on the same dataset using identical features and hyperparameter tuning strategies. Their performance was assessed using three key metrics: mean absolute error (MAE), root mean square error (RMSE), and the coefficient of determination (R^2). The results, presented in Table 3, show that the GBDT model achieved the MAE (0.659) and RMSE (0.979), and the highest R^2 (0.828), indicating strong predictive accuracy and goodness of fit. LightGBM and XGBoost yielded comparable results, with only marginal differences from GBDT. These findings suggest that all three gradient-boosting frameworks are suitable for momentum prediction tasks, with GBDT performing slightly better overall. In contrast, the KNN model demonstrated weaker predictive performance across all metrics. This significant gap indicates that KNN, which lacks the ability to model complex feature interactions and sequential dependencies, is less suited for the nuanced task of modeling momentum dynamics in tennis.

Overall, these results reinforce the effectiveness of the proposed GBDT-based model while confirming the robustness of gradient-boosted ensemble methods for this specific prediction problem.

Table 3
Model Comparison

Model	MAE	RMSE	R^2
GBDT	0.659	0.979	0.828
LightGBM	0.664	0.984	0.827
XGBoost	0.661	0.991	0.824
KNN	0.855	1.46	0.738

Results

Factor Analysis

To assess the selected indicators, the study first evaluated their orientation. It was determined that indicators such as ranking gap and double faults (DF) were negatively oriented, where lower values corresponded to better performance. Conversely, all other indicators were positively oriented. To ensure consistency in the weight analysis, negatively oriented indicators were inverted, aligning all indicators to follow a consistent trend.

Before proceeding with factor analysis, an independent sample T-test was performed (see Table 3). The test for homogeneity of variances yielded a significant P-value of 0.024** for average serve speed, indicating a violation of the homogeneity assumption. Consequently, this indicator was excluded from subsequent analyses, leaving a total of 12 indicators for consideration.

To identify relevant features for the model, Pearson correlation coefficients were calculated between each indicator and the player score. The magnitude of these coefficients provided insight into which indicators were most strongly correlated with player performance. Based on this analysis, five key indicators were selected for momentum calculation model: initial ranking, right to serve, point scored, break point won, and ACE occurrence.

During the model development phase, the latest ATP rolling rankings (from one week prior to each tournament) were used as initial input values. The processed dataset included quantitative variables such as point_no, server (referring to the player currently serving), point_winner, game_winner, p1_ace, p2_ace, p1_winner, p2_winner, p1_double_fault, p2_double_fault, p1_unf_err, p2_unf_err, p1_break_pt_won, and the result_gap from the previous point.In the modeling framework, result_gap served as the dependent variable, while the remaining indicators were used as predictors. To better interpret the magnitude of the statistical differences between winning and losing players, effect sizes (Cohen's d) were calculated alongside traditional significance tests.

Table 4 summarizes the statistical results for each performance factor, including F and P values, as well as corresponding effect sizes. Indicators such as Aces (d = 0.14), Distance Run (d = 1.50), and Winners Won Rate (d = 0.32) demonstrated varying degrees of impact. Particularly, Distance Run exhibited a large effect size, highlighting its relevance in distinguishing dominant performance patterns.

Kappa Coefficient Test

The Kappa coefficient of 0.96 demonstrates a nearly perfect alignment between the model's calculated momentum advantage and the actual set outcomes, validating its reliability. The test's significance levels (z = 33.081, $p < 0.01$) further confirm the statistical robustness of this alignment.

Model Testing Results and Evaluation

Figure 3 presents a partial prediction plot for the test dataset, comparing predicted values with actual values. In the plot, the blue line represents the true values, while the green line shows the predicted values. The model demonstrates a high degree of accuracy, as the predicted values closely follow the trend of the actual data, particularly around the 935th point of the season starting from the Round of 16. Some minor discrepancies are observed at smaller peaks and valleys, suggesting that while the model captures the general patterns effectively, there is room for refinement in specific intervals.

To systematically evaluate and address potential overfitting observed in Figure 3, the model was assessed using a 5-fold cross-validation approach. As shown in Table 5, the mean squared error (MSE), root mean squared error (RMSE), mean absolute error (MAE), and R^2 scores of the cross-validation set closely mirrored those of both the training and test sets. Specifically, the training set achieved an MAE of 0.576 and an R^2 of 0.851, while the 5-fold cross-validation yielded an MAE of 0.609 and R^2 of 0.829. The test set recorded a comparable MAE of 0.659 and R^2 of 0.828. These minimal performance gaps indicate that the model generalizes well and does not exhibit signs of overfitting. Additionally, the RMSE difference between training (0.808) and test set (0.979) was small relative to the scale of the target variable, and the standardized effect size (Cohen's d = 0.15) between the MAEs of training and test sets further confirmed negligible overfitting. Together, these results validate the stability and robustness of the proposed momentum prediction model.

Table 5
Model Comparison

Metric	Training Set	Cross-Validation	Test Set
MSE	0.653	0.749	0.959
RMSE	0.808	0.864	0.979
MAE	0.576	0.609	0.659
R^2	0.851	0.829	0.828

For both the training and test sets, the corresponding values are illustrated in Figure 4.

The close alignment between these metrics suggests that the model does not overfit the training data and maintains strong generalization capability.

Table 4
Factor Analysis Index

	Results (Standard Deviation)		F	P	Cohen's d
	1.0	0.0			
Aces	5.803	8.203	0.567	0.455	0.14
Ranking gap(converted to positive)	57.673	57.673	0.000	1.000	–
DF	2.966	3.425	0.537	0.466	0.31
Double faults (DF)	0.063	0.098	3.300	0.074 *	12.14 ★
First serve success rate (%)	0.063	0.114	4.119	0.047**	10.86 ★
First serve points won rate (%)	0.084	0.085	0.094	0.760	11.83 ★
Second serve points won rate (%)	3.290	5.438	5.325	0.024**	0.22
Average serve speed	0.114	0.115	0.002	0.968	8.73 ★
Net points won rate (%)	0.179	0.191	0.157	0.693	5.40 ★
Break point conversion rate (%)	0.066	0.090	2.058	0.157	12.67 ★
Winners won rate (%)	0.090	0.078	0.836	0.364	0.32
Unforced error rate (%)	3.041	2.815	0.395	0.532	0.34
Average distance run	0.722	0.605	0.168	0.684	1.50

Note: ***, **, * represent the significance levels of 1%, 5%, and 10%, respectively.
★ Values of d > 8 are likely inflated due to very small standard deviations (SD < 0.12).

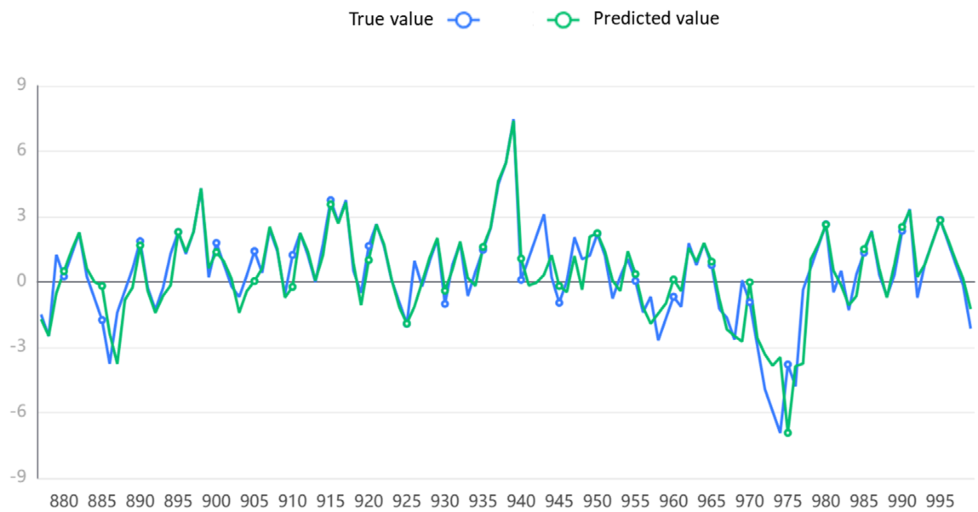

Figure 3. The Predicted Value Compared with The True Value

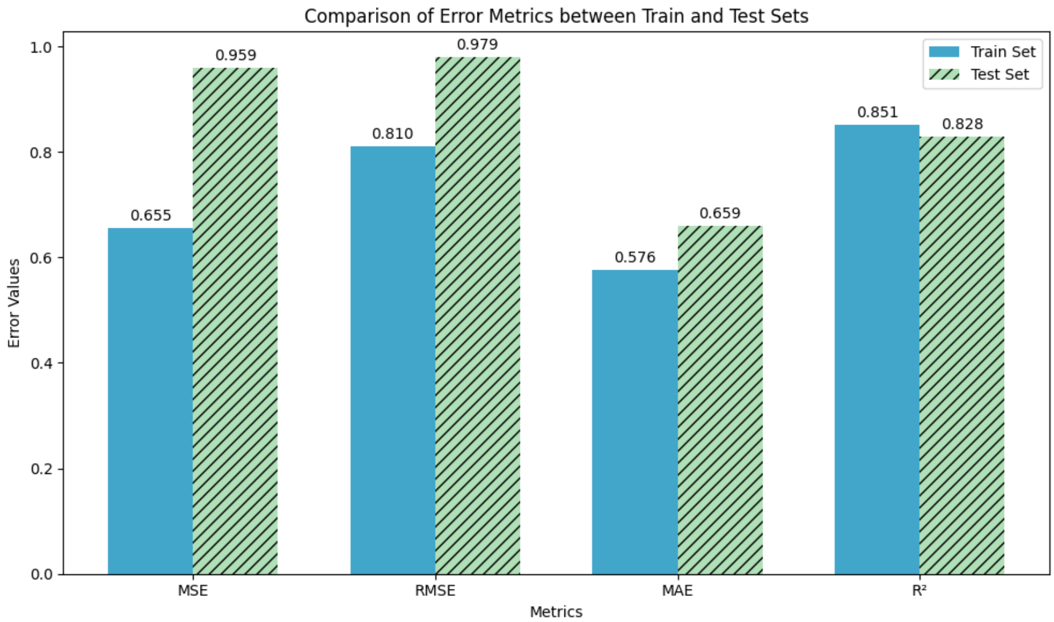

Figure 4. Comparison of Error Metrics between Train and Test Sets

While this level of performance is satisfactory, further parameter optimization or exploration of alternative algorithms could enhance predictive accuracy on unseen data.

Feature Importance

The analysis of feature importance provided insights into the relative impact of various factors on momentum shifts. Figure 5 illustrates the key predictors identified by the model. The server variable ranked as the most significant factor influencing momentum swings, followed by point_no, which represents the progression of the match, and point_winner, which indicates the winner of a specific point. These features were determined to have the greatest impact on predicting momentum dynamics during a match.

Model Application

Real-Time Momentum Visualization

To illustrate the model's effectiveness, the final match of the 2023 Wimbledon tournament between Carlos Alcaraz and Novak Djokovic was selected for visualization (Figure 6).

The visualization shows that Djokovic initially held the momentum advantage, while Alcalaz gained control midway through the match, resulting in a significant momentum shift. The model accurately tracks this transition, with both players experiencing

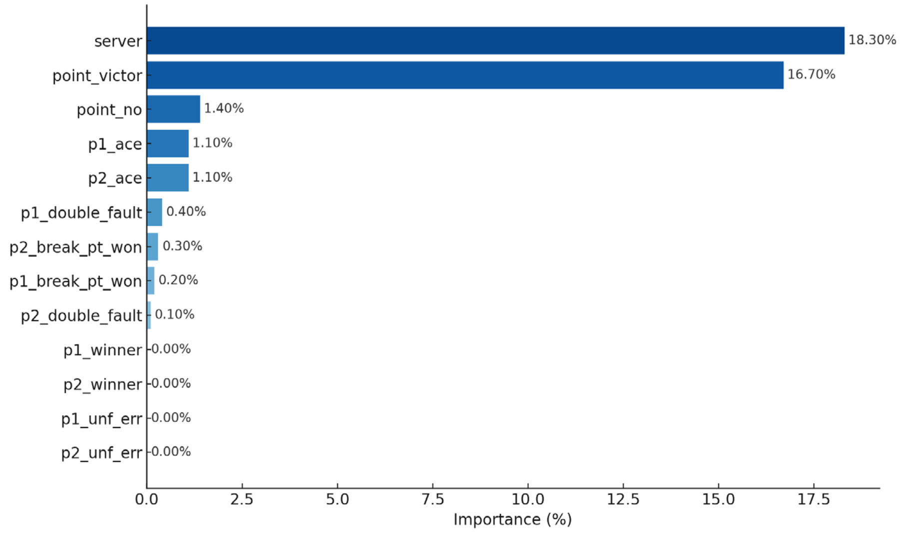

Figure 5. Feature Importance Ratio

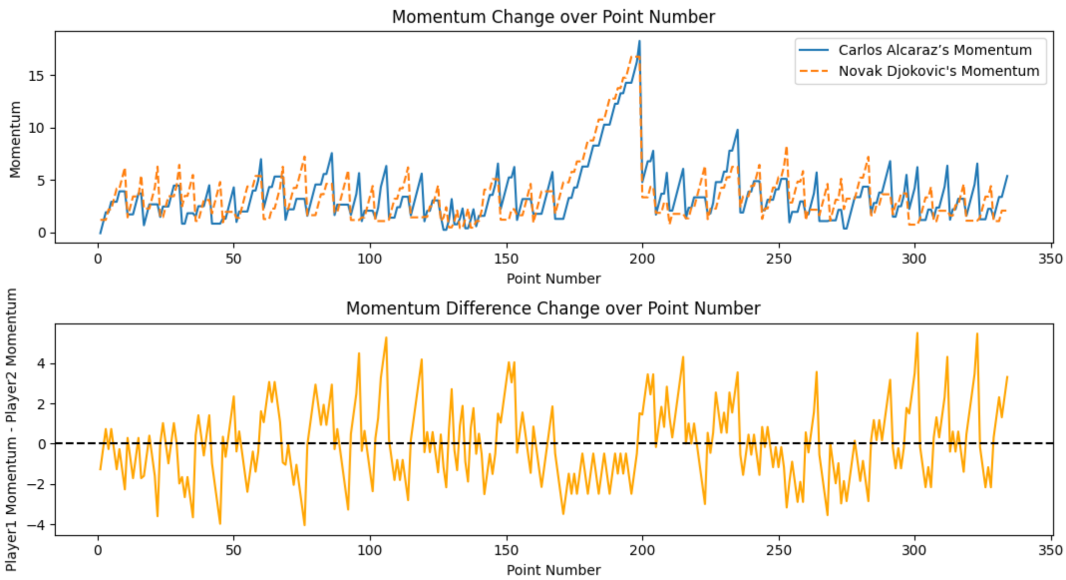

Figure 6. Momentum Visualization of the 2023 Wimbledon Men's Final

sharp momentum changes at critical points, indicating a close contest. Alcaraz's momentum eventually stabilized at a higher level, aligning with the actual match outcome, thereby demonstrating the model's capability to depict shifts in competitive advantage over time. The momentum differential graph offers a clear view of each player's relative advantage during the match.

The model was further applied to other matches, such as a round-of-16 match between Carlos Alcaraz and Nicolas Jarry (Figure 7), to illustrate different momentum patterns. By adjusting the match_id in the model code, momentum trajectories for various matches can be generated, showcasing the model's adaptability to different match dynamics.

This visualization depicts momentum patterns from another match in the tournament. Unlike the final, this match exhibited more consistent momentum patterns, with fewer abrupt shifts, highlighting the variability in competitive dynamics across matches.

Pre-Match Analysis and Opponent Profiling

The findings of this study demonstrate the model's suitability for pre-match analysis and opponent profiling. The model was used to calculate momentum turning points for Carlos Alcaraz and Novak Djokovic under various score scenarios during the U.S. Open and Wimbledon tournaments from 2022 to 2023, providing valuable insights into their strategic tendencies and performance shifts.

Figure 8 presents the momentum turning points for both Carlos Alcaraz across 22 matches and Novak Djokovic across 26 matches. Positive_Turning_Points indicate moments where momentum shifts from

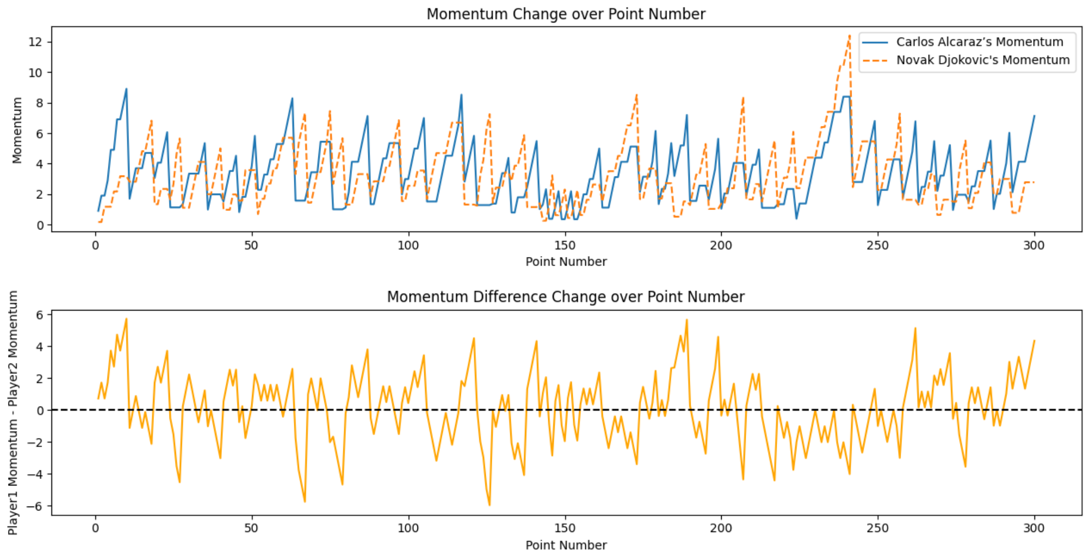

Figure 7. Momentum Visualization of a Round-of-16 Match

negative to positive, while Negative_Turning_Points represents shifts from positive to negative. For Carlos Alcaraz, at a score of 0:30, he encounters more negative turning points (75) than positive ones (62). Conversely, at 30:40, positive turning points (49) exceed negative ones (33). The lower sum values at scores such as 40:0, 40:15, and 40:30 reflect fewer momentum fluctuations, indicating greater stability at these moments. For Novak Djokovic, the total number of momentums turning points for Novak Djokovic is highest at a score of 15:0 (142), followed by 15:40 (132) and 15:15 (130). Negative turning points dominate at disadvantageous scores like 0:40 and 0:30, while critical moments such as 15:40 and 15:15 exhibit significant positive turning points.

Discussion

The primary objective of this study was to develop a comprehensive model for quantifying and analyzing momentum in tennis matches, addressing the challenges of capturing real-time trends and transforming the abstract concept of momentum into concrete, data-driven visual representations. Using data from six major tennis tournaments, this study successfully defined momentum and identified key influencing factors through factor analysis. This foundation enabled us to build a model capable of representing and calculating momentum shifts, which we visualized using real-time data. By incorporating the GBDT algorithm, the model demonstrated practical applications in identifying and analyzing momentum shifts throughout matches. Our analysis confirmed the critical role of momentum in tennis performance, offering practical recommendations for pre-match analysis, in-match tactical adjustments, and post-match reviews. Furthermore, the model showed potential for use in opponent research and preparation, providing new insights and tools for coaches and players.

A significant challenge addressed in this study was the quantification momentum, an inherently dynamic and elusive factor in sports. By integrating player performance metrics, such as serve success rates, ranking disparities, and point-by-point results, the model effectively captured momentum changes in real time, thus overcoming a key limitation in previous research. Application of the model to the 2023 Wimbledon Championship demonstrated a strong alignment between momentum indicators and actual match outcomes, as evidenced by a Kappa coefficient of 0.96. This high consistency validates the model's reliability, confirming the momentum can effectively represent match performance. These findings provide theoretical support for future momentum-based analysis and prediction in tennis.

Our findings align with previous research that has recognized momentum's predictive ability in tennis (Moss & O'Donoghue, 2015). The model incorporated a wider range of dynamic factors, such as point-by-point results, serve advantages, and match sequences, making momentum capture more comprehensive and accurate than current models (Lin et al., 2024). While Moss and O'Donoghue (2015) focused on serve game patterns, our approach expanded the scope to capture real-time momentum changes in every rally, providing a more detailed analysis of match flow. Furthermore, although Ahmed's (2014) probabilistic model emphasized match outcome prediction, it lacked continuous momentum analysis. In contrast, our model integrates both predictive and descriptive capabilities. demonstrated higher accuracy in identifying momentum shifts and their impact on

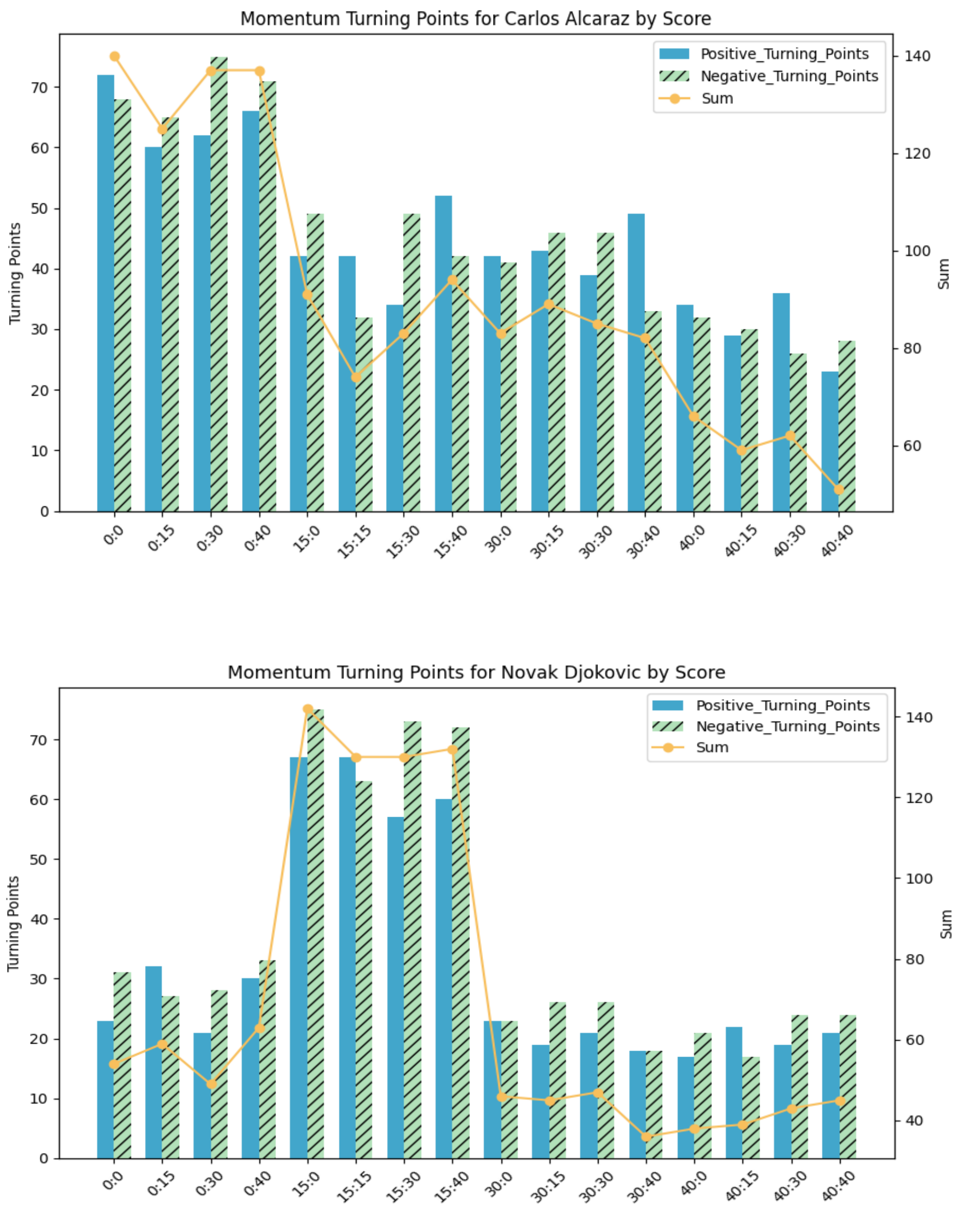

Figure 8. Momentum Turning Points for Carlos Alcaraz and Novak Djokovic

match outcomes. This advancement enhances our understanding the temporal dynamics in tennis and provides greater accuracy in identifying and interpreting momentum shifts and their effects on match outcomes.

From a practical perspective, the model offers actionable value for both coaches and players. For coaches, the visualization and quantification of momentum shifts can assist in real-time tactical decisions— for instance, determining the optimal timing for coaching interventions, adjusting player positioning strategies, or recognizing when an opponent is gaining momentum. Players can also use the model outputs to heighten their situational awareness during matches, allowing them to respond more effectively to turning points. Knowing when momentum is likely to shift enables players to manage psychological pressure and adapt their tactics accordingly. Post-match momentum analysis can further provide valuable feedback on performance patterns, helping players and coaching staff refine training and strategic planning.

The analysis of feature importance revealed that the *server* variable had the greatest impact on momentum shifts. This is consistent with conventional match analysis, where the server is often seen as having more control over the pace and dynamics of play. Players with a stronger serve are better able to influence momentum, particularly during critical moments when momentum shifts are most pronounced. The *point_no* variable also proved to be significant, with momentum shifts becoming more pronounced as the match progresses. This suggests that factors such as physical endurance and psychological resilience become more critical in the later stages of the match. Specifically, turning points often occur in pivotal moments like the seventh game of a set or during tiebreaks, where the psychological stakes are particularly high. The *point_winner* variable further underscores the importance of consistently winning points to build momentum, which influences the trajectory of the match. Players who accumulate consecutive points can generate significant momentum, which impacts overall match results.

Despite its contributions, this study has certain limitations. The accuracy of the model relies on the data quality and completeness, meaning that missing or incomplete data could affect the reliability. Additionally, there is potential to improve the predictive accuracy by exploring alternative algorithms. Furthermore, while the model primarily focuses on technical indicators, it does not fully account for tactical, physical, and psychological factors, limiting its comprehensiveness. Future research could integrate these elements to increase the model's practical applicability.

The results of this study are significant both theoretically and practically. Theoretically level, our model offers a robust framework for sports performance analysis by quantifying momentum, opening new avenues for exploring how momentum interacts with psychological, tactical, and physical performance, not only in tennis but also across other sports. Practically, coaches and players can use the model to better understand key momentum shifts and make informed strategic adjustments. By pinpointing when and how momentum changes occur, players can anticipate critical moments and adjust their tactics in real-time. Additionally, post-match momentum reviews provide insights for refining training and improving overall performance.

In conclusion, this study developed a data-driven model for analyzing momentum, which not only visualizes momentum changes but also predicts their impact on match outcomes. By integrating multiple dynamic factors, the model enhances predictive capabilities, making it a valuable tool for pre-match analysis and in-match tactical decision-making. These findings suggest that momentum is not solely a psychological concept but a quantifiable factor with a substantial impact on sports performance. Future research could expand on this model in incorporating additional variables, such as player fatigue and court conditions, to further refine momentum prediction. Ultimately, this study lays a solid foundation for the applying momentum in sports, with potential for broader applications across various competitive environments.

Conclusion

This study quantified momentum in tennis and modeled its impact on match outcomes by constructing a machine learning based model that captures real-time momentum shifts. Overall, momentum changes during matches played a substantial role in shaping player performance, especially at pivotal scoring moments. The turning points of momentum were closely associated with serve success, return effectiveness, and break points related performance indicators. Such findings evidence that momentum is not merely an abstract concept but a measurable factor that significantly influences match results. The results reveal the significance of understanding momentum when interpreting the performance of professional tennis players, informing adapted tactical decisions and training methodologies by coaches and players. The developed momentum model could serve as an efficient analytical tool for performance analysts during pre-match debriefing and post-match reviews. By integrating this model into long-term player development, coaches and performance analysts can systematically monitor players' technical, tactical, and physical performance while considering individual variations across match environments.

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