

Investigation of the workload profiles of male elite tennis players of different ages and playing strategies in relation to technical-tactical actions

Abstract of PhD Thesis

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1. INTRODUCTION

Tennis is one of the most complex and popular racket sports, undergoing continuous and spectacular evolution in technical, physical, and economic terms since the beginning of the "Open Era" in 1968. Today, it is actively played by over 100 million people worldwide. Its popularity stems not only from its recreational value and undeniable health benefits but also from the extraordinary complexity manifested at the competitive level. In modern tennis, success is now inseparable from a science-based approach; as Dobos (2023) posits, the sport is a game dominated by tactical and technical factors, resulting in a specific, intermittent rhythm of play. In this environment, the efficiency of training can no longer be based solely on subjective coaching observations. Consequently, when analyzing the sport, it is essential to define Key Performance Indicators (KPIs), which delineate the path of development across technical-tactical skills, motor abilities, and mental factors. Much like driving a car without a fuel gauge, managing training without KPIs would remain mere uncertain guesswork; objective monitoring and testing are the cornerstones of informed coaching decision-making and long-term strategic planning.

Throughout my career as an elite athlete and coach, I recognized early on that the isolated development of physical qualities—such as strength, endurance, or speed—does not guarantee victory on its own, even with the highest level of raw fitness. The global evolution of sports science clearly points toward an integrated approach (Ju, 2022), the essence of which is that physical performance must never be abstracted from the tactical context in which it manifests. As one of the fundamental tenets of modern sports analytics states: “*Context matters more than content*” (Buchheit and Harder, 2025). This mindset has guided my research: I examined on-court performance through the lens of various playing styles, match situations, and applied strategies, starting from the realization that in professional tennis, a high level of motor skills is now a baseline requirement, and the key to further progress lies in specific, player-tailored analysis. In my dissertation, I investigate the workload profiles of elite male tennis players of different age groups, playing styles, and strategies, aiming to organically link scientific results with domestic and international coaching methodologies, thereby assisting professionals in training more successful competitors and extending athletic careers.

In elite competitive sports, the most critical question has always been - and will remain - which high-level capabilities are necessary for victory and sustainable success (Tóth et al., 2025a, b). These include motor, technical, tactical, and mental abilities and skills, the synergy of which constitutes competitive performance. In most ball games, this is determined directly

by monitoring external and internal load values and technical-tactical actions during matches, or indirectly through laboratory or field tests measuring motor abilities in isolation (i.e., outside of match play). In the world's most widespread team sport, football (soccer), the relationship between a team's success and external load or running activity is most frequently established by comparing high-intensity running to league standings (Mohr et al., 2003; Di Salvo et al., 2009; 2013; Rampinini et al., 2009; Bradley et al., 2013, 2016). In this regard, Mohr and colleagues (2003) found that top-level professional footballers cover significantly greater distances in high-intensity running during a match than lower-level players and achieve superior results in conditional tests assessing aerobic endurance. Conversely, an examination of the English Premier League revealed that players from lower-ranked teams sometimes cover greater total distances and run more in high-intensity zones than members of more dominant, higher-level teams (Bradley et al., 2013). This demonstrates that success in sports games depends primarily on the effective application of technical and tactical knowledge rather than the mere quantity of physical qualities—a fact that, when applied to tennis, further emphasizes the role of tactical discipline (Bradley et al., 2013; Carling, 2013).

In tennis-specific research, a relatively large number of studies have sought differences between more and less successful players, as well as between winners and losers of matches, in terms of conditional abilities (Girard and Millet, 2009; Filipic et al., 2010; Baiget et al., 2014; Kramer et al., 2016, 2017; Ulbricht et al., 2016; Dobos et al., 2021). For instance, Dobos and colleagues (2021) investigated whether higher-ranked players proved superior in tennis-specific physical abilities. Their results showed a positive correlation between explosive power in the lower and upper limbs and ranking among girls in the U14 and U18 age groups, suggesting that extra explosiveness provides a direct competitive advantage in the youth female field. In contrast, no such significant correlation was found for any ability among boys, which the authors explained by the fact that in male tennis—even at the youth level—the complexity of technical and tactical skills dominates, while in females, neuromuscular capabilities gain more importance due to simpler tactical solutions. The work of Ulbricht and colleagues (2016) also supports these findings, pointing out that explosive power, especially of the upper body, is the most decisive predictor for the success of junior tennis players. Kramer et al. (2017) reached a similar conclusion, emphasizing the crucial role of maturation status and lower-limb explosiveness in age-group success. It must be noted, however, that these results primarily apply to youth categories, and further investigation is required to clarify which physical factors, technical-tactical knowledge, and mental factors contribute—and in what proportion—to

ultimate success in the professional adult field. For this, monitoring on-court activities from external and internal load perspectives under real competitive conditions is indispensable.

Galé-Ansodi and colleagues (2017b) compared players within a match context, establishing that higher-ranked players covered more distance per minute and achieved higher maximum speeds. Martínez-Gallego and colleagues (2013) similarly found that in winning conditions, tennis players ran more than in losing situations. In contrast, Fernandez-Fernandez and colleagues (2009b) observed that lower-ranked players ran more in high-intensity zones, suggesting they attempted to compensate for weaker technical skills with extra physical effort. However, it is important to note that these metrics are primarily locomotive in nature, providing a picture of running speed and distance, whereas in tennis, the examination of micro-movements—accelerations and decelerations—provides much more relevant information (Tóth et al., 2021a). Hoppe and colleagues (2014) demonstrated that in youth matches, high-intensity accelerations and decelerations occur three times more frequently than high-speed linear runs. In later studies (Hoppe et al., 2016), they also showed that winners performed significantly more accelerations toward the forehand side, indicating tactical dominance. Furthermore, "closed" condition studies by Tóth and colleagues (2021a) pointed out that increased micro-movements do not necessarily correlate with better hitting accuracy, underlining once again the importance of technical stability. All these results and practical experiences show that a high level of technical-tactical knowledge is essential for success, while conditional abilities serve as a fundamental requirement for reaching the elite level (Birrer et al., 1986; Reid et al., 2007).

As a player develops, the establishment of an individual playing style and strategy that fits their skill set and personality becomes increasingly important, requiring style-specific preparation in the training process (Hoppe et al., 2019, 2020). Previously, the workload profiles of playing styles were mostly based on subjective coaching experience, but modern performance analysis allows for their objective quantification. Bernardi and colleagues (1998) showed that rallies for offensive-style players are significantly shorter (4.8 s) than those of defensive players (15.7 s), causing marked differences in internal load (heart rate responses). Hoppe and colleagues (2019, 2020) highlighted that active and passive strategies in simulated matches result in significantly different running activities, technical responses, and physiological loads. The aim of this dissertation is to explore the specific technical-tactical elements and external and internal load factors that differ across various strategic contexts, with a particular focus on elite youth male tennis players, for whom scientifically grounded, individualized load management and methodological development are key to success and a long-term career.

2. AIMS

The primary objective of our first study was to identify the differences between offensive and defensive game strategy situations under "closed" match conditions in youth male tennis players, based on external and internal training load indicators. Based on these, the following hypotheses were formulated (related study: Tóth et al., 2025a):

H_{1/1}: Youth tennis players in a defensive strategy condition achieve higher PlayerLoad™ values—meaning they perform more accelerations across all three planes of motion—than those employing an offensive strategy.

H_{1/2}: Youth tennis players in a defensive strategy condition perform more low- and high-intensity changes of direction to both the left and right sides compared to those in an offensive strategy.

H_{1/3}: Youth tennis players in a defensive strategy condition hit both forehands and backhands with greater topspin than in offensive situations. However, there is no significant difference in ball speed between the two conditions.

H_{1/4}: Youth tennis players playing according to a defensive strategy report higher RPE (Rating of Perceived Exertion) values, as the volume of their micro-movements is significantly greater than that of offensive players.

The primary objective of our second study was to determine the differences manifested under "open" conditions between youth male tennis players characterized by offensive baseline and defensive baseline playing styles, based on their external and internal training load parameters. Furthermore, we sought to identify the main differences between match winners and losers. Additionally, we aimed to define the activity profiles of elite Hungarian youth matches and analyze their external training load indicators using a novel analytical method. Based on these, the following hypotheses were formulated (related study: Tóth et al., 2025b):

H_{2/1}: Defensive baseline players produce more high-intensity accelerations, decelerations, and changes of direction than offensive baseline players, resulting in a higher total external tennis-specific workload.

H_{2/2}: Defensive baseline players exhibit higher RPE values than players with an offensive baseline style.

H_{2/3}: Match losers produce more high-intensity accelerations, decelerations, and changes of direction than match winners, thus their total external tennis-specific workload is also higher.

H_{2/4}: Match losers exhibit higher RPE values than match winners.

3. METHODS

3.1. Comparison of offensive and defensive playing strategies

In this cross-sectional study, we investigated the differences between the two most frequent playing strategies in tennis—offensive and defensive situations—in light of running and hitting activities, as well as subjective internal load. Measurements were conducted in May 2023 on outdoor clay courts between 14:00 and 16:00 under controlled environmental conditions (temperature: 21.2–24.5°C; relative humidity: 44–56%; Kestrel 4000 Pocket Weather Tracker, Nielsen Kellerman, USA, Boothwyn, PA). Six elite youth male tennis players participated in the study (chronological age: 15.7 ± 1.0 years; height: 180.7 ± 6.5 cm; body mass: 71.0 ± 10.8 kg). Participants were selected via purposive sampling from a youth development academy to ensure a familiar environment for the measurements. Inclusion criteria were: (i) male players in the U16–U18 age groups, (ii) Hungarian national youth ranking ≤ 10 , (iii) right-hand dominance, and (iv) the ability to employ both offensive and defensive strategies. Exclusion criteria were: (i) suffering from injury or illness, (ii) orthopedic surgery within the past 12 months, and (iii) participation in high-intensity training within the previous 48 hours. The participants possessed extensive competitive backgrounds; several were ranked at the top of the ITF Junior World Rankings or held adult ATP points. Their weekly workload exceeded ten hours of tennis-specific training and three hours of physical conditioning. Prior to the measurements, all participants and legal guardians provided written informed consent. The study was approved by the Scientific and Research Ethics Committee of the Hungarian University of Sports Science (approval number: TE-KEB/02/2022; date of approval: February 6, 2022) and complied with the Declaration of Helsinki for human subjects research.

The measurement day began with anthropometric assessments, followed by a fifteen-minute general and a ten-minute tennis-specific warm-up. Players were paired based on skill level and ranking, and each played two ten-minute simulated matches in a tie-break format, with a five-minute passive rest period between them, using brand-new Slazenger Ultra Vis balls. Strategic conditions were ensured through written tactical instructions: the task in offensive situations was to actively finish points, while in defensive situations, it was to minimize unforced errors. To record on-court movements, GNSS-based microsensors (Catapult

OptimEye S5, Catapult Innovations, Australia, Melbourne) were used, operating at a 10 Hz sampling frequency, supplemented by a 100 Hz triaxial piezoelectric accelerometer, gyroscope, and magnetometer. The device was secured between the scapulae in a neoprene vest; the same sensor was assigned to the same player throughout the measurements to eliminate inter-device variability. To characterize external load, the PlayerLoad™ (PL) integrated metric was utilized, which measures the sum of accelerations in all planes and describes the neuromuscular load on the athlete in dimensionless Arbitrary Units (AU). Additionally, Inertial Movement Analysis (IMA) was used to examine the number of changes of direction (COD) in low- and high-intensity zones, where high intensity was defined as values above 2.5 m/s² and low intensity as values below 2.5 m/s².

To measure hitting activities, smart sensors mountable on the tennis racket (Zepp Tennis 2.2.1, Zepp Labs, USA, San Jose, CA) were used, secured to the butt of the rackets with the manufacturer-provided flex-mount adapter. Using an accelerometer and gyroscope, this system recorded the speed of forehand and backhand shots in kilometers per hour (km/h) and the spin rate in revolutions per minute (rpm). The sensors were connected via Bluetooth to separate smartphones to avoid interference, and data were recorded in the dedicated mobile application (Zepp Tennis, Zepp Inc., USA, Milpitas, CA). Internal load was determined immediately after the matches using the Borg CR-10 scale, where players rated their perceived exertion on a Likert scale from 0 to 10 (Rating of Perceived Exertion, RPE) in response to the question: "*How demanding was the match?*" (Murphy et al., 2014). The collected data were processed using Catapult OpenField software (v1.22.2; Catapult Innovations, Australia, Melbourne) and Microsoft Excel (16.49, Microsoft Inc., USA, Washington, DC) for subsequent statistical analysis.

3.2. Comparative analysis of offensive and defensive baseline playing styles, and a comparison of match winners and losers

The second part of this dissertation was also a cross-sectional study, which, unlike the first stage, was based on simulated matches conducted under "open" conditions. By "open," we mean that the tennis players were allowed to play through all matches without restrictions, according to their own individual styles, in contrast to the first study where the strategy to be applied was predefined. The primary objective of this investigation was to identify differences between the two most common playing styles—offensive baseline and defensive baseline players—as well as between match winners and losers, in terms of running activities and

internal training load. Additionally, regardless of playing style, we aimed to define the most characteristic activity profiles within this elite youth age group. The research took place in early December 2024 on indoor clay courts under controlled environmental conditions (temperature: 18.0–19.5°C; relative humidity: 45–51%; Kestrel 4000 Pocket Weather Tracker, Nielsen Kellerman, USA, Boothwyn, PA). Sixteen elite youth male tennis players from the same club in the capital participated in the study (chronological age: 16.0 ± 1.1 years; height: 179.2 ± 9.9 cm; body mass: 67.0 ± 10.4 kg), selected via purposive sampling. Inclusion criteria were: (i) male players in the U16–U18 age groups, (ii) Hungarian national youth ranking ≤ 30 , and (iii) offensive baseline or defensive baseline playing style. Exclusion criteria were: (i) suffering from injury or illness, (ii) orthopedic surgery within the past 12 months, and (iii) participation in high-intensity training within the previous 48 hours. Classification by playing style was conducted based on a previously validated protocol (Pokharel and Zhu, 2021), where players and their coaches independently identified the style; if the two choices differed, a second expert coach made the final decision. At the end of the process, 9 offensive and 7 defensive baseline players were included in the sample. On average, participants took part in 11.2 ± 1.0 tennis and 3.5 ± 0.5 physical conditioning sessions per week and competed in an average of 24.3 ± 4.1 tournaments during the season. Prior to the study, the players and their legal guardians were briefed in detail on the research process, and written informed consent was obtained. The study was approved by the Scientific and Research Ethics Committee of the Hungarian University of Sports Science (approval number: TE-KEB/02/2022; date of approval: February 6, 2022) and complied with the Declaration of Helsinki for research involving human subjects.

The measurement protocol spanned three days, during which each participant played three simulated matches in groups of four organized by skill level to ensure high-quality competition. A total of 24 simulated matches took place, each lasting 30 minutes according to official ITF rules, using brand-new Slazenger Ultra Vis balls. To record activity profiles, video cameras (GoPro Hero10 Black, GoPro Inc., USA, San Mateo, CA) were positioned at the side of the court at a height of 6 meters, recording at 60 frames per second. The video footage was analyzed using Kinovea 0.8.15 software by an ITF-certified professional, recording the number of rallies (NR), strokes per rally (SPR), duration of rallies (DR), rest time between rallies (RT), and effective playing time (EPT). Furthermore, rallies were differentiated by length into categories of 0–4 strokes, 5–8 strokes, and over 9 strokes. For measuring movement activity, portable microsensors (Catapult Vector S7, Catapult Innovations, Australia, Melbourne) were utilized, featuring 10 Hz GNSS and a 100 Hz Inertial Measurement Unit (IMU). The devices

were secured in neoprene vests between the scapulae, and each player wore the same sensor throughout the entire study.

Using the machine learning model of the Catapult sensor, a total of 14 running and hitting metrics were examined. The stroke-based PlayerLoad™ (sPL) metric included the load from forehand stroke load (FHSL), backhand stroke load (BHSL), serve load (SL), and other stroke load (OSL). The "other stroke" category included volleys performed at the net and shots taken from defensive, out-of-position situations. Simultaneously, movement-based PlayerLoad™ (mPL) was measured, which categorizes movements into four types: low-intensity load (LIL), alert load (AL), dynamic load (DL), and running load (RL). Comprehensive external load was provided by the total tennis load (TTL), encompassing all tennis-specific load variables. Inertial Movement Analysis (IMA) was used to examine high-intensity accelerations (HiA), high-intensity decelerations (HiD), and high-intensity changes of direction (HiCoD), with thresholds set above 2 m/s², utilizing a clock-based model to differentiate directions (Galé-Ansodi et al., 2019). To determine internal training load, the Borg CR-10 scale was used as in the previous study (Murphy et al., 2014), where players rated their Rating of Perceived Exertion (RPE) ten minutes after the matches. The data obtained were processed using Catapult OpenField software (v1.22.2; Catapult Innovations, Australia, Melbourne) and Microsoft Excel (16.49, Microsoft Inc., USA, Washington, DC) for subsequent statistical analysis.

3.3. Statistical analyses

Statistical analyses were performed using SPSS Statistics software (version 20.0; SPSS Inc., Chicago, IL, USA). For both studies, the distribution of the data was first subjected to normality testing using the Shapiro–Wilk test, which possesses adequate statistical power for small and medium-sized samples. Furthermore, skewness and kurtosis values were considered, alongside visual inspections of distributions using histograms and Q-Q plots. The assessment of normality was not based on a single criterion but on the joint interpretation of statistical tests and graphical methods. Since the dependent variables did not show a normal distribution in either study, non-parametric statistical procedures were employed for further analysis. In the first study, the Wilcoxon signed-rank test was used to determine differences between the offensive and defensive strategic conditions. In the second study, the Wilcoxon test was also applied to compare winning and losing match conditions, while the Mann–Whitney U test was performed to examine differences between independent playing style groups (offensive baseline vs. defensive baseline). During the second study, the inter-individual variability of

running activity and internal training load (RPE) variables was quantified using the coefficient of variation (CV). Additionally, the activity profiles of simulated matches were characterized using descriptive statistics, incorporating hitting activities and time dimensions. To interpret the practical significance of the statistical results, r-based effect sizes (ES) were calculated for all comparisons ($r = Z/\sqrt{N}$). Effect size values were interpreted based on Cohen's (1992) recommendations as follows: very small (< 0.1), small (0.1–0.3), medium (0.3–0.5), and large (> 0.5). The level of statistical significance was set at $p < 0.05$.

4. RESULTS

4.1. Comparison of offensive and defensive playing strategies

Regarding running activities, a statistically significant difference with a large effect size was observed between offensive and defensive game strategies for PlayerLoad™ ($T = 0.0$; $Z = 2.201$; $p = 0.031$; $r = 0.90$; large ES), as well as for low-intensity ($< 2.5 \text{ m/s}^2$) changes of direction to the right ($T = 0.0$; $Z = 2.201$; $p = 0.031$; $r = 0.90$; large ES). No significant differences were detectable between the two conditions for the following running parameters: low-intensity ($< 2.5 \text{ m/s}^2$) changes of direction to the left ($T = 2.0$; $Z = 1.782$; $p = 0.090$; $r = 0.73$; large ES), high-intensity (2.5 m/s^2) changes of direction to the right ($T = 3.0$; $Z = 1.572$; $p = 0.140$; $r = 0.64$; large ES), and high-intensity (2.5 m/s^2) changes of direction to the left ($T = 12.0$; $Z = 1.214$; $p = 0.279$; $r = 0.50$; medium ES). In terms of tennis hitting activities, a statistically significant difference with a large effect size was found between offensive and defensive strategic conditions for forehand spin ($T = 0.0$; $Z = 2.201$; $p = 0.031$; $r = 0.90$; large ES) and backhand spin ($T = 0.0$; $Z = 2.201$; $p = 0.031$; $r = 0.90$; large ES). In contrast, no significant differences were observed between forehand hitting velocity ($T = 6.0$; $Z = 0.365$; $p = 0.855$; $r = 0.15$; small ES) and backhand hitting velocity ($T = 16.0$; $Z = 1.153$; $p = 0.313$; $r = 0.47$; medium ES). When examining internal training load, no statistically significant difference was detectable between the two game strategy conditions for the RPE variable ($T = 1.5$; $Z = 1.633$; $p = 0.102$; $r = 0.67$; large ES).

4.2. Comparative analysis of offensive and defensive baseline playing styles, and a comparison of match winners and losers

4.2.1. *Playing styles*

Examining the number of strokes per rally, 0–4 stroke rallies occurred with the highest frequency (67.84 ± 5.73 %), followed by 5–8 stroke rallies (22.83 ± 6.08 %), and finally 9+ stroke rallies (8.63 ± 4.49 %). Individual rallies lasted an average of 7.15 ± 1.04 seconds, with average rest periods of 23.84 ± 2.15 seconds, resulting in an effective playing time of 20.61 ± 3.23 % during the simulated matches. Regarding running activities, offensive baseline players performed statistically significantly more high-intensity (-2 m/s^2) decelerations ($U = 268$; $Z = -2.435$; $p = 0.015$; $r = 0.35$; medium ES) and "other" stroke loads ($U = 158$; $Z = -2.628$; $p = 0.009$; $r = 0.38$; medium ES) with a medium effect size than their defensive counterparts. No significant differences were found between the matches of the two styles for other high-intensity micro-movement parameters, such as the occurrence of high-intensity (2 m/s^2) accelerations ($U = 268$; $Z = -0.322$; $p = 0.747$; $r = 0.05$; very small ES) and high-intensity (2 m/s^2) changes of direction ($U = 263$; $Z = -0.426$; $p = 0.670$; $r = 0.06$; very small ES). Furthermore, no statistically significant difference was observed between the two styles in tennis-specific movement-based PlayerLoad™ ($U = 254$; $Z = -0.624$; $p = 0.533$; $r = 0.09$; very small ES) as measured by the IMU sensor. The variables constituting this PlayerLoad™ parameter—namely low-intensity load ($U = 266$; $Z = -0.366$; $p = 0.714$; $r = 0.05$; very small ES), alert load ($U = 201$; $Z = -1.731$; $p = 0.084$; $r = 0.25$; small ES), dynamic load ($U = 266$; $Z = -0.364$; $p = 0.716$; $r = 0.09$; very small ES), and running load ($U = 247$; $Z = -0.770$; $p = 0.442$; $r = 0.11$; small ES)—similarly showed no significant differences between offensive and defensive styles. In a similar vein, no significant difference was found between the two conditions regarding stroke-based PlayerLoad™ ($U = 252$; $Z = -0.665$; $p = 0.506$; $r = 0.10$; small ES). No differences were observed in the indicators comprising this PlayerLoad™ variable, including forehand stroke load ($U = 219$; $Z = -1.354$; $p = 0.176$; $r = 0.20$; small ES), backhand stroke load ($U = 221$; $Z = -1.300$; $p = 0.194$; $r = 0.19$; small ES), and serve load ($U = 194$; $Z = -1.862$; $p = 0.063$; $r = 0.27$; small ES). Last but not least, there was no significant deviation in the sum of the grouped movement-based and stroke-based PlayerLoad™ variables, representing total tennis load ($U = 280$; $Z = -0.083$; $p = 0.934$; $r = 0.01$; very small ES). Regarding internal training load, no statistically significant difference was detectable in the

RPE parameter between tennis players employing offensive and defensive styles ($U = 277$; $Z = -0.137$; $p = 0.891$; $r = 0.02$; very small ES).

4.2.2. Match outcomes

Regarding match outcomes, among the running activities, a statistically significant difference with a medium effect size was observed only in the running load variable ($T = 29.0$; $Z = -2.471$; $p = 0.013$; $r = 0.50$; medium ES), in favor of match winners. For IMA-based high-intensity micro-movements, no significant differences were found between winners and losers in the number of high-intensity (2 m/s^2) accelerations ($T = 85.5$; $Z = -1.597$; $p = 0.110$; $r = 0.33$; medium ES), high-intensity (-2 m/s^2) decelerations ($T = 76.0$; $Z = -1.084$; $p = 0.278$; $r = 0.22$; small ES), or high-intensity (2 m/s^2) changes of direction ($T = 130.0$; $Z = -0.243$; $p = 0.808$; $r = 0.05$; very small ES). Similarly to the comparison of playing styles, no statistically significant difference was observed in match outcomes for tennis-specific movement-based PlayerLoad™ values ($T = 110.5$; $Z = -0.174$; $p = 0.862$; $r = 0.04$; very small ES). Furthermore, no significant differences were found in the parameters constituting this PlayerLoad™ metric, including low-intensity load ($T = 124.5$; $Z = -0.411$; $p = 0.681$; $r = 0.08$; very small ES), alert load ($T = 101.5$; $Z = -1.112$; $p = 0.266$; $r = 0.23$; small ES), or dynamic load ($T = 135.5$; $Z = -0.076$; $p = 0.939$; $r = 0.02$; very small ES). Consistent with the movement-based results, the aggregated stroke-based PlayerLoad™ ($T = 135.5$; $Z = -0.076$; $p = 0.939$; $r = 0.02$; very small ES) did not yield significant deviations between the two contexts. There were also no significant differences in its components, such as forehand stroke load ($T = 106.5$; $Z = -0.650$; $p = 0.516$; $r = 0.13$; small ES), backhand stroke load ($T = 137.0$; $Z = -0.030$; $p = 0.976$; $r = 0.00$; very small ES), serve load ($T = 135.0$; $Z = -0.091$; $p = 0.927$; $r = 0.02$; very small ES), or other stroke load ($T = 71.0$; $Z = -1.274$; $p = 0.203$; $r = 0.26$; small ES). Finally, for the parameter summarizing all the above—total tennis-specific load ($T = 126.0$; $Z = -0.365$; $p = 0.715$; $r = 0.07$; very small ES)—no significant difference was established between match winners and losers. In contrast to the aforementioned results, a statistically significant difference with a large effect size was observed in internal training load for the RPE parameter between winning and losing matches ($T = 3.5$; $Z = -3.815$; $p = 0.000$; $r = 0.79$; large ES), in favor of the losing match conditions.

5. CONCLUSIONS

The results of the first study of my doctoral research highlighted that for elite youth male tennis players, strategic conditions—specifically offensive and defensive game situations—fundamentally define the athletes' physical and technical profiles. It can be concluded that changes in strategic principles elicit different workload responses, which must be accounted for in training, as integrated monitoring reveals that tactical principles create distinct loading patterns (Tóth et al., 2025b). The results confirmed that when applying a defensive strategy, players achieved significantly higher PlayerLoad™ values, indicating an increase in cumulative neuromuscular load measured across three planes of motion (Cormack et al., 2013). This supports coaching experience suggesting that the primary goal of a defensive strategy is to force opponent errors while adhering to the principles of safety and persistence (Halmos, 1983), which inevitably involves more running and increased demand on three-dimensional acceleration capabilities (Pozsonyi and Schandl, 2019). In this context, players primarily occupy the rear, defensive court zone (Tiley, 2002) and spend more time in neutral or defensive phases of play (ITF, 1991). **Consequently, our first hypothesis (H_{1/1}), positing that the defensive condition results in higher PlayerLoad™ values and more accelerations across all three planes, is considered proven.**

A deeper analysis of running activities revealed that the number of low-intensity (< 2.5 m/s²) changes of direction to the right also increased significantly in defensive situations. This can be explained by the preference for the forehand in modern tennis during long rallies, which requires specific footwork and changes of direction. In contrast, during the offensive strategy, although the number of high-intensity changes of direction to the left showed a large effect size—indicating aggressive positioning inside the court (ITF, 1991)—the total workload remained lower. This is clearly attributable to higher work-to-rest ratios and less effective playing time (Hoppe et al., 2019, 2020). **Thus, our second hypothesis (H_{1/2}), which predicted more changes of direction in all directions and intensity zones during the defensive phase, was only partially supported.**

The examination of technical parameters confirmed that tactical constraints first impact shot execution, followed by locomotor and then internal load responses (Martínez-Gallego et al., 2013; Murphy et al., 2016). The significantly higher spin rates measured in defensive situations on both forehand and backhand sides serve the purpose of pushing the opponent back with deeper, safer shots, gaining time for the player to recover their own positioning (Crespo and Reid, 2009). Interestingly, no significant difference was found in average hitting velocity

between strategies, contradicting some previous research conducted on non-elite or female samples (Hoppe et al., 2019, 2020). This suggests that at this level, male players attempt to maintain high velocity even in the defensive phase, and strategic differences manifest primarily in ball arc and spin. **The third hypothesis (H_{1/3}), stating that spin is higher in defensive situations while hitting velocity does not change significantly, is considered proven.**

Finally, regarding internal training load, RPE values (ranging from 5.3 to 6.7) corresponded to match values described in international literature (Gomes et al., 2011). Although players reported higher subjective fatigue during defensive play, statistical analysis showed no significant difference, aligning with the findings of Hoppe et al. (2020). It appears that the magnitude of perceived exertion (Borg, 1970) at this level and duration does not sharply diverge based on strategic goals, even if the defensive style requires higher effective playing time and more micro-movements (Bernardi et al., 1998). **Consequently, the fourth hypothesis (H_{1/4}), assuming significantly higher internal load for the defensive strategy, must be rejected.** Overall, the study proved that for elite male tennis players, strategy shifts primarily impact technical spin metrics and the volume of accelerations across three planes of motion (PlayerLoad™).

In the second phase of my research, the focus shifted from "closed" strategic conditions to match situations dominated by individual playing styles under "open" conditions. In this context, the goal was to identify mechanical and subjective load differences between offensive and defensive baseline styles, as well as match outcomes (winner vs. loser). Analysis of activity profiles established an average rally duration of 7.15 ± 1.04 seconds (Kovacs, 2007) and an effective playing time of 20.61 ± 3.23 %, confirming that actual work time in tennis constitutes only a fraction of total match time (Bergeron et al., 1991; König et al., 2001). Notably, 0–4 stroke rallies made up 67.84 ± 5.73 % of matches, highlighting the decisive role of the first shots (serve and return) and the subsequent first touch (Fitzpatrick et al., 2021). For elite juniors, serve velocity correlates closely with the explosiveness of the upper body and limbs (Dobos and Tóth, 2021), where motor control of the wrist flexors (MVC and RFD) becomes critical as the final link in the kinetic chain at the point of impact (Elliott, 2003; Dobos et al., 2024). Targeted development of these motor skills, particularly through plyometric methods, is essential for fostering a modern, aggressive playing style (Colomar et al., 2022).

Data from the comparison of playing styles contradicted several traditional coaching beliefs. We found that offensive baseline players produced significantly more high-intensity (-2.5 m/s^2) decelerations (HiD) and other stroke loads (OSL) than their defensive counterparts. This is explained by offensive players more frequently dominating from the mid-court and

seeking to finish points at the net. These tactical solutions require intense accelerations followed by sudden decelerations in the sagittal plane for precise shot execution. Developing deceleration capacity—built on dynamic balance, eccentric, and reactive strength (Young and Farrow, 2006)—is therefore crucial for offensive players regarding injury prevention and hitting point stability (Kovacs et al., 2008). Conversely, for defensive players aiming to extend rallies from the back zone, strength endurance and the use of topspin shots are primary priorities (Sandford et al., 2019; Tóth et al., 2025a). **In light of these results, the first hypothesis regarding playing styles ($H_{2/1}$) had to be rejected, as certain mechanical load indicators were higher in offensive players. The second hypothesis ($H_{2/2}$) was also rejected, as no significant style-dependent difference was found in RPE values, likely due to the constant alternation of match phases (offensive, defensive, neutral).**

Analysis of match outcomes revealed that winners achieved significantly higher running load (RL) values, correlating with more linear, aggressive court positioning and frequent net approaches. Although 70% of tennis movements are lateral (Weber et al., 2007), efficiency in the early 0–10 meter acceleration phase (linear sprint) is also decisive for success, particularly through the horizontal force production of the hip extensors (Jiménez-Reyes and Morin, 2022). Interestingly, no difference was found in the number of high-intensity micro-movements (acceleration, deceleration, change of direction) based on outcome, confirming that success is based not just on the quantity of movement but on technical-tactical precision and adaptation to context (Reid et al., 2007; Tóth et al., 2021a). Research suggests that running performance is often a "by-product" of tactics rather than a standalone success indicator (Oliva-Lozano et al., 2023). **Accordingly, the third hypothesis ($H_{2/3}$), predicting higher external load for losers, was rejected.**

Finally, the investigation of internal load (RPE) showed that losers reported significantly higher subjective fatigue with a large effect size. Since the volume of physical work (PlayerLoad™) did not justify this difference, we conclude that the psychological burden of defeat—frustration, cognitive anxiety, and the associated rise in cortisol—is the underlying cause (Fernandez-Fernandez et al., 2015; Harris et al., 2021). This result is practically important because it highlights that for elite juniors, RPE is a reflection not only of mechanical work but also of mental state and emotional match outcome (Ding et al., 2024). **The fourth hypothesis ($H_{2/4}$) is therefore considered proven.** Overall, the study confirmed that success in modern youth tennis is based on the integration of technical-tactical efficiency, specific mechanical capabilities (e.g., deceleration), and psychological control.

Based on the research results, it can be concluded that while there are no sharp, all-encompassing differences in external training load between playing styles, modern tennis requires flexible variation of different game phases. Practical advice applies primarily to the elite, homogeneous youth age group, where encouraging a more offensive playing style is a key to success. The development of players' physical capabilities must always be planned considering the chosen playing style. For players employing a defensive strategy, developing both aerobic and anaerobic-lactic capacity is critical due to longer rallies and increased acceleration demands across three axes. In contrast, for offensive players, short explosive movements and high-intensity decelerations (HiD) dominate, making anaerobic-alactic capabilities and eccentric strength more prominent. This style-specific conditional development is primarily recommended during specific phases of the preparatory period, while a more holistic approach focusing on individual weaknesses is advised during the competitive season. For female players—due to generally longer rallies—even greater emphasis must be placed on anaerobic-lactic endurance.

For efficient development of energy systems, differentiated grouping of athletes based on the Speed Reserve Ratio (SRR) is recommended. This metric, the ratio of maximal sprint speed (MSS) to maximal aerobic speed (MAS), helps determine whether a player needs endurance-based or sprint-based high-intensity interval training (HIIT) (Sandford et al., 2019; Hattler et al., 2022). In practice, the SRR for defensive baseline players typically remains below 1.66, while for offensive players, it falls between 1.66 and 1.77, and for serve-and-volley specialists, it may exceed 1.89 (Parkes et al., 2022). Knowing these values allows coaches to calibrate on-court endurance work with pinpoint accuracy.

A major methodological takeaway is that coaches and sports scientists must place much greater emphasis on monitoring technical-tactical indicators related to shots and mechanical load, in addition to running performance—which is now a baseline requirement but not the sole deciding factor. Integrated management of parameters like tennis-specific PlayerLoad™, HiD, and RPE can significantly mitigate overtraining and injury risk. The Acute:Chronic Workload Ratio (ACWR) model (Gabbett, 2016) provides an excellent framework for this, comparing the last week of training to the average of the previous month. Maintaining the "sweet spot" in tennis (a ratio between 0.8 and 1.3) minimizes the risk of soft tissue injuries (Blanch and Gabbett, 2016).

Technological advancement opens new horizons: as of July 2024, the ATP Tour and Challenger events have officially approved the use of EPTS systems, including Catapult microensors (ATP, 2024). This allows professionals to design training sessions using real

workload profiles from official matches. Incorporating stroke count and PlayerLoad™ into the ACWR model not only aids in injury prevention but also enables the quantitative preparation of players for the actual physical demands of matches. In the future, tactical video analysis and match statistics must be managed integratively with workload data, as physical performance is always defined by the given tactical context. The domestic adaptation of these objective measurement protocols is crucial for maintaining and developing the international competitiveness of elite Hungarian youth tennis.

6. List of own publications

Publications related to the dissertation

Tóth, P. J., Dobos, K., Győri, T., Horváth, D., Sáfár, S. (2021) Korosztályos teniszesezők irányváltoztatással való futásgyorsaságának és az ehhez kapcsolódó fizikai képességeknék a fejlesztése pliometrikus edzésmodszerral. Magyar Sporttudományi Szemle, 22(4 (92)), 51–58.

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Publications unrelated to the dissertation

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Havanecz, K., **Tóth, P. J.**, Kopper, B., Bartha, C., Sáfár, S., Fridvalszki, M., Géczi, G. (2025) Relationship between GPS-derived variables and subjective questionnaires among elite youth soccer players. *Sports*, 13(8), 24.