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Time-based characteristics of knee extensors and flexors in young tennis players using Biodex system 4 isokinetic dynamometer

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Abstract
In tennis, the musculature of the lower extremities is subjected to high-intensity loads, sudden changes in direction, abrupt stops, and accelerations. Monitoring the physiological characteristics of tennis players' lower extremities can identify muscle imbalances and predispositions to injury, which can be addressed promptly through appropriate training programs. The aim of this study is to analyze the performance and time-based parameters obtained from isometric and isokinetic dynamometric measurements to provide a comprehensive evaluation of the physiological characteristics of junior tennis players. Methods Strength and time-based characteristics of the flexors and extensors of the knee joint were measured in two tennis players (A and B) at angular positions of 30°, 60°, 90°, and 100° and velocities of 60°/sec and 300°/sec, respectively, under isometric and concentric modes using an isokinetic dynamometer (Biodex 4 Pro, USA). Results The first tennis player exhibited weight, muscle mass, and fat mass above the optimal range for their age, while the second player was below the norm. The first player demonstrated very strong extensors with a short acceleration time. At 60°/sec, the non-dominant leg showed prolonged time to peak torque. This player displayed high work capacity and power during muscle contractions. The second tennis player generated slightly reduced peak torque values per kilogram of body weight. Acceleration time was within the normal range for both legs; however, the time to reach peak torque was prolonged. Conclusion Time-based and performance parameters enhance the comprehensive assessment of knee musculature in tennis players following dynamometric testing. Alongside strength characteristics, which provide key recommendations regarding knee joint musculature, these metrics indicate the presence of predispositions to non-contact knee injuries and the need for specialized training programs. Such programs should aim to maintain or improve components like work capacity, explosive strength, time parameters, agility, and other performance-related factors.

Keywords: Peak torque/body weight, time-based parameters, knee joint, junior tennis players

Introduction
Tennis is characterized by high-intensity activity involving sudden changes in direction, abrupt stops, accelerations, and rapid movement toward the ball. These dynamic movements place significant stress on the lower extremities, leading to selective activation of muscle groups and their subsequent adaptation to the specific demands of the sport. A comprehensive evaluation of the physical condition of the lower extremities requires the assessment of various physiological and biomechanical characteristics. Among these are muscle strength, expressed as joint torque and torque normalized to body weight, under different modes of muscle contraction; power; work performed per kilogram of body weight; acceleration time; and the time to reach peak torque [1].

Although less frequently studied, time-based parameters offer valuable insights into both the genetic predisposition of the athlete and the current functional state of their musculature. The time to reach peak torque reflects the duration (in milliseconds) from the start of movement to the achievement of maximal force. A shorter duration indicates better functional capacity, serving as a key indicator of a muscle's ability to generate force rapidly. Existing data on this parameter for athletes across various sports disciplines is limited but highlights its influence on athletic performance.

For example, the ability of knee flexors to quickly generate peak torque significantly affects the performance of sprinters, particularly in the initial 5 meters, which corresponds to the early phases of acceleration [2]. Conversely, prolonged time to peak torque in knee flexors is associated with an increased predisposition to non-contact knee ligament injuries [3].

Rapid peak torque generation is a critical characteristic across most sports disciplines. Assessing this parameter provides a more comprehensive understanding of the functional state of the musculature compared to analyzing peak torque alone [4]. Acceleration time, defined as the duration (in milliseconds) required to reach isokinetic speed, serves as an indicator of the neuromuscular system's responsiveness in initiating limb movement at the onset of the joint's range of motion. This parameter is closely related to explosive strength and has been studied in karate athletes [5]. The limited availability of literature and guidelines for analyzing acceleration time and time to peak torque complicates their application in the functional assessment of athletes. This underscores the necessity for further research to facilitate their routine use in sports science and training.

In contrast, power and work are relatively well-explored characteristics of the lower-extremity muscles. The game of tennis has evolved from a primarily technical to an explosive sport, becoming more dynamic and faster-paced. It is now characterised by strength, speed and power with higher shot and serve speeds, making the service a key factor in the success of the game [6]. Data on average power values in adolescent male and female tennis players suggests that knee extensor power plays a crucial role in shot accuracy during diagonal strikes [7]. Enhancing lower-extremity power has been shown to improve both ball speed and shot accuracy. This is because force generation in tennis begins from the knee joint [8]. Individual variations in the aforementioned parameters are substantial. Therefore, accurate evaluation of physiological and biomechanical characteristics requires individualized analysis to account for these differences effectively**.** On the other hand, same authors found evidence that the lower limbs are at the beginning of the kinetic chain of the tennis serve. Thus, lower limb movement would be important in initiating energy generation and transfer to the trunk, upper limb, and then to the racquet [9]. Also tennis requires quick, explosive movements, frequent direction changes, and high-intensity sprints, all of which heavily depend on the lower body. Greater knee flexion during the serve preparation phase allows a greater knee extension velocity to be achieved (as the acceleration is applied over a longer period of time), resulting in a more effective lower limb drive as more mechanical energy is added to the body [7]. Knowledge of typical or characteristic descriptive results from musculoskeletal tests is important for optimal interpretation of test results in individual athlete populations. Sport-specific descriptive data assist in the interpretation of these tests and help to identify characteristic adaptations inherent in certain homogeneous populations [9]. The aim of this study is to conduct an individualized analysis of key parameters, including isometric peak torque, peak torque normalized to body weight, time to reach peak torque, acceleration time, work per kilogram of body weight, and average power in the knee joint. This analysis seeks to provide a comprehensive evaluation of lower-limb musculature and incorporate the physiological characteristics of explosive strength and work capacity in junior tennis players. Additionally, the study aims to provide an exemplary assessment of junior tennis players using these parameters and their established normative values. To achieve this goal, the athletes underwent measurements of strength and time-based characteristics of knee extensors and flexors using an isokinetic dynamometer.

Materials and Methods

The study involved junior tennis players, from whom two cases (Tennis Player A and Tennis Player B) were selected for detailed analysis. Following the provision of informed consent, anthropometric data (age, height, weight, muscle mass, and fat mass) were collected for the participants using a bioimpedance analyzer. Subsequently, strength and time-based characteristics of the knee flexors and extensors were measured at angular knee positions of 30°, 60°, 90°, and 100°, and velocities of 60°/sec and 300°/sec, under isometric and concentric modes, respectively, using an isokinetic dynamometer (Biodex 4 Pro, USA). The isometric protocol consisted of two cycles of knee extension and flexion at each measured position. Muscle contractions lasted 3 seconds, with a 60-second rest interval between cycles. The concentric protocol consisted of 5 repetitions of knee extension and flexion at a velocity of 60°/sec and 15 repetitions at 300°/sec. Measurements were conducted bilaterally. Dynamometric data obtained were analyzed, and coefficients for unilateral strength ratios (H/Q ratios) and bilateral strength asymmetry were calculated.

Participants were positioned in the dynamometer chair and secured using chest and pelvic straps. The tested limb was additionally stabilized at the thigh, while the dynamometer attachment was secured above the ankle. The axis of knee joint movement was aligned with the axis of the dynamometer. After setting the range of motion for the joint, isometric and isokinetic measurements were performed.

Results and analysis

Tennis Player-A

The present study aimed to assess the isokinetic profile of knee extensors and flexors in young tennis players. The anthropometric analysis of Tennis Player-A (TP-A), a 15-year-old male with a height of 171 cm and a body mass of 71.1 kg, indicates that the body mass exceeds the upper limit of the normal range (57.8-70.1 kg) and is above the optimal weight for his age. Fat mass is 3.9 kg above the upper limit, while muscle mass is at the upper limit for his age. The elevated muscle mass suggests a capacity for generating high levels of force. Segmental impedance analysis was included to evaluate bilateral asymmetry of the lower limbs. The dominant leg (right) exhibited a lower fat mass (2.62 kg) compared to the non-dominant leg (left, 2.72 kg). Conversely, muscle mass was higher in the dominant leg (9.89 kg) than in the non-dominant leg (9.43 kg).

The maximal isometric strength of the knee extensors in the dominant leg was recorded at 254.2 Nm at an angular position of 90°, while the non-dominant leg achieved 253.6 Nm at 100°. These values are within the normative range.

The concentric testing parameters included peak torque normalized to body weight, acceleration time, time to reach peak torque, total work, and average power (Table 1). The peak torque per kilogram of body weight revealed very strong knee extensors in both limbs, with values of 3.03

Nm/kg for the dominant leg and 2.91 Nm/kg for the non-dominant leg at 60°/sec. Although the extensors of the non-dominant leg were slightly weaker, the differences were minor, and no bilateral asymmetry was observed.

Table 1: Values of muscle strength and time parameters, working capacity and power of knee extensors and flexors, in the concentric mode of isokinetic testing of tennis players (TP-A-male junior tennis player; TP-B-female junior tennis player)

Parameters	Dominant TP-A		Non-dominant TP-A		Dominant TP-B		Non-dominant TP-B	
	E	F	E	F	E	F	E	F
Peak torque/kg 60°/s (Nm/kg)	3.03	1.59	2.91	1.25	1.88	1.01	1.53	0.81
Peak torque/kg 300°/s (Nm/kg)	1.81	1.09	1.56	1.00	1.14	0.57	1.05	0.74
Acceleration time 60°/s (msec)	20	30	30	40	50	90	70	110
Acceleration time 300°/s (msec)	60	100	80	110	120	240	110	180
Time to peak torque 60°/s (msec)	310	530	720	680	860	1210	930	1380
Time to peak torque 300°/s (msec)	150	170	190	180	400	490	230	470
Total work 60°/s (J)	993	488	1149	562	486	229	435	181
Total work 300°/s (J)	1951	1356	2244	1528	912	327	956	382
Average power 60°/s (W)	149	75	142	69	53	26	44	18
Average power 300°/s (W)	284	181	283	172	90	29	100	34
60°/s H/Q ratio	52.4%		49.9%		53.8%		52.6%	
300°/sH/Q ratio	60.0%		64.0%		50.0%		70.1%	

TP-tennis player, E-extensors, F-flexors, H/Q ratio-Hamstrings/Quadriceps ratio.

The acceleration time and time to reach peak torque in the dominant leg were very low at both 60°/sec and 300°/sec (Table 1), indicating significant explosive strength and rapid activation of fast motor units. Player A demonstrated high work capacity and endurance (total work of 1149 J, corresponding to 352%/kg) and high power (average power across five contractions: 142 W).

At the slower velocity of 60°/sec, the non-dominant leg displayed a low acceleration time, within the normative range. However, the time to reach peak torque was slightly prolonged (720 ms) compared to existing norms [5]. At higher velocities, the time-based parameters of the non-dominant leg were within the normal range.

The knee flexors strength of the dominant and non-dominant legs, expressed as peak torque normalized to body weight, falls within the normative range and is relatively high for the participant's age. However, the flexors torque does not correspond to the extensors torque in either leg. Differences between antagonistic muscle groups within the same leg were assessed using unilateral strength asymmetry coefficients, as applied in a previous research [10]. At both low and high angular velocities, these coefficients were below the normal threshold for knee joint balance (Table 1). Deviations exceeding 10% in unilateral asymmetry coefficients are considered to pose a risk to the ligamentous apparatus and soft tissues of the knee joint. Unilateral asymmetry was more pronounced at lower velocities, where peak torque was higher, particularly in the non-dominant leg.

Tennis Player-B

The anthropometric analysis of Tennis Player B, a 12-year-old female with a height of 151 cm and body mass of 42.5 kg, reveals a body mass below the lower limit of the normal range, approximately 4.3 kg under the optimal weight. Fat mass was 7.3 kg, 0.5 kg below the lower limit of the normative range (7.8-12.8 kg). However, in percentage terms, fat mass was within the normal range for females at 17.2% (15.5-25.5%). Muscle mass was 2.0 kg below the lower limit for the participant's age. Segmental analysis of the lower limbs showed a trend toward higher fat mass in the left (non-dominant) leg, while muscle mass, although below the optimal range, tended to be greater in the right (dominant) leg. Despite the higher muscle mass in the dominant leg, the maximal torque values for the extensors of both knees were similar, and static strength asymmetry in the extensors across all angular positions was below 10%, the threshold value for athletes [11]. This indicates no predisposition to injury [6].

The isometric strength results indicated a maximum knee extensor torque of 119 Nm in the dominant leg at 90°, compared to 115 Nm in the non-dominant leg at 60°. A bilateral asymmetry of 23% was observed at 90°. The knee flexors of the dominant leg exhibited higher isometric strength than those of the non-dominant leg, with asymmetries of 35% and 28% observed at 90° and 100°, respectively.

The peak torque normalized to body weight during concentric testing of the dominant leg's knee extensors was 1.88 Nm/kg at 60°/sec and 1.14 Nm/kg at 300°/sec, which is close to the normative range (Table 1). Similarly, the non-dominant leg's extensors produced near-normative values of 1.53 Nm/kg and 1.05 Nm/kg at the same respective velocities. Acceleration time was slightly prolonged in both legs, with normative values observed only at 300°/sec in the dominant leg. The time to peak torque was also prolonged in the dominant leg, suggesting insufficiently refined neuromuscular control in mobilizing fast motor units. At 60°/sec, the non-dominant leg also displayed prolonged time to peak torque, similar to the dominant leg, with a value of 930 ms. At 300°/sec, the time to peak torque in the non-dominant leg was close to the normative range.

The flexor strength of the dominant leg was within the normative range at both tested velocities, while the non-dominant leg exhibited reduced peak torque at 60°/sec (0.81 Nm/kg). Acceleration time was slightly prolonged in all tests, except at 300°/sec in the non-dominant leg. The time to peak torque for the knee flexors was also prolonged, most notably at the slower velocity, with values of 1210 ms in the dominant leg and 1380 ms in the non-dominant leg. Prolonged time to peak torque in the knee flexors may serve as an indicator for identifying athletes with or without an increased predisposition to non-contact knee ligament injuries [3].

The unilateral asymmetry coefficients of the dominant leg were within the normative range (Table 1), suggesting no excessive strain on the ligamentous apparatus or cruciate ligaments under load. However, the knee flexor strength of

the dominant leg should be increased to optimize the balance between extensor and flexor strength. Additionally, targeted training is needed to enhance explosive strength and the mobilization speed of fast motor units in the extensors and particularly in the flexors of the dominant leg.
In the non-dominant leg, insufficient flexor strength resulted in a unilateral asymmetry coefficient significantly below the norm at 300°/sec. Slight bilateral asymmetry was observed during dynamic loading at lower velocities.
The strength characteristics of young male and female athletes differ due to factors such as hormonal influences, muscle composition, neuromuscular activation, and biomechanical differences. Given the increasing importance of power and speed in the modern game, and consequently in speed-specific training, and the lack of consistency regarding scientifically proven predictors of service performance, identifying the relationship between performance variables and service speed would be extremely valuable in the development, modification and refinement of training strategies [6], as well as in the establishment of talent identification programs. Therefore, knowledge of the factors that increase serve speed is of great importance to coaches and strength and conditioning professionals. By focusing on muscle strength characteristics and addressing any imbalances, young tennis players can improve both their performance and reduce the risk of injury.

Conclusion

In the case of Tennis Player A, no indications of predispositions to knee injuries were found, aside from a slight unilateral asymmetry. The second case (Tennis Player B) requires strengthening of both the flexor and extensor muscles in the knee joint. The prolonged time to peak torque observed in the knee flexors suggests an increased predisposition to non-contact knee injuries and highlights the need for the development of training plans aimed at improving explosive strength. The time-related parameters and work capacity indicators enhance the comprehensive assessment of knee musculature in tennis players following dynamometric testing. Together with the strength characteristics, which provide primary recommendations for knee musculature, these parameters help determine the presence of predisposition to non-contact knee injuries and indicate whether there is a need for specialized training programs to maintain or develop components such as work capacity, explosive strength, time parameters, agility, and more.

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