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RETROSPECTIVE STUDY OF THE WORKLOAD OF A FEMALE TENNIS PLAYER OVER TWO SEASONS - SINGLE CASE STUDY

RETROSPEKTIVNA ŠTUDIJA OBREMENITVE TENIŠKE IGRALKE V DVEH SEZONAH - ŠTUDIJA PRIMERA

ABSTRACT

In recent years, the use of advanced wearable technologies in tennis has improved the ability to monitor workload and performance indicators. Using the device Armbeep Tennis, attached to the wrist of an entry level female tennis player, we recorded 97% of the tennis training and all official matches over two annual competitive seasons. The aim of the study was to determine the variation of different workload indicators during the preparation and competition phases in one annual season and to compare the workload indicators between the two seasons. We found no significant differences in the results of the training, tournament, and performance indicators between the two seasons. Our tennis player trained more on average in the second year (Y1 = 90.9 min, Y2 = 97.5 min) and the percentage of active time was also higher (Y1 = 30.6%, Y2 = 32.4%). A higher number of shots per week (Y1 = 3109.1, Y2 = 2869.4) was observed in the first year, while the number of shots per hour was higher in the second year (Y1 =420.6, Y2 = 430.1). The pace of the rally was higher in the first year (Y1 = 24.6, Y2 = 23.4). The differences between the other workload indicators were not significant in the two years. This single case study provides good insight into the overall progression of training and competition over two annual seasons and can serve as a basis for determining workload indicators for novice tennis players or those just embarking on this path.

Keywords: wearable sensor, professional tournaments, periodisation, practice, match load.

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IZVLEČEK

V zadnjih letih napredna tehnološka oprema omogoča spremljanje obremenitve in uspešnost igranja v tenisu. Z uporabo Armbeep Tennis naprave, ki je bila pripeta na igralno roko teniške igralke smo spremljali 97 % vseh njenih treningov in uradnih teniških tekem v dveh teniških sezonah. Cilj raziskave je bilo ugotoviti razlike v obremenitvi v trenažnem in tekmovalnem obdobju ter primerjati obremenitev v prvi in drugi teniški sezoni. Analiza ni pokazala značilnih razlik obremenitev na treningih, tekmah in teniških kazalcihv dveh teniških sezonah. Teniška igralka je trenirala časovno več v drugem letu (Y1 = 90.9 min, Y2 = 97.5 min), prav tako je bil odstotek aktivnega igranja v drugem letu višji (Y1 = 30.6%, Y2 = 32.4%). Večje število udarcev na teden je bilo ugotovljeno v prvem letu (Y1 = 3109.1, Y2 = 2869.4), medtem ko je bilo število udarcev na uro višje v drugem letu (Y1 =420.6, Y2 = 430.1). Tempo udarcev v izmenjavi je bil višji v prvem letu (Y1 = 24.6, Y2 = 23.4). Ostali indikatorji obremenitve se niso značilno različni. Študija primera ponuja vpogled v splošno raven obremenitve na treningih in tekmovanjih v dveh zaporednih teniških sezonah. Podatki lahko služijo kot izhodišče za določanje obremenitve v tenisu za teniške igralke, ki vstopajo na profesionalno teniško pot.

Ključne besede: prenosne naprave, profesionalna tekmovanja, načrtovanje, trening, obremenitev med tekmo

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INTRODUCTION

Workload in sport can influence performance and injury risk in individual athletes (Colby et al., 2014). Workload is defined as the ratio between an athlete's short-term training load and the mean of their long-term training load (Blanch & Gabbett, 2016). The workload ratio has been previously quantified using various internal and external workload variables (Hulin et al., 2016).

Physical exertion in tennis involves high-intensity full-body work, including short-distance sprints (Fernandez-Fernandez et al., 2009). Most matches consist of work and rest periods of 5 to 10 s and 10 to 20 s, respectively, interspersed with longer (90 s) rest periods between changeover breaks (Ferrauti et al., 2003). During each point, players hit the ball an average of 2 to 3 times and make four changes of direction per rally (Deutsch et al., 1988). Currently, the best means of understanding the external loads that produce these responses are noted descriptions of hitting and movement loads during match play (Johnson & McHugh, 2006; O'Donoghue & Ingram, 2001) and practice (Murphy et al., 2014).

Match activity in women's tennis differs in certain characteristics and indicators from the play of men. O'Donoghue and Ingram (2001) have reported that analyses of rallies in Grand Slam women's singles matches were significantly longer (7.1 s/rally) than in men's singles matches (5.2 s/rally), along with a greater proportion of baseline rallies in women's singles. In addition, women played significantly fewer shots per second, hit fewer aces, won fewer service games, and made more double faults. In other studies, the average number of shots in women's matches was from 2.5 to 4.7 per rally (Fernandez-Fernandez et al., 2008; Hornery et al., 2007; Mendez-Villanueva et al., 2007). Match characteristics and indicators in tennis matches are influenced by the player's and opponent's age, playing style and level, playing surface, ball type, gender, and tactical strategy (Cooke & Davey, 2007; Smekal et al., 2001; Stare et al., 2015).

Little has been reported on the physiological responses, workload, hitting power, and hitting characteristics during on-court training exercises (Fernandez-Fernandez et al., 2005). As recently shown by Reid et al. (2008), the on-court drills performed by players were consistent with the average and maximum physiological demands of the tennis match. Reilly et al. (2009), among others, state that an appropriate level of physiological load can be associated with tennis-specific activities.

Modern measuring devices for trade are also making their way into tennis. Measuring devices can be attached to the racket or the body, or they can monitor the movement of the player and

the ball. Wearable sensors attached to the racket (Babolat Play, Zepp Tennis, Sony Tennis Sensor, Head) and to an athlete's body (Babolat Pop, Artengo, Kitris, Armbeep) typically measure various characteristics of shots production such as the number, type, and speed of shots played (Whiteside et al., 2017). If we assume that the sensors have reasonable reliability, they are a very useful tool for quantifying the workload of tennis players. At the same time, the use of measurable and objective data in monitoring and planning tennis practice can have a significant impact on optimizing workload. In this regard, Keaney and Reid (2018) found that racquet sensors (Babolat, Zepp) can be useful for coaches in monitoring training volume, number of shots and possible correlations with performance or injury risk.

While previous studies have provided valuable insight into the match movement and hitting workloads of tennis players, the next step is to also collect data for practice. The objectives of the study, conducted using modern mobile Armbeep Tennis technology, were to find out: 1) the changes in various load indicators during the preparation and competition periods in one annual season and 2) to compare the values of workload indicators between the two seasons.

METHODS

Study protocol

We have tracked female tennis player in practice and in official tournaments. In two competitive seasons, an estimated 97% of all practice sessions and all official singles matches were recorded. During tennis sessions, the athlete wore a IMU device - Armbeep Tennis Wrist Monitoring Device (Armbeep; version 1.0, Biometrika, Maribor, Slovenia). The Armbeep device was approved by International Tennis Federation. Hadžić et al. (2021) conducted an analysis of the validity and reliability of quantifying hitting load in tennis and concluded that the Armbeep device appears to be a suitable tool for monitoring hitting load during tennis practices and official matches. The sensor was placed laterally on the ventral surface of the forearm of the hitting arm, and data were collected throughout the duration of the practice session. The sensor collects accelerometer and gyroscope data for each shot (Kos & Kramberger, 2017). We used the wearable sensor to collect workload indicators for practice sessions and matches (Table 2). Daily data from the sensor were transferred to the personal dashboard. All sessions were exported in CSV format and prepared for further data analysis.

Participant

An entry professional female tennis player was included in the study (age: 20 years; height: 167 cm; weight: 65.5 kg; tennis years: 15; WTA ranking position at the beginning of the study: 1208). She had no recent history of muscle, joint, or bone injury (24 months). The study was conducted in accordance with the Helsinki Declaration, and all procedures were approved by the Faculty Ethics Committee.

Statistical analysis

Descriptive statistics (mean, standard deviation, range) were calculated for all workload indicators. Statistical analysis was performed using the SPSS version 26.0 software package (SPSS Inc., Chicago, IL, USA). Graphical representations were created using the program Datawrapper (Datawrapper GmbH, Berlin, Germany).

RESULTS

Data of annual practises, tournaments and performance characteristics are presented. In the first year, the player completed 161 practice sessions in 26 training weeks. On average, she completed 6.2 practice sessions per week, for a total of 17 hours per week. She participated in 21 tournaments (ITF W15 and ITF W25) and played 58 matches, which equals 2.8 matches per week. In the first year she had 5 weeks off with no tennis activities. She won 36 singles matches and lost 19. At the end of the year she was ranked 663 in the WTA rankings.

In the second year, she trained for 22 weeks and completed 153 tennis practice sessions during that time. She completed 7 practice sessions per week, for a total of 19.1 hours per week. She competed in 23 competitions and played 57 official singles matches, averaging 2.5 matches per week. She had 7 transition weeks during the annual season. In singles, she won 34 matches and lost 23. At the end of the second year, she was ranked 536th in the WTA rankings. The player did most of her tennis practices indoors or on outdoor clay courts. Most of the matches (80%) were played on clay courts.

Table 1. Data on completed practice and match sessions, tournaments and the performance indicators of a female tennis player in two annual seasons.

	Year 1	Year 2
Practice weeks (no.)	26	22
Practice sessions (no.)	161	153
Practice sessions per week (no.)	6.2	7
Practice hours per week (no.)	17	19.1
Tournament weeks (no.)	21	23
Matches (no.)	58	57
Matches per week (no.)	2.8	2.5
Rest weeks (no.)	5	7
Win:lose ratio	36:19	34:23
End year ranking (WTA)	663	536

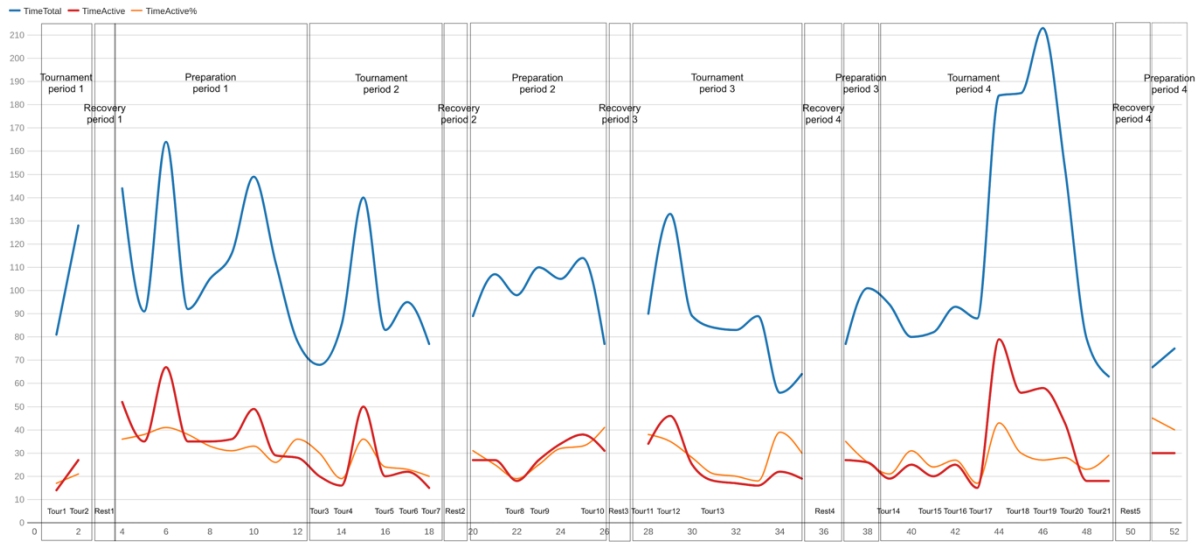
*Table 1 presents the results of the descriptive statistics on the workload indicators for each year separately.

Descriptive statistics on workload indicators in two seasons

Table 1 presents the results of the descriptive statistics on the workload indicators for each year separately. In the second year, the total time of practice sessions and matches was higher on average (Y1 = 90.9, Y2 = 97.5). This was also true for active time (Y1 = 26.8, Y2 = 27.5) and percentage of active time (Y1 = 30.6, Y2 = 32.4) to total session time. In the first year, the player performed more shots per week on average (Y1 = 3198, Y2 = 2869). The average number of shots in a single session did not differ significantly between the two seasons (Y1 = 634, Y2 = 630.1). The average number of shots per hour, which could be a suitable standardized measure of specific tennis workload, also did not differ between the two years (Y1 = 420.6, Y2 = 430.1). There were also no differences in the number of shots per rally between the two years (Y1 = 4.7, Y2 = 4.5). The number of shots per minute is also referred to as tempo or rally pace by tennis coaches. It is the actual or expected number of shots a player makes if the rally lasts or would last 1 minute. Shots per minute is an indicator of workload, the value of which is influenced by the technical skill of the player and opponent, the game situation (serving, receiving, baseline play, net play), and ultimately the surface. The values of shots per minute were slightly lower in the second year (Y1 = 24.6, Y2 = 23.4). There were no differences in the number of rallies in each practice or match play session (Y1 = 159.4, Y2 = 156.1). The length

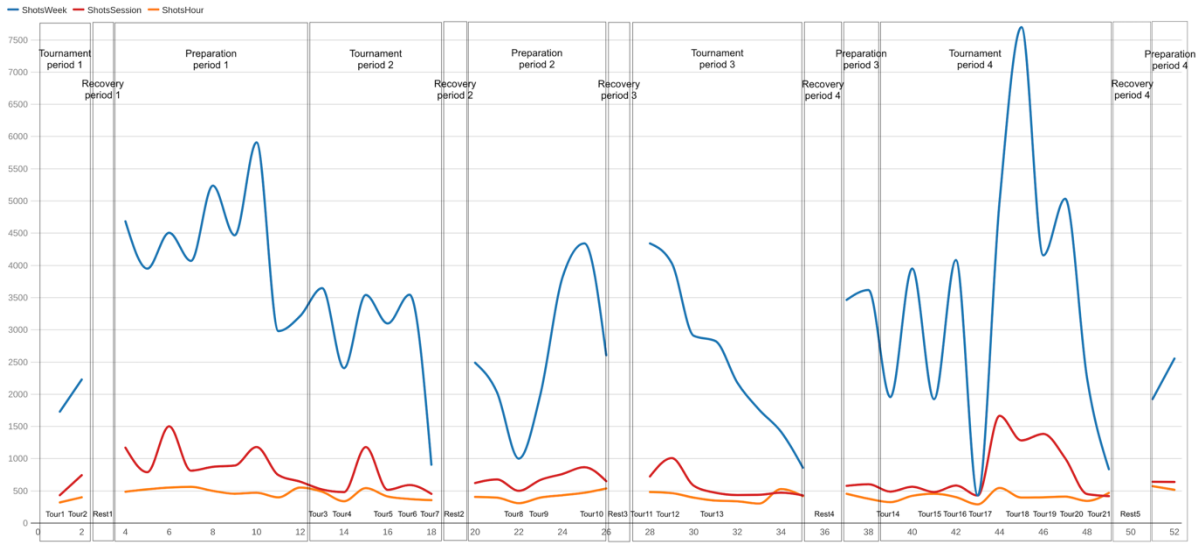
of rallies is divided into 5 groups according to the number of shots in a rally, and the values are given as a percentage. As expected, the highest percentage for rallies was up to 2 shots (Y1 = 56.9, Y2 = 54.7), followed by rallies with up to 4 shots (Y1 = 18.3, Y2 = 18.6), and then rallies with 9 or more shots (Y1 = 11.3, Y2 = 13.2). The values did not differ between the two years.

Figure 1. Total time, active sessions, and percentage of active time in the first year.



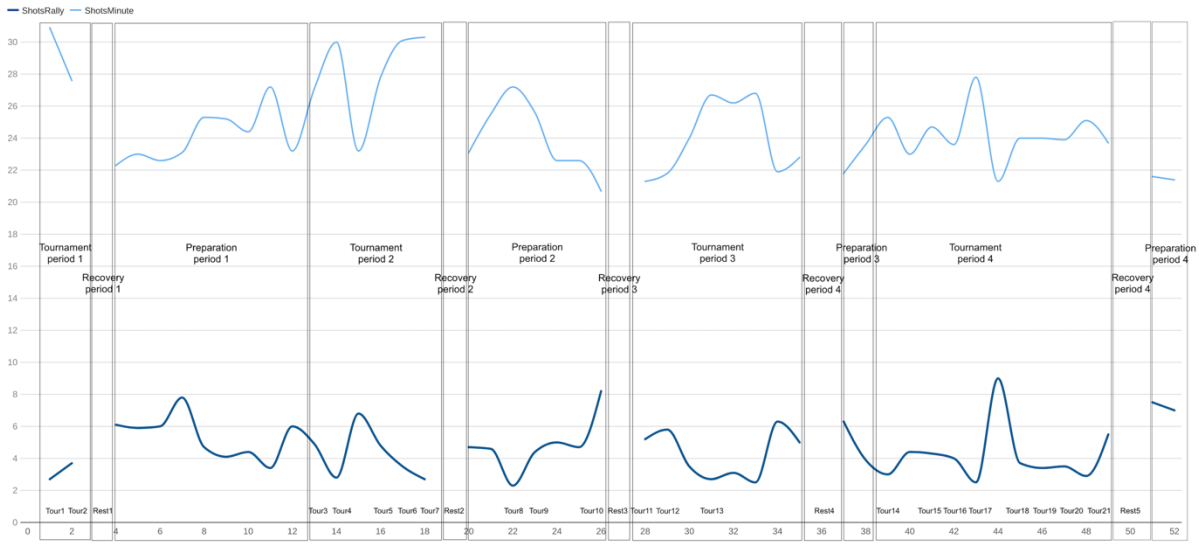
Legend: Tour 1-Tour 21 (tournament 1-tournament 21); Rest 1-Rest 5 (rest period).

Figure 2. Shots per week, session, and hour in the first year.



Legend: Tour 1-Tour 21 (tournament 1-tournament 21); Rest 1-Rest 5 (rest period).

Figure 3. Shots per rally and minute in the first year.



Legend: Tour 1-Tour 21 (tournament 1-tournament 21); Rest 1-Rest 5 (rest period).

With the graphical representations, we wanted to show clearly the change in each workload indicator separately for both seasons. The annual season is divided into three types of periods: Preparation, Tournament (competition), and Recovery (transition). In the lower part of the plot, the competitions are marked in individual weeks. The box shows the tournaments in which the player has reached the semi-finals or finals.

Figures 1, 2 and 3 show the distribution of individual periods and competitions in the first year, while Figures 3, 4 and 5 show the values for the second year. Figure 1 shows that more practice sessions and active sessions were held overall during preparation period 1 and weeks 15 and 44, which were designated for practice. The percentage of active time varied between 20% and 40% of total practice sessions or match time, regardless of the time period. In Figure 2, a significant increase in shots per week can be seen in Preparation Phase 1.

Figure 4. Total active session time and percentage of active time in second year.

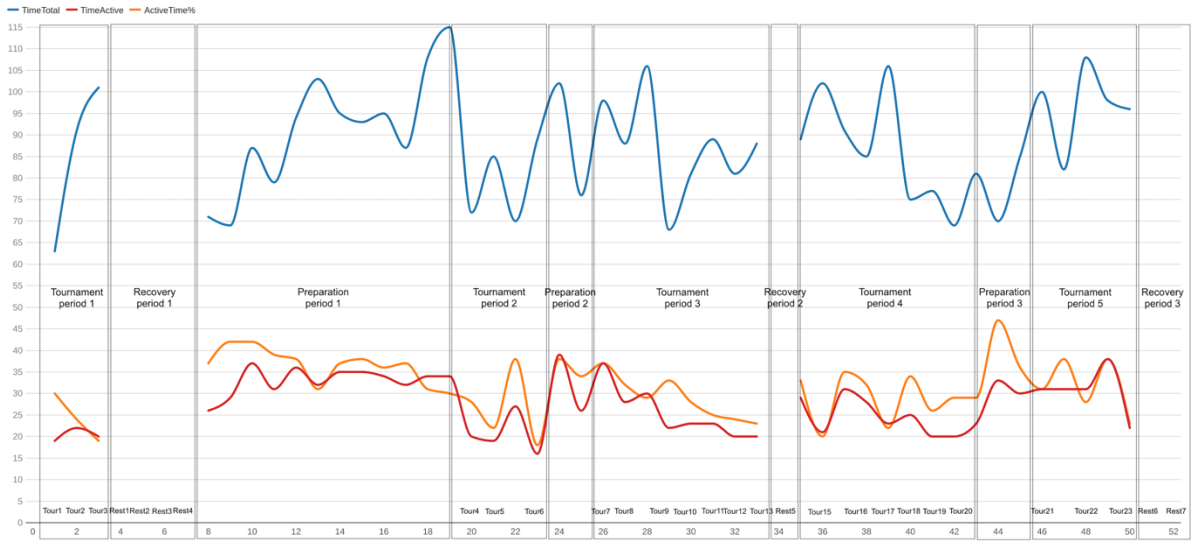
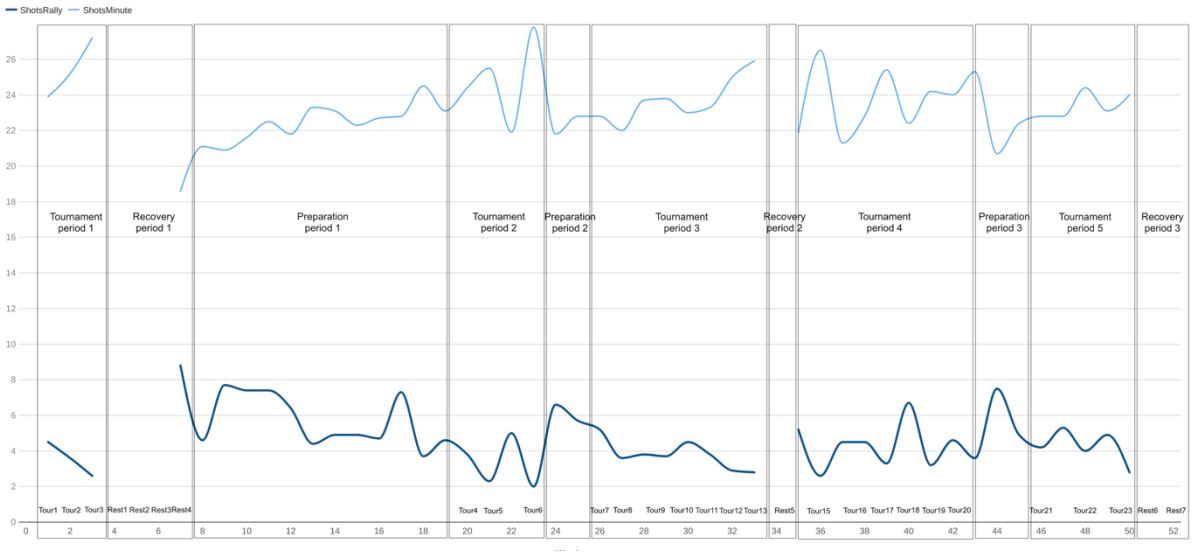


Figure 5. Shots per week, session, and hour in second year.

Figure 6. Shots per rally and minute in second year.



Higher values in shots per week are recorded at the end of preparation period 2 and in the 45th week of tournament period 4. The number of shots per session does not change depending on the type of period or the type of week (practice or match). The values range from 500 to 1500 shots per session. The same is true for the values of shots per hour, which average 420 and range from 290 to 530 shots. Figure 3 shows the values of shots per rally, which are higher in practice weeks (e.g. 7, 12, 15, 34, 35, 44, 51, 52) and range between 6 and 10 shots per rally. Higher values for shots per minute (tempo) are recorded in tournament weeks (e.g., 14, 18, 31, 32, 33, 43) and range from 26 to 30 shots per minute.

In Figure 4, it can be seen that the total time spent in practice sessions in preparation period 1 gradually increases towards the end of the period. The values for active time and percentage of active time are higher in the practice weeks. The number of shots per week (Figure 5) changes in both the preparation and tournament periods, showing no relationship with week or type of period. Throughout the annual season, the values for shots per session (average 630.1) and shots per hour (average 430.1) change accordingly. In Figure 6, the values for shots per rally are higher than 6 in weeks (e.g., 9, 10, 11, 12, 17, 24, 44), while in tournament weeks the values for shots per minute are higher than 24 (e.g., 1, 2, 23,25, 32, 33, 36, 40, 48).

DISCUSSION

Tennis is one of the sports that requires a high total training volume due to its complexity, the ratio between total and active training time and various game situations. Elite tennis players spend a lot of time improving their tennis skills through technical and tactical training. The International Tennis Federation recommends 15-20 hours of technical training per week to achieve a high level of competition (Crespo & Miley, 2002). In our study, the female tennis players trained in accordance with the recommendations in both years. In the second year, they slightly reduced the total number of training sessions, but increased the average number of training sessions per week and the weekly training volume.

In terms of workload indicators related to practice sessions, it is also important to highlight the way in which practice is conducted. As Ferrauti et al. (2001) has noted, the number of players on the court, the organization of the practice, and the different hitting power, running pressure, or running volume have a significant impact on the workload and indirectly on the active time and the percentage of active time. The observed player spent most of the morning practice sessions on the court with another player or coach. She completed a maximum of three afternoon practice sessions in teams with 2 other players on the court.

There are numerous differences between the two years in the observed workload indicators. The total time of sessions increased in the second year, mainly due to the longer matches in the tournament weeks, which also lasted 2 hours or more. While a coach and a player can plan the workload in training (volume and intensity), this is impossible in matches. Match duration is influenced by the opponent's style of play, tactical plan, surface, and game formats (Kovalchik & Ingram, 2018). In terms of total match time, players were most successful when the matches lasted between 60 and 90 minutes. The percentage of time spent in active practice sessions was higher in the second year, reaching 30 to 35% of the total time. According to numerous studies (Fernandez-Fernandez et al., 2008; Murias et al., 2007), this is certainly the golden standard, especially when it comes to practice sessions. For tournament weeks, the range of percentage of active time was lower, often less than 20% of total time (Whiteside & Reid, 2011). As Fernandez-Fernandez et al. (2008) noted, active playing time is higher in women's singles than in men's singles.

Studies that have examined the number of shots over a period of time have mostly been on matches. We did not find data on the number of shots per week in these studies. In our study, the player performed 4000 to 6000 shots in the preparation phases, while the number of shots

in tournaments was 1000 to 4000 per week. In each year, the number of shots per week exceeded the values of the training practice weeks' values in exactly one particular competition week. It can be concluded that the number of shots in tournament weeks is influenced by the number and duration of matches.

Manual notation (Gescheit et al., 2015) found that players take approximately 700 shots per match. Whiteside and Reid (2011) used Hawk Eye technology at the Australian Open and came up with 1400 shots per female matches. Reid and Schneiker (2007) found that tennis players average 1000 shots per game. In our case, the player performed 630 shots in a practice session or match. The values were higher in practice weeks. Since the number of shots per game depends on the duration of the match, sets, games and rallies, it is advisable to use the relative value, i.e. the number of shots per hour. In our study, the values ranged from 420 to 430 shots per hour, and there was a trend that our tennis player made more shots per hour during the practice weeks. A comparison of the number of shots performed showed no differences between the two years. The values found in our study for shots per rally are consistent with the studies (Carboch et al., 2018; Hornery et al., 2007; Mendez-Villanueva et al., 2007).

It is also important to highlight an indicator of workload that determines the number of shots per minute, namely the pace or speed of the rally. In our case, the pace slowed down despite our tennis player's rise in the rankings. This can also be attributed to stronger opponents who tend to dictate the game and play faster than the observed player. On the other hand, we found a difference in a higher tempo when rallies started with serve or return. The tempo values in our study are lower than those of Smekal et al. (2001), who measured male tennis players and conducted the study on hard courts.

The distribution of rallies by number of shots did not change between the two seasons. As expected, most rallies (more than 50%) contained up to 2 shots, and about 18% of rallies ended after 4 completed shots. A number of researchers have found a similar distribution of the frequency of rallies as a function of the number of shots (Fernandez-Fernandez et al., 2007). The number of rallies with 9 or more shots is similar in both years. Given the usual structure of tennis practice, longer rallies are associated with the introductory part of the practice, where the player performs tennis drills for warm-up, concentration, focus, and shot control. Such training sessions, even if shorter (up to 30 minutes), were often also conducted during the competition phases as part of match preparation.

The limitations of the study lie primarily in linking workload data and performance success in female tennis players, which would provide even more insight into how the values of the observed indicators and outcomes change during competition. In addition, comparison of specific workload values (number of shots per week, hour, and minute) was difficult due to the lack of comparable data in other studies or because they were collected on other groups of players (juniors, male tennis players). Therefore, a large amount of data on the workload of female tennis players over a two-year period does not allow generalization and transfer of conclusions to other age and quality groups of female tennis players. It is also not possible to transfer conclusions to male tennis players.

The single case study gives a good insight into the whole training and competition process in a 2-year seasons. Tennis certainly requires the introduction of data analysis and metrics into the process of planning, training and monitoring impact. Objectification of load in individual training periods, such as mesocycles and microcycles, is necessary. In the future, it will also be necessary to determine the optimal loads for individual qualities and age groups of tennis players. This is especially true for younger and developing players, for whom the workload increases from year to year and from period to period. Finally, thresholds need to be found for individual workload indicators that may increase the risk of injury. The study provides a good insight into the workload of an entry professional female tennis player and is useful for planning the training of players at a similar level as well as players who want to reach this level.

CONCLUSION

This study provides a comprehensive overview of the workload of professional tennis player. In a two-year study, we found many differences between workload indicators during two annual training seasons. Based on these results, we can propose some workload values for workload during training and tournament periods for entry-level professional tennis players. Furthermore, the use of different training routines combining different volumes and intensities allows for functional overload, athletic progression, and minimization of injury risk. These results suggest the need to monitor workload indicators and adapt them to gender, age, playing style and level of play. This means that the analysis and planning of the long-term development of players must be based on data and not on the intuition of the coach.

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Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

REFERENCES

Blanch, P., & Gabbett, T. J. (2016). Has the athlete trained enough to return to play safely? The acute:chronic workload ratio permits clinicians to quantify a player's risk of subsequent injury. *British Journal of Sports Medicine*, *50*(8), 471–475. https://doi.org/10.1136/bjsports-2015-095445

Carboch, J., Placha, K., & Sklenarik, M. (2018). Rally pace and match characteristics of male and female tennis matches at the Australian Open 2017. *Journal of Human Sport and Exercise*, *13*(4), 743–751. https://doi.org/10.14198/jhse.2018.134.03

Colby, M. J., Dawson, B., Heasman, J., Rogalski, B., & Gabbett, T. J. (2014). Accelerometer and GPS-derived running loads and injury risk in elite Australian footballers. *Journal of Strength and Conditioning Research*, *28*(8), 2244–2252.

Cooke, K., & Davey, P. R. (2007). The physiological cost of velocity coupling during tennis groundstrokes. *Journal of Sports Sciences*, *25*(7), 815–821. https://doi.org/10.1080/02640410600875184

Crespo, M., & Miley, D. (2002). *Advanced coaches manual* (M. Crespo & D. Miley (eds.)). International Tennis Federation.

Deutsch, E., Deutsch, S. L., & Douglas, P. S. (1988). Exercise training for competitive tennis. *Clinics in Sports Medicine*, *7*(2), 417—427. http://europepmc.org/abstract/MED/3292069

Fernandez-Fernandez, J., Fernandez-Garcia, B., Mendez-Villanueva, A., & Terrados, N. (2005). Exercise intensity in tennis: Simulated match play versus training drills. *Medicine and Science in Tennis*, *10*, 6–7.

Fernandez-Fernandez, J., Mendez-Villanueva, A., Fernandez-Garcia, B., & Terrados, N. (2007). Match activity and physiological responses during a junior female singles tennis tournament. *British Journal of Sports Medicine*, *41*(11), 711–716. https://doi.org/10.1136/bjsm.2007.036210

Fernandez-Fernandez, J., Sanz-Rivas, D., Fernandez-Garcia, B., & Mendez-Villanueva, A. (2008). Match activity and physiological load during a clay-court tennis tournament in elite female players. *Journal of Sports Sciences*, *26*(14), 1589–1595. https://doi.org/10.1080/02640410802287089

Fernandez-Fernandez, J., Sanz-Rivas, D., & Mendez-Villanueva, A. (2009). A review of the activity profile and physiological demands of tennis match play. *Strength and Conditioning Journal*, *31*(4), 15–26. https://doi.org/10.1519/SSC.0b013e3181ada1cb

Ferrauti, A., Bergeron, M. F., Pluim, B. M., & Weber, K. (2001). Physiological responses in tennis and running with similar oxygen uptake. *European Journal of Applied Physiology*, *85*(1–2), 27–33. https://doi.org/10.1007/s004210100425

Ferrauti, A., Weber, K., & Wright, P. R. (2003). Endurance: Basic, semi-specific and specific. In M. Reid, A. Quinn, & M. Crespo (Eds.), *Strength and Conditioning for Tennis* (pp. 93–111). International Tennis Federation.

Gescheit, D. T., Cormack, S. J., Reid, M., & Duffield, R. (2015). Consecutive days of prolonged tennis match play: Performance, physical, and perceptual responses in trained players. *International Journal of Sports Physiology and Performance*, *10*(7), 913–920. https://doi.org/10.1123/ijspp.2014-0329

Hadžić, V., Germič, A., & Filipčič, A. (2021). Validity and reliability of a novel monitoring sensor for the quantification of the hitting load in tennis. *PLOS ONE*, *16*(7), e0255339. https://doi.org/10.1371/journal.pone.0255339

Hornery, D. J., Farrow, D., Mujika, I., & Young, W. (2007). An integrated physiological and performance profile of professional tennis. *British Journal of Sports Medicine*, *41*(8), 531–536. https://doi.org/10.1136/bjsm.2006.031351

Hulin, B. T., Gabbett, T. J., Caputi, P., Lawson, D. W., & Sampson, J. A. (2016). Low chronic workload and the acute:Chronic workload ratio are more predictive of injury than between-match recovery time: A two-season prospective cohort study in elite rugby league players. *British Journal of Sports Medicine*, *50*(16), 1008–1012. https://doi.org/10.1136/bjsports-2015-095364

Johnson, C. D., & McHugh, M. P. (2006). Performance demands of professional male tennis players. *British Journal of Sports Medicine*, *40*(8), 696–699. https://doi.org/10.1136/bjsm.2005.021253

Keaney, E. M., & Reid, M. (2018). Quantifying Hitting Activity in Tennis with Racket Sensors : New Dawn or False Dawn? *Sports Biomechanics*, *December*(12), 1–9. https://doi.org/10.1080/14763141.2018.1535619

Kos, M., & Kramberger, I. (2017). A wearable device and system for movement and biometric data acquisition for sports applications. *IEEE Access*, *5*(c), 6411–6420. https://doi.org/10.1109/ACCESS.2017.2675538

Kovalchik, S. A., & Ingram, M. (2018). Estimating the duration of professional tennis matches for varying formats. *Journal of Quantitative Analysis in Sports*, *14*(1), 13–23. https://doi.org/10.1515/jqas-2017-0077

Mendez-Villanueva, A., Fernandez-Fernandez, J., & Bishop, D. (2007). Exercise-induced homeostatic perturbations provoked by single tennis match play with reference to development of fatigue. *British Journal of Sports Medicine*, *41*(11), 717–722. https://doi.org/10.1136/bjsm.2007.037259

Murias, J. M., Lanatta, D., Arcuri, C. R., & Fernando A Laino. (2007). Metabolic and functional responses playing tennis on different surfaces. *Journal of Strength and Conditioning Research*, *21*(1), 112–117.

Murphy, A., Duffield, R., Kellett, A., & Reid, M. (2014). Comparison of athlete-coach perceptions of internal and external load markers for elite junior tennis training. *International Journal of Sports Physiology and Performance*, *9*(5), 751–756. https://doi.org/10.1123/IJSPP.2013-0364

O'Donoghue, P. G., & Ingram, B. (2001). A notational analysis of elite tennis strategy. *Journal of Sports Sciences*, *19*(2), 107–115. https://doi.org/10.1080/026404101300036299

Reid, M., Duffield, R., Dawson, B., Baker, J. D., & Crespo, M. (2008). Quantification of the physiological and performance characteristics of on-court tennis drills. *British Journal of Sports Medicine*, *42*(2), 146–151. https://doi.org/10.1136/bjsm.2007.041624

Reid, M., & Schneiker, K. (2007). Strength and conditioning in tennis: Current research and practice. *Journal of Science and Medicine in Sport*, *11*, 248–256. https://doi.org/10.1016/j.jsams.2007.05.002

Reilly, T., Morris, T., & Whyte, G. (2009). The specificity of training prescription and physiological assessment: A review. *Journal of Sports Sciences*, *27*(6), 575–589. https://doi.org/10.1080/02640410902729741

Smekal, G., von Duvillard, S. P., Rihacek, C., Pokan, R., Hofmann, P., Baron, R., Tschan, H., & Bachl, N. (2001). A physiological profile of tennis match play. *Medicine and Science in Sports and Exercise*, *33*(6), 999–1005. https://doi.org/10.1097/00005768-200106000-00020

Stare, M., Zibrat, U., & Filipcic, A. (2015). Stroke effectivness in professional and junior tennis. *Kinesiologia Slovenica*, *21*(2), 39–50.

Whiteside, D., Cant, O., Connolly, M., & Reid, M. (2017). Monitoring hitting load in tennis using inertial sensors and machine learning. *International Journal of Sports Physiology and Performance*, *12*(9), 1212–1217. https://doi.org/10.1123/ijspp.2016-0683

Whiteside, D., & Reid, M. (2011). External match workloads during the first week of Australian Open tennis competition. *International Journal of Sport Nutrition and Exercise Metabolism*, *32*, 1–44. https://doi.org/10.1123/ijspp.2015-0012