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Performance Analysis in Table Tennis

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I Summary

Sports performance is a complex construct of various components. In addition to the athletes' technical and tactical skills, medical, physiotherapeutic and sports psychological care, active regeneration, nutrition and performance analysis (PA) play an increasingly important role.
Due to the integration of new innovative technologies and methods, an enormous development in the field of PA can be observed in table tennis in recent years.
Starting from this, the dissertation first presents the status quo of scientific PA in table tennis (1). This is followed by a proposal for a sports specific observational system with a positive cost/benefit calculation (2) and a new analysis approach (3) to improve support for coaches and athletes and to improve the knowledge about PA and the popularity and acceptance of PA in the table tennis community.

The published review article gives an overview about existing popular methods in performance/match analysis in table tennis such as performance indices or simulative approaches for theoretical PA approaches and additionally introduces two best practice examples (Japan and China) for practical PA approaches. Additionally, research topics and areas that need more investigation and necessary developments are identified. The article serves as a reference work and a starting point for scientists who are interested in the field of PA in table tennis.

The second article is a pioneer study on game characteristics in elite para table tennis and gives a first insight in the basic game characteristics rally length and impact of serve in elite para table tennis (class 1-10). The influence of sex, standing or sitting position of the player and the severity of the impairment on these variables are investigated. A shorter rally length in standing para table tennis compare to Olympic table tennis or the remarkably shorter rally length in class 6 compared to other standing classes are examples for results which provide para table tennis specific or even class specific information which could be used for practical implications for training and education. Overall, the study serves as a starting point for future studies on para table tennis with more in-depth analysis, especially in the technical/tactical area.

The third study introduces a new structural model for a table tennis rally including the "first offensive shot" (FOS) as the central point of a rally. Consequently, a corresponding observational system was also developed for this. Besides the various gained information about the FOS behaviour of men and women of different level categories itself (e.g. techniques used for FOSs, shot number of the FOSs, winning probability for the FOS player), an important innovation of this study is also the shot-number-independent approach of the technical/tactical analysis of the FOS coming with the introduced model and the used observational system.

Many different aspects and areas of PA in table tennis are covered by this dissertation. Regarding the methodology, known approaches are applied to new samples, but also new approaches are developed and introduced. Paralympic table tennis is covered with a fundamental study and Olympic table tennis, for which fundamental studies are already available, is covered with an in-depth study on a very important and yet unresearched characteristic of the sport. This dissertation and the studies it contains are an initiative to increase knowledge about PA in table tennis and to advance this field, yet there is still much room for further development:

Current methods of PA in table tennis can be further developed or adapted to the current state of the art in the sport and current technology. In addition, there are possibilities to apply methods from other sports to table tennis.

There is also great potential in the technological area: technologies that are already part of everyday life in other sports (such as automated placement or stroke detection or artificial intelligence for analysing data) must find their way into table tennis in order to better utilise and increase the great potential of performance and match analysis.

Last but not least, the understanding and acceptance of scientific PA needs to develop further among players, coaches and officials in table tennis. PA must continue to gain importance among these stakeholders in order to make an even greater contribution to the individuals, but also to the sport itself and its representation in the future.

II Zusammenfassung

Sportliche Leistung ist ein komplexes Konstrukt aus verschiedenen Komponenten. Neben den technischen und taktischen Fähigkeiten der Athleten spielen die medizinische, physiotherapeutische und sportpsychologische Betreuung, die aktive Regeneration, die Ernährung und die Wettkampfdiagnostik (PA, aus dem Englischen für „performance analysis") eine immer wichtigere Rolle.
Durch die Integration neuer innovativer Technologien und Methoden ist im Tischtennis in den letzten Jahren eine enorme Entwicklung im Bereich der PA zu beobachten.
Davon ausgehend stellt die Dissertation zunächst den Status quo der wissenschaftlichen PA im Tischtennis dar (1). Daran schließt sich ein Vorschlag für ein sportartspezifisches Beobachtungssystem mit einer positiven Kosten-Nutzen-Rechnung (2) und ein neuer Ansatz der Spielanalyse (3) an, um die Unterstützung für Trainer und Athleten zu verbessern und das Wissen über PA sowie die Popularität und Akzeptanz von PA in der Tischtennisgemeinde zu erhöhen.

Der veröffentlichte Review-Artikel gibt einen Überblick über bestehende populäre Methoden der Wettkampfdiagnostik/Spielanalyse im Tischtennis, wie z.B. Leistungsindizes oder simulative Ansätze als Ansätze der theoretischen PA und stellt zusätzlich zwei Best-Practice-Beispiele (Japan und China) für Ansätze aus der praktischen PA im Tischtennis vor. Darüber hinaus werden Forschungsthemen und -bereiche identifiziert, die weitere Untersuchungen und notwendige Entwicklungen erfordern. Der Artikel dient als Nachschlagewerk und Ausgangspunkt für Wissenschaftler, die sich für den Bereich der PA im Tischtennis interessieren.

Der zweite Artikel ist eine Pionierstudie über Spielcharakteristika im Weltklasse Para Tischtennis und gibt einen ersten Einblick in die grundlegenden Spielcharakteristika Ballwechsellänge und Einfluss des Aufschlags im Para Tischtennis (Klasse 1-10). Der Einfluss von Geschlecht, stehender oder sitzender Position der Spieler und der Schwere der Behinderung auf diese Variablen wird untersucht.
Eine kürzere Ballwechsellänge in den stehenden Klassen im Para Tischtennis im Vergleich zum olympischen Tischtennis oder die signifikant kürzere Ballwechsellänge in der Klasse 6 im Vergleich zu anderen stehenden Klassen sind Beispiele für

Ergebnisse, die Para Tischtennis spezifische oder sogar klassenspezifische Informationen liefern, die für praktische Implikationen für Training und Ausbildung genutzt werden können. Insgesamt dient diese Arbeit als Ausgangspunkt für künftige Studien zum Para Tischtennis mit detaillierteren Analysen, insbesondere im technisch-taktischen Bereich.

In der dritten Studie wird ein neues Strukturmodell für einen Tischtennis-Ballwechsel vorgestellt, das den "ersten Angriffsschlag" (FOS, aus dem Englischen für „first offensive shot") als zentralen Punkt eines Ballwechsels beinhaltet. Hierfür wurde auch ein entsprechendes Beobachtungssystem entwickelt. Neben den vielfältigen gewonnenen Informationen über das FOS-Verhalten von Männern und Frauen unterschiedlicher Leistungsklassen (z.B. verwendete Techniken für FOSs, Schlagnummer der FOSs, Gewinnwahrscheinlichkeit für den FOS-Spieler) ist eine wichtige Innovation dieser Studie auch der von der Schlagnummer unabhängige Ansatz der technisch-taktischen Analyse des FOS, der mit dem eingeführten Modell und dem verwendeten Beobachtungssystem einhergeht.

Viele verschiedene Aspekte und Bereiche der Wettkampfdiagnostik im Tischtennis werden durch diese Dissertation abgedeckt. Hinsichtlich der Methodik werden bekannte Ansätze auf neue Stichproben angewandt, aber auch neue Ansätze entwickelt und eingeführt. Paralympisches Tischtennis wird mit einer Grundlagenstudie und olympisches Tischtennis, für das bereits Studien vorliegen, wird mit einer vertiefenden Studie zu einem sehr wichtigen und noch unerforschten Merkmal der Sportart abgedeckt. Diese Dissertation und die darin enthaltenen Studien sind eine Initiative, um das Wissen über PA im Tischtennis zu erweitern und diesen Bereich voranzubringen. Dennoch gibt es noch viel Raum für weitere Entwicklungen: Aktuelle Methoden der PA im Tischtennis können weiterentwickelt oder an den aktuellen Stand der Sportart und der Technik angepasst werden. Darüber hinaus gibt es Möglichkeiten, Methoden aus anderen Sportarten auf Tischtennis zu übertragen.
Großes Potenzial besteht auch im technologischen Bereich: Technologien, die in anderen Sportarten bereits zum Alltag gehören (wie z.B. automatisierte Platzierungs- oder Schlagerkennung oder künstliche Intelligenz zur Datenanalyse), müssen im Tischtennis Einzug halten, um das große Potenzial der PA und der Spielanalyse besser nutzen und sogar steigern zu können.

Nicht zuletzt muss sich das Verständnis und die Akzeptanz für wissenschaftliche PA bei Spielern, Trainern und Funktionären im Tischtennis weiterentwickeln. PA muss bei diesen Stakeholdern weiter an Bedeutung gewinnen, um in Zukunft einen noch größeren Beitrag für den Einzelnen, aber auch für den Sport selbst und seine Repräsentation leisten zu können.

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V List of Abbreviations

AI : artificial intelligence 1, 2, 56

BISp : Federal Institute of Sport Science 22

FOS : first offensive shot .... passim

ITTF : International Table Tennis Federation 1, 3, 49

JCI : journal citation indicator 42, 44

JIF : journal impact factor 42, 44

PA : performance analysis .... passim

PRISMA : preferred reporting items for systematic reviews and meta-analyses 12, 14

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Fuchs, M., Liu, R., Malagoli Lanzoni, I., Munivrana, G., Straub, G., Tamaki, S., Yoshida, K., Zhang, H., & Lames, M. (2018). Table tennis match analysis: a review. Journal of Sports Sciences, 36(23), 2653-2662. https://doi.org/10.1080/02640414.2018.1450073

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Fuchs, M., & Lames, M. (2021). First Offensive Shot in Elite Table Tennis. *International Journal of Racket Sports Science, 3*(1). https://doi.org/10.30827/Digibug.70278

1 Introduction

“Using big data and AI, we can precisely simulate and predict how the winning rate will change when players change certain tactics.” (Zheijang University, 2021)

This impressive statement by Prof. Yingcai Wu would probably be associated with one of the big and financially strong sports like American football, football or tennis, but in this particular case the quote refers to the sport of table tennis. Prof. Hui Zhang alongside Prof. Wu are the leading scientific researchers for the Chinese national table tennis team who developed – with a big team – an intelligent big data analysis platform to strongly support the national team in data analysis and tactical research. The amount of time, money and human resources that have been put into the development of this platform (which has already processed and stored the data of more than 8000 matches) is a good indicator of the development that is currently taking place in table tennis.

1.1 Professionalisation in table tennis – scientific support

A progressive professionalisation can be observed in table tennis. On the one hand, the governing body, the International Table Tennis Federation (ITTF), is trying to improve on a commercial and economic level with their commercial brand “World Table Tennis” (WTT) (International Table Tennis Federation, 2019). On the other hand, developments on a sporting level can be observed. Players and federations are professionalising their structures and placing an increasing emphasis on scientific support to optimise their performance in various areas. Scientists and experts in the areas of nutrition (Kimura & Adachi, 2014), sports psychology (Probst, 2018; Przybyl, 2022) and strength and conditioning (ASV Grünwettersbach, 2017; Hinz, 2019) are often already the norm, but recently also performance/match analysts are being increasingly engaged with by players and associations also and are slowly becoming a part of the “team behind the team” (Table Tennis Australia, 2021).

In particular the host of the recent Olympic and Paralympic Games, Japan, has put a lot of effort and has invested a lot in the area of scientific support in recent years (probably also due to the funds available due to the Tokyo 2020 Olympics/Paralympics) and, in addition to increasing and improving its “internal” scientific support system, has even invited international experts from different fields to an annual meeting from 2014 - 2019 where scientific findings were exchanged (International Table Tennis Federation, 2020). This investment in the scientific support system (as part of the overall structure) seems to have paid off for Japan, as with a total of four medals at the Tokyo 2021 Olympics, including a gold medal for the first time (Mima Ito and Jun Mizutani in the newly introduced Mixed Doubles), Japan was second behind China in the medal rankings. It was the first time since 2004 that not all gold medals went to China (International Olympic Committee, 2022).

But also China, the country that has dominated table tennis in the last two to three decades, where the sport of table tennis in general has a very high status (Zhang & Zhou, 2019) and the national team seems to have a comprehensive scientific support system already (Zhang & Hu, 2010; Zhang et al., 2010; Zhang et al., 2008), is always trying to develop its scientific support, for example by hiring even foreign experts as strength and conditioning coaches for the top players of the Chinese national team (Bozic, 2019; Wojczynski, 2018).

In addition to the players and associations who recognise the increasing importance of scientific support all over the world, technological developments could also contribute to the professionalisation of table tennis. Technological tools such as match analysis software, video-based tracking technologies and artificial intelligence (AI) are already used in other more popular and financially stronger sports like football, tennis, baseball and basketball (Akenhead & Nassis, 2016; Lopez, 2013; Owens et al., 2003; Sony., 2020; Woodie, 2020) and would also have great potential in table tennis – especially in PA – but are not yet or hardly used in table tennis.
However, their introduction or implementation in table tennis depends on a number of complex factors. Some technologies still have to be improved, adapted or empirically validated for use in table tennis, which would be the task of scientists. In addition, financial hurdles and (sport) political obstacles often have to be overcome (in most parts of the table tennis world).

In China, these hurdles hardly seem to be a problem due to the importance of table tennis, the structural conditions and the prevailing state support (the development of the intelligent big data analysis platform mentioned at the beginning might be a good indicator of that). These general structural advantages probably also lead to the fact that China has been the benchmark in the sport for over 25 years. China has collected 27 of 29 gold medals at Olympic Games since 1996 and is also very strong, if not the strongest, in the field of table tennis science. This is evident from the fact that there are table tennis study programmes in universities all over the country and China has even a specialised table tennis university, the China Table Tennis College in Shanghai. The large number of articles related to table tennis in the China National Knowledge Infrastructure (CNKI) (Zhang et al., 2018) and the amount of contributions by Chinese speaking authors at the ITTF Sports Science Congress (Kondric et al., 2017; Kondric & Paar, 2019; Kondric et al., 2015) which is held every two years, are a good indication of the importance of research in table tennis in China.

In order to prevent this sporting and scientific gap between China and the rest of the world from widening, the above-mentioned professionalisation in the other countries in all areas including the scientific support, is urgently needed.

1.2 Performance analysis – status quo in table tennis

As explained in the previous paragraph, in the course of professionalisation in table tennis, scientific support is becoming more and more important.

One area, however, that is too often not yet covered professionally, especially in the non-Asian region, is performance and match analysis. For para table tennis, this is not only the case for the non-Asian region, but worldwide, as the human and financial resources are often even lower than in able-bodied table tennis.

While coaches and players are becoming more aware of the benefits that performance/match analysis can bring (more general knowledge of the sport, revealing strengths and weaknesses of players/opponents, creating match plans, etc.), the methods for scientifically sound and data-based match analysis are unfortunately too often not known or not used.

Instead, the common PA practice often consists of unsystematically watching (not analysing) video by players or coaches. In many cases PA relies very much on the subjective opinions and experiences of individual coaches, but is not based on scientifically sound data like it is in popular and financially strong sports like baseball, football and tennis. However, in order to optimise future performance, a scientifically based PA with valid and reliable feedback is necessary (Hughes et al., 2019). That was the starting point of this dissertation.

1.3 Line of thought of the dissertation

According to Paré et al. (2015), “the accumulation of knowledge is an essential condition for a field to “be scientific” and to develop”. It is further stated that “conducting effective literature reviews is essential to advance the knowledge and understand the breadth of the research on a topic of interest, synthesize the empirical evidence, develop theories or provide a conceptual background for subsequent research, and identify the topics or research domains that require more investigation”.

This was the initial motivation for a review article – to give an overview about the existing popular methods in performance/match analysis in table tennis, to identify research topics that need more investigation and to explore gaps in that field which are not yet investigated at all. The review article should serve as a starting point for me, but also for other scientists who are interested in this field and who can use the article as a foundation or source of reference for their own research.

Due to the high inclusiveness of the sport, certain research is beneficial for para as well as able-bodied table tennis. Nevertheless, there are also specific differences between para and able-bodied table tennis and due to the different states of research, it is of interest to bring approaches from able-bodied to para table tennis. Along the same lines, further insights in able-bodied table tennis have the potential to be applied later in para table tennis as well which was the reason to carry out studies in para as well as able-bodied table tennis.

Furthermore, the motivation of this thesis was to create more general knowledge and a better understanding of table tennis/para table tennis and of PA in table tennis (i) by using established approaches of PA in (para) table tennis on unresearched samples/variables and (ii) by transferring concepts of PA from other sports to (para) table tennis.

Through this knowledge, the scientific use of performance and match analysis in (para) table tennis should be improved in countries which already included it in their scientific support system on the one hand and on the other hand also promoted in countries where scientific PA is not yet part of everyday practice.

In the specific case of the author's association, the introduction or improvement of scientifically based match analysis should also serve to keep top level table tennis at the international level competitive or even to gain a competitive advantage over other countries.

2 Paralympic Table Tennis

Besides the Olympic sports, also Paralympic sports have gained more attention during the last couple of years in many countries (Blauwet & Willick, 2012). It appears that the medal race, typically seen in regular sports (De Bosscher et al., 2009), also started in para sports. Since Paralympic athletes with different degrees of impairments generally compete in different classes, there are many medals at stake in para sports. It also seems for that reason that national sport associations are investing more in para sports (International Paralympic Committee, 2017; Sportscotland, 2014). This has led to more awareness, attention and financial support and thereby to an ever increasing professionalisation in Paralympic elite sport in recent years (Bundon, 2021) including the awareness of a comprehensive scientific support system (Eskau, 2016).

Regarding the table tennis sport, the idea of the game in Paralympic table tennis does not differ from the Olympic table tennis. The sport is even that inclusive that a Paralympian (in a wheelchair) and Olympian table tennis players could practice together (Lang, 2021) and Paralympic athletes may even be capable of qualifying for the Olympic games (European Table Tennis Union, 2016; Faulkner & International Paralympic Committee, 2021).

The decisive difference, however, is in the capabilities of the athletes due to their respective impairments. These differences serve as the foundation for the current classification system, in which players are assigned to different competition classes according to their capabilities. The system is divided into classes 1 to 5, in which wheelchair athletes are classified, and classes 6 to 10, in which standing athletes are classified. The less impaired a player is, the higher the classification. Class 11 includes all players with intellectual impairments. Figure 1 shows an overview of the classification breakdown in para table tennis with a short description of each class.

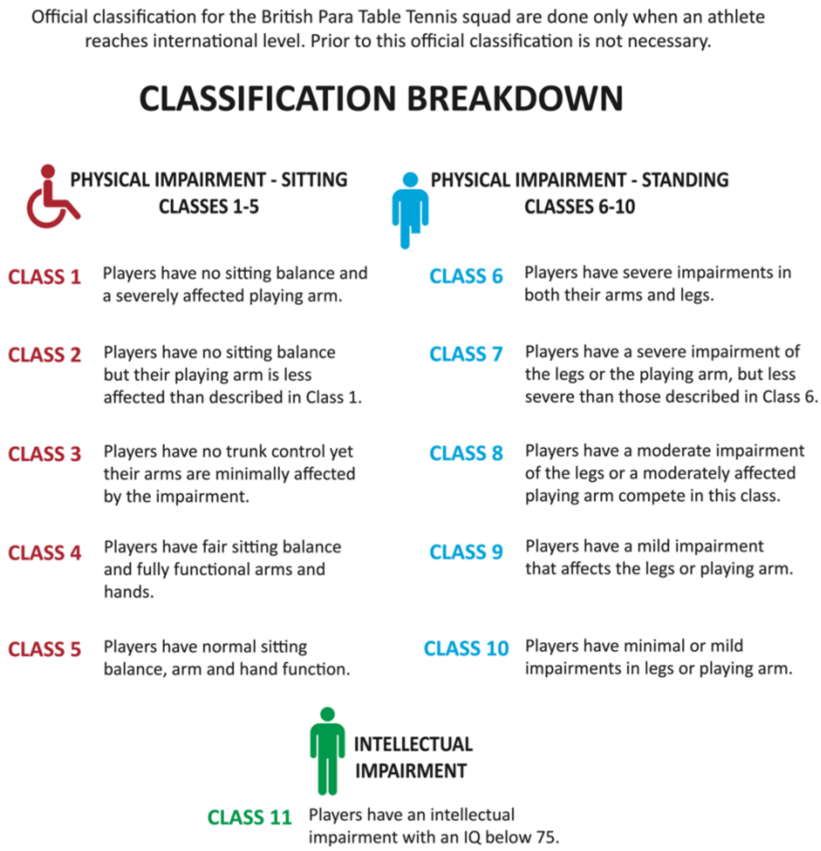

Figure 1: Overview of para table tennis classes (Table Tennis England, 2022)

Due to the fact that the physical abilities of players with disabilities are limited, the tactical aspects of the game come into focus even more than in able-bodied table tennis. Due to the different impairments (also within one competition class), it is important to avoid one's own physical weaknesses as much as possible and to exploit the opponent's weaknesses. In order to realise this in competition, detailed tactical preparation with valid and reliable information is required and could possibly gain even a bigger advantage than in Olympic table tennis.

For these reasons, performance/match analysis has great potential especially in Paralympic table tennis, which is why Paralympic table tennis should explicitly be part of the research within this thesis.

3 Integration Into the Context of Sports Science

“Training science is the sports science discipline that deals with the scientific foundation of training and competition in the application fields of sport from a holistic and applied perspective” (Hohmann et al., 2020) with its three subject areas: training, performance and competition.

Sports PA in general is concerned with the analysis of actual performance (O'Donoghue, 2014) in training or competition whereby the studies of this dissertation focuses especially on PA of competitions.

Following the previously mentioned subject areas of training science by Hohmann et al. (2020), the studies can be allocated to the areas “performance” and “competition”. Nevertheless, the third subject area “training” is still an important part of the big puzzle as “the most valuable results from a practical point of view and the most challenging from a scientific point of view are obtained by looking at the interaction between the individual areas” (Hohmann et al., 2020). The analysis of competition is leading to performance requirements which are the theoretical foundations for setting suitable training objectives. The training itself is not carried out for self-purpose but “always carried out with regard to the test situation of competition and in non-sporting fields of application always with regard to a lasting change in performance” (Hohmann et al., 2020). Thus, the success of training is measured in competition and performance is largely determining the success in competition.

Figure 2 shows the complete interaction between the subject areas of training science.

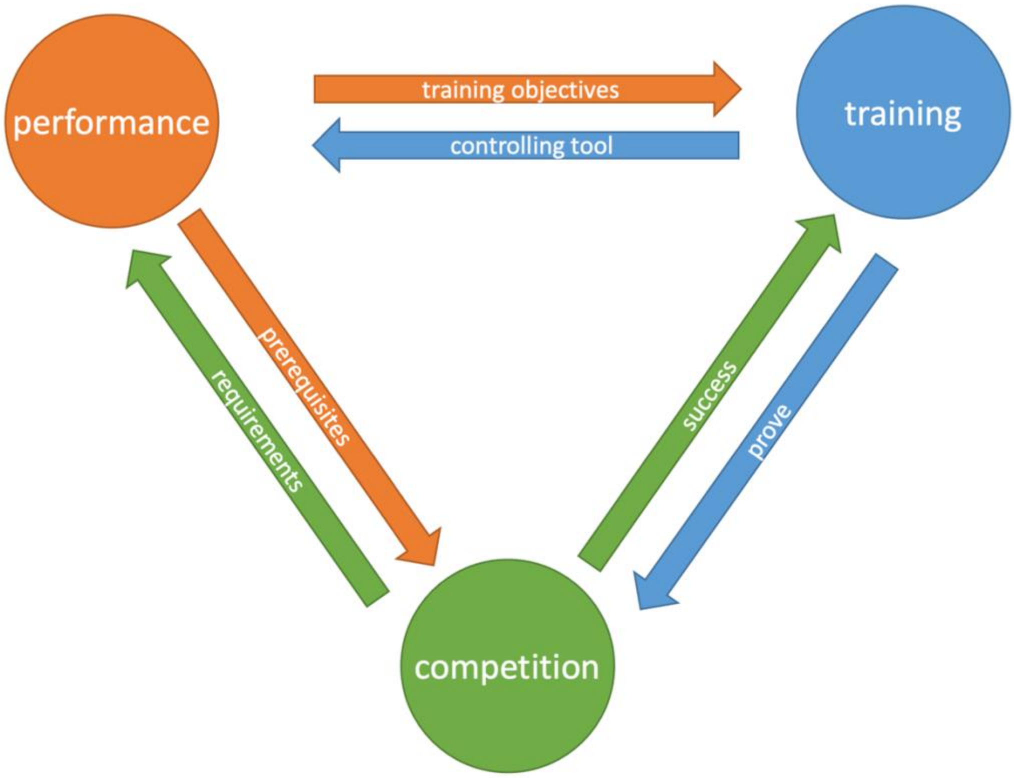

Figure 2: Interaction between subject areas of training science (according to Hohmann et al. (2020))

The particular importance of competition/match analysis (in table tennis) can be explained due to the special characteristics of the origination of performance in game sports in general (Pfeiffer & Hohmann, 2008). The actual performance is a result of the complex interaction of the two players in the match and not a direct representation of certain skills or abilities of the players (see Figure 3) which emphasizes the great importance of competition for our studies in the game sport table tennis (Lames, 1994).

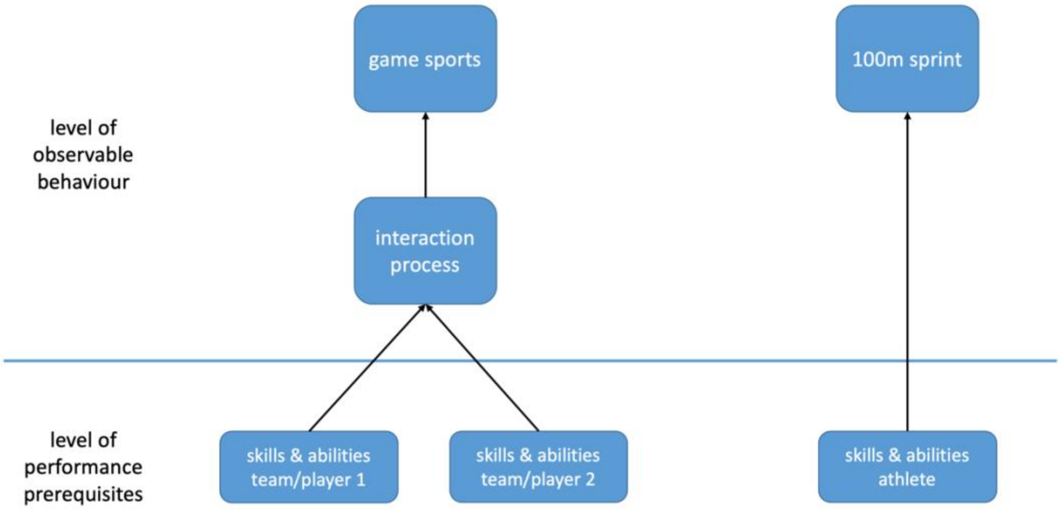

Figure 3: The differences between game sports and other sports as illustrated by the relation between observable behaviour and performance prerequisites (according to Lames and McGarry (2007))

Two basic aims of PA with respect to competition/matches can be distinguished – a theoretical aim and a practical aim (Letzelter & Letzelter, 1982). The aim of theoretical PA is to explain and understand the structure of the sport, involving for example the identification of performance variables or patterns of performances which are common and important for the sport. Theoretical PA seeks to explain sports behaviour using general models whose empirical foundations provide useful information for sports practice (Lames & McGarry, 2007). The aims of practical PA, on the other hand, are more connected to individual processes: analysing individual athletes and teams (including own players, but also opponents) and identifying their weaknesses or strengths. The objectives are to derive hints for training and to create an optimum match strategy for the upcoming competition (Hohmann et al., 2020; Lames & McGarry, 2007).

The aim of study one is to give a review on different approaches of match analysis in table tennis using the just described classification with examples both in theoretical and practical PA. Study two and study three are using approaches of theoretical PA – study two in para table tennis using statistical approaches and study three in (able-bodied) table tennis using a modelling approach.

Based on the above-mentioned theoretical background and the thematic content of the publications which include different areas and approaches of PA in the game sport table tennis, the thematical area of this dissertation is to be assigned to the field of training science.

4 Methods

4.1 Literature Review

New findings in a particular field can either build on prior existing work or are the first, fundamental findings in that field. In the latter case, however, it must be identified beforehand that there are certain gaps or no research yet in that area (Xiao & Watson, 2019).

In order to put future research in the field of PA in table tennis - as a very specialised and not widespread research area - on a good foundation, it was therefore necessary to identify methods/approaches that have been researched/used so far and thereby also indirectly show which areas/topics have not yet been investigated.

Therefore, study one – a literature review on the most commonly used match analysis methods in table tennis – was carried out.

The typology of literature reviews includes many different types of reviews (Paré et al., 2015): Narrative reviews, descriptive reviews, meta-analysis, qualitative/quantitative systematic reviews and umbrella reviews to name just a few possible examples.

Ferrari (2015) distinguishes more generally between two standard types: systematic and non-systematic/narrative reviews. Systematic reviews need to follow strict guidelines such as PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement (Moher et al., 2009; Page et al., 2021). The PRISMA 2009 item checklist for systematic reviews contains a total of 27 items, including items for each section of the article (title, abstract, introduction, methods, results, discussion and funding).

Table 1: Excerpt of the PRISMA 2009 item checklist (Moher et al., 2009) which were utilized as part of the narrative review

Section	Topic	Item #	Checklist item
Title			
	Title	1	Identify the report as a systematic review, meta-analysis, or both.
Abstract			
	Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions

			and implications of key findings; systematic review registration number.
Introduction			
	Rationale	3	Describe the rationale for the review in the context of what is already known.
	Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).
Methods			
	Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number.
	Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.
	Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.
	Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.
	Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).
Results			
	Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.
	Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.
Discussion			
	Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).

Conclusion	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.

As the main objective of systematic reviews is "to formulate a well-defined question and provide a quantitative and qualitative analyses of the relevant evidence, followed or not by a meta-analysis" (Ferrari, 2015) – although it has certain advantages especially in the methodological area – the (unsystematic) narrative review seemed to be the better choice for *study one* as it is a "comprehensive narrative syntheses of previously published information" (Green et al., 2006) on a certain subject or topic and summarizes and/or evaluates the content of each chosen study, show the current lack of knowledge and might give rationales for future research (Ferrari, 2015).
Although narrative reviews are not underlying any acknowledged guidelines like systematic reviews (Ferrari, 2015; Paré et al., 2015), the methodological items #6, #7 and #8 of the PRISMA checklist (see Table 1) were included in *study one* to minimise subjectivity in the selection process. It is precisely determined in which electronic databases or journals studies are searched and the selection criteria are specified. Additionally, the exact search strategy is explained. Based on the hits in the databases, basic methods of PA most common in table tennis are identified by the authors who are all experts in a certain area of the field of match analysis in table tennis. For each of those methods an exemplary study is selected which is then summarised and discussed in detail. Using expert opinion in the literature selection process is common practice for narrative reviews and can even reduce "the risk of suboptimal reporting" (Ferrari, 2015). The structure of *study one* has the standard IMRaD format (introduction, methods, results and discussion) in which the results section (main body) contains a historical outline of match analysis approaches in table tennis, followed by the narrative reviews of the approaches selected by the experts for detailed discussion which are sectioned in theoretical and practical PA approaches.

4.2 Notational Analysis

The major task of coaches is to enhance their athletes' performance by providing feedback about their performance. This information has to be accurate, precise and objective (Nevill et al., 2008; O'Donoghue, 2014). Different studies have shown that the memory and recall ability of humans is limited (Franks & Miller, 1986; Laird & Waters, 2008). Provided information just from the coaches' observations would not be accurate or objective enough for high-performance athletes (Hughes et al., 2019). Thus, suitable methods and objective tools are necessary to provide information at the required quality standard to enable a valuable feedback process. One method with a long tradition in many different sports (and even longer outside the sports field (Bartlett, 2001)) that can provide such quality of information is notational analysis (Hughes et al., 2019). Notational analysis has been defined as an “objective way of recording performance so that key elements of that performance can be quantified in a valid and consistent manner” (Hughes, 2005). In the beginning of sport-specific notational systems, the notation of the information was carried out by hand (Fullerton, 1912; Messersmith & Bucher, 1939). The first publication in the field of racket sports notation was published by Downey (1973) who developed a very detailed notational system for lawn tennis matches which has also served as a useful base for the development of systems for use in other racket sports (Hughes & Franks, 2004). With the rapid development of technology, computerised notation is state of the art nowadays as it brings many advantages – in data input as well as in data output/processing (Hughes & Franks, 2004; Hughes et al., 2019): Faster or even (semi-)automized data gathering, creation of large databases, coupling of data with video for better feedback, availability of computerised graphics and automatic statistics are only a few examples.

The application of notation/notational analysis have been defined as (Hughes, 1988, 1998; Hughes et al., 2019; O'Donoghue, 2009):

- tactical evaluation
- technical evaluation
- analysis of movement
- development of a database and modelling, and
- for educational use with both coaches and players

Most researches using notation will span more than one of these purposes. Tactical and technical evaluation as well as development of a database and modelling are the three application areas that have been featured in the publications for this dissertation (*study two* and *study three*).

4.3 Systematic Game Observation

The importance and reason of the notation of information and also the application fields of notational analysis in sports science have been described in the previous chapter. In addition to that, how to observe and then notate accordingly is equally important. This chapter explains the essential theoretical foundations of systematic game observation.

Literature in research methods describes different variants of observation, each of which is described by a dichotomy/continuum/spectrum (Greve & Wentura, 1997; Lames, 1994; Petermann & Rudinger, 2002):

Direct versus indirect

In contrast to direct observation of the match behaviour itself, indirect observation means that traces of behaviour are observed (e.g. imprint of a tennis ball on a sand court).

Mediated versus live

When behaviour is not assessed live but mediated, it is assessed via technical devices (video or sound recordings).

Active versus passive versus no participation

The observer can be involved in social interactions that produce the behaviour. Active participation means that the observer plays an active part of the action, e.g. as a coach. When the observer is present, but does not influence the interaction, it is classified as passive participation. No participation means that the observer is physically not present or invisible, thus, is not part of the interactions.

Knowing versus unknowing

The fact of being subject to observation is known or unknown to the observed subjects respectively. As sports events are (mostly) public events, it is the daily business for athletes to be observed. Thus, media and spectators should not create any reactivity (at least in top level sports).

Open versus standardized/systematic

This variable describes the degree of fixing observed variables in advance. If there is no fixing in advance, it is an open observation. At standardized/systematic observation, all variables of observation are fixed in advance. If there are fixed variables as well as open categories, it is called half-standardized observation.

Systematic game observation can be described as standardized observation of game behaviour (= direct), mostly from video recordings (= mediated) where the observer is not participating in the interactions and the athletes at very least know that they are observed.

Every systematic game observation is based on an observational system that emerges from thorough conceptual considerations. The construction of an observational system is to be understood as a modelling process, in which the original (sports game) is projected onto a representation of it (Lames, 1994). This representation consists of concrete data of the game. It needs to be mentioned that this data is limited to the perceivable surface of the behaviour as inner processes (e.g. motivation, mood, perception, decision making, etc.) are not directly subject to observation.

Types of observational systems

Three basic types of observational systems are distinguished in general behavioural observation: Sign systems, categorial systems and rating systems (Cranach & Frenz, 1969). Sign systems are recording “signs” which are precisely defined events (e.g. goal, fouls). Events can be assigned to one, several but also to no signs at all. In rating systems, the observer is rating a behaviour/event on a predefined scale (Seidel & Prenzel, 2010). The course of events is not directly and fully depicted. Actions/events are just represented by a rating which is not detailed enough to gain relevant information for coaches and players (e.g. the grading of a player after a match does not give differentiated information about his strengths and weaknesses). Thus, the only suitable type of observational system to be able to describe processes and interactions in a sports game without gaps and thus to represent a game completely, is the categorial system (Lames, 1994). This system records a match by a continuous sequence of events where at each point in time there is a category describing the actual state. The match may be reconstructed with the recorded data.

<u>Observational units, observational attributes and levels of attributes</u>

The choice of the unit to be observed is of central importance for the quality of an observational system. This observational unit is defined as the "smallest, not reducible event necessary for the analysis of the behaviour" (Cranach & Frenz, 1969). The choice of a fine-grained unit (e.g. ball contact, stroke) versus a coarse-grained unit (e.g. rally) determines the level and depth of the analysis. Following Lames (1991, 1994), the selection of the attributes to observe is depending on three criteria: Relevance for the purpose of observation, economy (cost-benefit-relation) and the observability. Possible types of observational attributes in game sports are general attributes (e.g. player, team, score), temporal attributes (e.g. playing time, start/end of observational unit), spatial attributes (e.g. hitting/landing spots of ball, position of players, trajectories of ball), technical attributes (e.g. type of technique from comprehensive systematic, laterality, speed, direction, spin) and tactical attributes (e.g. individual tactics, group tactics, team tactics). For a systematic game observation, the attributes to observe are fixed before the observation. After selecting the observational attributes, corresponding attribute levels must be specified to complete the observational system. The following criteria must be fulfilled with regard to the attributes and their respective attribute levels (Lames, 1994):

1. Uniqueness: one event may only meet the definition of one level
2. Completeness: All possible variants of events must be mapped onto an attribute level. For each observation unit, one attribute level must apply to the current behaviour.
3. Operational definition: unique recording prescription for each attribute level
4. Relevance in terms of content: levels should be derived from documented pre-assumptions, e.g. a sports specific, professional classification. Their number should represent an optimum between detail and complexity of the attribute.

The levels can be discrete or continuous. It may be necessary in certain scenarios in sports to introduce a "residual level" because not all behaviours can be mapped onto a definition of an existing attribute level.

4.4 A Table Tennis Observational System

According to Lames and Hansen (2001), any observational system can be considered as the result of a model building process. The authors stated that there isn't "the one" model for one sport, but for each different purpose there might be a specific model that fits best. Based on that, a table tennis-specific observational system which covers the needs for systematic game analysis in table tennis in terms of technical-tactical analysis was developed.

Two possible observation units "rally" and "stroke" were derived from the table tennis specific basic structure of a match. As both units are of great importance and interest for a comprehensive analysis, a particular structure was developed to be able to cover both units, collect data to each of them and model the relation between both units.

Table 2 shows all attributes of the respective unit with a short description and their attribute levels.

Table 2: Attributes, descriptions and attribute levels of the observation units "rally" and "stroke"

Attribute	**Description**	**Attribute levels**
Rally:		
ID	Unique ID of the rally	GUID (8-4-4-4-12 format)
Number	Number of the rally within the match	"1",…,"x"
Winner	Winner of the rally	"First", "Second"
Server	Server of the rally	"First, "Second"
Start	Starting time of the rally	(in milliseconds)
End	End time of the rally	(in milliseconds)
Comment	Comment on a rally	
Length	Rally length = number of ball contacts	"1",…,"x"
CurrentRallyScore:	(at the beginning of the respective rally)	
First	Current points of player 1	"0",…,"x"
Second	Current points of player 2	"0",…,"x"
CurrentSetScore:	(at the beginning of the respective rally)	
First	Sets currently won by player 1	"0","1","2","3", "4"
Second	Sets currently won by player 2	"0","1","2","3", "4"
Stroke:		
Number	Number of the stroke within the corresponding rally	"1",…,"x"
Player	Player performing the stroke	"First", "Second"

Side	Side/laterality of the stroke	"Forehand", "Backhand"
Servicetechnique	Technique used for the service	"Pendulum", "Reverse", "Tomahawk", "Special"
PointOfContact	Position relative to the table where the player hits the ball	"over", "behind", "half-distance"
Quality	Quality of the stroke	"good", "bad", "normal"
Aggressiveness	Aggressiveness of the stroke	"aggressive", "Control", "passive"
Playerposition	Position of the server when serving	"0" – "152,5" (in cm,mm)
Specials	Special events (touch of net, edge)	"EdgeRacket", "EdgeNet", "EdgeRacketNet"
OpeningShot	Stroke was the first offensive shot in the rally	"true", "false"
StepAround	Step around footwork/Pivot forehand	"true", "false"
Spin:		
US	Underspin	"0", "1"
TS	Topspin	"0", "1"
SL	Sidespin left	"0", "1"
SR	Sidespin right	"0", "1"
No	No spin	"0", "1"
Placement:		
WX	X-coordinate of the placement	"0" - "152,5" (in cm,mm)
WY	Y-coordinate of the placement	"0" - "274" (in cm,mm)
Stroketechnique:		
Type	Type of the technique used	"Push", "Flip", "Topspin", "Block", "Smash", "Counter", "Lob", "Chop", "Tetra", "Special"
Option	Additional option using a particular technique	"Spin", "Tempo", "Banana", "Chop", "aggressive"

The respective attribute levels are based on textbooks of the German Table Tennis Association (Deutscher Tischtennis Bund, 2007), the experiences from projects in other sports and the current developments in para and able-bodied table tennis.

Table 3 illustrates the multi-levelled structure of the observational system including the observation units "rally" and "stroke" and their respective attributes. One match is represented by a list of rallies (rally #1 to #X). A rally has its own "rally attributes", additionally consists of a list of strokes (stroke #1 to #X). A stroke has then again its own multiple "stroke attributes".

Table 3: Multi-level structure of the observational system with the observation units “rally” and “stroke” and their respective attributes

Level 0	Level 1		Level 2	
Rallies:				
	Rally #1:	ID, Number, Winner, Server, Start, End, Comment, Length		
		CurrentRallyScore: First, Second		
		CurrentSetScore: First, Second		
		Strokes:		
			Stroke #1:	Number, Player, Side, Servicetechnique, PointOfContact, Quality, Aggressiveness, Playerposition, Specials, OpeningShot, StepAround
				Placement: WX, WY
				Stroketechnique: Type, Option
				Spin: US, TS, SL, SR, No
			Stroke #X:	…
				…
	Rally #X:	…		
		…		

The introduced observational system is the underlying foundation for the systematic game observation and notational analysis in the later presented *study two* and *study three* and the development of the Table Tennis Analysis System TUM.TT (see chapter 4.6). If necessary, the system can also be extended accordingly to new future developments in table tennis or if special requirements, e.g. for para table tennis specific areas, are not yet covered.

4.5 Technological tools – Development of Sports Specific Analysis software

When checking the market for sports analysis software, a distinction can be made between two different types of match analysis software. Cross-sport software solutions (e.g. Dartfish, Utilius VS, SportsCode) allow the analysis of multiple sports. On the other hand, sports specific software solutions can be identified that are designed for the analysis of one specific sport.

One advantage of solutions like SportsCode or Dartfish is that they can be adapted for different sports, thus they are universally usable (which might be more an advantage for a company regarding target group/customers). But that universality is only possible to a certain degree which is also the decisive disadvantage of those kind of software solutions. Lames (1994) stated that, in general, it can be assumed that cross-sport “standard” solutions cannot meet the user’s sports specific requirements or at least not all. Link and Ahmann (2013) confirmed those disadvantages of cross-sport “standard” solutions compared to sports specific software with the following:

- A negative cost-benefit calculation from the user's point of view because of the high complexity of the cross-sport analysis systems.
- A lack of efficiency in data collection, as sports specific characteristics and correlations are not taken into account.
- Insufficient evaluation options, as tools should not only add up frequencies, but must also adequately represent the sports specific correlations.
- The graphical user interface, which is more oriented towards database structures instead of sports specific issues. A simple interface design is needed that allows PA questions to be answered and presented with just a few clicks.

Based on these deficits of cross-sport systems, a sports specific game analysis system for table tennis was designed and developed by the author, assisted by his colleague of the chair Sebastian Wenninger, in projects founded by the Federal Institute of Sport Science (BISp) (BISp funding number: 070602/14-15, 071604/17, 071618/17-18) on the basis of the experience gained in former projects in beach volleyball (BISp funding number: 070708/10, BeachScouter: 071604/11, BeachViewer: 071603/11) and goalball (BISp funding number: 070405/12-13). The system went through various development stages and got extensions throughout the different projects, e.g. the extension with para table tennis specific stroke techniques, new visualisations of the result rallies or the integration of the first offensive shot.
The key features and functionalities of the table tennis analysis system TUM.TT are presented in the following chapter.

4.6 Table Tennis Analysis System TUM.TT

In the development of the table tennis-specific match analysis software TUM.TT, the area of data collection is of particular importance. At many international tournaments, players sometimes play several matches per day (European Championships, World

Championships, Olympics/Paralympics; World Tour). Thus, an optimised cost-benefit calculation has high priority. Ideally, a match must be annotated shortly after the match is finished. Initial information must be available to the coaches as soon as possible in order to be able to filter, quantify, analyse and validate it to prepare for upcoming matches (Hansen & Lames, 2001). For this reason, a requirements profile was drawn up in close consultation with sports practice, which the software must be able to handle. The central points of this requirements profile are:

- Coupling of collected data and video
- Efficient data collection
- Consideration of technical features

<u>Coupling of data and video</u>

Database-video coupling must be regarded as a "standard" feature of modern match analysis systems. Matching performance-relevant match information with the corresponding video sequences offers coaches and players the opportunity to check their personal impressions and draw conclusions about match events. This important function was implemented in the software by creating observation units (rallies or individual strokes). Each observation unit is linked to the corresponding video sequence by means of a time stamp. All collected attributes are contained in one unit and can be targeted.

<u>Efficient data collection</u>

In table tennis, as in other sports, as many performance-relevant characteristics as possible should be captured in a short period of time. The software meets these requirements by applying the following concepts:

- Two-phase data collection structure
    - Live data collection (“Live Mode”): observation unit "rally"
    - Post-processing (“Remote Mode”): observation unit "stroke"
- Reduction of manual inputs by taking into account table tennis-specific game characteristics
- Optimisation of manual inputs with the help of shortcuts and clicks directly into the video image

The logic and design of the user interface are designed to minimise the necessary user inputs.

Consideration of technical features

Based on the prior introduced observational system, the “Live Mode” covers first only the rally related attributes (level 1 of the multi-level observational system), aspects of single strokes are to be recorded in the post-processing in addition to the features already recorded for a rally. The technical features to be annotated in the “Remote Mode” according to the developed table tennis observational system are the laterality of the stroke (forehand/backhand), the stroke/service technique, the position relative to the table where the player hits the ball, the placement of the strokes and the opening shot and step around variables. In addition, subjective characteristics such as aggressiveness and quality can be recorded as well.

4.6.1 Software design

The decision to develop two separate software tools was made taking into account that data collection and evaluation are, in terms of content, two independent processes that are often carried out by different people.

The separation into two independent software tools has the advantage that each one can be kept leaner and clearer (Link & Ahmann, 2013). The collection of performance-relevant game data is carried out with the software "TUM.TT Scouter". The "TUM.TT Viewer" software is the tool for data evaluation.

4.6.2 TUM.TT Scouter

Data collection with the TUM.TT Scouter generally proceeds in three steps. First, general information about the match to be analysed and the participating players must be entered. Then the first analysis phase is carried out in the live mode and finally the analysis can be refined in a post-processing mode. The execution of the individual stages is always a prerequisite for the following stage, i.e. the live mode can only be used after the general information has been entered and the post-processing mode can only be used after pre-structuring the match in the live mode.

4.6.2.1 Start/Configuration/General Information

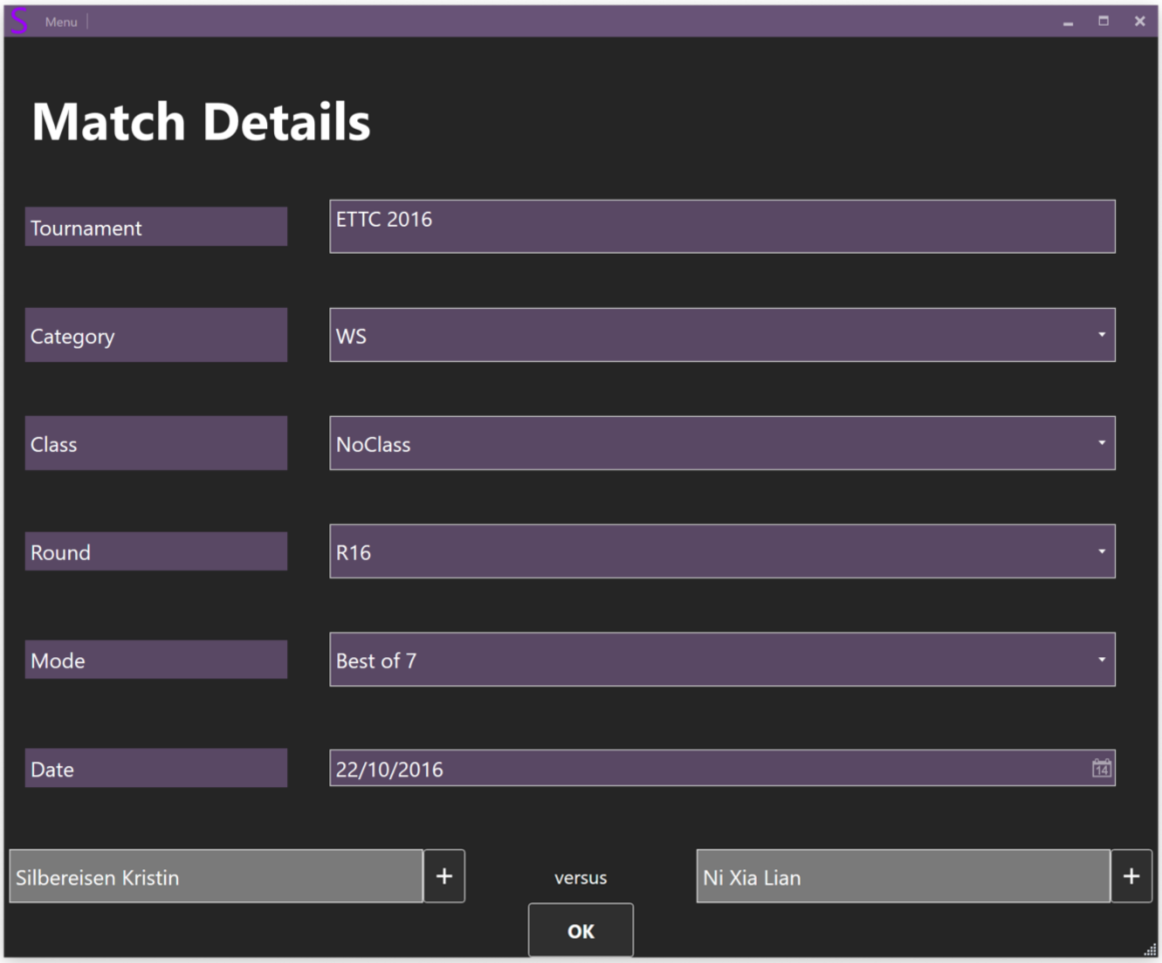

Figure 4: TUM.TT Scouter - match information window

When opening the TUM.TT Scouter, the start screen offers the option of starting a new game or opening an existing game. In the case that an existing game is opened, the data from the file is read in and the live mode is opened.

If a new match is started, the configuration process begins with a window (see Figure 4), in which the general information regarding the match to be observed can be entered (tournament, competition category, impairment class, round, mode, date). Within this window, the two participating players can also be added. Here, a click on the "+" opens a new window (see Figure 5), in which the information about the respective player can be entered (name, nationality, ranking position, playing system, material on forehand, material on backhand, grip and handedness).

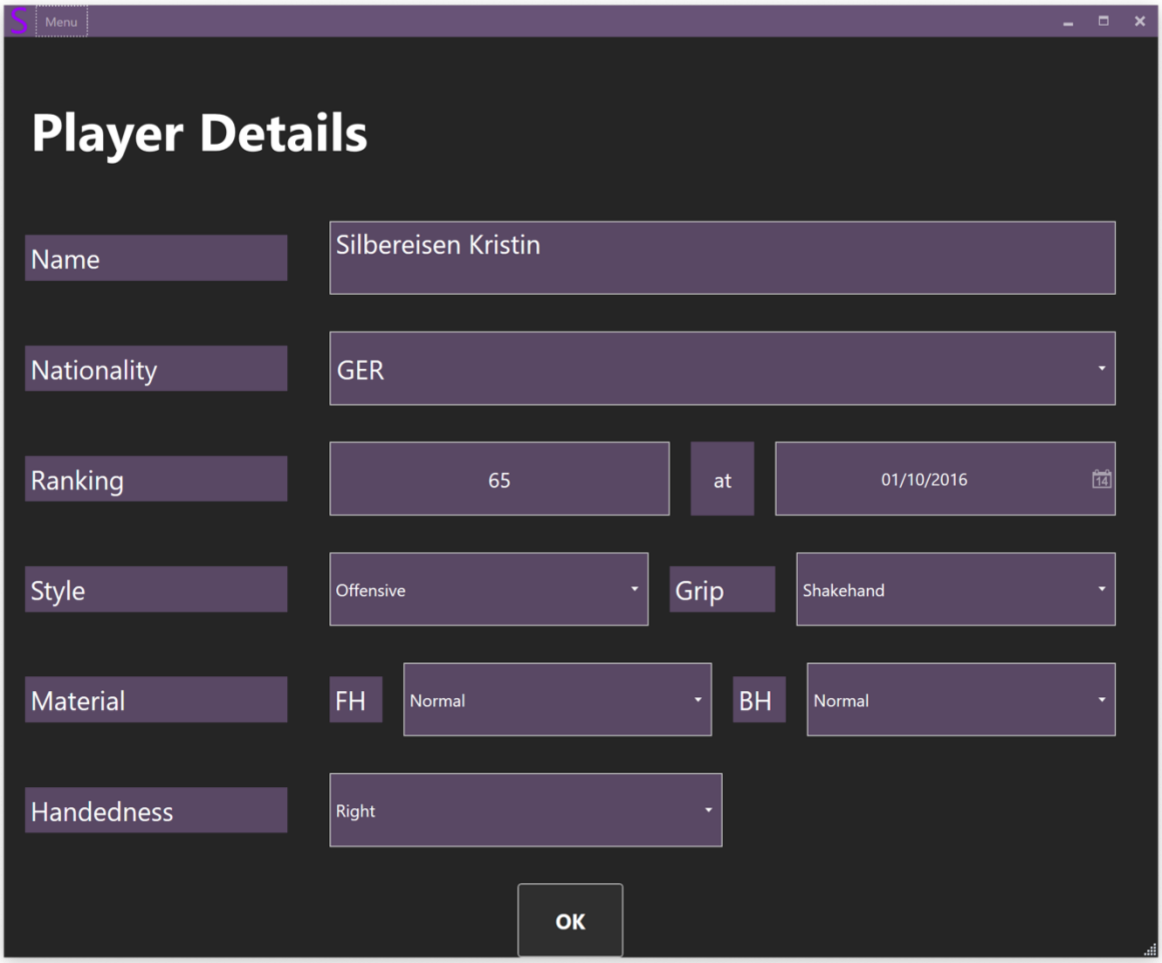

Figure 5: TUM.TT Scouter - player information window

After entering match and player information, the user must select whether the live mode is carried out with or without a video file. After that, the configuration is complete and the analysis in the live mode can be started.

4.6.2.2 Live Mode

The general structure of the live mode is shown in Figure 6. A large part of the window is taken up by the video or timer (if without video file was chosen previously) in the upper left part. Below the video there is a score display including a display of the server. Below that are the control elements for the actual scouting. The right third of the screen is occupied by the list with the created rallies including rally number, score, winner of the rally and rally length and the text field for comments on a rally. The checkbox labelled "marked" inserts a rally directly into the "marked" playlist for the TUM.TT Viewer. This way, important rallies can also be marked directly by the analyst during live scouting for coaches and players.

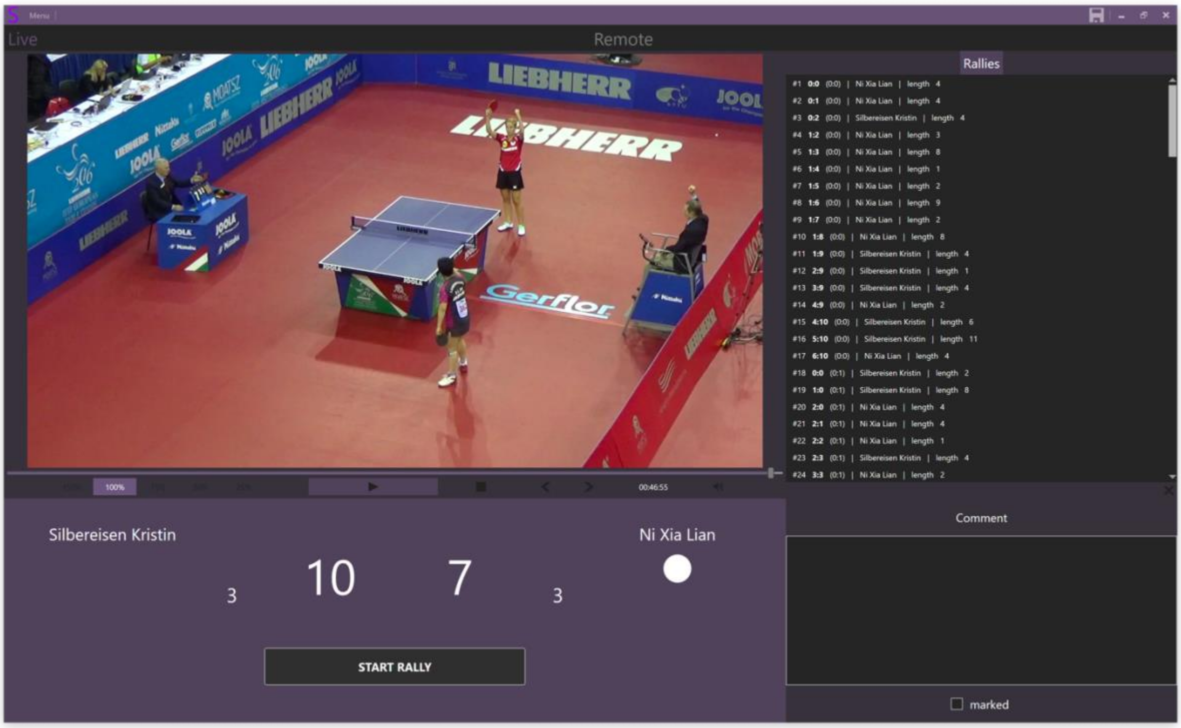

Figure 6: TUM.TT Scouter - live mode with video

Before the scoreboard and controls can be displayed, work in live mode begins with the players' side selection. This is a preparatory input for the post-processing mode, in which the pitch for entering the placement is then adjusted accordingly for possible inputs at each stroke (depending on which side the currently batting player is on). After that, the player who will start serving at the beginning of the match must be selected. By setting the first server, the server of all following rallies is automatically set according to the table tennis specific serving rules.

After these preparatory inputs, the actual scouting process begins.
By clicking on the "Start Rally" button, the current time of the video is recorded as the start time of the current rally for an analysis with video (see Figure 6). For an analysis without video, the current time of the running timer is used accordingly. After the start of the rally, the "Start Rally" button disappears and the input options for the rally length and the winner of the rally appear (see Figure 7).

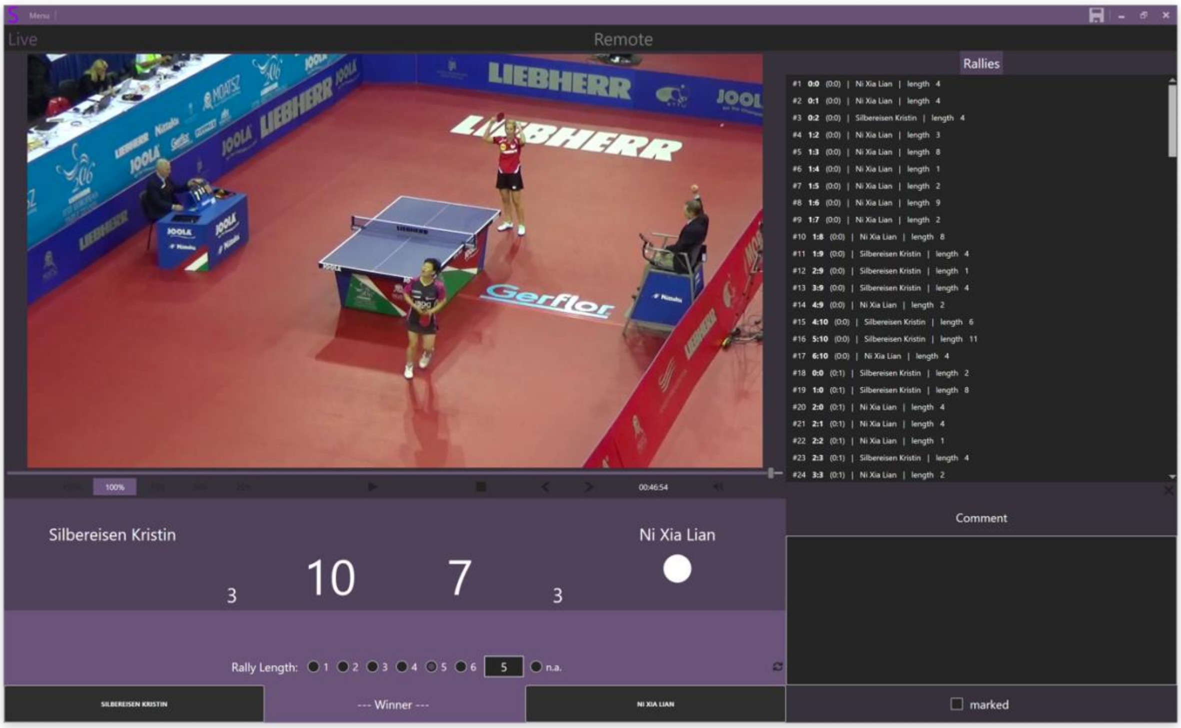

Figure 7: TUM.TT Scouter - live mode - rally length and winner

By entering a number in the text field or clicking on one of the radio buttons for the rally length 1-6, the rally length is changed. By clicking on one of the buttons, the winner of the rally is notated and the current time is also saved (without an extra click) as the end time of the rally. Thus, the notation of a rally in live mode is completed and the "Start Rally" button for the next rally appears again. This way, the entire match can be notated in the live mode.

In addition to the attributes mentioned, additional attributes are automatically recorded. Depending on the winner of the rally, the current score is changed accordingly. This score is automatically saved in the respective rallies.

Thereby, it is possible to filter in the TUM.TT viewer not only by the server (which is also automatically recorded), the winner and the length of the rally, but also by individual sets or the decisive phases within a set ("crunch time"). The chronology of the match is also represented through the current scores saved in the rallies. The number and ID of a rally are also created automatically. These, like the score, later provide a way of sorting the rallies in the TUM.TT Viewer.

4.6.2.3 Remote/Post-processing Mode

The prerequisite for using the post-processing mode is a created rally from the live mode and the input of a video file. If these prerequisites are met, the tab for the post-processing mode in the program window of the TUM.TT Scouter becomes active and can be clicked.

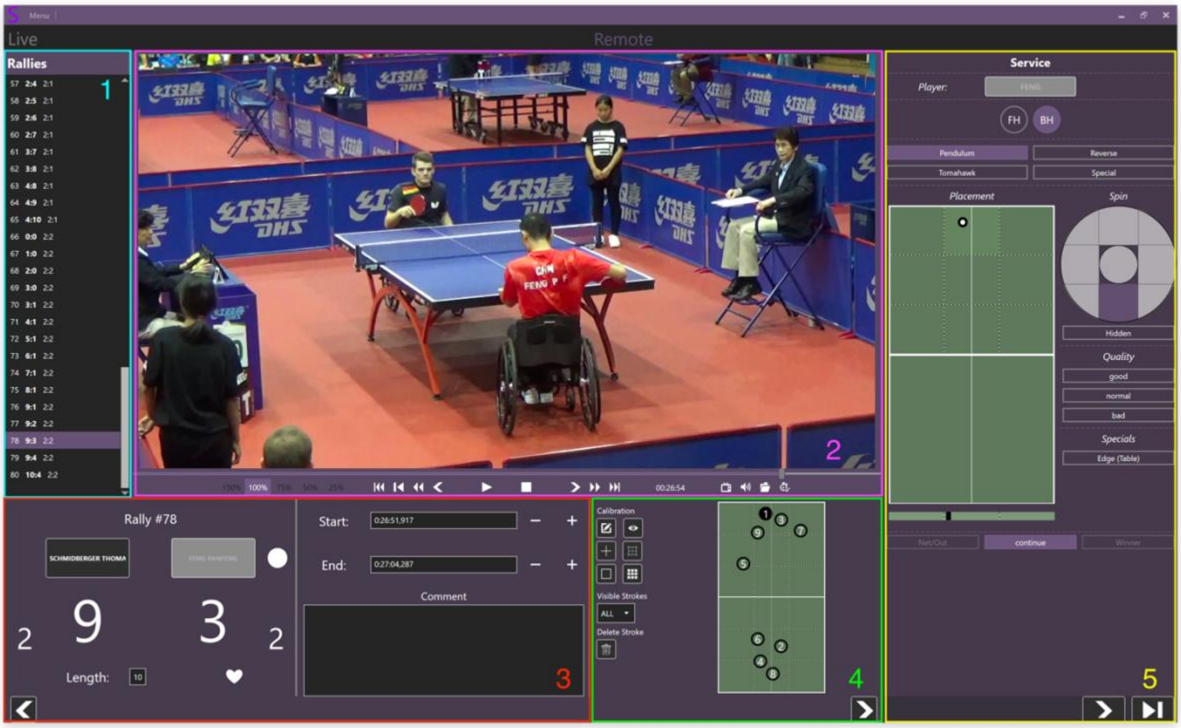

Figure 8: TUM.TT Scouter - remote mode

4.6.2.3.1 General structure of the TUM.TT Scouter remote mode

The structure of the remote mode is shown in Figure 8. The window has the following components:

Area (1) shows the list with the created rallies from live mode, sorted in chronological order. The largest part of the window is used by the video player with its controls in the middle (2). Below the video player is the so-called rally sub-view (3), which contains information on the selected rally from live mode. These can also be edited here. Area (4) is responsible for capturing and calibrating the table to record the placements and shows the overview of the placements of all shots of the selected rally. The right-hand area of the remote mode takes up the stroke view (5).

4.6.2.3.2 Video player

In remote mode, the video player has additional operating options compared to the live mode (with video). Three different playback modes can be selected. In standard mode, clicking on a rally in the list plays it directly, but the video simply continues to run after the rally. In repeat mode, the selected rally is always repeated and in infinite mode, after the end of one rally, the video jumps directly to the beginning of the next rally. In addition, there are buttons with which you can jump to the next or previous rally or start a rally from the beginning. Buttons are also available to jump the video one or five frames forward or backward. Another button provides the option to load another video.

4.6.2.3.3 Rally view

In the rally view area (see Figure 8 (3)), the rally length (by entering it in a text field), the start and end time of the rally (either by entering it in the text field or by using the "+" and "-" buttons) and the comment (by entering it in the text field) for a rally can be edited. The serve or the winner of a rally can no longer be changed in remote mode, as this would affect all subsequent rallies, making them useless or incorrect.

4.6.2.3.4 Stroke view

The right area of the remote mode (see Figure 8 (5)) can be used to enter the stroke information. Here, templates are prepared for the number of strokes entered in the rally length in rally view or in live mode.
Two different types of stroke templates must be distinguished: One specifically for the service (see Figure 9) and another for all other strokes (see Figure 10).

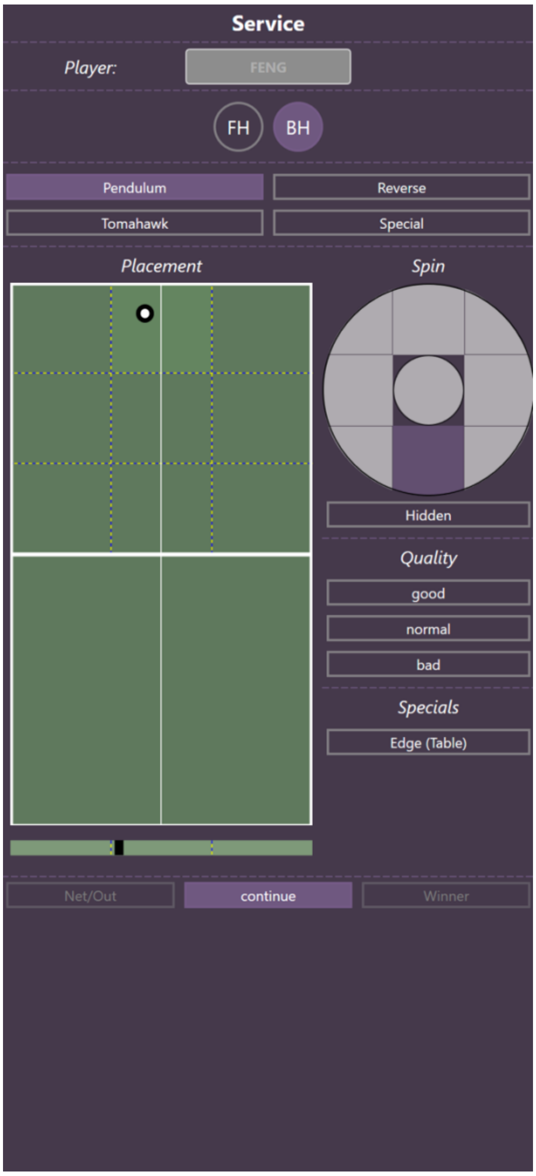

Figure 9: TUM.TT Scouter - remote mode - service template

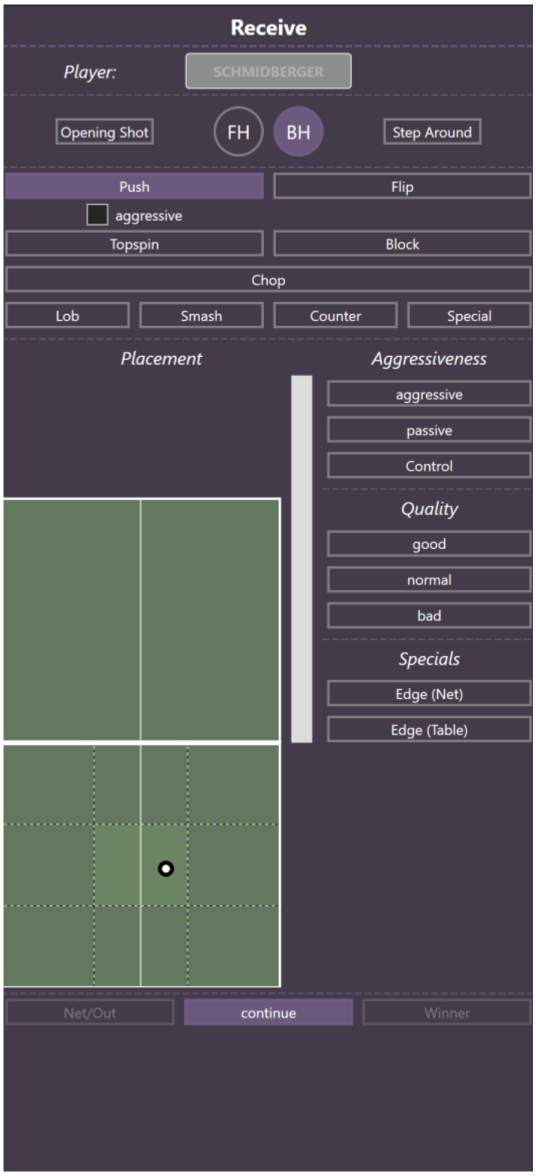

Figure 10: TUM.TT Scouter - remote mode - stroke template

<u>Service template</u>

Since the service is different from all other strokes, a separate template had to be developed. The distinction is due to the special serving techniques, the position of the server (which is not influenced by a previous stroke) and the special importance of the rotation.

The player performing the serve is automatically inserted and is always at the top. Below this is the area for recording the technique (forehand/backhand and type of serve technique). The input of the rotation is done via a button in the form of a ball, in which certain areas can be clicked depending on the type of rotation (topspin,

underspin, sidespin, combinations and no rotation). The analyst also has the possibility to record an assessment of the quality of the serve and special events.
A large part of the service template is taken up by the two-dimensional table, on which the position of the server and the placement of the serve can be recorded.

Stroke template

As with the serve template, for all other strokes, the player performing the stroke is displayed at the top.
Below, there is also the area for recording the technique, in each case with forehand/backhand and type of stroke technique. In the stroke template, checkboxes for additional options appear for some stroke techniques. By clicking on the button "opening shot" one can record whether a stroke was the first offensive shot in a rally. Clicking on the "step around" button notes whether a player used a pivot step before a stroke.
In addition to the quality, the aggressiveness or passivity of a stroke can also be recorded in the stroke template. As special events, the contact with the edge of the net and the edge of the table can be noted.
From the second stroke on, it is no longer possible to record the horizontal position of the server as in the service template, but it is possible to record the (vertical) position relative to the table where the player hits the ball. The possibilities for recording the placement remain the same as in the service template.

4.6.2.3.5 Collecting the placement data

Collecting the placement data was a particular challenge. Often, the table is divided into nine equal fields (short/half-long/long and backhand side/middle/forehand side) and the placement is then assigned to one of the fields. However, since a comparatively large amount of information is lost when recording (not evaluating) the placement, it would be an advantage if the software could record the placement as an x-y coordinate on the table. A grouping into fields could still be done afterwards during the evaluation, if needed.
The TUM.TT Scouter now provides two options for recording the exact placement:

1. by clicking on the two-dimensional table model in the service or stroke template
2. by clicking on the video image after calibrating the table

An overview of all placements of a rally is displayed in the two-dimensional table model of the rally view (see Figure 8 (4)). The numbers in the displayed circles represent the stroke numbers. The positions of the individual strokes can be changed by clicking and simultaneously dragging in the half intended for the stroke. A right-click on a marker deletes the placement of the corresponding stroke. By left-clicking on a marker, this marker is filled in black colour and the information of the corresponding stroke is displayed in the stroke template on the right of the window.

4.6.3 TUM.TT Viewer

The TUM.TT Viewer is an analysis tool specially optimised for table tennis and the needs of coaches, in which the following concepts are central:

1. use of a clearly structured user interface with three columns
2. availability of table tennis-specific filter options
3. various visualisations of the filtered rallies
4. creation of a report with statistics and visualisations to answer performance diagnostic questions

4.6.3.1 General structure of the TUM.TT Viewer

The TUM.TT Viewer offers a simple interface that can be operated with just a few clicks, without window hierarchies and branches. The program essentially consists of a window with three columns (see Figure 11). The left column contains various filter options (area 1). The middle column shows rallies as a result of the filter settings (area 2) and the winning statistics for these rallies (area 3). The right column contains a video player window with the usual controls (area 4), an area where individual playlists can be created and managed (area 5) and a comment field (area 6).

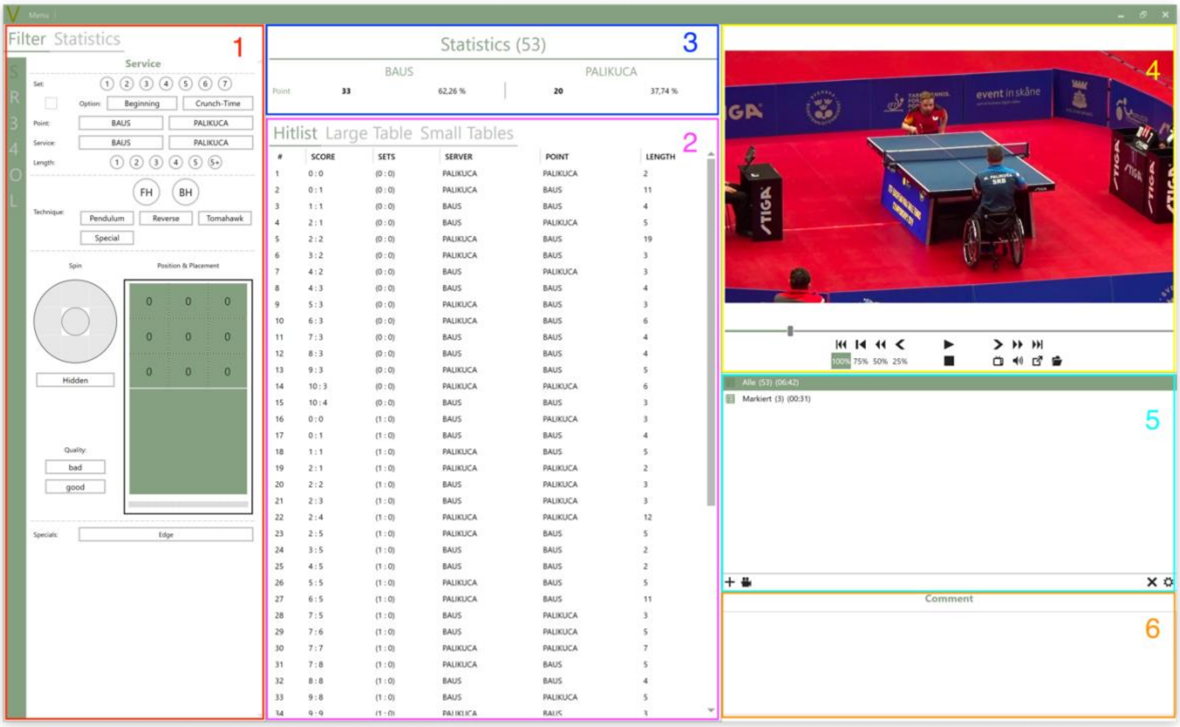

Figure 11: TUM.TT Viewer

4.6.3.2 Filter options

The core feature of the TUM.TT Viewer are hierarchically organised filter options that make it possible to select rallies according to certain criteria (see Figure 12 and Figure 13). Here, a distinction is made between filters for an entire rally ("basic filter" - upper level) – shown in Figure 12 area 1 – and filters for individual characteristics of specific shots (lower level) – shown in Figure 12 area 2. Filters are available for the first four, the first offensive and the last successful stroke. The respective stroke can be selected on the left side (see Figure 12 area 3).

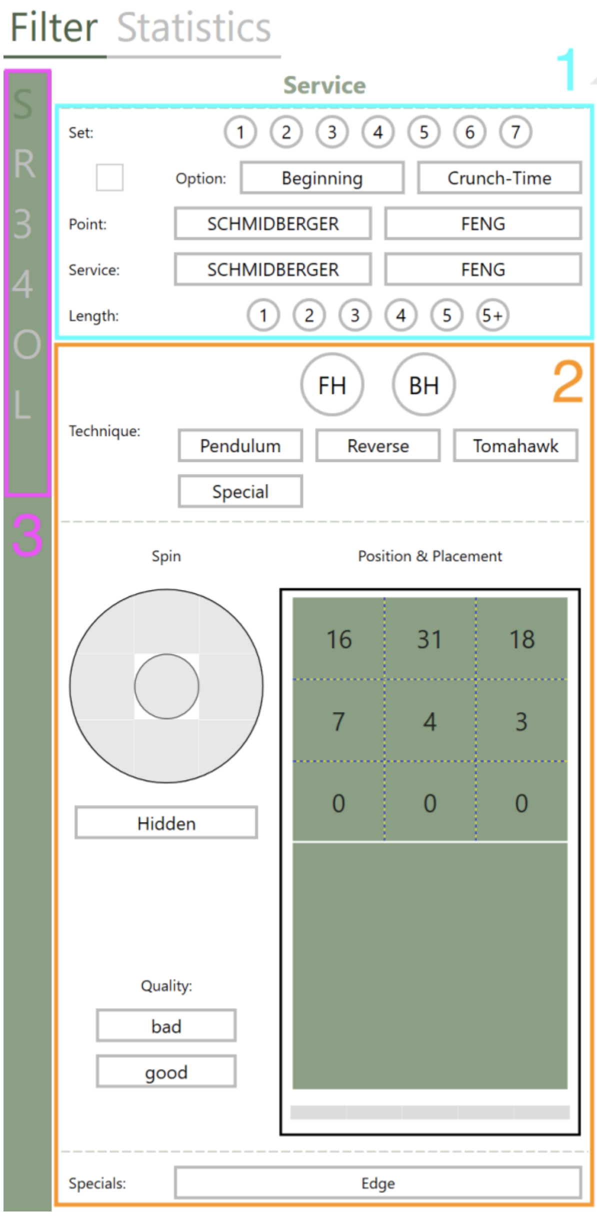

Figure 12: TUM.TT Viewer – filter (service)

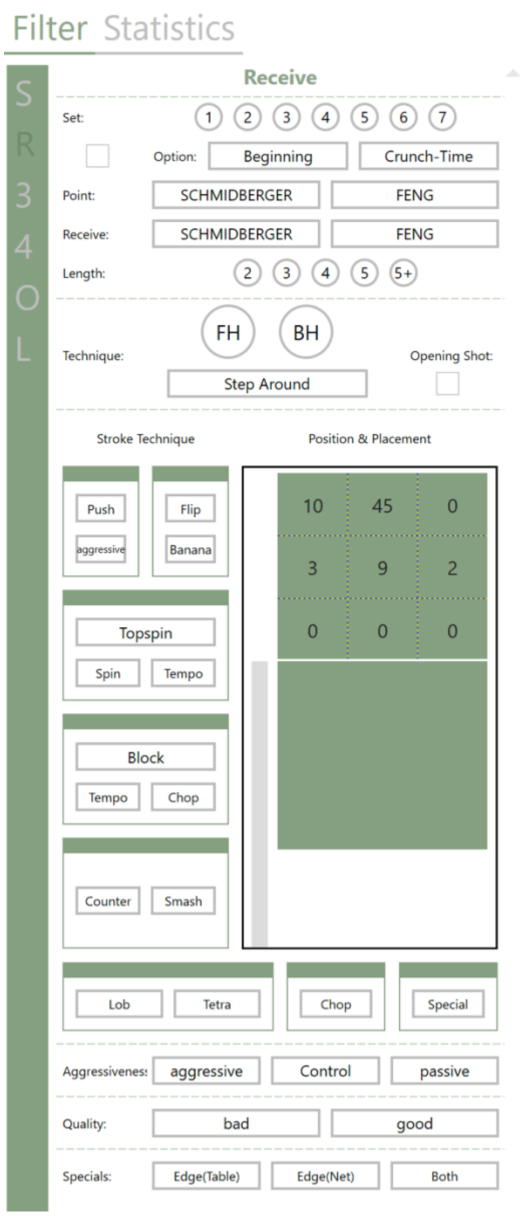

Figure 13: TUM.TT Viewer – filter (receive)

The basic filters contain the filters for the sets, the winner of a rally, the server of a rally, the length of the rally and the beginning/crunch time. These basic filters can be combined with filters for individual stroke characteristics (stroke laterality, stroke technique, spin (serve), placement, contact point, step around, first offensive shot, aggressiveness, quality). The attribute values of one attribute are linked with an OR operator (e.g. "rally with short or half-long serve" - OR connection of short and half-long placement). Between different attributes, the AND operator is used ("rally with short serve and undercut" - AND connection between placement and spin). Combined with the basic filters, all rallies from the first set can be displayed, for example, in which player A scored a point with a short or half-long backhand undercut serve in a rally that has at least four strokes (means the player scored either directly with his serve or with his follow up stroke). All filters can be combined without any restriction.

4.6.3.3 Visualisations of the result rallies

There are three options for visualising the result rallies:

1. hitlist
2. large table
3. small tables

Hitlist

In the list view (see Figure 11 (2)), the filtered rallies are all displayed one below the other as list items with information about the rally (rally number, result, server, winner, rally length). It is possible to sort the list by any of the above features.

Large table

The second way to visualise the result rallies is the large table (see Figure 14). It represents a top view of a table tennis table, which is divided into two halves in the middle by a line symbolising the net. On the large table, all strokes corresponding to the current filter selection are displayed at the same time. This view provides a way to analyse tendencies of individual shots (in our example in Figure 14 all 3rd shots of one player are displayed).

All arrows on the large table are always drawn from bottom to top, regardless of the corresponding player or the number of the stroke in the rally. However, since the position of the strokes are recorded in absolute coordinates of the table tennis table, it was necessary to convert them if necessary and mirror them on both axes.

Several coding dimensions were introduced in order to present as much data as possible without compromising clarity. These dimensions show up in the attributes of the arrows: Colour, shape, width and dash. The colour, shape and width encode stroke techniques. Serves are also shown in a uniform colour and with a straight arrow. The shape is either straight lines or different curves. Finally, dashing is used to distinguish forehand (solid line) and backhand (dashed line) strokes.

A legend describing all possible colours and shapes is presented in Figure 15 and can be displayed in the program at any time.

The large table is also interactive. The arrows, like the hitlist entries, can be selected individually. When one arrow/rally is selected, the corresponding video will be played.

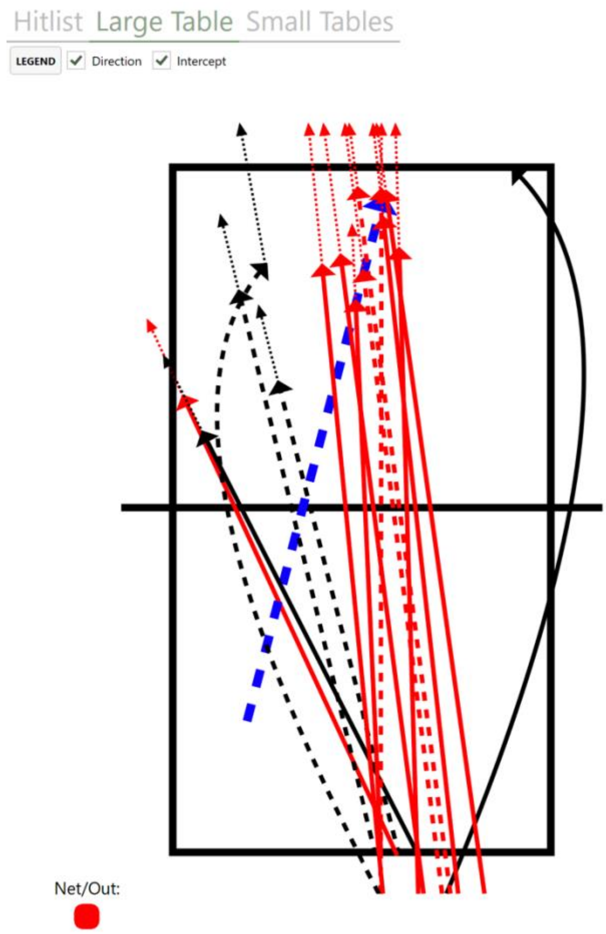

Figure 14: TUM.TT Viewer - large table

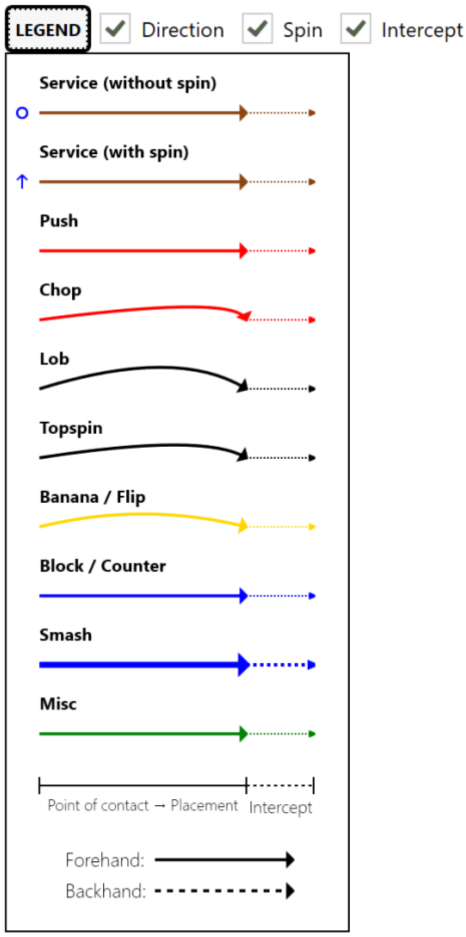

Figure 15: TUM.TT Viewer – colour and shape coding

<u>Small tables</u>

In contrast to the large table, on which only one stroke is displayed, the small tables are designed to analyse rally patterns. Each table therefore represents one rally with the first four consecutive strokes of that rally displayed (see Figure 16).

The general layout and colour coding is identical to the large table. The biggest difference is that arrows are not only drawn from bottom to top, but change sides according to the course of play.

The individual arrows are no longer clickable on the small tables, but entire rallies (i.e. the respective tables) can be selected and will thus be played in the video area.

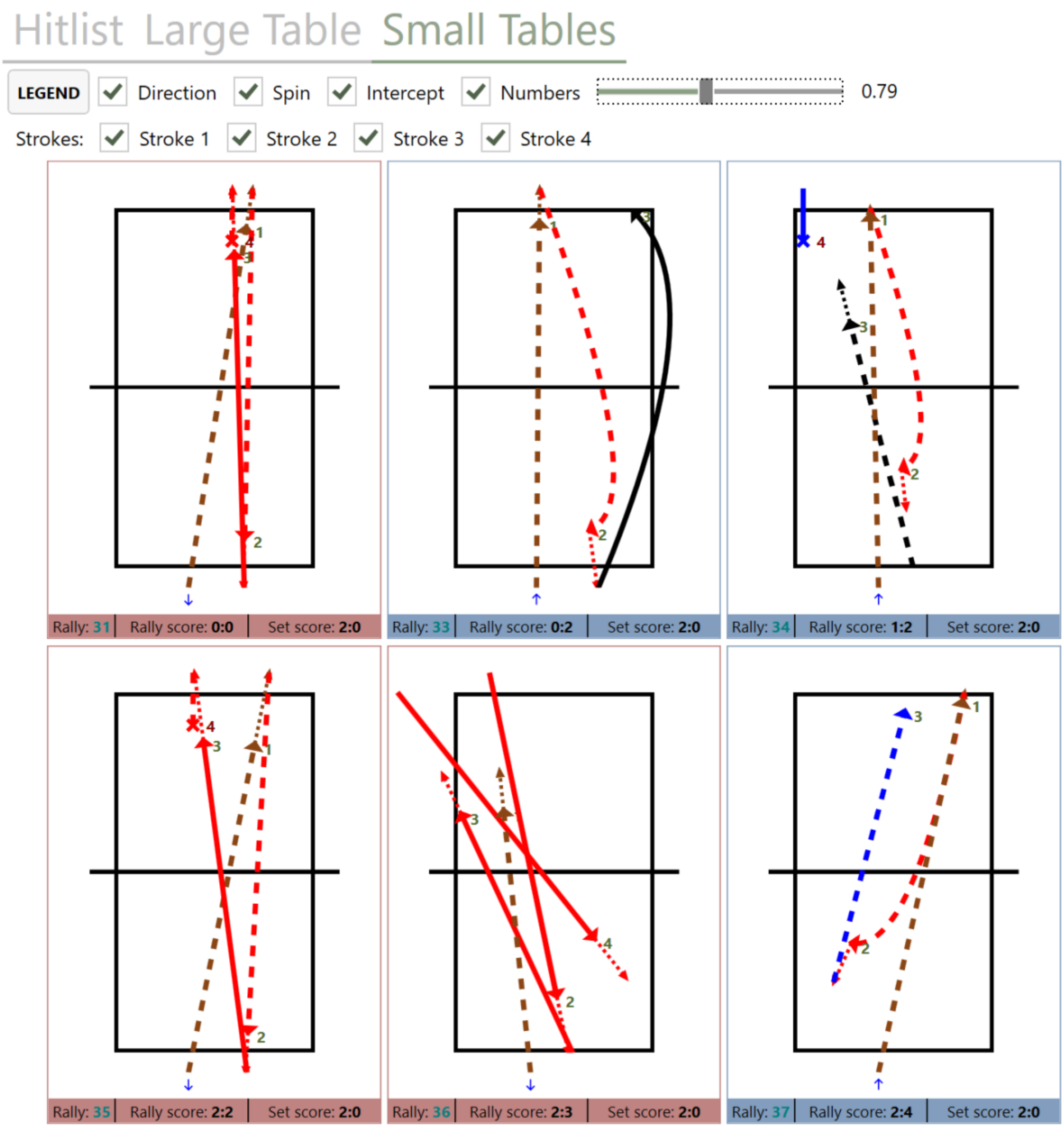

Figure 16: TUM.TT Viewer - small tables

4.6.3.4 Playlists

An important functionality of the TUM.TT Viewer, especially for the practical PA, is the creation of playlists (see Figure 11 area 5). Rallies that are not connected through a filter, thus would not be together in the hitlist, can be put together. For example, an

analyst can prepare a TOP 10 playlist of the most important rallies of the match for the coach, who then only has to use this playlist for an analysis.
Basically, there are two "basic playlists" which are always available. One playlist that contains all rallies of a match and one that contains the rallies marked in the live scouter.
Basically, the following applies: The filters in the TUM.TT Viewer are always executed on the set of rallies of the currently selected playlist! Consequently, filters can also be used on a "TOP 10" playlist.
A playlist can also be exported as video file to share it. In this way, the corresponding rallies can also be played back outside the TUM.TT software without disturbing pauses, e.g. on mobile devices.

4.6.3.5 Report

With the report function, a possibility was created to export the various statistics into a PDF file. This enables a certain "offline" functionality. The report is completely adaptable and can be created according to the needs of the coaches and players.
The following things and analysis approaches can be included in the report:

- in the general section:
    - scores and basic statistics
    - scoring process
    - rally length statistics
    - match dynamics/momentum analysis
    - transition matrix
    - multiple performance indices/three phase method (usage & scoring rates of strokes, technical efficiency index)
- in the sections for each player:
    - statistics and diagrams (incidences and winning probabilities) for the first four and the last successful stroke for the following attributes: laterality, spin, stroke technique, placement, step around
    - statistics can be generated for the complete match, all sets individually and for each possible combination of sets

5 Publications

The following chapter presents the publications underlying this thesis. Thematically, *study one* serves as an overview about established approaches of match analysis in table tennis which are classified into theoretical or practical PA approaches.

For the two other studies which are both original papers I wanted to cover not only (able-bodied) table tennis, but also para table tennis as Paralympic sports have gained more attention during the last couple years and should be considered to give a complete picture about PA in table tennis as it is a very if not the most inclusive sport out there.

On the one hand, both studies have in common that they are representing the field of match analysis in table tennis. But on the other hand, they have different objectives/focus due to the different state of research in para table tennis and (able-bodied) table tennis respectively.

Study two investigates very fundamental parameters of para table tennis as – to the best of the author's knowledge - there were no studies available that have investigated game characteristics in para table tennis before. Whereas *study three* examines a very specific and detailed area in able-bodied table tennis as several studies about the basic game characteristics in able-bodied table tennis have been already carried out (Fuchs & Lames, 2017; Malagoli Lanzoni et al., 2013, 2014; Malagoli Lanzoni et al., 2007). *Study two* is using theoretical PA approaches (notational analysis/shot number based analysis) to give a better understanding of the basic characteristics in elite para table tennis by analysing rally length and the impact of serve. Additionally, the influence of sex and impairment class on those parameters is analysed as well.

Study three investigates the first offensive shot in able-bodied table tennis. Compared to prevailing methods in table tennis match analysis, which are based on fixed shot numbers, using a state transition model and taking the first offensive shot as object of analyses is an innovative new approach focusing on the tactical meaning of shots that is not expressed in shot number.

5.1 Table tennis match analysis: a review

Fuchs, M., Liu, R., Malagoli Lanzoni, I., Munivrana, G., Straub, G., Tamaki, S., Yoshida, K., Zhang, H., & Lames, M. (2018). Table tennis match analysis: a review. Journal of Sports Sciences, 36(23), 2653-2662. https://doi.org/10.1080/02640414.2018.1450073

This review paper was published in 2018 in the Journal of Sports Sciences (Volume 26, Issue 23, Page 2653-2662). At the time of publication in 2018, Journal of Sports Sciences had a journal impact factor (JIF) of 2.811 and an impact score of 2.75. The journal citation indicator (JCI) was 1.17. Its rank in the category sports sciences was 20/83 (ranked by JIF) and 18/115 (ranked by JCI), in both rankings in the Q1 Quartile. According to web of science, the paper was cited 29 times and according to ResearchGate, the paper was cited 48 times and had 2894 reads since its publication until the submission of this dissertation in September 2022.

5.1.1 Contribution of the Author

The research idea for this study was developed together with the doctoral supervisor. The doctoral candidate was responsible for the conceptual design and the writing of the manuscript. The sections “introduction”, “methods of review”, “simulative performance analysis: Markov-chain-modelling” and “discussion” were exclusively written by the doctoral candidate. The writing of the other sections was done together with the co-authors. The completion of the manuscript was exclusively done by the doctoral candidate. The doctoral supervisor assisted with feedback on manuscript drafts.

5.1.2 Summary

The aim of this paper was to give a review on some of the most acknowledged scientific methods of match analysis in table tennis since the first ones in the 1960s. Electronic database searches for studies related to match analysis in table tennis were conducted in PubMed, Web of Knowledge (Sport Sciences), SPORTDiscus, SURF, Google Scholar and CiNii. Additionally, searches in the International Journal of Table Tennis Sciences and on the website of the China National Knowledge Infrastructure

(CNKI) were conducted. The selection criteria were specified (peer-reviewed or in the case of CNKI, at least published in Chinese academic journals). Additionally, the exact search strategy was explained (advanced search term: (“analysis” OR “performance analysis” OR “match analysis” OR “game analysis”) AND “table tennis”). The following numbers of hits per database were found: PubMed (79), Web of Knowledge (37), SPORTDiscus (332), SURF (190), Google Scholar (34.600) and CiNii(70). Based on those hits, basic methods/approaches of PA most common in table tennis were identified by the authors who are all experts in a certain area of the field of match analysis in table tennis. For each of those approaches an exemplary study was chosen.

The first chapter of the main body presented a historical overview of match analysis from all over the world. The second part reviewed the chosen approaches in more detail, using the PA classification of theoretical and practical PA. The review included the most actual theoretical PA techniques in table tennis: performance indices, simulative approaches, momentum analysis, footwork analysis, and finally an approach which uses top expert knowledge for a comprehensive technical-tactical analysis. In the section of practical PA, the paper presented two “best practice” examples describing PA procedures of the two most successful countries of the last Olympics: China and Japan. The paper highlighted the heavy impact of PA on the practical work of the leading nations, but stated also that only a few nations make serious efforts to introduce it to their national teams as a routine in practical work. The paper ended with an outlook on possible (and necessary) developments like automatic position/placement detection to make the usage of PA more widespread in table tennis and with some limitations of the review.

5.2 Game characteristics in elite para table tennis

Fuchs, M., Faber, I. R., & Lames, M. (2019). Game characteristics in elite para table tennis. German Journal of Exercise and Sport Research. https://doi.org/10.1007/s12662-019-00575-4

This original paper was published in 2019 in the German Journal of Exercise and Sport Research (Volume 49, Issue 3, Page 251-258). At the time of publication in 2019, German Journal of Exercise and Sport Research had a journal impact factor (JIF) of 1.106 and an impact score of 1.11. The journal citation indicator (JCI) was 1.17. Its rank in the category sports sciences was 84/116 (ranked by JCI), resulting in Q3 Quartile. According to web of science, the paper was cited 2 times and according to ResearchGate, the paper was cited 5 times and had 292 reads since its publication until the submission of this dissertation in September 2022.

5.2.1 Contribution of the Author

The research idea for this study was developed together with the doctoral supervisor. The processing of the data and the data evaluation was carried out by the doctoral candidate. The co-author Irene R. Faber provided support in the writing of the introduction and discussion section and gave feedback on manuscript drafts. The other sections of the manuscript were exclusively written by the doctoral candidate. The doctoral supervisor assisted with methodological decisions and the conceptual design of the manuscript.

5.2.2 Summary

The intention of this study was to give a first insight in the basic game characteristics in elite para table tennis (class 1–10). As probably the first study on game characteristics in elite para table tennis ever, it focuses on the basic variables rally length and the impact of the serve, i. e. the winning probability when serving. The influence of sex, standing or sitting position of the player while competing and the severity of the impairment, and their possible interactions are investigated. A total of 227 matches of elite para table tennis players (class 1–10) ranked in the top 20 of the world ranking lists in their class were analysed. The results of this study revealed a

significant main effect of sex with small effect sizes in the three-factor factorial model (sex versus sitting/standing versus severity of disability) and medium to large effect sizes in the individual comparisons on the rally length and the winning probabilities directly from service and first attack. Moreover, an interaction effect of sex and sitting/standing was found with small (for serve winning probabilities) to medium (for rally length) effect sizes. Female players in the sitting classes showed a lower rally length compared to their male peers. This is accompanied with significantly higher winning probabilities directly from the serve and the first attack in the sitting female players compared to their male counterparts. The results of the male class 1 showed a remarkably shorter rally length and higher winning probabilities directly from the serve and the first attack when compared to the other sitting classes in men. Class 6 for men, the standing class with highest severity, also seemed to follow the same trend: the rally length was lowest with the highest winning probabilities while serving when compared to other standing classes.

In conclusion, the significantly smaller rally length combined with the higher winning probabilities of short rallies when serving in almost all female sitting classes compared to the respective male classes supports the importance of serve and maybe even more the receive game in those female classes and should be an important part in training and education. The same can be stated for the male class 1 and class 6. The shorter rally length in the standing para table tennis classes compared to the Olympic table tennis for both females and males emphasizes the importance of a good serve and receive game also in standing para table tennis. Additionally, the value of the third stroke attack especially for males with an average rally length lower than 4 in all standing classes was highlighted for standing male para table tennis players.

This study provides a first overview of typical game characteristics in para table tennis and is a starting point for future studies on this sport with more in-depth analyses. Detailed technical/tactical analyses would give more precise knowledge on the structure of the sport and could lead to more practical implications for training and education.

5.3 First Offensive Shot in Elite Table Tennis

Fuchs, M., & Lames, M. (2021). First Offensive Shot in Elite Table Tennis. *International Journal of Racket Sports Science, 3*(1). https://doi.org/10.30827/Digibug.70278

This original paper was published in July 2021 in the International Journal of Racket Sports Science (Volume 3, Issue 1, Page 10-21). This open access online journal was established in 2019 and has no impact factor or impact score yet. Nevertheless, it was consciously chosen as the journal is specialised in the publication of articles related with racket sports. According to web of science and ResearchGate, the paper was not cited yet and had 50 reads on ResearchGate since its publication until the submission of this dissertation in September 2022.

5.3.1 Contribution of the Author

The research idea for this study was developed together with the doctoral supervisor. The processing of the data, implementation of the model, data evaluation and writing of the article were all carried out independently by the doctoral candidate. The doctoral supervisor provided support in the methodology for the new introduced model and in the conceptual design of the manuscript.

5.3.2 Summary

In this study a new structural model for a table tennis rally including the “first offensive shot” (FOS) was introduced and a corresponding observational system focusing on recording properties of the FOS was developed. FOS may not be defined based on a shot number in the rally (like serve, receive, third shot, fourth shot etc.), because it is not known a priori which shot will be the FOS. FOSs are semantically similar shots defined as the first shot in a rally without any kind of backspin (serves excluded). After the introduction of the innovative new observational system, the aim of this study was to analyse the following characteristics regarding the FOS in a rally in elite table tennis:

- techniques used for FOSs
- position where the FOSs are performed (over vs. behind the table)
- shot number of the FOSs

- serving or receiving players performs the FOS
- differences between men and women and between top ranked and lower ranked players regarding the FOS behaviour
- winning probability for the FOS player

Two independent variables were used in this study. First, matches of male and female players were compared. Second players were divided into two player categories (“top 50” and “over 50”), resulting in three possible match categories (“top 50 vs. top 50”, “top 50 vs. over 50” and “over 50 vs. over 50”). This leads to a two-factor factorial design (sex versus match category). A total of 90 matches of the 2016 Olympic Games were analysed, including 45 men’s and 45 women’s matches (15 matches per match category). The 90 analysed matches led to a total number of 7449 analysed rallies, 3889 rallies of men’s matches and 3560 rallies of women’s matches respectively. All matches were analysed with the table tennis video analysis tool “TUM.TT”.

From 7449 analysed rallies, 6771 (90.9%) rallies contained a FOS. In 668 (9.0%) rallies there was no FOS because of prior rally termination (serve winner (6.0%), serve error (13.8%), defensive shot winner (17.5%) and defensive shot error (62.7%)). Four laterality-technique-position combinations (out of twelve) cover 98.3% of all 6771 analysed FOSs. The typical FOSs are: Forehand topspin behind the table, forehand flip over the table, backhand topspin behind the table and backhand flip over the table. Most used for FOS overall was FH topspin (37.4%), followed by BH topspin (29.3%) and the BH flip (22.3%). FH flip was used least often (10.9%).

A different frequency order for men and women was obtained when analysed separately. FH topspin is still the most used FOS for both men (35.9%) and women (39.1%). But different to the overall order, the second most popular shot for men is the BH flip (27.2%) and not the BH topspin (23.2%). For women, BH topspin (36.1%) is on second place, followed by BH flip (17.0%).

Chi-square tests revealed a significant relation between sex and these typical FOSs. Regarding the match categories, the tests prove a significant relation between match categories and FOS tactics for both genders.

In both genders the majority of FOSs (women: 96.9%, men: 94.9%) were performed with the second, third or fourth shot in a rally. A difference in the FOS tactics between the serving and the receiving player was found as well. The winning probabilities show that using topspin (Forehand and Backhand) as FOS was an advantage in every match category, whereas using flip as FOS led mostly to a winning probability below 50% for the FOS player.

The FOS is arguably a crucial moment in a rally, but the advantage/disadvantage by performing the FOS might be neutralized in longer rallies. Over 60% of all rallies (women: 62.3%; men: 63.5%) were finished with a maximum of two offensive shots after the FOS, and almost three quarters were finished with three or less shots after the FOS (women: 73.5%; men: 74.2%). When talking about the intention the FOS player should have, the statistics were clearly showing that it was more successful for the FOS player if a rally was finished with a direct impact of the FOS (meaning rallies which finished latest with the follow up attack after the FOS of the FOS player.

This study provided a first overview of the FOS behaviour in elite table tennis using a new shot-number-independent approach with detailed technical/tactical analyses of the FOS behaviour, including the analysis of the winning probabilities. The reliable information about different FOS behaviour for men and women or for the serving and receiving player respectively, the differences between match categories and the differences of winning probabilities could lead to practical implications for training and competition and also to adaptions in the tactical education in the development of (young) athletes.

6 Discussion

The publications of this thesis deal with the field of performance/match analysis in the sport of table tennis. In this chapter, in addition to some of the content-related findings that are mainly discussed in the publications themselves, primarily those things that have an impact in a wider context or are important on a meta-level will be discussed.

6.1 Table tennis match analysis: a review

In order to have a good foundation for further research, an article was written that reviews the most popular scientific approaches of performance/match analysis in table tennis. One challenge in this article was to select the approaches that would be presented. Since it was not a systematic review as described in the methods section, the selection can be considered subjective. However, the authors' proven expertise in the field of match analysis in table tennis, whether as match analysts of the Chinese or Japanese national team, or as renowned authors or members of the ITTF Sports Science and Medical committee who have published several studies in this field, can be seen as the maybe best possible basis for an objective, meaningful and representative selection of approaches.

The selected approaches are described, explained and discussed. By collecting that information about the most popular approaches within one article, the article can serve at a higher level as a reference for other researchers as well as for those generally interested in the subject.

Through the distinction between theoretical and practical PA approaches, in addition to the more methodical explanations of the theoretical PA approaches, the best practice examples of the leading nations China & Japan (which come from first-hand sources, as several co-authors have worked as scientists and match analysts for the respective national team) can serve as kind of a step-by-step instruction on how to actually work with certain methods in everyday practical life.

One tendency that became evident as a result of the study is that the most prominent techniques in PA are made use of also in table tennis. Some approaches share the same disadvantages when applied in table tennis as they do when applied in other sports, for example that expert knowledge for assessing technical-tactical elements might be based on empirical subjective data if a larger number of experts are not included who show a high level of agreement in the evaluation of technical-tactical activities (Munivrana, Furjan-Mandić, et al., 2015; Munivrana, Petrinović, et al., 2015). But nevertheless, in the game of table tennis some approaches provide specific solutions partly even with sustainable practical impact, for example performance indices like the technique effectiveness and competition performance values which can help to quantitatively evaluate players' performance and identify those techniques most related to their competition performance which can provide pertinent guidance in training and competitions and further promote technical and tactical capabilities of players (Zhang et al., 2013).

Besides the partial lack of knowledge, however, it seems that one big reason why, apart from Japan and China, only a few countries make serious efforts to introduce PA to their national teams as a routine in practical work, is the very time-consuming data collection which at the present time requires either a lot of in-house manpower or financial expenditure if the work is outsourced to a company. The automation of data collection therefore holds great potential and underlines – as there have only been sporadic trials so far (see Outlook) and the approaches are not yet really applicable in everyday life – the need for scientific and technical developments to improve and promote PA in table tennis. Automatic motion/pose detection of players or placement detection of the ball by image recognition could lead to a big simplification of the analysis process also in table tennis. According to this trend, match analysis could shift to utilization of enormous data that is automatically collected. To deal with that big amount of data, fields like machine learning, artificial intelligence and data mining may have an important role in table tennis match analysis in the future as well (Yu et al., 2008). By using well-structured and well-presented data, not only the performance of players can be enhanced, but also the education of coaches. Last but not least the broadcasting for TV spectators can benefit from that development, thus, the general promotion of table tennis can be improved.

6.2 Game characteristics in elite para table tennis

Similar to the professionalisation in Olympic sport, Paralympic sport is also gaining more and more popularity and importance, which goes hand in hand with an ever-increasing professionalisation, para table tennis included. In terms of research, however, para table tennis is still in its infancy. Overall, very few studies have been published in para table tennis and especially in performance/match analysis no studies have been published in scientific journals so far. Consequently, there is little to no scientifically sound data available in this area.

The content-related findings from the study, such as the particular importance of the serve/receive game in all women's wheelchair classes as well as in the men’s classes 1 and 6, which are not complete surprises, but rather confirm and scientifically substantiate the experiences from practice, lead to scientifically based practical indications for training and competition. In addition, the significance of the study on a meta-level should not be neglected.

The present study, as a pioneering study in this field, provides a first overview of typical game characteristics in para table tennis and is a starting point for future studies on this sport with more in-depth analyses. Detailed technical/ tactical analyses could give more precise knowledge on the structure of the sport and could lead to more practical implications for training and education. Analyses of, for example, the reasons for a player's dominance in a certain class could support the future fairness of the sport by giving input for possible changes in the classification system.

In summary, two basic strategies could be considered for future studies: (i) PA methods from able-bodied sport in general or specifically from able-bodied table tennis are applied to para table tennis to collect new data in para table tennis which are only currently available in able-bodied table tennis yet and (ii) studies on para specific things like competition classes or wheelchair specific techniques are conducted.

The strategies do not, of course, exclude the possibility of examining para specific issues with known methods applied to para sports. It is rather the approach that differs. In (i), a known method is the starting point. In contrast, in (ii), the foundation of a study is the para specific item to be investigated.

The conducted *study two* is therefore an example of strategy (i), as systematic game observation and notational analysis (as popular PA methods) combined with performance indices (included in the review article as popular approach in table tennis) are used to gather data in para table tennis. Of course, data for individual competition classes also emerge from the study, however, the competition classes are not examined as such, but are sub-samples, so to speak, and serve as independent variable.

6.3 First offensive shot in elite table tennis

As with *study two*, it is essential to look at the impact of this study from two different perspectives.

On the one hand, new table tennis-specific data and thus knowledge about the sport is generated. On the other hand, the general methodological approach is of considerable importance for the further development of PA in the sport of table tennis (or also for other little-researched sports).

Regarding the data obtained from the study, there are several important findings with possible practical implications for training and competition. Statistically, it was an advantage to be the player who played the first offensive stroke in a rally, taking the initiative for offensive play, so to speak. The most used and most successful technique was, for both men and women, the forehand topspin. It is interesting to note, however, that a technique that has just really evolved in the last decade and is now very popular among players – the backhand flip, also known as Chiquita or banana flip – is statistically disadvantageous for the player executing it. It is interesting precisely because there is or at least was the trend, especially in the men's game, to use more and more this "innovative" technique, to open the game. This trend was confirmed by the study as in the men's game, the backhand flip was the second most used technique. Another important result of the study for practice was that the possible advantage from the first offensive shot should be quickly exploited by the player with the intention to finish the rally with the follow up shot. Otherwise, the possibly existing advantage was lost in the course of a longer rally, as in longer rallies the advantage was then with the opponent statistically.

These content-related findings alone could already be valuable for table tennis and lead to adjustments in tactical education in the development of athletes. In the author's opinion, however, it might be even more important – especially for the field of PA in table tennis – on which idea or with which methodological approach this data could be generated.

A method – in this case state transition modelling – previously applied to other sports (Lai et al., 2012; Lam et al., 2021; Lames & McGarry, 2007), is applied to table tennis. This is paradigmatic for applying existing methods to specific features of a sport. In this case, the sport-specific peculiarity is that the first offensive shot has a special significance, as it might be considered as the turning point in the rally. With the support of the developed state transition model, in which the FOS was modelled as the central and important state, it was then possible to develop a corresponding observational system focusing on recording properties of the FOS. Another innovation of this study was the shot-number-independent analysis approach that was then applied. Typically, PA in table tennis is based on a shot-number based approach, e.g. the three-phase-method in Japan and China, which gives feedback regarding attributes of specific shot numbers (Tamaki et al., 2017; Zhang et al., 2013). The problem with shot-number based approaches is that the shot number itself doesn't reflect necessarily the semantics or meaning of a shot, which also applies for the FOS because it is defined by specific conditions that have to be fulfilled and not per se by one fixed shot number. All in all, this study not only provided new data that gained more precise knowledge about table tennis, but also showed that, on the one hand, methods from other sports can be transferred and applied to table tennis and, on the other hand, already proven approaches in table tennis sometimes have to be changed or adapted in order to be able to explore new things.

6.4 Limitation

As mentioned earlier, China is not only dominant in table tennis in the sporting area, but also in research, where probably no other country is making such a great effort. Although this dissertation and its research has probably received the best possible access to Chinese-language literature and first-hand information of the absolute highest level that one can get as a foreigner through the Chinese co-authors of the review paper, the further research in *study two* and *study three* is nevertheless based on the existing English- and German-language research.

Thus, it cannot be entirely ruled out that studies on certain areas might already exist, but have been published exclusively in Chinese and are simply not accessible to the English-speaking research community or to non-Chinese and thus could not be taken into account in this dissertation.

7 Outlook

Although PA is becoming increasingly popular in table tennis and is also being used more frequently in practice, there is still a lot of room for development and improvement. Other, more popular and financially strong sports can serve as role models and provide possible forecasts for table tennis.

Three areas for future developments should be distinguished here:

- methodological area
- technological area
- acceptance and importance of PA in table tennis

7.1 Methodological area

As already addressed in this paper, PA approaches used in other sports, especially in other racket sports, could also be of interest for table tennis. The FOS has been analysed in study 3 and has been denoted as the turning point in a rally because it is the transition from defensive to offensive play and can swing the momentum of the point heavily in favour of one player. Regardless of the significance of this shot, it does not automatically mean that this is the shot that decided the rally. The perturbation/relative phase approach already introduced in squash (McGarry et al., 1999) and tennis (Lames, 2006) could be an interesting method to find the decisive shot in a rally, which does not necessarily have to be the last valid shot in a rally or the already mentioned FOS. Another interesting approach which was used in the study of Link and Wenninger (2019) in beach volleyball is dealing with the so called "cold hand" phenomena. The study explores the influence of sideout failure on tactical decisions in the next sideout, meaning if athletes change their tactics after they lost a point using a certain tactic. Regarding table tennis, this could be of big interest especially for the tactical behaviour in the serve/receive game. Exploring the opponent's serve/receive tactics as a first step has been carried out already in several studies (Andreas et al., 2022; Djokic et al., 2020; Luini et al., 2021), but also knowing if or when an opponent will most likely change his/her tactics and maybe even knowing what tactics the opponent will use would be a big "upgrade" in the match preparation for players and coaches.

Another important point to be explicitly mentioned regarding the methodological area is that PA in table tennis not only has great potential exclusively in the technical/tactical area, but can also be used as a methodological support tool for other areas such as sports psychology (Leber & Höner, 2021). For example, in addition to tactical match preparation or opponent analysis, selected match scenes from the video analysis can also be used for sport psychological interventions in order to verify or underline possible observations of the psychologist or to clarify certain aspects for the athletes.

7.2 Technological area

Artificial intelligence is finding its way into various "big" sports like basketball (Li & Xu, 2021), football (Ks, 2020; Tuyls et al., 2021) and tennis (Moorhead, 2021; Smith, 2020; Yin, 2021) and is also being used in table tennis in a few cases already (e.g. OSAI from Russia (OSAI AFORA LTD., 2022), betterplay.ai from Israel (Miroshnik & Iturriaga, 2022) and different projects in China (Cao, 2014; Yujiao et al., 2018; Zheijang University, 2021). AI has a lot of potential in recognising certain patterns/tactics and could be a great help in evaluating opponents or preparing for matches. Image recognition for automatic data gathering is another big topic connected with AI and table tennis, as the manual data gathering process is still the bottleneck of the PA process in many cases. "Simple" tasks like collecting the score automatically or who is the server might already be in use and approaches to collect the ball placement automatically have been carried out, e.g. by OSAI (Voeikov et al., 2020). But in most cases – especially for ball placement - a very specific and fixed setup of equipment is necessary. Thus, in most cases it is not an option for players/coaches who only have access to their own equipment and recordings. One step further would be an automatic gathering of stroke techniques used. But table tennis is a very complex sport and every individual athlete is developing his/her individual technique based on his/her anthropometrics and physical prerequisites. Additionally, different styles or technique guidelines come into play throughout the players' table tennis education. Thus, it is not an easy task to get this data automatically collected by a machine or an algorithm because of the very individual (not to mention 'different') movements for the same shot techniques. Maybe machine learning could be the solution for automatic technique/movement detection which would be a big gamechanger for PA in table tennis.

If one goes another step further and data can be collected not only automatically but also in real-time, it would be of great benefits to several stakeholders. On the one hand, media could use that data for real-time statistics while broadcasting to give a better presentation of the sport and enrich the spectators' experience. On the other hand, a new sector for table tennis could be opened with that kind of data: real-time support for coaches during a match. So far, this is not an issue at all in table tennis, but depending on the type of information, the headset could be a possible tool used by coaches in the future, much like its use in American football.

If, in the course of professionalization in table tennis, one speaks of an ever-growing "team behind the team" in which the performance analyst(s) will also become more and more important, then, on the one hand, communication between these teams of specialists (e.g. coaches, performance analysts, doctors/physiotherapists, psychologists, fitness trainers, etc.), and on the other hand, the integration of data from the different experts (PA data such as match analyses, game plans, player profiles and video databases, but also health data, training documentation, injury documentation) must be guaranteed. For this purpose, comprehensive information systems are increasingly being used e.g. in professional football clubs/teams that are specially adapted to their needs and that centrally collect or combine the data of the expert teams and offer additional possibilities for communication as well as tools for organisation within the sub-teams and the team as a whole (Blobel & Lames, 2020). Such systems could also be a useful tool in table tennis, e.g. for national teams where the number of involved coaches has grown and a variety of additional experts/scientists are involved. In particular, the storage/organisation, distribution or presentation of data from match analyses is still often carried out without a central information system, which would significantly improve communication between the individual parties involved. For the realisation of such customised systems, however, there are currently (at least outside China) various political, financial and informatic barriers to overcome.

7.3 Acceptance and importance of PA in table tennis

The third and last, but also most fundamental area with great potential for development is the area which could be summarized as acceptance and importance of PA in table tennis, which needs to be approached from different directions.

The value of PA in table tennis and also the understanding and knowledge about it needs to be improved. Thus, more positions for PA experts, not only in the scientific field, but also in the sporting and practical field of table tennis, need to be created. In general, the support culture in table tennis needs to be improved with regular exchanges between coaches and scientists, as equals, – like Australia, for example, recently tried to do (Table Tennis Australia, 2021). Furthermore, PA should also be integrated as an integral part of player education. Science-based methods need to be taught to players at a young age and the great potential of match analysis needs to be shown so that they learn to use it correctly at an early age and learn to reap the benefits for themselves. In other sports, such as football, this image and understanding has already been developed. PA is a fixed part in many clubs and their youth academies (Fjelldal, 2019; Martinez Arastey, 2021; TSG Hoffenheim, 2020a) and more and more rethinking among coaches and officials to use scientific based methods of performance and video analysis can be observed (Deutscher Fußball-Bund (DFB), 2017; Finke & Notzon, 2014) – maybe also because there is more pressure from outside than in table tennis, e.g. to use new technical innovations or simply to use every possible (new) tool for improvement of their performance (TSG Hoffenheim, 2017). Analysts increasingly even take up positions in the coaching team and are a close confidant of the head coach (Lotz, 2021; TSG Hoffenheim, 2020b).

Due to the high status, the greater financial resources and also the development of an economic market with sports data (Link, 2018), the whole process in terms of the use and thereby also in terms of the acceptance and importance of PA is simply several years ahead in big sports like football (Bauer, 1992; Leser, 2007). In table tennis, this process is unfortunately still in the beginning stages in most of the countries and there is often pioneering work to be done to convince players, coaches and associations of the value of PA.

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Table tennis match analysis: a review

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ABSTRACT

In table tennis, many different approaches to scientific founded match analysis have been developed since the first ones in the 1960s. The aim of this paper is to give a review on some of the most acknowledged methods of match analysis in table tennis. The first chapter presents a historical overview of match analysis from all over the world. The second part reviews different approaches to match analysis in more detail, using the performance analysis classification of theoretical and practical performance analysis. The review includes the most actual theoretical performance analysis techniques in table tennis: performance indices, simulative approaches, momentum analysis, footwork analysis, and finally an approach which uses top expert knowledge for a comprehensive technical-tactical analysis. In the section of practical performance analysis, the paper presents two "best practice" examples describing performance analysis procedures of the two most successful countries of the last Olympics: China and Japan. The paper ends with a summary on the impact of the different approaches and gives an outlook on promising new developments.

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Table tennis; match analysis; performance analysis; racket sports

Introduction

The roots of the game known today as table tennis trace back to England in the second half of the 19th century. The first World Championship was held in 1926 in London during which the International Table Tennis Federation (ITTF) was founded (International Table Tennis Federation, 2017a). Nowadays, ITTF is the sports federation with the highest number of members in terms of national associations (226). Although no up-to-date statistics are available, in 1995 it was estimated that almost 300 million people play table tennis worldwide (Sklorz & Michaelis, 1995), including 40 million competitive table tennis players (Olympics, 2016). Thus, table tennis is a wide-spread sport and this review could have positive effects on the further development of the sport. Additionally, it could improve the daily work and consequently the performance of players and coaches.

Table tennis – like all game sports – can be conceived as a dynamic interaction process. The performance of a player depends always on the performance of the opponent (Hughes & Bartlett, 2002) and a match is a singular event (Lames & McGarry, 2007). Due to these circumstances, players and coaches need to analyse carefully and in detail not just their own, but also their opponent's performance as well, in order to derive hints for future training and improve their competitive abilities to gain advantages for future competitions.

Great advancements in the methodology of training, e.g. applying principles of motor learning, started in the 1960s and reached their full swing in the 1970s (International Table Tennis Federation, 2017a). At that time, the first approaches to table tennis match analysis have been recorded (Czwalina, 1976; Wu, 1963). Due to growing popularity and prevalence of table tennis, supported by the fact that table tennis became an Olympic sport in 1988, not only the methodology of training improved. The entire table tennis sport aimed to become more professional, including the search for a science based method for match analysis.

Particularly in China, match analysis started to grow. A lot of studies were carried out and match analysis became an integral component of the preparation of the national team before major championships (Li, 1977; Li, Zhuang, & Liang, 1981; Li, Zhuang, Liang, & Xu, 1983; Zhang, Zhou, & Hu, 1982). Due to this innovation, China may not only be seen as the dominating country in table tennis throughout its recent history, but also as a pioneer in table tennis match analysis. But also in other Asian and European countries different approaches were developed (e.g., Baca, Baron, Leser, & Kain, 2004; Boguschewski & Meiberth, 1993; Malagoli Lanzoni, Lobietti, & Merni, 2007; Pfeiffer, Zhang, & Hohmann, 2010; Tamaki, Yoshida, & Yamada, 2017).

The aim of this paper is to give a review on different approaches of match analysis in table tennis. The first chapter presents a historical overview of match analysis from all over

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the world, whilst the rest of the paper reviews different approaches to match analysis in more detail, using the following performance analysis classification.

Performance analysis with respect to competitions/matches can be distinguished into two subject areas – theoretical performance analysis and practical performance analysis (Lames & McGarry, 2007). The general aim of theoretical performance analysis is to explain and understand the structure of the sport. This involves identifying performance variables or patterns of performances which are common and important for the sport, analysing and quantifying the relation between different performance variables, and identifying key performance variables, which are, for example, highly correlated with being successful. The review includes the theoretical performance analysis approaches of performance indices, simulative approaches, momentum analysis, footwork analysis, and finally an approach which uses top expert knowledge for a comprehensive technical-tactical analysis. Practical performance analysis, on the other hand, aims at analysing individual athletes and teams and at identifying their weaknesses or strengths (Hohmann, Lames, & Letzelter, 2002; Lames & McGarry, 2007). The goals are to derive hints for training and to create an optimum match strategy for the upcoming competition. The review presents two "best practice" examples of practical performance analysis describing the two most successful countries of the last Olympics in Rio 2016, which also spent the most effort in doing match analysis in table tennis over the last years: China and Japan. An overview of the reviewed performance analysis approaches is given in Figure 1.

Methods of review

Electronic database searches for studies related to match analysis in table tennis were conducted in PubMed, Web of Knowledge (Sport Sciences), SPORTDiscus, SURF, Google Scholar and CiNii. Additionally, searches in the International Journal of Table Tennis Sciences and on the website of the China National Knowledge Infrastructure (CNKI) were conducted. The selected studies were either peer reviewed studies, or in the case of CNKI at least published in Chinese academic journals. The search was conducted using the keywords "table tennis", "match analysis", "performance analysis", "game analysis" or simply "analysis".

The advanced search term connects the four analysis keywords with a logical "or" and the four analysis keywords with "table tennis" with a logical "and" (("analysis" OR "performance analysis" OR "match analysis" OR "game analysis") AND "table tennis"). We found the following numbers of hits per database: PubMed (79), Web of Knowledge (37), SPORTDiscus (332), SURF (190), Google Scholar (34.600) and CiNii(70). Based on these hits we identified basic methods of performance analysis most common in table tennis. For each of those methods we choose an exemplary study and discuss this study in detail. The other studies applying this method are enumerated in the respective section. We discuss two examples for the popular method of performance indices and one example for the methods of model building and simulation. Momentum analysis is a traditional field of performance analysis since the works of Hughes (Hughes, Fenwick, & Murray, 2006; Hughes et al., 2015; Murray & Hughes, 2001). Representing studies of relationships between behavioural details and overall competition we report on footwork in table tennis. Finally, a quite different but also frequent and fruitful approach for generating knowledge in performance analysis, reconstruction of expert opinion is presented. Due to the heterogeneous nature of the subject a detailed qualitative content analysis did not seem to be appropriate, so that each subtopic was treated in a narrative review. All procedures performed in the study were in strict accordance with the Declaration of Helsinki as well as with the ethical standards of the Technical University of Munich.

Table tennis performance analysis

Historical approaches and contemporary trends

Regarding the tactical analysis of table tennis matches, one can distinguish two approximately continuous traditions: the Chinese and the European tradition. While the origin of the Chinese tradition can be traced back to the 1960s (Wu, 1963), the European tradition is somewhat younger, probably starting with Czwalina´s research seminar (Czwalina, 1976). In China, Wu´s three-phase method of performance diagnosis has evolved into a mainstream approach, fundamentally

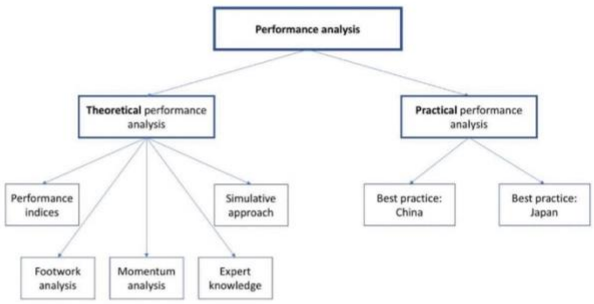

Figure 1. Overview of the reviewed performance analysis approaches.

based on a working group to study table tennis matches, which was established around the year 1987 (Zhang, 2006). In Europe, diverse approaches have been developed to record all or certain essential strokes (e.g.,Trupkovic, 1978; Vecko, 1979). Besides tools that were meant for coaches, the first empirical studies in Europe were carried out, as well (Hudetz, 1980; Perger & Hoerner, 1979a, 1979b, 1979c; Pfeffermann, 1984; Scherak, 1981).

According to Muster (1999), academic approaches developed in central Europe at the beginning of the 1990s explored the reciprocal dependency of actions and reactions of players. On the one hand, this went along with systematically relying on the video-based visualization of initial, typical, or final situations of the rallies (e.g., Baca et al., 2004; Sialino, 1996). On the other hand, at the start of 1990s, the idea of simulating tactical behaviour in table tennis was developed. Based on data patterns, it was possible to manipulate the probability of occurrence in regard to single shots, as well as with respect to transitions between strokes being linked to each other, and right up to the simulation of entire rallies. With the aid of simulation results, one tries to receive some indication about the performance relevance of tactical behaviour patterns (Boguschewski & Meiberth, 1993). Regarding the mathematical-simulative performance diagnosis, German and Chinese research activities became historically intertwined (e.g., Pfeiffer et al., 2010).

The latest developments in China have become very sophisticated and grounded in artificial neural networks, data mining, Markov chains, and the rough set theory (Zhang, Liu, Hu, & Liu, 2014). Compared with this, in Europe three descriptive procedures are frequently used to observe table tennis matches. The oldest approach still in use is the one of Djokic and colleagues (e.g., Djokic, 2002; Djokic, Munivrana, & Levajac, 2015). Weber and Baumgärtner (2008) focus on match analysis, whereas Malagoli Lanzoni, Di Michele, and Merni (2014) present a notational analysis of footwork in table tennis.

From an applied viewpoint, systematic match analysis in table tennis has reached practical significance in the areas of preparation for top events (Yoshida, 2013; Zhang, Yu, & Hu, 2010) as well as coach education (Straub & Klein-Soetebier, 2017).

Theoretical performance analysis in table tennis

Performance indices: three-phase-method/shot number based analysis

Wu and Li (1992) were the first to introduce a method which analyses the performance of the following three phases of a rally: "attack after service" on the first and third shot, "attack after receive" on the second and fourth shot, and "rally" after the fourth shot. This method has been widely adopted in match analysis for table tennis (Hao, Tian, Hao, & Song, 2010; Hsu, 2010; Hsu, Chen, & Wang, 2014). The key idea of this method is to divide a rally into multiple phases by shot number (or the number of a shot in a rally). The performance indices used in this method are `scoring rate' $W_i$ and `usage rate' U_i, which are defined as follows:

$$W_i = \frac{n_i}{n_i + m_i} \tag{1}$$

$$U_i = \frac{n_i + m_i}{n_{all} + m_{all}} \tag{2}$$

where n_i is the number of shots scored at the i-th shot number, and m_i is the number of shots lost at the i-th shot number. Note that a high W_i does not always indicate good scoring ability because it may be high when m_i is small. Therefore, it is necessary to consider the two indices together. Zhang, Liu, Hu, and Liu (2013) proposed a method to integrate the indices into `technique effectiveness' E_i, which is defined as follows:

$$E_i = -\left(1 + \sqrt{2}/2\right) + \left(1.5 + \sqrt{2}\right) Eo_i - \sqrt{2} Eo_i^2/2 \tag{3}$$

$$Eo_i = (1 + U_i)^{W_i - 0.5} \tag{4}$$

The coefficients in the equation of E_i represent the relationship between W_i, U_i, and E_i. Zhang et al. (2013) also proposed evaluation criteria for technique effectiveness in an analysis of 244 singles matches. Using this method, the authors successfully showed the quantitative difference between Chinese players and players from other countries. Chinese players performed far better in all three phases, corresponding to the reality of world rankings.

In recent research, the frequency of (or number of shots for) each shot number was introduced. Tamaki et al. (2017) proposed another definition of the scoring rate W_i and effectiveness E_i, and an additional index `losing rate' L_i, which are defined as follows:

$$W_i = \frac{n_i}{S_i} \tag{5}$$

$$L_i = \frac{m_i}{S_i} \tag{6}$$

$$E_i = W_i - L_i \tag{7}$$

where S_i is the number of shots for the i-th shot. The key idea of this method is to compute the number of shots from the scoring player and the shot number of the scoring shot. Conventionally, performance indices were computed without the number of neutrals. `Neutral' indicates the shot result where nobody scores a point. The proposed method of Tamaki et al. (2017) counts the number of neutrals as part of the number of shots. While an additional parameter is considered, the inputs of the method are unchanged. By introducing the losing rate, returning skills can be evaluated separately from scoring skills. In addition, the indices can be compared among players without evaluation criteria, because the value can be converted into a unit of points by multiplying the assumed number of shots. Through an analysis of 70 singles matches, it was demonstrated that the indices computed with the number of shots provides better results than the conventional three-phase-method.

As a conclusion of index techniques in performance analysis of table tennis it has to be mentioned that there is a general problem to model aspects of complex behaviour in a competition in one single figure. Nevertheless, in chapter best practice it will be shown that both methods are successfully made use of in national support systems for the respective national teams.

Simulative performance analysis: Markov-chain-modelling

As described in the previous chapter, several studies on applied match analysis in table tennis try to assess performance by using performance indicators (Hughes & Bartlett, 2002; Malagoli Lanzoni, Di Michele, & Merni, 2012a). Typically, these performance indicators give summative statistics on the player behaviour for the whole match. This can be criticised (Lames & McGarry, 2007) for missing important aspects of the game, e.g. the dynamics of a match and the context of each action. Alternative approaches employ probabilistic models to calculate the outcome of matches (Newton & Aslam, 2009; Strauss & Arnold, 1987).

Lames (1991) proposes a performance analysis in tennis using mathematical simulation, which was applied to table tennis by Zhang (Pfeiffer et al., 2010; Zhang, 2006). This approach is based on transition matrices as a summative match description. Assuming specific properties, transition matrices can be treated as finite Markov chains. This allows for computing various statistics, e.g. expected rally length, which may be used for validating the assumptions. But most importantly, by working with mathematical structures, the impact of a tactical behaviour may be derived by simulation. Recently, Wenninger and Lames (2016) introduced an improved method to capture the relevance of tactical behaviours. Instead of modelling the difficulty of changing certain behaviours, which was an essential part of the original method (Lames, 1991; Pfeiffer et al., 2010; Zhang, 2006), they used high-dimensional numerical derivation.

Pfeiffer et al. (2010) analysed the "performance relevance" of tactical behaviours in four different state models (game action, stroke position, stroke direction and stroke technique). Wenninger and Lames (2016) use one state model with rally length to analyse the relevance of each stroke number and the tactical behaviour of "risk-taking" on the winning probability. Pfeiffer et al. (2010) obtained the following results with their simulation: In the game action state model, they found the highest performance relevance in the tactical behaviour pattern called "both players strike with attack techniques" (transition "neutral" to "neutral"). For the stroke position model, the tactical behaviours "strike long line from the forehand side" (transition "forehand" to "backhand") and "strike cross from the backhand side (transition "backhand" to "backhand") showed relatively high performance relevance compared to other tactics. In the stroke direction state model, the transition "long backhand" to "long backhand" showed very high performance relevance. The greatest performance relevance among all observed transitions between stroke techniques was the tactical behaviour "topspin technique against block technique" (transition "topspin" to "block") (Figure 2).

Another, more general result of Pfeiffer et al. (2010) was the stronger influence of the error rate in comparison to the weaker influence of direct points. This result was confirmed by the simulation of Wenninger and Lames (2016). In addition to the high impact of errors in comparison to direct points, they found that long rallies with more than five strokes have a very high impact and that the use of a riskier playstyle is more rewarding to the losing player, rather than to the winning player.

Although stochastic modelling and simulation seem to have some obvious potential for answering practical questions, more elaborate studies addressing less superficial elements of table tennis are still missing as well as a successful implementation in practice. The big advantage of stochastic modelling and simulation is that tactical behaviours which actually did not appear in the match can be analysed and possible resulting effects can be simulated. Nevertheless, the entry barrier to these methods is quite high because it requires a certain degree of mathematical background.

Momentum analysis: double moving average

The concept of momentum is derived from psychological momentum, a well-known construct in the humanities (Adler, 1981). In sports, there are several approaches to modelling momentum (Ferreira, 2013; Taylor & Demick, 1994), sometimes focusing on critical incidents (Burke, Burke, & Joyner, 1999). In performance analysis, momentum analysis comprises methods designed especially for assessing the dynamic, interactive nature of game sports. It tries to assess the momentary strength or dominance of the two players/teams. This specific concept of momentum analysis was first introduced by Murray and

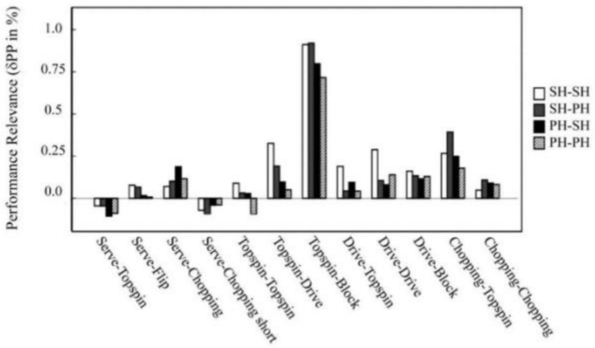

Figure 2. Results of stroke technique model (Pfeiffer et al., 2010).

Hughes (2001) in squash. Initially, it consisted of a simple score difference line, but more sophisticated models were soon developed and applied to a number of sports such as rugby, basketball, squash and volleyball (Hughes, Bürger, Hughes, Murray, & James, 2013; Hughes et al., 2015).

In table tennis, Liu (2013) presented a momentum analysis model in her master's thesis. This work is based on Lames (2006), who introduced a double moving average (DMA; double backward moving average of length 4) on the sequence of successful/not successful ball possessions in handball. She found that a length of 4 is a good compromise between stability and flexibility for assessing momentary strength, and she further improved the method by using first a forward moving average and then a backward one (formulae (1) and (2)), thus optimally synchronising the match with the time series of momentum.

$$MA_{forward,k}(n) = \frac{1}{k}\sum_{i=0}^{k-1} Score(n+i) \quad (1)$$

Formula (1) shows the calculation of the first moving average (MA), where n is the number of rally, k is the length of the moving average, and $Score(n)$ is the result of the rally with 0 or 1 indicating winning or losing the rally from the point of view of the analysed player.

$$\begin{aligned} DMA(n) &= MA_{backward,k}(MA_{forward,k}(n)) \\ &= \frac{1}{k}\sum_{i=0}^{k-1} MA_{forward,k}(n-i) \quad (2) \end{aligned}$$

Formula (2) shows how to calculate the double moving average as a backward moving average on the time series of forward moving averages. DMA may take on values between 0 and 1, with values close to 1 indicating a strong period for a player and a DMA close to 0 indicating a weak phase.

Liu (2013) classified performance momentum as advantage period ($0.625 \leqq DMA \leqq 1$), stalemate period ($0.375 < DMA < 0.625$) and disadvantage period ($0 \leqq DMA \leqq 0.375$). For validation, she made a comparison between 32 winning matches and 28 losing matches from eight elite male players. Results showed consistently that, in winning matches, the distribution characteristics of the three periods are advantage >stalemate >disadvantage, and in losing matches they are disadvantage >stalemate >advantage.

Liu, Shi, and Kong (2015) presented detailed application principles and analyses using DMA in match analyses with China's national table tennis team. Summarizing the experiences collected with DMA for momentum analyses so far, it can be said that DMA is a valid model for interaction and dynamics in table tennis. In practical performance analysis, it is now possible to examine a past match of the player to find out weak and strong phases, thus providing information to guide further in-depth video analyses of rallies. Moreover, one can investigate several matches of a player and look for hints for constant or volatile game conduct as a stable trait, thus generating valuable hints for training. These applications have already been successfully carried out with international top level players.

Theoretical performance analysis includes the study of the typical dynamical properties for table tennis matches. One could characterize the normal variability of performance level over a match and specify deviations from that norm. A further option is to calculate a separate DMAs for serving player. This reveals the dynamics of the service game of each player and makes it possible, for example, to study the interaction between momentary success of player A and player B with potentially very interesting analyses for both practical and theoretical performance analysis.

Footwork analysis

Footwork analysis in table tennis is the process of recording and analysing movements made by players during matches to move the body in the direction of the ball. In 2003, Tepper and Olvech (2003) presented a basic classification and description of the main steps. In 2007, Malagoli Lanzoni et al. (2007) created an overall standard definition of the different types of steps used by table tennis players: one step, short steps (chassé, slide, turn/pivot), crossover, and "stroke without step". Malagoli Lanzoni et al. (2012a, 2012b, 2014) identified the most important performance indicators in table tennis and the intra-and inter-observer reliability necessary for reliable data collection. Globally, these studies showed a high intra-observer (Krippendorff's alpha = 0.99) and inter-observer reliability (Krippendorff's alpha = 0.96) for the following list of steps: one step, chassé, slide, pivot, crossover and no step.

Malagoli Lanzoni et al. (2007) collected data on four top-class table tennis players, revealing that the most frequent steps are: one step (37.3%), turn/pivot (21.1%), chassé (15.2%), stroke without step (11.5%), slide (7.5%), and cross-over (7.3%). In 2009, Malagoli Lanzoni and Lobietti (2009) compared the footwork technique used by two groups of national and international level players. Results confirmed that the most used step is the one step, which showed significant differences to the other steps. International players prefer the turn step (pivot), representing footwork typical of a modern and offensive style of play. National players prefer to move the body in front of the table (chassè) or not moving the feet.

Malagoli Lanzoni, Di Michele, and Merni (2013a) analysed the distribution of stroke and footwork types and their relation, comparing top-level men and women players. Results showed significant differences between the two groups. The most used step for males is one step (31.9%) and stroke without step for females (43.6%). One step is mainly used by male players to return services with a forehand push (39.0%) and female players play many backhand block and topspin not moving their feet. In 2013, the same authors (Malagoli Lanzoni, Di Michele, & Merni, 2013b) studied different categories of players, comparing senior, junior and cadet athletes. Their analysis confirmed previous studies showing that the most used step is the one step (32%, 28%, and 31%). Differences among groups were observed for the chassé (24%, 15%, and 15%) and stroke without step (18%, 29%, and 28%).

Malagoli Lanzoni et al. (2014) also compared Asian and European players. This study showed that the main difference in the type of footwork is that pivot and crossover are used more often by Asians, while the conservative chassé is more frequently used by Europeans. The statistical analysis, based on a selected log-linear model, included the relations between footwork/stroke, continent/footwork, continent/stroke and stroke/outcome. Results show that, as such footwork is not linked to a specific outcome, but the outcome is achieved because of the association of the footwork with a specific stroke.

This in no way diminishes the importance of footwork technique in table tennis. Indeed, it must be considered the most important technical aspect that allows the player to arrive in the right position to perform his/her best shot. With studies of this type, analysing the relevance of certain skills for overall success, performance analysis in table tennis contributes to a scientifically founded base for training.

Expert knowledge for assessing technical-tactical elements

Knowledge on the impact of different technical-tactical elements on performance in table tennis is crucial information for training in table tennis and each game sport at top level as well as on youth stages. Typically, this information is sought for by match analysis (e.g., Baca et al., 2004; Sialino, 1996; Zhang, Li, & Fu, 2005). In investigating frequency and efficiency of technical-tactical elements in a representative sample, one may arrive at a typical profile for a population of players. Although this method is very common and valid, it only reflects behaviour in matches that is observable in competition. Match behaviour may be conceived as the outcome of singular interaction processes between the two players, though (Lames & McGarry, 2007). This implies that elements used and effective in matches do not have to be necessarily the most important ones for training.

For example, a player may choose a weaker element of his repertoire in order to avoid the opponent using a very strong stroke. He is forced to do so because of this strength of his opponent which then does not occur in a match analysis but is nevertheless a worthwhile element that was acquired in training. Also, there may be other reasons than usage in competition giving importance to an element for training, for example its role as an important intermediate step in the learning process of table tennis skills.

For these reasons, in addition to match analyses, an alternative approach to assess technical-tactical elements may be considered: expert knowledge. Recently, a study using this alternative method was conducted in table tennis (Munivrana, Furjan-Mandić, & Kondrič, 2015; Munivrana, Petrinović, & Kondrič, 2015). First, a comprehensive list of technical-tactical elements in table tennis was developed. Starting from eight basic table tennis techniques ("drive" attack; topspin attack, block, backspin defense, chop, attack over the table "flick", balloon defense, service) each for forehand and backhand, the most relevant technical-tactical elements, including combinations with prior strokes of the opponent were considered (except service), resulting in a list of 110 elements (Munivrana et al., 2015, 2015). The appropriateness and completeness of this list was approved by experts.

The experts for the main study were eight coaches having successfully trained or played at international top level (medal in top events or finals of a European club competition). They were presented a questionnaire where they gave ratings for frequency and effectiveness of the 110 elements with respect to 21 variables. These variables stand for different aspects of table tennis games like spatial variables, e.g. basic system of play (short distance offensive, middle distance offensive, defensive), distance from table (3 variables), and hitting spot over the table (3 variables). Moreover, the phase of the game (3 variables), grip style (shake-hand, penholder), materials used (3 variables), and basic tactical aspects (speed, placement, spin) were in the questionnaire. Assessments were given by a 5-level Likert scale ranging from 1 = Not at all important or hardly important to 5 = Extremely important, thus requiring 2.310 scores per expert. Expert agreement was controlled by several criteria and showed good to very good results (Cronbach's alpha >.90, except for grip style shake-hand alpha = 0.757).

The results provide a detailed description of the relevance of each element with regard to the 21 variables. A cluster analysis identifies elements with similar profiles. A 3-cluster and a 7-cluster solution is presented (Munivrana et al., 2015, 2015) with significant differences between clusters for the most important variables like playing style.

Although relying on subjective expert opinions, the study provides valuable insight into the structure and role of technical-tactical elements of table tennis. It gives a detailed description of their importance with regard to many important aspects of table tennis matches, thus providing valuable information for training. Expert opinion should be acknowledged as alternative source of information on importance and relevance of elements of table tennis because it doesn't necessarily depend on having a really huge and representative sample of observed matches. It depends upon knowledge of top class experts that have undergone through hundreds of matches at the highest level of the game and who have knowledge that is based on experience that can be legitimately used as a source of information for game analysis. Thus, the main advantage of the expert analysis method is that in cases of a small and not necessarily representative sample it could facilitate collection of the overall data by relaying on expert knowledge and experience, and could even be potentially more comprehensive than other more objective methods which need bigger samples.

The main disadvantage of the expert evaluation method is that it is based on empirical subjective data. Thus, it is necessary to have a larger number of experts included and they have to show a high level of agreeing in evaluating technical-tactical activities for results to be recognised as valid ones.

Practical performance analysis in table tennis

Best practice: China – Olympic Games 2008 & 2012

In both the Beijing 2008 Olympic Games and London 2012 Olympic Games, the Chinese team won all the gold, silver and bronze medals possible for a single country. This was attributed not only to the technical strength of the Chinese players but also to their adequate preparation before matches, the most important part of which was match analysis. Figure 3 shows the framework of the Chinese team's preparation for the Olympic Games.

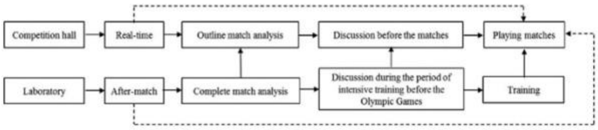

Figure 3. The framework of the Chinese team's preparation for the Olympic Games.

Real-time and after-match data collection

Table tennis match analysis can be categorized into real-time analysis conducted in the competition hall and after-match analysis conducted in the laboratory (Yu, Zhang, & Ling, 2008a, 2008b; Zhang et al., 2005, 2010). Real-time analysis is mainly adapted to analysing matches between players who will become the Chinese players' opponent in the next round. Due to the limitation of observation time, real-time analysis takes each "rally" as an observation unit and records the result (scoring or losing) of the last stroke technique in each rally, so as to offer an outline match analysis to coaches and players during their preparation in the Olympic Games. After-match analysis takes "each stroke" as an observation unit, and records the stroke techniques, stroke placements, stroke positions and tactical situation (offensive, defensive, controlling or in a stalemate) of both players. This method of data collection, recording almost all the information related to matches, offers a complete match analysis, thus satisfying the various needs of coaches and players as well as laying a foundation for advanced match analysis like modelling and data mining.

Outline match analysis and complete match analysis

The main focuses of outline match analysis (including videos and statistical data) are: the placements of scored serves, the results (scoring or losing) of stroke techniques in receiving, the third stroke and the fourth stroke, as well as the results of forehand stroke techniques and backhand stroke techniques after the fourth stroke.

Complete match analysis is a comprehensive analysis of several matches including the same player, either between one foreign player and several Chinese players (left-handed, right-handed, pen-hold grip, shakehand grip) or between one foreign player and one Chinese player. Apart from offering videos and data analysis of stroke techniques and placements of the first four strokes and after-fourth strokes, complete match analysis also includes analysing changes in score and tactics in the beginning part (1–4 point) and in the crucial part (after 9 point), as well as comparing data in winning games and losing games, data of players with different playing styles, and data of the same player in different stages, etc. Moreover, important tactics can be shown in an animated display with detailed descriptions, in order to analyse why a certain tactic scored or lost in the match and to put forward relevant suggestions (Yu, Zhang, & Ling, 2009; Zhang, Yu, Liu, & Wang, 2008).

Preparation before matches and discussion during the period of intensive training

As only one match round of table tennis will be held per day during Olympic Games, coaches and players have abundant preparation time for the next match. When preparing for the next match, a player is supposed to watch the video of his opponent's last match and study the outline match analysis to remember the important tactical features of his opponent.

While during the period of intensive training, the Chinese team are likely to spend much time discussing the tactical features of their opponents, who were categorized into three levels. For the opponents at the first level, the whole team (including coaches, players and researchers) will have a discussion together and adopt complete match analysis to analyse each opponent, and then apply the corresponding suggestions to training; while for the opponents at the second and third level, only players or small groups (one coach and some players) will watch and analyse relevant match videos and reports of outline match analysis (Huang, Zhang, & Liu, 2014; Zhang et al., 2008).

Best practice: Japan – Olympic Games 2012

During the 2012 Olympic Games, 136 matches played at the stadium of the table tennis event were analysed for use by the Japanese national table tennis team (Tamaki, Saito, Yoshida, Yamada, & Ozaki, 2012; Yoshida, 2013). In an important milestone, Japan's national team had employed scientific methods in a practical scenario for the first time. For the analysis, a computer program was developed to optimise the analysis procedure. This program was designed to conduct shot number based analysis (described in "Performance indices: three-Phase-Method/Shot number based analysis") and an in-depth analysis of the played shots (hereinafter referred to as `detailed analysis'). A key feature of the program was optimising data collection, consisting of the following functions: server and receiver prediction from the game and point scores, scored player determination from the server, shot number of the scored shot, automatic update of the game scores and point scores from the scored player, and keyboard short-cuts for every operation.

When limited time is available for data collection, one of the most difficult challenges is posed by error correction. For example, the shot number of the scored shot was sometimes miscounted. If many operations are required to correct the error, a few rallies could be missed in a real-time scenario. In the program, it was possible to correct the shot number using only two clicks. Such functions allowed for real-time data collection for the shot number based analysis. Since data for the detailed analysis (placement of ball, hitting type, etc.) were not collected in real time, shot data were designed to collect after the matches. The analysis results were summarised on one sheet for one match and on several sheets for games. Moreover, the functions for video analysis were implemented. If a specific scene from the video was required for analysis, the program could develop a video showing the required rallies in a row. As described above, the program was designed for statistical analysis as well as subjective analysis using videos.

Using the developed program, performance analysis was carried out for Japan's national table tennis team at the 2012 Olympic Games. Data were collected by seven individuals. Four individuals collected data for the shot number based analysis at the stadium and fed back the results immediately after the matches. Three individuals collected data for the detailed analysis by observing videos in Japan and fed back the results by the morning following the matches (note: there is a nine-hour time difference between the United Kingdom and Japan). In total, 136 matches were analysed. The head coach of the women's team requested for the analysis results, implying that the analysis was used to formulate tactics. Although the impact of the analysis on the matches was unclear, the use of the analysis revealed the challenges involved. The head coach of the men's team said, "The game analysis data was great". However, we were unable to sufficiently tie it into our game strategies (Yoshida, 2013). As the comment implies, the frequent usage of statistical analysis and the training to use it were the primary challenges. Automatic data collection was also identified as indispensable to conducting a detailed analysis in a short time. Since then, such challenges are being gradually met. In 2013, a full-time employee was hired to conduct performance analysis for Japan's national table tennis team. Further, automatic data collection was partially realized using computer vision technologies (Tamaki & Saito, 2015; Tamaki, Saito, & Yoshida, 2015). Performance analysis is improving through practice and is expected to become more practically useful in the future.

Discussion

This review provides an overview of many historical approaches in table tennis match analysis. Starting with first approaches in China, there has been a strong development throughout the recent history. The use of performance indices for match analysis is still very common, but is flanked by simulative and biomechanical approaches nowadays. In addition, momentum analysis, which gives fast feedback about momentary dominance of a player, as well as analysis on footwork, which is the base of every stroke, is getting more and more important for players and coaches during the analysis process.

The most important result of this study was the review of existing literature in performance analysis of table tennis revealing that the most prominent techniques in performance analysis are made use of in table tennis. As mentioned, these techniques share the same disadvantages as applications in other sports, but nevertheless, in the game of table tennis some approaches provide specific solutions partly even with sustainable practical impact.

The given best practice examples of the leading nation China and, the probably most improving nation in the recent years – Japan – showed the heavy impact of performance analysis on the practical work of the leading nations. Despite this high level of development of game analysis, only a few nations make serious efforts to introduce it to their national teams as a routine in practical work.

It may be expected that usage will become more widespread when further improvements are implemented in practice. The main obstacle until now is that data collection is very time-consuming. Thus, automatization of the data collection has great potential. For example, Tamaki and Saito (2015) developed an algorithm to reconstruct the 3D trajectory of a ball with unsynchronized videos, which is usable for match analysis. Oku and Iida (2017) applied an auto pan-tilt technology to shoot high-resolution images of a ball in high sampling rate. Oku and Iida's method could make it easier to calculate the spin of a ball. In Tennis, there are already solutions for automatic match analysis using vision based technology (e.g., Reno et al., 2017).

Automatic position/placement detection of the ball by image recognition could lead to a big simplification of the analysis process also in table tennis. According to this trend, match analysis could shift to utilization of enormous data that is automatically collected. To deal with that big amount of data, fields like machine learning and data mining may have an important role in table tennis match analysis in the future as well (Yu, Zhang, & Hu, 2008). By using well-structured and well-presented data, not only the performance of players can be enhanced. Also, the education of coaches can benefit from that development.

At the 2016 Rio Olympics, the net reach for the table tennis events was 552,300,000 viewers (International Table Tennis Federation, 2017b). Thus, match analysis in table tennis, for example with descriptive and graphic real-time statistics, has high potential not only to improve the development programmes of young players (Faber, 2016), the performance of competitive players or to educate coaches, but also to improve the broadcasting for TV spectators and the promotion of table tennis.

Finally, some limitations of the review must be acknowledged. First, national studies which were published only within a certain country are probably missing in the international scientific databases because of language limitations. Secondly, practical performance analysis studies are often rather published in national coaching journals than in scientific journals. Thus, these kinds of studies are missing in the used databases as well. Furthermore, some types of match analysis studies were not reviewed. For example, studies who analyse the level and the development of the sport as such are missing because in table tennis none of these studies are published in international scientific journals yet. Also studies on the influence of material and the impact of rule changes were not taken into account.

Another limitation is that the most table tennis studies are carried out only in a few countries where table tennis is very popular. Regions where other sports are prevalent contributed very few table tennis studies. Thus, countries like USA, Australia and Great Britain which are usually very active and important in sports science are very rarely involved in table tennis research.

In addition to the low spreading of table tennis research, the different standards of scientific levels have to be mentioned as well. Especially in practical performance analysis, the main focus is not on the enlightenment of the structure of table tennis by the use of scientific methods but on the production of practical information for training which are often generated with lower awareness of the used methods.

This review has shown that promising developments have been accomplished over the last decades but there is still a long way to go for sports analytics in table tennis to reach the level it has in different popular sports, such as soccer or American football. To achieve that aim, more countries have to be involved in table tennis research and the scientific level, especially the methodological level in the practical performance analysis has to be increased.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Main Article

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Game characteristics in elite para table tennis

Introduction

Paralympic sports have gained more attention during the last couple of years in many countries (Blauwet & Willick, 2012). It appears that the medal race, typically seen in regular sports (De Bosscher, De Knop, van Bottenburg, Shibli, & Bingham, 2009), also started in para sports. Countries are striving for podium position at the international events. Since para athletes with different degrees of impairments generally compete in different classes, there are many medals at stake in para sports. It also seems for that reason that more national sport associations are investing in para sports and setting up talent developmental programs to support para players aiming for the top level. This has led to more awareness, attention and financial support for para sports from the spectrum of recreational sport participation to elite level.

In para table tennis the players are classified by official classifiers in class 1–11 (International Paralympic Committee, 2015). The classification depends on the capabilities of the players. The underlying causes for the impairments can vary between players; players with growth, genetic, neurological and orthopaedic disorders or players with impairments caused by a trauma can compete in the same class. Players that compete in a wheelchair are classified within class 1–5 and those who compete standing within 6–10. The less impaired a player is, the higher the classification. Class 11 is reserved for players with intellectual impairments (e.g. difficulties with pattern recognition, sequencing and memory, or with a slower reaction).

Due to the number of classes, elite para table tennis players can compete for up to 33 medal positions in both men and women individual competition. In addition to this there is also a team competition in which nations can be represented by a team consisting of two players. Classes are often combined for the team competition. Both the individual and the team events are interesting for national table tennis associations as they are often evaluated and granted based on their success, i.e. the number of medals, in official international events by their government.

The definition of handicap classes is a central problem of para table tennis, since only if this issue is solved satisfactorily will competitions be fair and attractive. On the other hand, there is the dilemma of not creating too many classes for organizational reasons, e.g. there should be enough players per class to promise attractive and open competitions. Besides knowledge on the physical consequences of certain impairments, performance analysis can provide information about the structure of male and female matches depending on handicap class and thus provide a background for future adjustments of handicap classes. Moreover, a general task of theoretical performance analysis is the description of the structure of sports for many purposes such as training optimization, talent development, media information or event enhancement. In other Paralympic sports like wheelchair tennis, studies about competition parameters (Sánchez-Pay, Torres-Luque, & Sanz-Rivas, 2015) and game characteristics (Sánchez-Pay, Torres-Luque, & Sanz-Rivas, 2017) have already been conducted to serve exactly these purposes.

To the best of the authors' knowledge, there are no studies available that present the game characteristics in para table tennis (class 1–10). Up to now, only a few studies have been conducted in the field of para table tennis, which mostly deal with players with intellectual impairments. These studies focused on the cognitive profiles (Van Biesen, Mactavish, McCulloch, Lenaerts, & Vanlandewijck, 2016b), the relationship between cognition and the tactical proficiency (Van Biesen, Mactavish, Kerremans, & Vanlandewijck, 2016a) and the technical or tactical proficiency of intellectually impaired athletes (Van Biesen, Mactavish, Pattyn, & Vanlandewijck, 2012; Van Biesen, Mactavish, & Vanlandewijck, 2014). Besides those studies about players with intellectual impairments, only two pilot studies were found on functional abilities and shoulder injuries in wheelchair-bound, physically impaired table tennis players (Lim, Bin, Tan, Li, & Teng, 2015; You, Lee, Lee, Jang, & Lee, 2016). However, basic features of performance analysis in para table tennis are crucial to set up adequate aims for training and to guide players to a higher level. Consequently, this study focuses on the game characteristics of elite para table tennis of class 1–10.

As observed in able-bodied table tennis, the rally length and serve are important characteristics (Fuchs et al., 2018; Geske & Müller, 2010; Molod-

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Table 1 Data sample: match distribution according to impairment class and sex

Class	Sex		Total
	Female	Male	
C01	–	11	11
C02	11	10	21
C03	10	16	26
C04	16	10	26
C05	12	13	25
C06	11	13	24
C07	12	13	25
C08	11	12	24
C09	12	12	24
C10	12	10	22
Total	107	120	227

zoff, 2008; Tamaki, Yoshida, & Yamada, 2017). Rally length provides information on which strokes (e.g. serve, receive, third stroke) are the most used ones (to finish a rally). More specifically, if the information about the server and the winner of a rally is also available, it is possible to collect information about the last stroke of the winner of the rally. Thus, it is possible to collect data about the frequency of the stroke numbers with which points are scored. There might be a difference between classes regarding rally length and thus which stroke actually is the most important one to score a point in the respective class. In that case, different advice for future training should be given to para table tennis players in different impairment classes. Besides the possible variation between classifications in para table tennis, one needs to investigate whether the gender itself has the same impact on the rally length as shown in able-bodied table tennis. Fuchs and Lames (2017) showed in their study on able-bodied players that the mean rally length in women's table tennis is significantly higher than in men's table tennis (women 5.111 ± 0.666 versus men 4.731 ± 0.417; $t = -4.641$, $p < 0.001$, $d = 0.729$). In their discussion, the authors assign the physical advantages of the men to be able to finish the rally earlier as a possible reason. It is hard to predict whether these results can be generalized to para table tennis. Perhaps the interactions between physical impairment class and gender have a different impact on rally length.

The serve is part of every rally and has a great impact on the consecutive strokes. It is often a decisive stroke in the game while being the only situation in which the serving player has total control over how and where to play the ball. The serve might be even more important in para table tennis than in able-bodied table tennis; a para player might experience problems to "kill" the ball during a long rally or even to reach the ball as the rally gets longer due to his limitations as a consequence of his/her impairment.

This study focuses on rally length and impact of the serve, i.e. the winning probability when serving, in elite para table tennis (class 1–10) to provide a better insight into the task characteristics of para table tennis. The influences of sex and the level of impairment and their possible interactions will be taken into account. The results of this study may serve as a starting point for many current issues in para table tennis such as the definition of fair handicap classes, background information for talent development programs as well as training and monitoring para table tennis players.

Methods

Data collection

Matches of elite para table tennis players (class 1–10) ranked in the top 20 of the world ranking lists in their class were analysed for this study. Video recordings of the Paralympic Games 2016, the European Championship and World Team Championship in 2017 and of World Tour Tournaments in 2017 (Slovenia Open) and 2018 (China Open, Italian Open, Slovakia Open and Slovenia Open) were used for this purpose. By entering official International Table Tennis Federation (ITTF)/ITTF Paralympic Table Tennis Committee (IPTTC) events, participants release all rights, or rights held by their agents or sponsors, in all matters relating to television and web casting coverage, video and motion picture coverage, as well as photographic coverage of any kind and hence accept such coverage during the event. All data were recorded in an anonymous dataset. Procedures performed in the study were in strict accordance with the Declaration of Helsinki as well as with the ethical standards of the Technical University of Munich, Germany.

A total of 227 matches were analysed, including 120 men's and 107 women's matches. The 227 analysed matches led to a total number of 15,743 analysed rallies, 8498 rallies of men's matches, 7245 of women's matches. **Table 1** shows the distribution of the matches according to impairment class and sex. Only matches with two players of the same class were chosen for the analysis, even if the match was taken from a competition with a combined class (e.g. a class 4–5 match with two class 4 players belongs to the statistics for class 4). The aim was to include a minimum of 10 matches for each classification in both male and female players. This leads to the exclusion of women's class 1 for this study as not enough matches were available for this class with only three female players currently classified and ranked in this class.

Data analysis

All matches were analysed with the table tennis video analysis tool "TUM.TT" (Lames, Fuchs, & Wenninger, 2018). After collecting general information about a match (tournament, date, category, round, class) and the players (name, playing style, hand, grip), the analysis was done with the real-time-system of TUM.TT. In this mode, the software splits a match into single rallies and collects the following parameters of a rally: current score (automatically), start and end of the rally in the video, server (automatically), rally length and winner of the rally. The three latter parameters were used to calculate the outcomes for this study regarding rally length and serve. Interobserver reliability tests for the rally length variable resulted in an interclass correlation coefficient of 1.000 (95% confidence interval with a lower bound at 0.999 and an upper bound at 1.000). For the other two variables, reliability was also not a critical value, since they were either collected by the analysis system automatically (server) or assigned by the respective umpire in the matches (winner of a rally).

Rally length

In this study the definition of rally length is the count of ball contacts in a single rally. This count includes the last legitimate ball contact of a player even if that stroke was not successfully played on the table. Therefore, it doesn't matter whether the ball barely missed the table or not. The median for grouped data was chosen as the representative unit of the rally length per match, since it is a robust measure of central tendency especially in the case of skewed distributions as one has with rally length (Bortz & Schuster, 2010; Willimczik, 1997).

Serve

The impact of the serve is measured with the winning probability (WP) of rallies for the serving player, while distinguishing between: (1) all rallies that are won by the server (WP Serve), (2) direct points after serve (server wins a rally with a rally length <3; WP $Serve_{rl<3}$) and (3) points with first attack after serve (server wins a rally with a rally length <5; WP $Serve_{rl<5}$). This is due to the consideration that the direct impact of the serve on the outcome of a rally might get lower in longer rallies. The three values are calculated for both players separately per match.

Independent variables

Three independent variables were used in this study. First, sex was used to be able to compare matches of male and female players. Second, following the concept of the ITTF concerning their world ranking structure in para table tennis, the classes 1–10 were split into sitting (C01–C05) and standing players (C06–C10) (International Paralympic Committee, 2015). Third, the severity of the impairment is represented by a value from 1 in both the sitting and standing players (C01/C06 = 1, C02/C07 = 2 … C05/C10 = 5). This leads to a three-factor factorial design (sex versus sitting/standing versus severity).

Abstract · Zusammenfassung

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Game characteristics in elite para table tennis

Abstract

This study focuses on the rally length and the impact of the serve, i.e. the winning probability when serving, in elite para table tennis (class 1–10) to provide a better insight in the task characteristics of para table tennis. The influences of sex and the level of impairment and their possible interactions are studied. Matches (*n* = 227) of elite para table tennis players (class 1–10) ranked in the top 20 of the world ranking lists in their class were analysed. The results of this study revealed a significant main effect of sex with small effect sizes in the three-factorial model and medium to large effect sizes in the individual comparisons on the rally length and the winning probabilities directly from service and first attack. Moreover, an interaction effect was also found of sex and sitting/standing for the same outcomes with small (winning probabilities) to medium (rally length) effect sizes. Finally, the severity of class 1 affected these outcomes significantly with large effect sizes, when comparing the outcomes of this class to the ones of the other sitting classes in male players. In conclusion, due to shorter rallies and a high direct impact of the serve for all female sitting players and for male sitting and standing para players with the highest level of impairments, serve and especially receive training should be an important part of the training for these para table tennis players.

Keywords

Racquet sports · Para sports · Match analysis · Table tennis · Rally length

Spielcharakteristika im Paratischtennis auf Hochleistungsebene

Zusammenfassung

In der vorliegenden Studie wurden die Länge der Ballwechsel und die Bedeutung des Aufschlags, genauer die Gewinnwahrscheinlichkeit bei eigenem Aufschlag, im Paratischtennis auf Hochleistungsebene (Klasse 1–10) untersucht, um die Anforderungsmerkmale in diesem Sport besser zu verstehen. Die Einflüsse des Geschlechts und des Beeinträchtigungsgrads sowie deren mögliche Wechselwirkungen wurden analysiert. Spiele (*n* = 227) von Spitzensportlern im Paratischtennis (Klasse 1–10), die unter den Top 20 der Weltrangliste in ihrer Klasse rangierten, wurden berücksichtigt. Die Untersuchungen zeigten einen signifikanten Haupteffekt des Geschlechts mit geringen Effektgrößen im dreifaktoriellen Modell und moderaten bis hohen Effektgrößen in den Einzelvergleichen auf die Ballwechsellänge und die Gewinnwahrscheinlichkeiten direkt nach Aufschlag und erstem Angriff. Des Weiteren wurde eine Wechselwirkung von Geschlecht und Sitzen/Stehen für dieselben Ergebnisparameter mit geringen (Gewinnwahrscheinlichkeit) und moderaten (Ballwechsellänge) Effektgrößen gefunden. Zuletzt beeinflusste der Schweregrad in Klasse 1 diese Ergebnisparameter signifikant mit hohen Effektgrößen, wenn die Ergebnisparameter dieser Klasse mit denen der anderen sitzenden Klassen bei Männern verglichen wurden. Bedingt durch kürzere Ballwechsel und einen stärkeren direkten Einfluss des Aufschlags bei allen sitzenden Spielerinnen sowie bei sitzenden oder stehenden Spielern mit dem höchsten Grad der Beeinträchtigung sollten Aufschlag- und insbesondere Annahmeübungen einen wichtigen Bestandteil des Trainings dieser Gruppen von Paratischtennisspielern ausmachen.

Schlüsselwörter

Rückschlagspiele · Behindertensport · Spielanalyse · Tischtennis · Ballwechsellänge

Statistical analysis

IBM SPSS Statistics 25 (IBM Corp., Armonk, New York, USA) was used for the statistical analyses. Descriptive statistics are presented for both rally length and serve winning probability in the three-factorial model. Due to the missing women's class 1, this model is unfortunately not complete. Thus, the severity value 1—this means matches of men's class 1 and 6 und women's class 6—were excluded in order to be able to conduct a three-way factorial ANOVA.

By splitting the design in sitting and standing matches, as well as in female

Table 2 Descriptive statistics of the rally length, WP Serve, WP $Serve_{rl<3}$ and WP $Serve_{rl<5}$ in the complete three-factor factorial model

Sex	Sitting/standing	Severity	Class	Rally length			WP Serve			WP $Serve_{rl<3}$			WP $Serve_{rl<5}$		
				$Mean^1$	SD	N^1	$Mean^2$	SD	N^2	$Mean^2$	SD	N^2	$Mean^2$	SD	N^2
Male	Sitting	1	C01	2.778	0.218	11	0.5273	0.117	22	0.2526	0.076	22	0.4474	0.094	22
		2	C02	4.287	1.352	10	0.5053	0.127	20	0.1472	0.086	20	0.3269	0.111	20
		3	C03	4.429	1.040	16	0.5583	0.113	32	0.1458	0.103	32	0.3401	0.137	32
		4	C04	4.529	0.587	10	0.5399	0.128	20	0.1422	0.093	20	0.3020	0.120	20
		5	C05	4.753	0.681	13	0.5292	0.099	26	0.1361	0.065	26	0.2821	0.105	26
	Standing	1	C06	3.481	0.445	13	0.5552	0.086	26	0.2119	0.095	26	0.4207	0.099	26
		2	C07	3.871	0.417	13	0.5387	0.121	26	0.1724	0.082	26	0.3818	0.118	26
		3	C08	3.967	0.439	12	0.5441	0.130	24	0.1542	0.053	24	0.3654	0.077	24
		4	C09	3.780	0.352	12	0.5205	0.114	24	0.1562	0.070	24	0.3932	0.112	24
		5	C10	3.695	0.276	10	0.4892	0.146	20	0.1381	0.082	20	0.3731	0.139	20
Female	Sitting	1	C01	–	–	–	–	–	–	–	–	–	–	–	–
		2	C02	3.333	0.743	11	0.5412	0.129	22	0.2299	0.118	22	0.4158	0.141	22
		3	C03	3.642	0.480	10	0.5285	0.144	20	0.1854	0.085	20	0.4056	0.121	20
		4	C04	3.966	0.678	16	0.5731	0.087	32	0.1931	0.091	32	0.3898	0.107	32
		5	C05	3.979	0.945	12	0.5294	0.145	24	0.1725	0.083	24	0.3595	0.129	24
	Standing	1	C06	4.275	0.712	11	0.5288	0.113	22	0.1421	0.059	22	0.3465	0.120	22
		2	C07	3.850	0.606	12	0.5500	0.146	24	0.1962	0.104	24	0.3687	0.131	24
		3	C08	4.032	0.669	11	0.5169	0.133	22	0.1686	0.075	22	0.3500	0.127	22
		4	C09	4.258	1.120	12	0.5606	0.147	24	0.1734	0.100	24	0.3567	0.144	24
		5	C10	3.814	0.357	12	0.5475	0.107	24	0.1690	0.075	24	0.4095	0.107	24

WP winning probability, $Mean^1$ mean of the grouped median of rally length per match, $Mean^2$ mean of the winning probability, *SD* standard deviation, N^1 number of matches, N^2 number of winning probabilities (two per match)

and male matches, class 1 and 6 can be included and one-way ANOVAs with Bonferroni or Games-Howell (when Levene's test is significant) post hoc tests were conducted to analyse differences between classes per sex (separated by sitting and standing classes). For pairwise comparisons between female and male in each class, t-tests for independent samples (C02–C10) were conducted. Before performing t-tests and ANOVAs, the sample was tested for normality. Violations of the assumption of normality tested with the Kolmogorov-Smirnov test were only found in three groups (women's class 5 and class 9, men's class 2). As these groups showed only small *n* but unimodal, almost symmetric distribution and considering the robustness of ANOVA against moderate violations of normality assumptions, this was accepted (Blanca, Alarcón, Arnau, Bono, & Bendayan, 2017). Alpha was set at 0.05 for all analyses. Partial η^2 (three-way ANOVA), η^2 (one-way ANOVA) and Hedges g (t-tests for independent samples with different sample size) were used as effect size (Cohen, 1988; University of Cambridge, 2009).

Results

Rally length

The descriptive statistics of our three-factor factorial model regarding the rally length are shown in Table 2. Fig. 1 gives an overview of the respective means of the rally length in the different subgroups.

After excluding the incomplete severity group 1 (C01/C06), the three-way ANOVA showed that sex has a significant main effect with a small effect size ($F = 8.046$, $p = 0.005$, partial $\eta^2 = 0.044$), whereas the variables sitting/standing ($F = 3.688$, $p = 0.056$, partial $\eta^2 = 0.021$) and severity ($F = 1.380$, $p = 0.251$, partial $\eta^2 = 0.023$) showed no significant effect on the rally length. Looking at the interaction of the three independent variables, only the interaction of sex and sitting/standing has a significant effect on the rally length, again with a medium effect size ($F = 18.700$, $p < 0.001$, partial $\eta^2 = 0.096$). The remaining interactions gender × severity ($F = 0.773$, $p = 0.510$, partial $\eta^2 = 0.013$), sitting/standing × severity ($F = 1.847$, $p = 0.140$, partial $\eta^2 = 0.031$) and gender × sitting/standing × severity ($F = 0.037$, $p = 0.990$, partial $\eta^2 = 0.001$) showed no significant effect on rally length.

A one-way ANOVA showed a significant difference with large effect size between classes for the male sitting classes (Welch's F (4, 23.954) = 43.555, $p < 0.001$, $\eta^2 = 0.403$); post-hoc tests showed a significantly lower rally length for male class 1 to all other male sitting classes. Also, a significant difference with large effect size was found in the male standing classes ($F(4,55) = 2.762$, $p = 0.037$, $\eta^2 = 0.167$); post-hoc tests showed a significantly lower rally length in class 6 compared to class 8 (Fig. 1). No significant differences were found between the classes within the sitting and between the classes within the standing female players. Individual comparisons of the rally length between female and

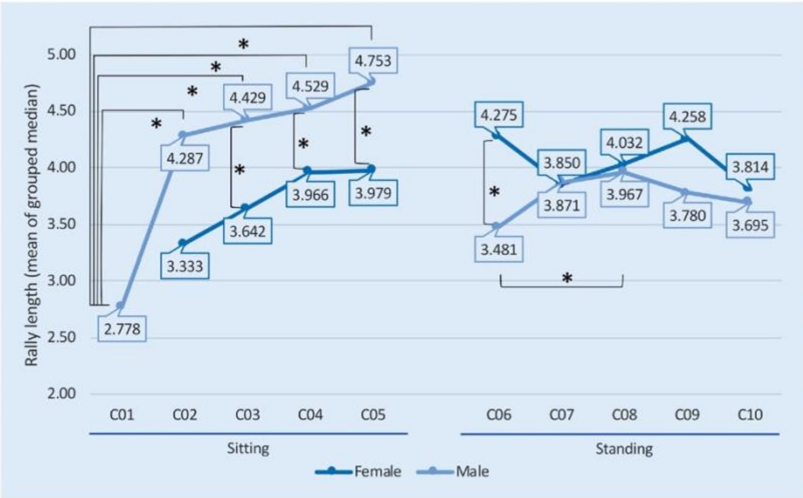

Fig. 1 ◀ Rally length classified by class and sex. * Significant difference between these two groups

male matches within one class showed significantly lower rally length in females with large effect sizes in class 3 ($t=2.613$, $p=0.016$, $g=0.901$), class 4 ($t=2.166$, $p=0.040$, $g=0.873$) and class 5 ($t=2.364$, $p=0.027$, $g=0.946$) and a significantly higher rally length with a large effect size in females in class 6 ($t=-3.331$, $p=0.003$, $g=1.365$) compared to males (**Fig. 1**).

Serve

Table 2 shows the descriptive statistics for WP Serve, WP Serve$_{rl<3}$ and WP Serve$_{rl<5}$. **Fig. 2** shows the three different variables WP Serve (**Fig. 2a**), WP Serve$_{rl<3}$ (**Fig. 2b**) and WP Serve$_{rl<5}$ (**Fig. 2c**) separately. The statistic shows a disadvantage (i.e. WP Serve <0.5) for a player when serving only for the men's class 10 (**Table 2**). For all remaining classes, the winning probability for rallies when serving (WP Serve) is higher than 0.5. Worth mentioning for the highest WP Serve$_{rl<3}$, which are the direct serve points, are the men's classes 1 and 6 (= severity class 1) with a winning probability of 25.26 and 21.19%, respectively. The same two classes have the highest WP Serve$_{rl<5}$ values (44.74% and 42.07%, respectively), but are not the leading classes in the overall winning probability for rallies when serving, which are the women's class 4 and 9.

Only one main effect was revealed for sex on Serve$_{rl<3}$ ($F(1,368) = 16.977$, $p<0.001$, partial $\eta^2 = 0.044$) and WP Serve$_{rl<5}$ ($F(1,368) = 8.470$, $p = 0.004$, partial $\eta^2 = 0.022$) with small effect sizes. No significant main effects for sitting/standing and severity were found. Only one significant interaction effect of sex and sitting/standing with a small effect size was found for WP Serve$_{rl<5}$ ($F(1,368) = 12.111$, $p = 0.001$, partial $\eta^2 = 0.032$). The other interactions showed no significant effects on any of the winning probabilities. The comparisons between classes within the sitting and within the standing players showed a significantly higher WP Serve$_{rl<3}$ and WP Serve$_{rl<5}$ for male class 1 compared to all other male sitting classes (WP Serve$_{rl<3}$: Welch's $F(4, 54.229)=8.959$, $p<0.001$, $\eta^2=0.202$; WP Serve$_{rl<5}$: $F(4,115)=6.924$, $p<0.001$, $\eta^2=0.194$) with large effect sizes and a significant higher WP Serve$_{rl<3}$ for male class 6 to male class 10 ($F(4,115) = 3.136$, $p = 0.017$, $\eta^2 = 0.098$) with a medium effect size. Individual comparisons of winning probabilities between female and male players within one class showed significantly higher WP Serve$_{rl<3}$ in class 2 for female ($t(40) = -2.574$, $p = 0.011$, $g = 0.795$) and for male in class 6 ($t(46) = 2.976$, $p = 0.005$, $g = 0.862$) and significantly higher WP Serve$_{rl<5}$ for female in class 2 ($t(40) = -2.259$, $p = 0.029$, $g = 0.698$), class 4 ($t(50) = -2.747$, $p = 0.008$, $g = 0.783$), class 5 ($t(48) = -2.336$, $p = 0.024$, $g = 0.649$) and for male players in class 6 ($t(46) = 2.345$, $p = 0.023$, $g = 0.679$). These individual comparisons showed medium to large effect sizes.

Discussion

This study aimed to provide insight into the task characteristics of para table tennis for physically impaired players (class 1–10). For that purpose, rally length and the winning probability when serving has been analysed while taking into account the influence of sex, standing or sitting position of the player while competing and the severity of the impairment. The results of this study revealed a significant main effect of sex with small effect sizes in the three-factorial model and medium to large effect sizes in the individual comparisons on the rally length and the winning probabilities directly from the serve (WP Serve$_{rl<3}$) and the first attack (WP Serve$_{rl<5}$). Moreover, an interaction effect of sex and sitting/standing was also found with small (WP Serve$_{rl<3}$ and WP Serve$_{rl<5}$) to medium (rally length) effect sizes. Finally, the severity of class 1 affected these outcomes significantly with large effect sizes, when

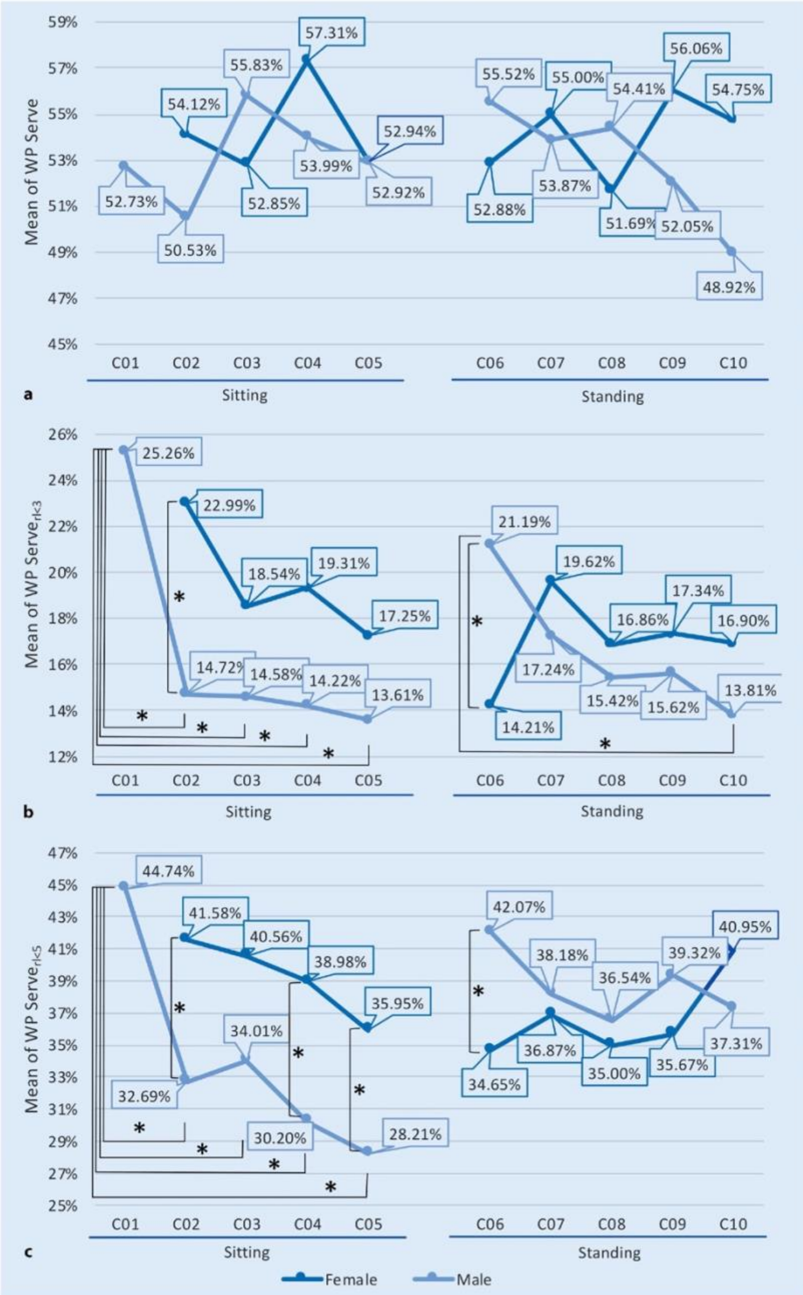

Fig. 2 ◀ Winning probability for rallies when serving (**a**), for rallies when serving with rally length <3 (**b**) and for rallies when serving with rally length <5 (**c**). * Significant difference between these two groups

comparing the outcomes of this class to the ones of the other sitting classes in male players.

Female players in the sitting classes showed a lower rally length compared to their male peers. This is accompanied with significantly higher winning probabilities directly from the serve and the first attack in the sitting female players compared to their male counterparts. The differences between the female and male players in the sitting classes are probably best explained by the differences in physical constraints between women and men that determine the functional reach. Functional reach is an important performance aspect in para table tennis players classified in the sitting classes (Lim et al., 2015). Since men are generally taller, including greater torso and arm length, their functional reach is suggested to be greater (Malina, Bouchard, & Bar-Or, 2004). Moreover, the functional reach might also be influenced by the level of anxiety of the player to topple over the chair when they overreach. There might be a difference between male and female players with regard to this aspect; perhaps male players are more inclined to take a risk that increases their sweep area. If this is the case, then the better functional reach in the sitting classes in men seems to ensure better chances of returning the ball successfully and keeping the rally alive. And on the other hand, the better functional reach does not simultaneously increase the probability of winning the rally directly after serve or at the first attack in the sitting classes.

Nevertheless, since the service rules in wheelchair table tennis prevent services that cross the side-lines of the table and short services are generally unpopular as they can bring disadvantages to the server himself/herself, explanations for the differences between female and male para players other than functional reach should also be explored. Perhaps the relative difference between female and male players regarding the quality of serve receive plays a role. Female players might be more challenged due to their relatively lower and closer position to the table as a consequence of their sitting height and arm length. In the case of long (fast) services, they need to deal with a relatively shorter timeframe to return the ball compared to men. Moreover, female players might have more difficulties in dealing with the rotation of the ball than males, which could be caused by differences in visuospatial perception (Sneider et al., 2015). Good perception of the direction and the amount of the spin is essential to successfully return the serve and create a good chance to win the point. Nevertheless, it appears that the direct impact of the serve is high in female sitting classes. This implies that both service training and receive training are specifically important.

The results of class 1, based only on the matches of male players, show a remarkable shorter rally length and higher winning probabilities directly from the serve and the first attack when compared to the other sitting classes in men. It seems that the severity of the impairments in this class cause such substantial physical constraints that player's options (i. e. technical/tactical strategies) to return the ball are reduced or even minimized (International Paralympic Committee, 2015). For that reason, it is obviously more difficult to keep the rally 'alive' after the serve. The severity of the impairments seems to influence the rally length and winning probabilities largely for this class. Class 6 for men, the standing class with highest severity, also seemed to follow the same trend: the rally length was lowest with the highest winning probabilities (WP $\text{Serve}_{rl<3}$ and WP $\text{Serve}_{rl<5}$) when compared to other standing classes. However, this did not reach the level of significance.

Two limitations of the study need to be acknowledged. First, it was not possible to include sufficient matches of class 1 in women para table tennis players. For that reason, the full factorial analyses could not be run including class 1 and 6 matches. Since class 1 in male players showed some remarkable results, it seems beneficial to also include the female peers in a next study. Second, no information on the players' physical appearance (e. g. height, sitting height, arm length), impairments, playing styles or technical/tactical behaviour has been taken into account. Consequently, it is only possible to speculate about the underlying mechanisms. Including the above-mentioned parameters will increase insight into the game characteristics of para table tennis.

In conclusion, the significantly smaller rally length combined with the higher winning probabilities of short rallies when serving in almost all female sitting classes compared to the respective male classes supports the importance of serve and maybe even more the receive game in those female classes and should be an important part in training and education. The same can be stated for the male class 1 and class 6. The shorter rally length in the standing para table tennis classes compared to the Olympic table tennis (Fuchs & Lames, 2017) for both females and males emphasizes the importance of a good serve and receive game also in standing para table tennis. Additionally, the value of the third stroke attack especially for males with an average rally length lower than 4 in all standing classes was highlighted for standing male para table tennis players.

This study provides a first overview of typical game characteristics in para table tennis and is a starting point for future studies on this sport with more in-depth analyses. Detailed technical/tactical analyses would give more precise knowledge on the structure of the sport and could lead to more practical implications for training and education, whereas analyses concerning reasons for the dominance of one player in a class can support the future fairness of the sport by giving input for possible changes in the classification system.

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Compliance with ethical guidelines

Conflict of interest M. Fuchs, I.R. Faber and M. Lames declare that they have no competing interests.

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1975 Helsinki declaration and its later amendments or comparable ethical standards.

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A.5 Study 3 – Permission for the inclusion in dissertation

David Cabello Manrique, as the Editor in Chief of the International Journal of Racket Sports Science (ISSN 2695-4508)

Certifies

Michael Fuchs has carried out the role of author for this publication. His work was executed for the first issue, third volume of the Journal, that was published on June of 2021, with the article *First Offensive Shot in Elite Table Tennis*. According with our Open Access Politics, users (for this case, the author) are allowed to read, download, copy, distribute, print, search or link to the full texts of the articles, or use them for any other lawful purpose.

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In witness whereof, I sign this certificate in Granada, December the 29th of 2021.

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A.6 Study 3 – Original article

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First Offensive Shot in Elite Table Tennis

El primer golpe ofensivo en el tenis de mesa de élite

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Abstract

From the very first shots in table tennis, players face a basic tactical decision: either return the ball short and defensively or attack it with an offensive shot. Thus, the real turntable of a rally is the shot - in this study called "first offensive shot" (FOS) – which is the transition from defensive to offensive play. This study investigates the FOS, which is defined as the first shot after the serve without any kind of backspin/side-backspin, for 90 matches (nrally = 7449) of the 2016 Rio Olympic Games. The FOS parameters – laterality, technique and position to the table at the point of contact – and the respective winning probabilities are analysed. The influences of sex and the players' ranking (resulting in three different match categories) on those parameters are studied. Descriptive statistics about the incidences of the FOSs show that four typical FOSs cover 98% of all FOSs. Chi-square tests reveal a significant relation between sex and these typical FOSs. Regarding the match categories, the tests prove a significant relation between match categories and FOS tactics for both genders. A difference in the FOS tactics between the serving and the receiving player is found as well. The winning probabilities show that using topspin (Forehand and Backhand) as FOS was an advantage in every match category, whereas using flip as FOS led mostly to a winning probability below 50% for the FOS player. Compared to prevailing methods in table tennis match analysis, which are based on fixed shot numbers, taking the FOS as object of analyses of rally opening is an innovative new approach focusing on the tactical meaning of shots that is not expressed in shot number.

Keywords: *First offensive shot, racket sports, table tennis, match analysis.*

Resumen

En los primeros golpes del tenis de mesa, los jugadores se enfrentan a una decisión táctica básica: devolver la pelota en corto y de forma pasiva o atacarla con un golpe ofensivo. En el primer caso, hay menos riesgo, pero no hay presión para hacer el punto; en el segundo caso, se crea presión, pero con un alto riesgo porque el servicio y los previos golpes "pasivos" tratan de dificultar al máximo un golpe ofensivo, que normalmente es corto y plano. Por lo tanto, el verdadero punto de inflexión de un peloteo es este golpe –en este estudio llamado "primer golpe ofensivo" (FOS, por su sigla en inglés)–, el cual es la transición del juego pasivo al ofensivo. Este estudio investiga el FOS, el cual se define como el primer golpe después del servicio sin ponerle efecto a la pelota, para 90 partidos (n_{rally} = 7449) de los Juegos Olímpicos de Río 2016. Se analizan los parámetros del FOS –lateralidad, técnica y posición en la mesa en el punto de contacto– y las respectivas probabilidades de victoria. Se estudian las influencias del género y de la clasificación de los jugadores (lo que da lugar a tres categorías de partidos diferentes) en esos parámetros. La estadística descriptiva sobre las incidencias de los FOS muestra que cuatro FOS típicos cubren el 98

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% de todos los FOS. Las pruebas x^2 revelan una relación significativa entre el género y estos FOS típicos. En cuanto a las categorías de los partidos, las pruebas demuestran una relación significativa entre las categorías de los partidos y la táctica del FOS para ambos géneros. También se encontró una diferencia en la táctica del FOS entre el jugador que sirve y el que recibe. Las probabilidades de victoria muestran que usar el efecto (de derecha o de revés) como FOS fue una ventaja en todas las categorías de los partidos, mientras que el uso del *flip* como FOS condujo en su mayoría a una probabilidad de victoria inferior al 50 % para el jugador del FOS. Excepto por el *flip* derecho en los partidos femeninos, siempre fue una mayor ventaja para el jugador del FOS si este podía terminar el peloteo de último con el ataque subsiguiente después del FOS, lo que significa que la probabilidad de victoria para el jugador del FOS disminuyó en los peloteos más largos. En comparación con los métodos predominantes en el análisis de partidos de tenis de mesa, que se basan en los números fijos de golpes, tomar el FOS como objeto de análisis del inicio del peloteo es un innovador y nuevo enfoque que se centra en el significado táctico de los golpes que no se expresa en el número de golpes

Palabras clave: *Primer golpe ofensivo, deportes de raqueta, tenis de mesa, análisis de partidos.*

Introduction

After the beginning of the sport in the second half of the 19th century, table tennis has progressed enormously. Not only the International Table Tennis Federation (ITTF) has been growing to the sports federation with the highest number of members in terms of national associations (226), but also the sport itself has been always going through developments in different areas. Due to different rule changes and technological developments, the material of the players developed as well. Big milestones in this area were the invention of the sponge rubber in the 1950s, the invention of the speed glue in the 1970s, the change from 38mm to 40mm ball diameter in 2000, and latest the ban of the speed glue with volatile organic compounds (VOCs) as well as the introduction of the celluloid-free balls in 2014 (Clemett, 2010; Küneth, 2020).

The players did not only adapt their material over the years, but also their way of playing – from changing to a more spin-oriented game style with the invention of the sponge rubber in the 1950s ending up with new shot techniques called “Strawberry” or “Chiquita” in recent years. Until the late 2000s it seemed to be normal to play the short game until the push of one player gets long enough to attack with topspin. But especially since Zhang Jike (World and Olympic Champion) trademarked the sidespin-topspin backhand flip – the so called “Chiquita” – and made it popular, more and more players seem to leave the short game early using this technique which has developed quite fast in recent years (Townsend, 2017). With this specific technique which is used by players not only in backhand side, but also in the forehand side, players can get quite easily out of a rather defensive short game into the offensive game.

This transition from the defensive short game to the offensive attacking game is a very crucial and decisive tactical decision in almost each rally in table tennis: On one hand a player can gain advantage putting the opponent in a defensive position by attacking first, on the other hand, as the first offensive technique in a rally, we call it “first offensive shot” (FOS) is technically difficult and has mostly to be played against a short ball and/or a ball with some backspin played with the intention of not allowing for an offensive shot, the FOS is a risky shot. Besides the risk of a direct error, there is the risk of a FOS of too low quality, so that it can be countered immediately and successfully.

The FOS might be seen as a rewarding technique, if effectively executed, but rather disadvantageous when not being played with high quality. Thus, playing the FOS is a basic tactical decision in almost each table tennis rally (the only exceptions are the very rare serve winners and errors).

On one hand, this is a situational decision of players in the match dependent on the quality of the serve or prior defensive shot, but on the other hand it is also a tactical element of a match strategy for players and coaches to decide whether to go for the FOS or leave it to the opponent. This decision should be supported by match analysis and data collected on the specific opponent.

In this study a new structural model for a table tennis rally including the FOS and develop a corresponding observational system focusing on recording properties of the FOS was introduced. FOS may not be defined based on a shot number in the rally (like serve, receive, third shot, fourth shot etc.), because it is not known a priori which shot will be the FOS. FOSs are semantically similar shots defined as the first shot in a rally without any kind of backspin (serves excluded). Figure 1 shows the process model of a table tennis rally.

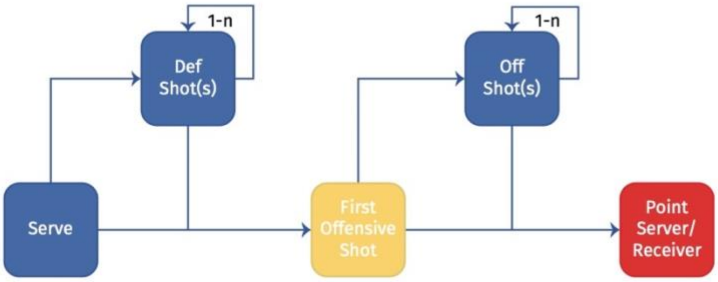

Figure 1. Process model of table tennis rally with first offensive shot.

The model separates the rally in three phases: The first phase consists of serve and defensive shot(s), second and central phase is the FOS, and the third phase contains the following offensive shot(s) until the end of the rally. Accordingly, phase one and three might include a different number of shots in each rally (from 0 to n) and the shot number of the FOS might vary in each rally. The (rare) occasions of point/error with serve or defensive shot are not depicted.

It must be mentioned that this model does not apply to matches with a defensive player as in this case the FOS is most likely followed by defensive shots of the defensive player again and the process would be repeated from phase one within a rally. As only 3% of the current top 100 ranked men and 12% of the current top 100 ranked women in the world ranking are defenders (in January 2021) (International Table Tennis Federation, 2021) these players/matches are neglected in this study.

Different approaches like notational analysis, footwork analysis, performance indices and simulative approaches have been used in table tennis analysis (Fuchs et al., 2018; Malagoli Lanzoni et al., 2014). By analysing existing literature, regardless the approach of the analysis, the FOS has not been addressed in previous table tennis research. Performance analysis in table tennis is typically based on a shot-number based approach, e.g. the three-phase-method in Japan and China, which gives feedback regarding rally length, winning probabilities and error rates of specific shot numbers (Tamaki et al., 2017; Wu & Li, 1992; Zhang et al., 2013). The problem with shot-number based approaches is that the shot number itself doesn't reflect necessarily the semantics or meaning of a shot, e.g. shot #4 may be an all-in attacking forehand topspin shot, a short, defensive backhand push or the first offensive shot in a rally. As a consequence, performance indicators based on shot-number based approaches, e.g. technique effectiveness (Zhang et al., 2013) suffer from this ambiguity. Although this problem has been acknowledged, for example including the techniques used in shot number base approaches, e.g. for shot #1 (serve) and shot #2 (receive) (Djokic et al., 2017; Zhang & Zhou, 2017), the problem remains that semantically similar shots are hard to analyse in these approaches if they have different shot numbers (Zhang & Zhou, 2017).

The aim of this study is to design an observational system to analyse the following characteristics regarding the FOS in a rally in elite table tennis:

- techniques used for FOSs
- position where the FOSs are performed (over vs. behind the table)
- shot number of the FOSs
- serving or receiving players performs the FOS
- differences between men and women and between top ranked and lower ranked players regarding the FOS behaviour?
- winning probability for the FOS player

Methods

First offensive shot (FOS) & prevalent FOS techniques

The FOS in a rally is defined as the first shot after the serve without any kind of backspin/side-backspin. Thus, the serve itself is excluded by this definition, regardless of its spin. Considering the spin condition with the resulting fact that there is either a serve or a defensive backspin/side-backspin shot prior the FOS, possible techniques for the FOS are Flip (including Chiquita), Topspin, Smash, Drive and Special (any other offensive shots which can't be assigned to the other categories) whereas Smash, Drive and Special are summarized as "other" due to their rare use as FOS.

Position relative to table at the point of contact

The position relative to the table at the point of contact is defined as the location where the player hits the ball considering the actual shot movement. In our study we distinguish between two possible positions. The first is "over the table", where techniques need to be adapted because the table poses an environmental constraint (Newell, 1986). The second is "behind the table", where the player hits the ball close to the edge or behind the table and is not restricted in his/her movement range (especially at the backward movement phase of the shot due to the table. Balls hit after going off the side of the table (and not off the back) and are hit on the side with a full backswing are considered as behind the table shots as well.

Independent variables

Two independent variables were used in this study. First, matches of male and female players were compared. Second, using the ITTF world ranking list published on August 1st, 2016 (current ranking lists at the 2016 Olympic games), players were divided into two player categories ("top 50" and "over 50"), resulting in three possible match categories ("top 50 vs. top 50", "top 50 vs. over 50" and "over 50 vs. over 50"). This leads to a two-factor factorial design (sex versus match category).

Data collection and sample

Matches of the 2016 Olympic Games were analysed using video recordings of the International Table Tennis Federation (ITTF)/International Olympic Committee (IOC). By entering the Olympic Games, participants agree to be filmed, televised, photographed, identified and/or otherwise recorded during the Olympic Games, and that their captured or recorded image, together with their name, likeness, voice, performance and biographical information, may be used in any content, format and through any media or technology whether now existing or created in the future (International Olympic Committee, 2016). All data were recorded in an anonymous dataset. Procedures performed in the study were in strict accordance with the Declaration of Helsinki as well as with the ethical standards of the Technical University of Munich, Germany.Matches with players who have a defensive playing style (choppers) and/or use non-attacking rubbers like long pimples were excluded from the sample as they are expected to bias the FOS statistics due to their non-attacking style as mentioned in the previous chapter. 53 different female players (15 left-handed, 38 right-handed; one with one half-long pimple rubber, six with one short pimple rubber, 46 with two backside rubbers) from 34 countries and 48 different male players (twelve left-handed, 36 right-handed; all with two backside rubbers) from 34 countries are included in the sample. All players were using the shakehand grip.

A total of 90 matches were analysed, including 45 men's and 45 women's matches. 15 matches per match category were chosen. Especially matches with "over 50" players were limited as only one woman and four men of this category made it into the round of 16 of the singles competition. Thus, all possible matches of the singles competition with "over 50" players involved were chosen and complemented with matches from the team competition. For the "top50 vs top50" category, matches of the finals and semi-finals of both competitions were analysed and complemented with matches from earlier stages. The 90 analysed matches led to a total number of 7449 analysed rallies, 3889 rallies of men's matches and 3560 rallies of women's matches respectively. Table 1 shows the distribution of matches and rallies according to match categories and sex.

Data analysis and observer agreement

All matches were analysed with the table tennis video analysis tool "TUM.TT" (Lames et al., 2018). For this study only the FOSs were analysed in the deep-analysis-mode of TUM.TT. Therefore, the observer had to identify if there has been a FOS in the rally and mark this shot. For those marked FOSs, the following parameters were collected additionally: Laterality (Forehand (FH)/Backhand (BH)), technique (Flip, Topspin, Smash, Drive and Special) and position relative to table at the point of contact (over/behind the table). Based on the collected variables, three more variables were defined and subject to analyses: FOS by server/receiver, number of shots after FOS and FOS direct impact (yes/no winner/error?).

The inter-observer reliability test calculating an intraclass correlation coefficient (model: two-way mixed, type: absolute, confidence interval=95%) was conducted using a randomly chosen sample of 6 matches (one from each match category) with 517 rallies. These rallies were analysed by two independent observers (one of the authors and a German B-licenced table tennis coach from a Bundesliga club). Reliability was assessed with a two-step approach: First, the identification of the observational unit, i.e. a shot as a FOS in a rally, was tested and resulted in perfect agreement expressed by an intraclass correlation coefficient of 1.000. Second, agreement of assigning levels of the observed variables was tested. The intraclass correlation coefficients for laterality, technique and position relative to table at the point of contact were 1.000, .957 (Lower 95% confidence interval (L95%) at .949) and .940 (L95% = .920) respectively. Thus, for all recorded variables the inter-rater agreement was excellent (Koo & Li, 2016).

Statistical Analysis

IBM SPSS Statistics 25 (IBM Corp., Armonk, New York, USA) was used for the statistical analyses. Descriptive statistics for FOS shot number, laterality-technique-position-combination of the FOS are presented in dependence of sex and match category. The shot number of FOS was tested for normal distribution with the Kolmogorov-Smirnov test and proved violations of normality for FOS shot number (heavily right skewed distribution).

Cross tables and chi-square tests with the Monte Carlo method if necessary were used to identify relations between the independent variables (sex, match category) and the dependent (calculated) variables (FOS laterality, FOS technique, FOS by server/

receiver). For comparison of the FOS shot number between female and male and the match category groups, Mann-Whitney tests and Kruskal-Wallis tests were conducted.

Alpha was set at 0.05 for all analyses. Correlation coefficient r was used as effect size for the Mann Whitney U test as well as for the pairwise comparisons of the Kruskal-Wallis-test in case of significance (Cohen, 1988; Fritz et al., 2012).

Results

From 7449 analysed rallies, 6771 (90.9%) rallies contained a FOS. In 668 (9.0%) rallies there was no FOS because of prior rally termination (serve winner (6.0%), serve error (13.8%), defensive shot winner (17.5%) and defensive shot error (62.7%)). Ten (0.1%) rallies had to be excluded from the sample as the (potential) FOS was not visible in the video footage due to replays or a blocked view.

Four laterality-technique-position combinations (out of twelve) cover 98.3% of all 6771 analysed FOSs. Therefore, we excluded the other eight categories from subsequent analysis. The descriptive statistics of our two-factor factorial model regarding these four laterality-technique-position combinations are shown in Table 2.

The typical FOSs are: Forehand topspin behind the table, forehand flip over the table, backhand topspin behind the table and backhand flip over the table. As topspin is always connected to the behind the table position and flip to the over the table position, we will drop the explicit mentioning of the relative position to the table at time of ball contact in the next sections when talking about topspin and flip. Most used for FOS overall was FH topspin (37.4%), followed by BH topspin (29.3%) and the BH flip (22.3%). FH flip was used least often (10.9%).

A different frequency order for men and women was obtained when analysed separately. FH topspin is still the most used FOS for both men (35.9%) and women (39.1%). But different to the overall order, the second most popular shot for men is the BH flip (27.2%) and not the BH topspin (23.2%). For women, BH topspin (36.1%) is on second place, followed by BH flip (17.0%).

The chi-square test proves a significant relation between sex and the selection of the laterality-technique-position combination for the FOS (χ^2 (3,N=6654)=264.31,p<.001).

Table 1.
Data sample: match and rally distribution according to match category and sex.

		Match Category							
		Top50 vs Top50		Top50 vs Over50		Over50 vs Over50		Total	
		Matches	Rallies	Matches	Rallies	Matches	Rallies	Matches	Rallies
Sex	Female	15	1120	15	1081	15	1359	45	3560
	Male	15	1143	15	1294	15	1452	45	3889
	Total	30	2263	30	2375	30	2811	90	7449

Table 2.
Descriptive statistics of FOS laterality-technique-position combination in the two-factor factorial model after excluding marginal shot types.

Sex	Match Category	Forehand				Backhand				Total
		Topspin		Flip		Topspin		Flip		
		behind the table		over the table		behind the table		over the table		
		Count	%	Count	%	Count	%	Count	%	Count
Female	Top50 vs Top50	355	34.9	96	9.4	386	38.0	179	17.6	1016
	Top50 vs Over50	361	37.1	68	7.0	360	37.0	184	18.9	973
	Over50 vs Over50	521	44.2	85	7.2	396	33.6	176	14.9	1178
	Total	1237	39.1	249	7.9	1142	36.1	539	17.0	3167
Male	Top50 vs Top50	383	36.5	159	15.2	238	22.7	268	25.6	1048
	Top50 vs Over50	426	36.6	165	14.2	230	19.8	343	29.5	1164
	Over50 vs Over50	442	34.7	154	12.1	342	26.8	337	26.4	1275
	Total	1251	35.9	478	13.7	810	23.2	948	27.2	3487
Total	Top50 vs Top50	738	35.8	255	12.4	624	30.2	447	21.7	2064
	Top50 vs Over50	787	36.8	233	10.9	590	27.6	527	24.7	2137
	Over50 vs Over50	963	39.3	239	9.7	738	30.1	513	20.9	2453
	Total	2488	37.4	727	10.9	1952	29.3	1487	22.3	6654

Looking at the match categories within each sex, the chi-square tests show a significant relation between the match category and the FOS laterality-technique-position combination for women (χ^2 (6,N=3167)=26.74,p<.001) as well as for men (χ_2 (6,N=3487)=21.86,p=.001). Regarding frequencies, it has to be mentioned that for women in the Top 50 vs. Top50 category BH topspin is most used as FOS, for Top50 vs. Over 50 category FH topspin and BH topspin are more or less equal whilst in the Over50 vs. Over50 category the FH topspin is clearly the most used FOS. For men, in the Over50 vs. Over 50 category the BH topspin is the second most used FOS, whilst for the other categories the BH Flip is on second position (in all men categories FH topspin is the most used FOS).

Regarding the position relative to the table, men intend to open the rally more likely over the table than women (40.9% for men vs. 24.9% for women). The chi-square tests confirmed a significant relation between sex and the position to the table at the point of contact (χ^2 (1,N=6654)=191.68,p<.001). A significant relation is also shown between the match categories and the position relative to the table at the point of contact within each sex (women: χ^2 (2,N=3167)=7.82,p=.020, men: χ^2 (2,N=3487)=6.65,p=.036). For the women's categories a trend towards more over the table FOS was recognizable for the categories with more Top50 players (Over50 vs. Over50: 22.2%, Top50 vs. Over50: 25.9%, Top50 vs. Top50: 27.1%). Within the men's categories the Top50 vs. Over50 (43.6%) had the highest percentage of over the table FOS (Over50 vs. Over50: 38.5%, Top50 vs. Top50: 40.7%).

After describing what was used as a FOS and in which position to the table it was used, the next important point is to get information when in the rally the FOS was used by the players.

A Mann-Whitney-U-Test was calculated to determine if there were differences in the FOS shot number between women and men. The test proved a statistically significant difference in the shot number between women and men (U = 5307059.00 , Z = -2.965 , p = .003 , r = -.036) even though the effect size is very small (Cohen, 1992). The means ($mean_{women}$ = 2.74, $mean_{men}$ = 2.83) and grouped medians (grouped $median_{women}$ = 2.64, grouped $median_{men}$ = 2.69) show only a very small difference, too.

Figure 2 shows the distribution of the FOS shot number in a rally separated by gender. In both genders the majority of FOSs were performed with the second, third or fourth shot in a rally ($women_{\#FOS}$<=4= 96.9%, $men_{\#FOS}$<=4 = 94.9%).

A Kruskal-Wallis-Tests indicated first that there is a significant difference in the FOS shot number between the different match categories for women (H(2) = 6.729, p = .035), but the post-hoc tests couldn't show any significances. For men no significant difference was found (H(2) = .404, p = .817). This shows that the situations and the moments within a rally when FOS were performed are statistically very similar throughout all male or female match categories respectively, regardless of the FOS player's and the opponent's ranking. Thus, no different tendencies of an earlier or later attacking was found.

By analysing the FOS shot number, we got also the information whether the server (odd shot numbers) or the receiver (even shot numbers) performed the FOS. Figure 3 and Figure 4 show the distribution of the FOS technique for both groups separated for women and men respectively.

In both genders the distribution of the FOSs technique is different whether the server or the receiver performs the FOS. If the server is performing the FOS, topspin (FH+BH) has a much higher percentage than if the receiver is performing the FOS (women: 91.2% topspin (FOS by server) vs. 63.7% topspin (FOS by receiver); men: 74.5% topspin (FOS by server) vs. 49.1% (FOS by receiver)). In men's matches, in case the receiving player is performing the FOS, flip technique (50.9%) is even more often used than the topspin technique. In particular the different use of the BH flip needs to be mentioned. The chi-square tests proved the significant relation between the FOS technique and FOS by serving/ receiving player for men (χ^2 (3,N=3487)=401.21,p<.001), women (χ^2 (3,N=3167)=322.67,p<.001) and overall (χ^2 (3,N=6654)=678.93,p<.001). Thus, it can be said that the FOS behaviour of the receiving player is different from the one of the serving player.

After analysing the distribution and incidences of the different FOS variables, we were interested in the respective rally winning probabilities (wp) for the FOS player. Table 3 shows the incidences of won rallies and winning probabilities for the FOS player in our two-factor factorial model.

For our typical FOSs, the winning probabilities showed clear tendencies. The winning probability for the FOS player was always over 50% when using topspin (FH or BH) as FOS with a minimum of 50.4% in the women's Top50 vs. Top50 category for the FH topspin and 50.4% in the men's Top50 vs. Top50 category for the BH topspin. Using flip as FOS was a disadvantage for the FOS player in two of three categories for men as well as women while executing the flip with FH, and in all categories except the men's Top50 vs. Over 50 category with BH. Table 3 shows that the FH flip is only a "weapon" between two Over50 players as they might not be able to handle the opponents' flip – in contrast to the Top50 players. As the total incidences of the FH flip technique are the lowest among all used techniques, the winning probabilities might also be influenced by the skill of a certain player and probably have greater fluctuation than the winning probabilities of other techniques with greater incidences.

Table 3.
Incidences of won rallies and winning probabilities (in %) for the FOS player for the "typical FOSs" in the two-factor factorial model.

Sex	Match Category	Forehand				Backhand				Total	
		Topspin		Flip		Topspin		Flip			
		behind the table		over the table		behind the table		over the table			
		Count	%	Count	%	Count	%	Count	%	Count	%
Female	Top50 vs Top50	179	50.4	45	46.9	200	51.8	89	49.7	513	50.5
	Top50 vs Over50	211	58.4	24	35.3	190	52.8	77	41.8	502	51.6
	Over50 vs Over50	294	56.4	43	50.6	201	50.8	77	43.8	615	52.2
	Total	684	55.3	112	45.0	591	51.8	243	45.1	1630	51.5
Male	Top50 vs Top50	226	59.0	55	34.6	120	50.4	122	45.5	523	49.9
	Top50 vs Over50	232	54.5	74	44.8	130	56.5	175	51.0	611	52.5
	Over50 vs Over50	259	58.6	79	51.3	193	56.4	164	48.7	695	54.5
	Total	717	57.3	208	43.5	443	54.7	461	48.6	1829	52.5

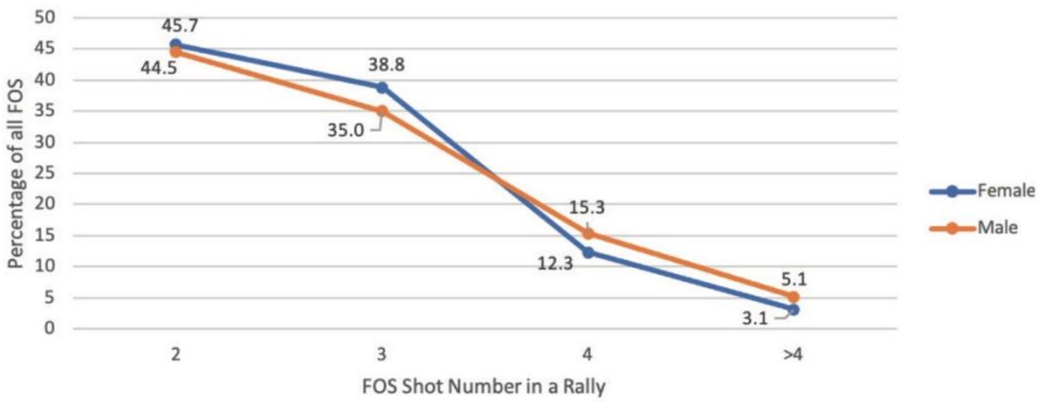

Figure 2. Distribution of the FOS Shot Number in a Rally.

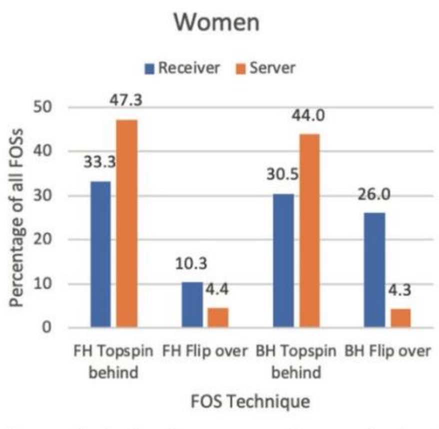

Figure 3. Distribution of FOSs separated by server/receiver for women.

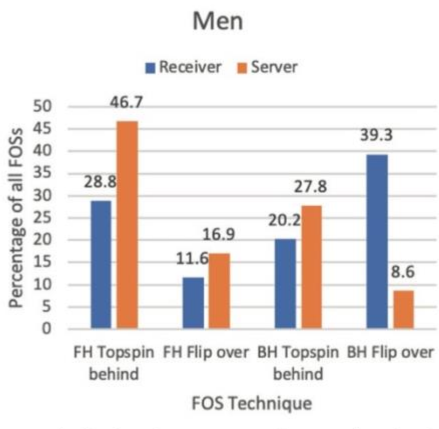

Figure 4. Distribution of FOSs separated by server/receiver for men.

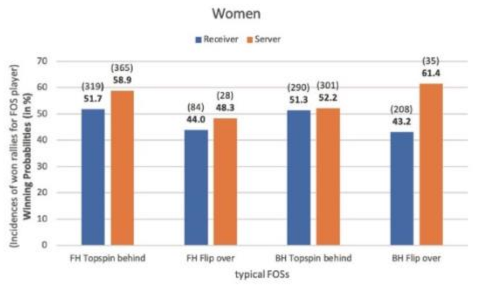

Figure 5. Incidences of won rallies and winning probabilities for the FOS player using the typical FOSs separated by serving or receiving player is performing the FOS for women's matches.

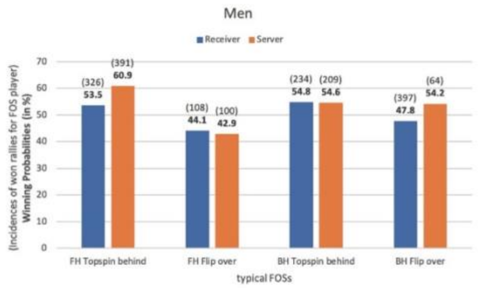

Figure 6. Incidences of won rallies and winning probabilities for the FOS player using the typical FOSs separated by serving or receiving player is performing the FOS for men's matches.

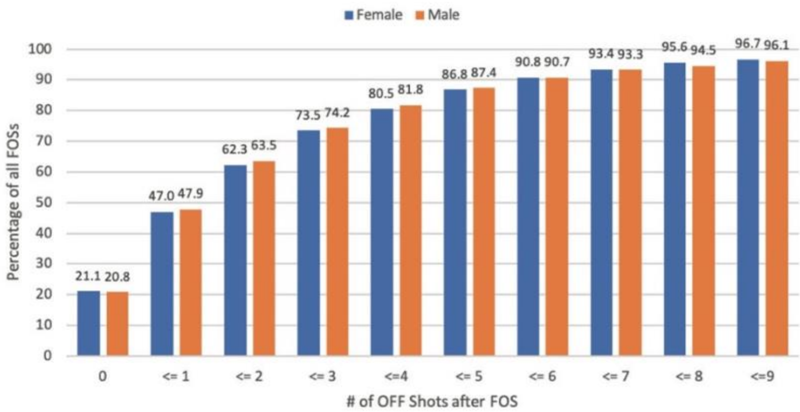

Figure 7. Distribution of the number of offensive shots after the FOS.

Figure 5 (for women) and Figure 6 (for men) show the incidences of won rallies and winning probabilities for the FOS player using the typical FOSs separated by serving or receiving player is performing the FOS.

Topspin with FH or BH as FOS was always an advantage for the server as well as for the receiver. In contrast, using the flip was always a disadvantage except when the server could perform a BH flip as FOS (wp BH flip$_{mServer}$ = 54.2%, wp BH flip$_{wServer}$ = 61.4%).

The biggest difference in FOS winning probabilities between the serving and receiving player were found for the FH topspin (wp FH topspin$_{mReceiver}$ = 53.5% vs. wp FH topspin$_{mServer}$ = 60.9%, wp FH topspin$_{wReceiver}$ = 51.7% vs. wp FH topspin$_{wServer}$ = 58.9%) and the BH flip (wp BH flip$_{mReceiver}$ = 47.8% vs. wp BH flip$_{mServer}$ = 54.2%, wp BH flip$_{wReceiver}$ = 43.2% vs. wp BH flip$_{wServer}$ = 61.4%) in both genders with the higher winning probabilities for the serving player.

The FOS is arguably a crucial moment in a rally, but the advantage/disadvantage by performing the FOS might be neutralized in longer rallies. Figure 7 shows the distribution of the number of offensive shots after the FOS in a rally.

Over 60% of all rallies (women: 62.3%; men: 63.5%) are finished with a maximum of two offensive shots after the FOS, and almost three quarters are finished with three or less shots after the FOS (women: 73.5%; men: 74.2%).

To get a better indication of the direct impact of the FOS, the sample was additionally split into two subsamples. The upper limit for the direct impact of the FOS was derived by an inspiration of the first phase of the Three-Phase-Model approach (Wu & Li, 1992) with the FOS as starting point. As direct impact we defined rallies which finished latest with the follow up attack after the FOS of the FOS player (including a possible mistake of the opponent with the following shot) which leads to the first, the "direct impact of FOS" subsample. The second ("no direct impact of FOS") subsample includes all remaining rallies with more offensive shots after the FOS. Figure 8 and Figure 9 show the incidences of rallies with a direct impact or no direct impact of the respective FOSs. The figures show the same trend, regardless of the used FOS. More rallies are finished with a direct impact of the respective FOS.

When talking about the intention the FOS player should have, Figure 10 and Figure 11 are clearly showing that it was more successful for the FOS player if a rally was finished with a direct impact of the FOS. Only the rallies in women's matches with FH flip as FOS showed a higher winning probability for the FOS player in the longer rallies compared to the "direct impact of FOS" rallies (wp FH $\text{flip}_{\text{wDirectImpact}}$ = 44.1% vs. wp FH $\text{flip}_{\text{wNoDirectImpact}}$= 47.6%).

Discussion

This study aimed to give a better understanding of the FOS in a rally in top level table tennis. For that purpose, FOS shot number, FOS laterality, FOS technique and FOS position towards the table at the point of contact have been analysed while taking into account the influence of sex and the respective player/match category. Additionally, the winning probabilities for the FOS player have been analysed. The inter-observer reliability tests for all variables showed excellent inter-rater agreements. For the identification of the FOS and the laterality of the FOS an almost perfect agreement was expected as the differences between defensive and offensive shots and FH/BH can be identified easily. Although assigning the levels of the other observed variables for the FOS (technique and position) is not trivial, still a high agreement between experienced coaches was expected as only very few situations, e.g. short BH topspin movements vs. BH flip after a half-long ball, might result in different value assignments. But in most cases, the techniques and the position relative to the table is clearly recognizable by (experienced) observers.

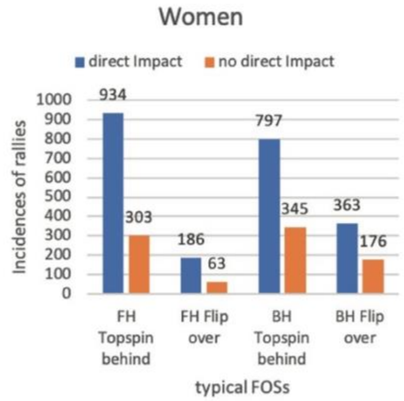

Figure 8. Incidences of typical FOSs separated by impact of FOS for women.

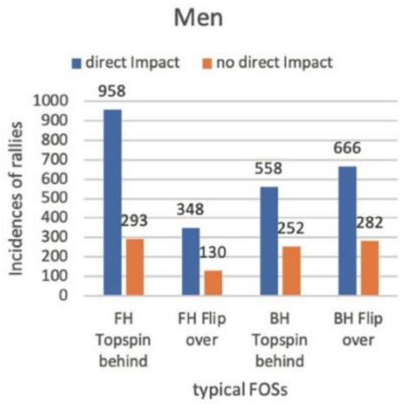

Figure 9. Incidences of typical FOSs separated by impact of FOS for men.

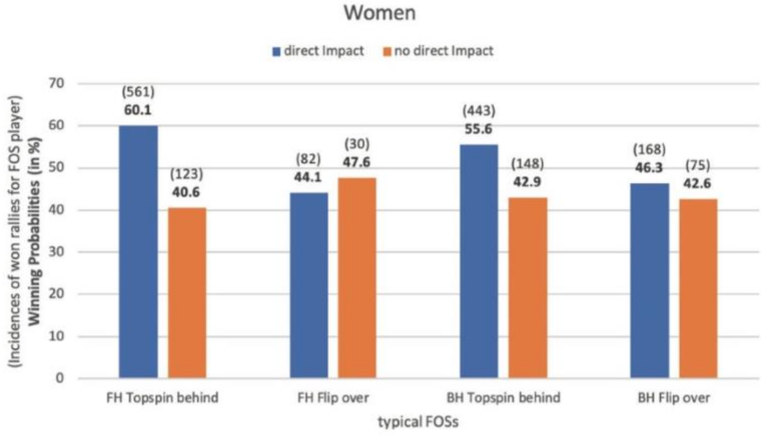

Figure 10. Incidences of won rallies and winning probabilities for the FOS player using the typical FOSs separated by direct or no direct impact of the FOS for women's matches.

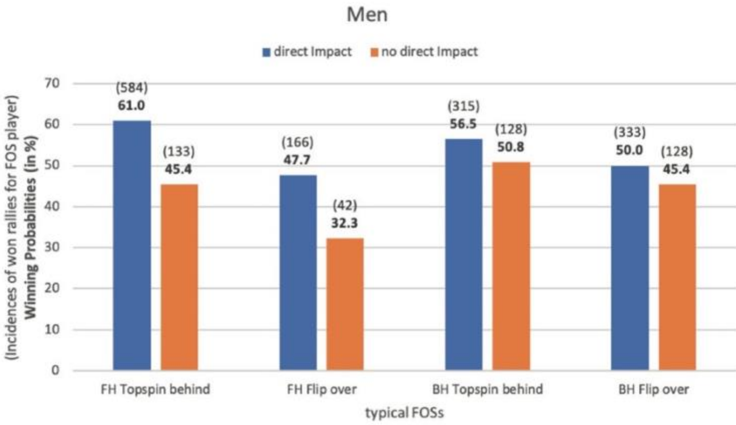

Figure 11. Incidences of won rallies and winning probabilities for the FOS player using the typical FOSs separated by direct or no direct impact of the FOS for men's matches.

The results of this study revealed that there are four typical FOSs covering 98% of all FOSs. The women's more frequent use of backhand as FOS might be caused by the fast and close to the table (and because of that often more backhand oriented) playing style of women compared to men.

The FH topspin is the most used FOS in all men's match categories and in two of three women's categories. Only in the women's Top50 vs. Top50 category the BH topspin is more often used than the FH topspin. Overall, female players prefer the topspin technique (FH and BH topspin clearly on first and second place covering together more than 73% of FOSs in all categories) over the flip technique. The flip technique is more often used in men's compared to women's matches leading to a significantly different distribution of the techniques between men and women. Especially the more frequent use of the backhand flip in the men's matches (which is tantamount to more over the table FOS) is probably explained by a different serve and receive game in the different genders. Men are more likely serving short – which is confirmed by the study of Djokic et al. (2020) – to avoid a direct full swing topspin of the opponent whilst – following Zhang and Zhou (2017)– women don't seem to be afraid to serve or push with the receive more frequently half long or long because the opponents opening topspin can be controlled or even countered. This might be based on differences in physical capabilities between men and women which lead to a possibly stronger FOS topspin in the men's game which opponents are afraid of.

A similar average FOS number for men and women (grouped $\text{median}_{\text{women}}$ = 2.64, grouped $\text{median}_{\text{men}}$ = 2.69) with the different FOS behaviour explained before supports the explanation that the FOS might be highly affected or rather controlled by the serve as not too much short-short game is going on for both genders. To prove this hypothesis, additional research on the shot(s) prior to the FOS needs to be done.

The different FOS behaviour between server and receiver might also be explained by the receiving game of the majority of players, especially for men. The popularity of the BH banana flip directly as receive might be one reason. The difficulty to receive really short a second one. It seems that if the receiver doesn't attack directly, but plays a defensive push, the server can (or needs to) attack that push very often with a topspin. This can happen due to a failed short push which went half long or long but also due to the conscious decision to receive with an aggressive long push. The second option seems to get more and more popular. With a controlled long push, the receiver provokes a topspin with more spin from behind the table, which might also be easier to control. The attempt to push short involves always the risk of a qualitatively bad or too high short ball which can be easier killed than a long push loaded with backspin.

Regarding the winning probabilities, explanations for certain results are very hard to give as so many factors come into play. Noticeable is that the winning probabilities for topspin techniques as FOS were always >50% and always bigger than the winning probabilities for the flips.

Using the flip as FOS was a disadvantage for the FOS player in nine out of twelve cases (Table 3). Only the FH flip in the women's and men's Over50 vs Over50, as well as the BH flip in the men's Top50 vs Over50 category showed winning probabilities >50%. There may be diverse reasons why the flip as FOS is not an advantage. For example, in the male Top50 vs Top50 category (wpFH flip = 34.6%), the non-FOS player might be able to counter the flip with high quality. The flip technique itself might be the problem in that category as it is simply not strong enough in terms of spin (opponent can control the top-/sidespin) and speed (opponent is fast enough and has very good anticipation) which might be different in categories with lower ranked players involved.

Although it can be stated that topspin is the more successful FOS than flip, exclusively using topspin as FOS is not an option. Using flip (especially as a receiver) might be highly influenced by the opponent's serve which might give no possibility to topspin and at the same time makes it very difficult to play a good short ball. Thus, players are almost forced to play a flip in those situations.

Following the analysis of the post FOS shot number and the respective winning probabilities, the intention for the FOS should be to finish the rally with his/her follow up shot. Especially when using topspin as FOS, the winning probabilities for the FOS player were way higher in the rallies finished quickly after the FOS compared to the longer rallies. This means, when opening the rally with a topspin, the FOS player should try to kill the ball with his/her next shot at the latest. Otherwise, the advantage will decrease noticeably (decrease for women matches at 19.5% (FH topspin) and 12.7% (BH topspin), decrease for men's matches at 15.6% (FH topspin) and 5.7% (BH topspin)). For the flip as FOS, no clear trend could be found (big decrease for FH flip in men's matches, but even an increase for FH flip in women's matches; decreases for BH flip <5% for both genders). Thus, no general advice for the tactical behaviour after the flip as FOS can be given based on the study's results as it seems to be a more individual consideration whether and when the FOS player is successful with the flip as FOS.

Following the findings of our study, some practical suggestions for players and coaches can be given: As flip was a disadvantage and topspin was an advantage overall, the importance of a good quality short push instead of opening the rally with a flip should be taken into account in the daily work. Closing the rally with the follow up attack after a player could take the initiative with a topspin is a second important finding for players and coaches not only for competitions, but also in the design of competition-like exercises in training.

Some limitations of the study need to be acknowledged. First, the FOS behaviour and the FOS winning probabilities are highly influenced by the placement and quality of the shot prior to the FOS which is not analysed in this study. This information could help to identify e.g. after which placement certain FOSs are (successfully) performed. Second, the world rankings of the players - especially in first round matches including wild card players – show larger variance. Thus, although players belong to the same player category, there might be a difference in the level of skills which might have an influence on the FOS behaviour especially on the winning probabilities of certain techniques.

Despite these limitations, the conceptual advantages of the introduced process model for a table tennis rally could be clearly shown. Tactical behaviour for the first offensive shot could be analysed without any dependency on a specific shot number. The results for the FOS number underlined the necessity of such a shot-number-independent approach as the FOS number was spread over a range of shot numbers. Moreover, ambiguities in shot-number-based approaches – a third shot may be a defensive short push as well as an all-in attacking shot – speak as well in favour of the presented, shot number independent FOS analysis.

Conclusion

This study provides a first overview of the FOS behaviour in elite table tennis using a new shot-number-independent approach. The detailed technical/tactical analyses of the FOS behaviour, including the analysis of the winning probabilities gives more precise knowledge about the structure of the sport. The reliable information about different FOS behaviour for men and women or for the serving and receiving player respectively, the differences between match categories and the differences of winning probabilities could lead to practical implications for training and competition and also to adaptions in the tactical education in the development of (young) athletes.

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