Float like a feather, smash like a hammer

A padel ball to help amateurs learn the smash faster

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Graduation project Niek van der Horst

Delft, August 2024

Delft University of Technology

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Master Integrated Product Design (IPD)

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Preface

My passion has always been sports. Throughout my IDE career, I have strived to work on a sports-related project, and my graduation project provided the perfect opportunity to pursue this interest.

From my own experience, I often observe that beginners in a new sport struggle with fundamental techniques and therefore feel discouraged to keep playing, leading many to give up before they can truly experience the fun of the game. I also noticed this for padel, a sport I took up only just last year, where many beginners struggle with the smash. Conversely, experienced players who have mastered this technique gain a significant advantage, not only scoring more points but also enhancing their enjoyment of the game. My aim is to break the barrier of newcomers into padel that struggle with the smash, leading to feelings of discouragement by designing a solution that accelerates the learning process, encouraging continued participation and enjoyment of the sport.

I would like to thank the people I was able to talk and spar with about my project, especially the padel trainers and padel club owners who also made courts available for my research. Special thanks to the research participants for their enthusiasm and feedback.
Furthermore, I would of course like to thank my supervisors Arjen Jansen and Bart van Trigt for their invaluable guidance, support and enthusiasm during this project. Making my wish to connect design with sports a reality.

Executive Summary

Padel is a rapidly growing sport with a large base of amateur players. One crucial technique for winning points, which many amateurs struggle with, is the smash. The combination of its importance and difficulty makes it a compelling topic for design innovation. The central question is: how can padel amateurs learn the smash faster?

This report describes the development and testing of a padel ball with fuzzy felt designed to improve amateur players' smash performance. The project began with conceptualising various ideas that were based on literature research on 1) the sport padel, 2) the smash in padel, 3) biomechanics of the smash, 4) motor learning and 5) coordination. The fuzzy padel ball concept is selected due to its multidisciplinary characteristics and discovered gap in the market. It has the potential to lower ball speed when the amateur player receives a lob, providing them with more time to set up their smashes. This approach aims to improve the learning experience.

The manufacturing process of standard padel balls can in theory be modified slightly to create a fuzzier felt that covers the rubber balls. Machines are used to break the weaving structure of the felt that goes around the balls. This production step raises the fuzziness of the felt and causes an increase in drag, which slows down the ball. Going through this machine multiple times will increase the fuzz even more, something that existing padel ball companies already do to make their ball travel slightly slower through the air than their competitors. Since it was not possible to use professional rubber balls glued with fuzzier felt right away, prototypes were created using different fabrics glued to padel and tennis balls to simulate the concept.

The prototypes are used for multiple tests that investigate which of them travels slower through the air. These tests consist of a drop test (to measure the fall speed of the prototypes) and a smash test (to measure the smash performance of the best prototypes). In the smash test, nine participants received multiple lobs which they had to smash at a target mat at the other side of the net. Their smash accuracy and speed were recorded and combined to produce a smash performance score. Results showed no significant difference in smash performance between normal and fuzzy balls. However, players provided qualitative feedback on timing adjustments and perceived a slower ball speed during the lob and an increase in weight. In conclusion, padel amateurs can learn the smash faster by integrating biomechanics, motor learning, and coordination. The fuzzy felt padel ball concept provides a promising tool for achieving this, although further refinement and testing are necessary.

Future prototype development should use high-quality felt with varying fuzziness and explore different internal pressures to counteract damping effects. Glueing felt directly onto rubber balls improves prototype quality. Additionally, investigating the durability of prototypes, creating removable fuzzy covers for existing balls, and collaborating with established manufacturers could provide further insights. Another qualitative finding of this study was the psychological impact of sensory feedback. One player perceives that louder smashes are correlated with higher smash speeds, which is not the case. This aspect should be examined more closely in future research.
Future studies should refine the smash test setup, use a round target for better statistical comparisons, and engage a professional padel trainer for consistent lobs. Improved filming techniques, including slow motion and higher-quality cameras, will enhance data accuracy.
Although the primary hypotheses were not supported, the study provided valuable insights into the differences between the effect of using normal and fuzzy padel balls.

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(BNL Italy Major Premier Padel, n.d.)

1. Introduction

Padel's popularity has increased rapidly in recent years, as evidenced by the growing number of players and rising participation rates. In 2023, the sport was named the fastest growing sport in the Netherlands and the number of people actively playing padel and tennis exceeded 778,000, a 11% increase from the previous year (Van Dooijeweert, 2023; KNLTB, 2024). This upward trend reflects the appeal of the sport and its ability to attract a wide range of enthusiasts, especially young adults, from casual players to experienced competitors.

Securing dominance at the net in padel is known as a main strategy for scoring points and ultimately winning matches. Research shows that more than 80% of winning points are gained from the offensive position and that winning players perform more attacking strokes per point and per game (Sánchez-Alcaraz et al., 2020).
Yet, this advantageous position is constantly contested by opponents who try to disrupt this attacking location to attain it for themselves, often resorting to high lobs aimed to move the attacking team away from the net. Receiving balls that fly above the heads of the team that is standing close to the net, gives them opportunities for over-head strokes; the smash. This countermove presents a prime chance to seize control of the point again. Mastery of this technique appears to be essential for success in padel matches. The effectiveness of the smash as a match-winning shot depends on multiple factors, such as the area, direction, velocity and accuracy of its execution (Sánchez-Alcaraz, Perez-Puche, et al., 2020).

The smash is a challenging technique to master and execute, yet it is crucial for scoring points in padel. Amateurs, in particular, struggle with this shot due to their lack of technique. With the sport experiencing rapid growth, the number of amateur players has increased significantly. Informal interviews with these players indicate that the smash is the most difficult skill for them to execute (see Appendix A).

Proper use of the smash can secure a point, while poor execution can lead to losing one. The combination of its importance and difficulty makes it a compelling topic for design innovation. The central question is: how can padel amateurs learn the smash faster?

This research delves into the creation and development of various concepts that can help amateurs learn the smash faster. Brainstorming sessions are used to generate creative and diverging ideas. These sessions are based on research about the smash, literature research on learning and executing complex skill movements, and conversations with padel trainers and club owners. Four ideas are selected and developed into detailed concepts by using reverging and converging methods (Heijne & Van Der Meer, 2019). These concepts are then evaluated using a Harris Profile to choose the final concept.

For the final concept, multiple prototypes are created, and various tests are conducted to validate the performance of different prototypes, with a final test to assess whether the functional prototypes can improve the smash performance of amateur players. The results of this research could lead to the development of training aids that help beginners learn essential techniques more quickly and effectively.

1.1 The sport padel

Padel is a racket sport that combines elements of tennis and squash. Padel is played by four people on a rectangular court surrounded by walls from which the ball can bounce back from. The walls of the court, usually a combination of glass and fencing, offer a unique and dynamic playing experience and differentiate padel from other racket sports (Padelwereld.nl, n.d.). The closed and compact court of 20 by 10 metres offers players more opportunities to keep rallies going, which distinguishes padel from tennis which has an open and bigger court (see figure 1). Moreover, the ball's high bounce offers players more reaction time when it hits the ground and the walls compared to squash. These unique features make padel a very accessible sport to players of different levels.

The rules of padel are similar to those of tennis, with players having to play the ball over the net and into the opponent's court. However, there are notable differences, such as the fact that in padel, underhand serving is permitted and players are allowed to play the ball off the walls after it has first hit the ground (KNLTB, n.d.).

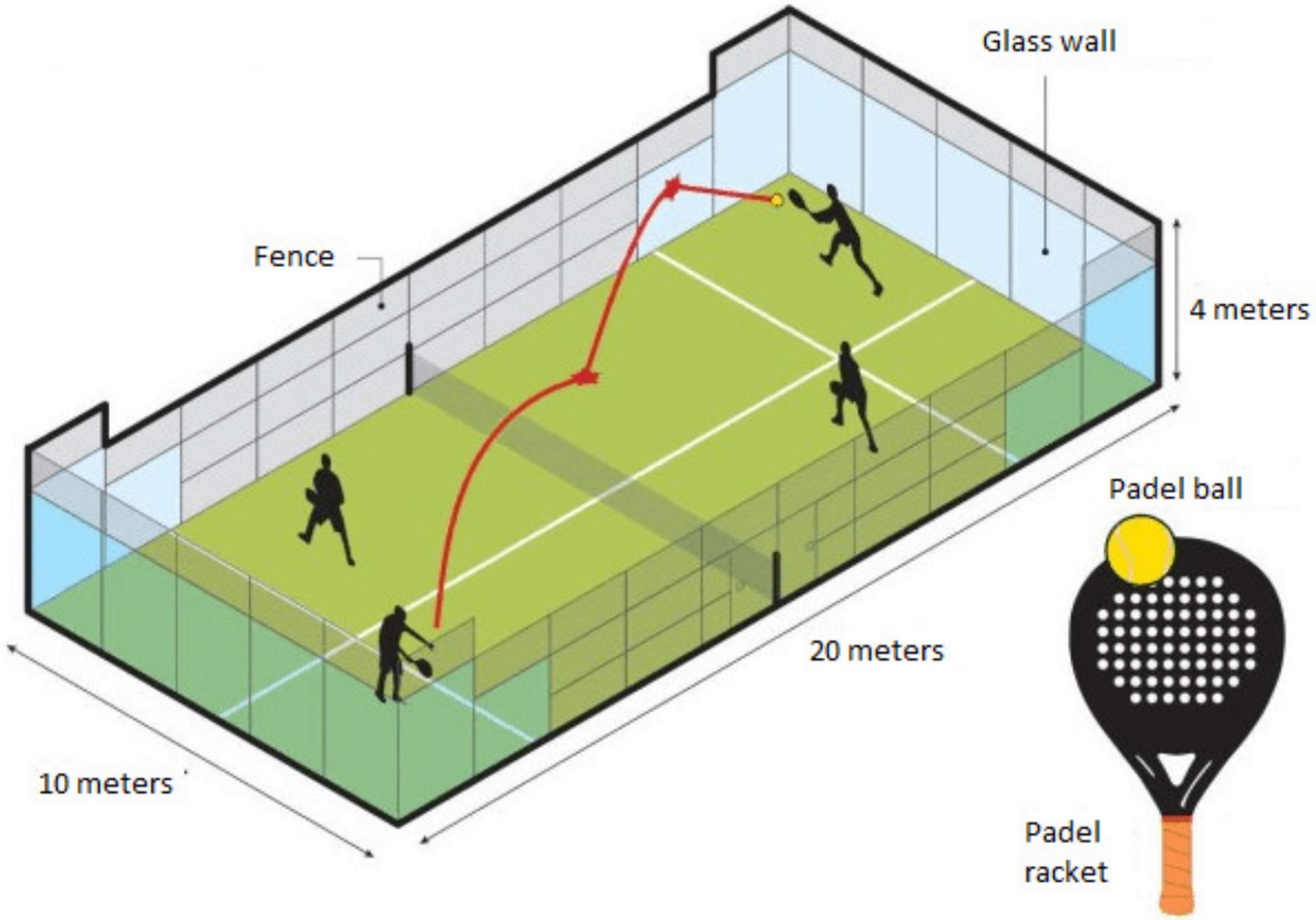


Figure 1: Illustration of a padel court with general dimensions (De Nethe, n.d.)

1.2 The smash in padel

To know how to improve smash learning in padel, it is important to know which types of smashes there are. In general there are four types of smashes in padel. The Bandeja (tray/backspin smash), flat smash, Vibora (sidespin smash) & topspin smash (see figure 2, figure 3, figure 4 & figure 5). However, depending on how, when and where these smashes are executed, can lead to variations that result in different tactical purposes (Meerpadel.nl, 2023; The Padel School, 2023).

Appendix B provides detailed descriptions of these smashes. The main differences among them include the difficulty level of the technique, whether they are defensive or attacking smashes, and their optimal positions on the court.

The Bandeja and flat smash are basic-level techniques, while the Vibora and topspin smash require a more advanced skillset. Defensive smashes, such as the Bandeja, are used to maintain tactical positioning at the net rather than to win points. In contrast, attacking smashes like the flat smash and the Vibora are designed to secure points. The topspin smash can function as both a defensive and an attacking shot, depending on whether it is executed from the back of the court (defensive) or near the net (attacking).

Regarding court positioning, defensive smashes are typically executed from the back of the court, away from the net, while attacking smashes are used closer to the net. The Vibora is an exception, as it is employed from a mid-court position.

Figure 2: Basic defensive Bandeja smash generating backspin

Figure 3: Basic attacking flat smash generating no spin

Figure 4: Intermediate attacking Vibora smash generating sidespin

Figure 5: Advanced attacking & defensive topspin smash generating topspin

(Buffo, n.d.)

2. Understanding the smash

While the four different smashes described in the previous chapter are essential to consider when designing a product to help teach the smash techniques faster, it is very important to understand how people perform the correct technique and how players learn this movement. In figure 6 below are three main categories shown that play a role when the smash is performed; biomechanics, motor learning and coordination.

In this chapter, the three main categories and their connections to specific aspects are explained. The terms highlighted in bold throughout this chapter reappear in figure 6 and later in figure 7. Appendix B presents a more extensive report about these three topics.

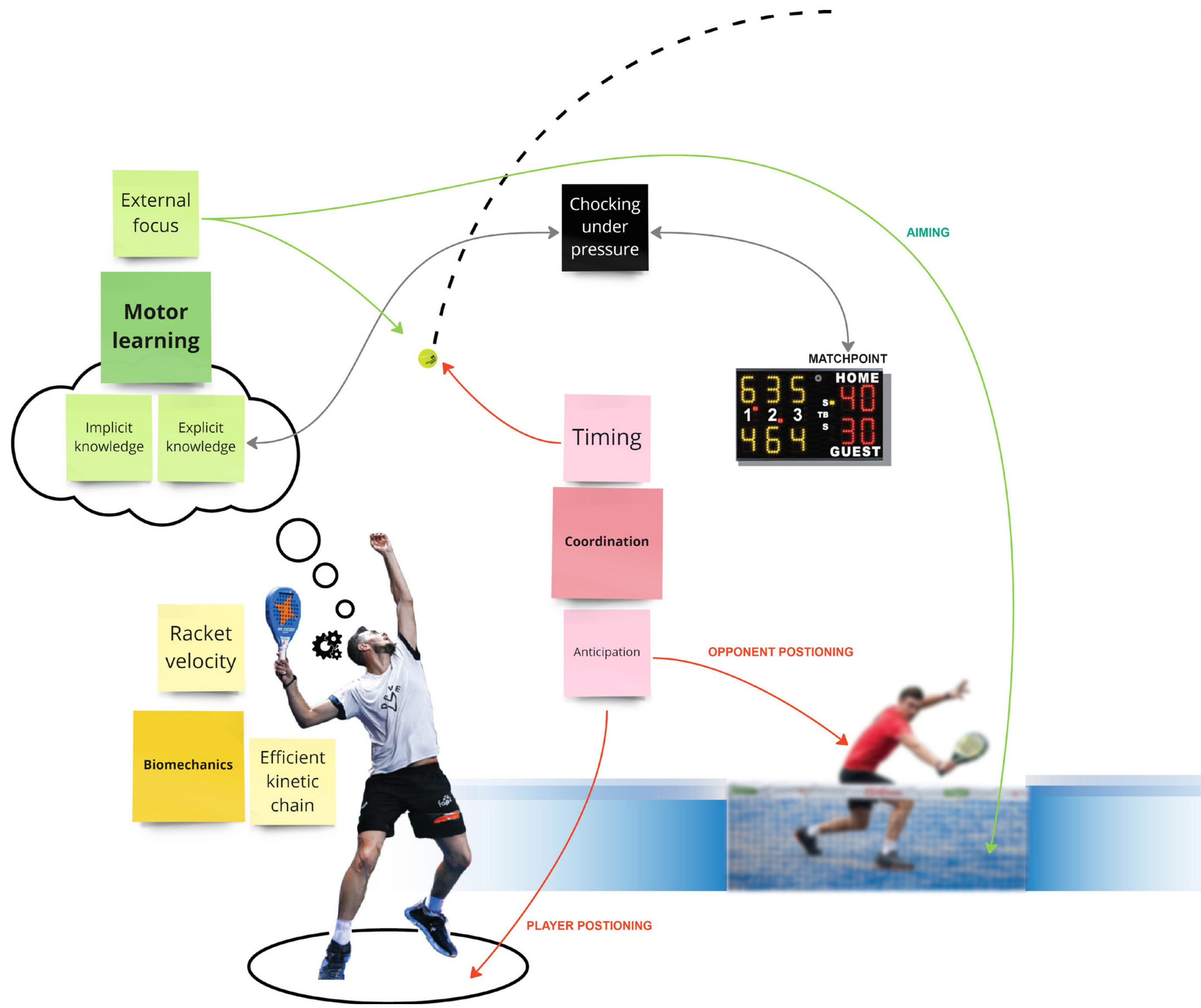


Figure 6: Overview of the body processes during a smash based on literature research divided in three main categories; biomechanics, motor learning & coordination

2.1 Biomechanics

To perform a smash in padel, the body must generate power to hit the ball fast to the ground. No direct research has been conducted specifically for the padel smash. However, parallels can be drawn between the flat/topspin smash & the tennis serve, tennis smash, badminton smash and baseball pitch, which despite the different nature of these sports, share a similarity in their movement patterns.
Kovacs and Ellenbecker (2011) conducted a study on the tennis serve, revealing that 51-55% of the kinetic energy and force directed to the hand originates from the legs and trunk. This is also true for executing a smash, where energy stored in the legs and trunk translates into high velocity in the arm through a mechanism known as the kinetic chain.

2.1.1 Kinetic chain

The concept of the kinetic chain originates from engineering principles applied to human movement. It conceptualises the human body as a system composed of rigid, interconnected segments linked by joints, wherein movement at one joint influences movement at another (Ellenbecker & Davies, 2001; Kovacs & Ellenbecker, 2011).
The padel smash features an open kinetic chain, meaning that distal smaller, lighter and faster segments (like the hand) move freely in space and receive movement energy from larger, heavier, slower central body segments (like the legs and trunk). This is called proximal-to-distal sequencing (Marshall & Elliott, 2000; Ellenbecker & Davies, 2001).

2.1.2 Energy flow and technique

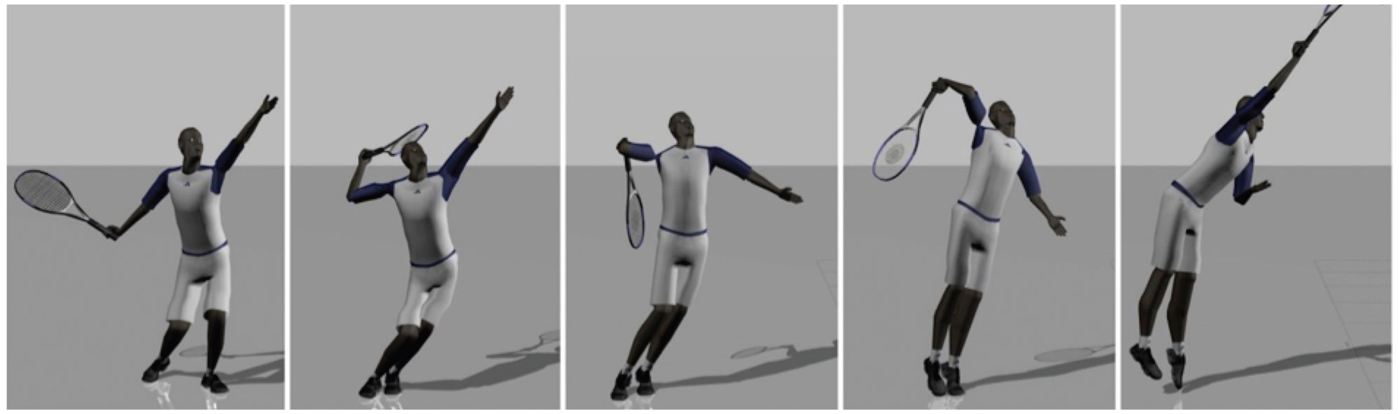
Scarborough et al. (2018) outlines the sequence of motion in overhead baseball pitches which we can compare to the padel smash: pelvis - trunk - arm - hand - forearm. An efficient kinetic chain, indicating good technique, results in higher hand/racket velocity.

On the other hand, incorrectly applied technique can lead to higher injury risks because of increased joint loading due to an inefficient energy flow (Martin et al., 2014; Rusdiana et al., 2021). Fatigue or pressure situations can compromise technique, consequently affecting hand velocity and increasing injury risk (Heirbaut, 2019).

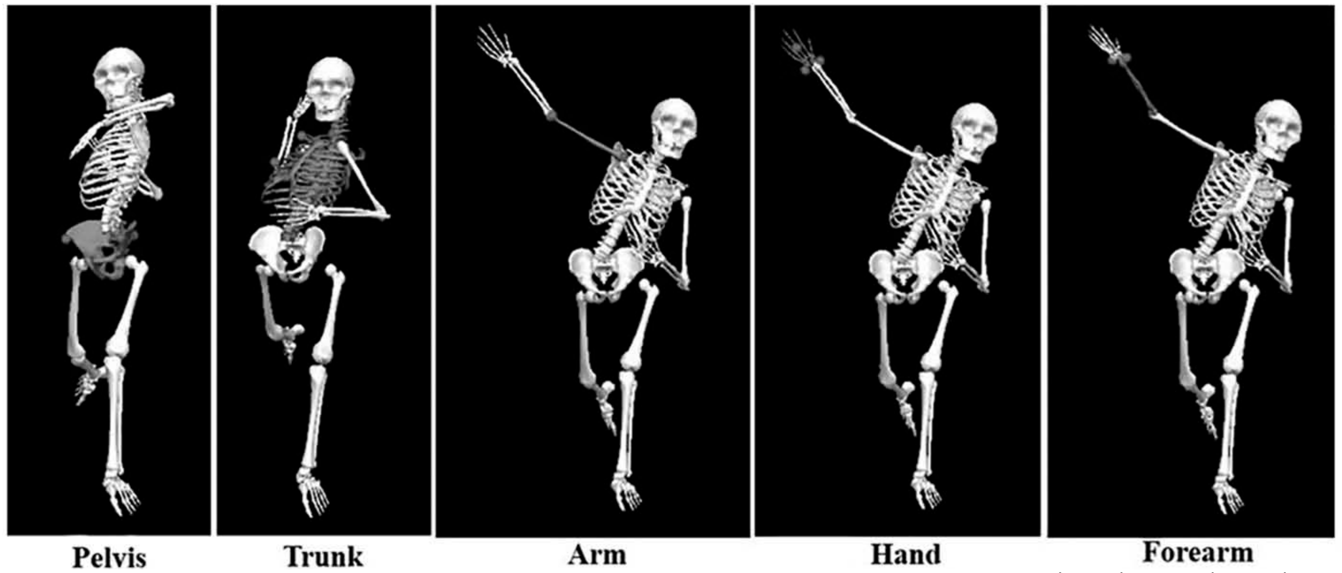
Furthermore, an efficient kinetic chain can be developed during practice sessions. Padel trainers frequently advise their athletes to maintain a loose swing rather than forcefully muscling the ball (The Padel School, 2022). Optimal utilisation of the kinetic chain is hindered when attempting to generate brute force solely through the arm. Forced swings bypass the interplay of joints and muscles within the kinetic chain, compromising both power and efficiency in the stroke. By prioritising fluidity and allowing the kinetic chain to function naturally, players can harness the full potential of their body's biomechanics to deliver more effective and controlled shots (Martin et al., 2014).

In contrast to its influence on the technique of the smash, the kinetic chain does not determine whether the ball goes in or out. This outcome depends on the angle at which the ball is hit, which is decided in only milliseconds prior to hitting the ball (Whiteside et al., 2013).

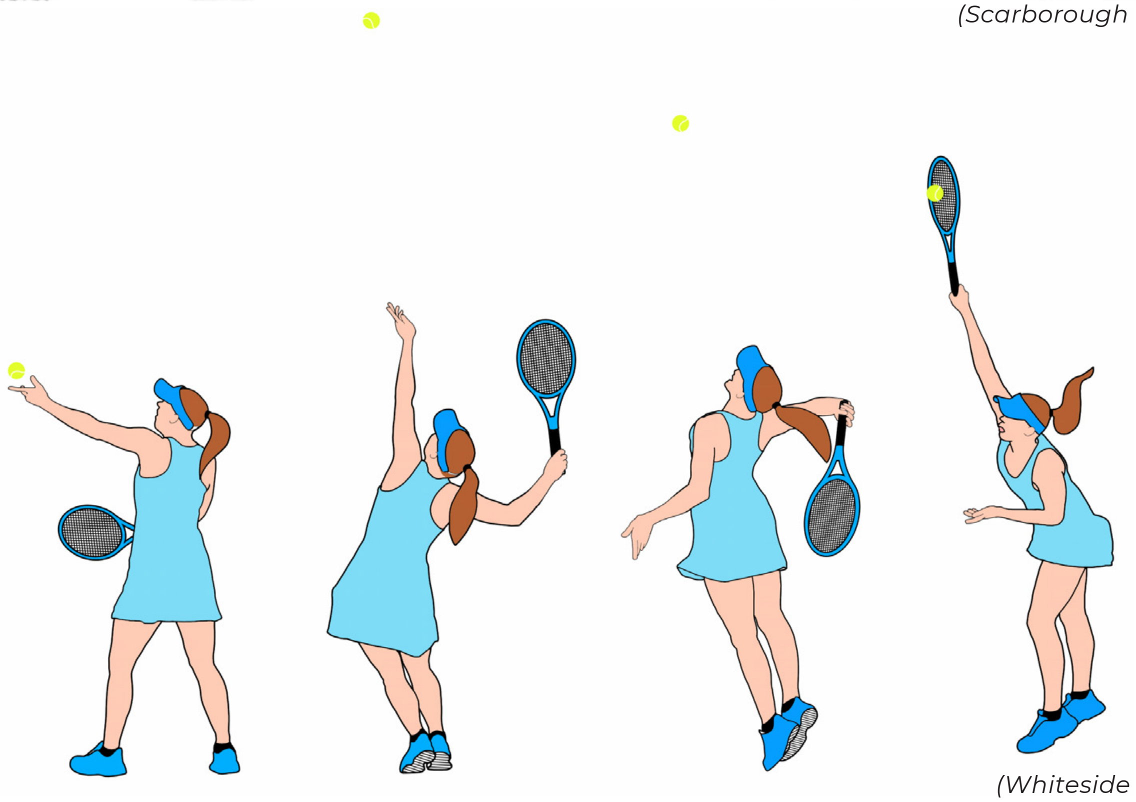
Motion sequences from research papers



(Martin et al., 2014)



(Scarborough et al., 2018)



(Whiteside et al., 2013)

2.2 Motor learning

Motor learning is a process that results in changes in behavioural potential, particularly related to movement, through specific experiences with the environment (Beek, 2011a). For padel amateurs to master the smash, it is crucial to understand the specific situations requiring a smash, use this knowledge to respond optimally, and improve with each attempt. Optimising motor learning is essential for enhancing athletic performance and skill acquisition. However, there is no universal method for motor learning; the optimal approach varies based on the individual athlete, coach, and context. The process of motor learning involves understanding what an athlete learns in a training session and its ability to be reproduced in the future (Beek, 2011a).

2.2.1 Stages of Motor Learning

1. Cognitive Phase: This initial stage involves comprehending the movement mechanics and techniques of the padel smash. Players focus on learning the basic elements of the smash.

2. Associative Phase: At this stage, players begin to understand cause-and-effect relationships, such as how different ball trajectories and timing impact the success of the smash.

3. Autonomous Phase: Through intensive repetition, players reach a level where the padel smash is executed effortlessly and consistently under various conditions. This stage involves deliberate practice, which is goal-oriented and focuses on refining the skill (Beek, 2011a).

2.2.2 Knowledge Acquisition

- **Explicit Knowledge**: Facts and rules that players are aware of and can verbalise. This type of knowledge is crucial for understanding the mechanics and strategy behind the smash but can lead to performance issues under pressure if relied upon too heavily. However, beginners in a new sport need some explicit knowledge to grasp the general idea of the movement and understand its goal. For the rest of this research, it is assumed that amateurs already have this knowledge.
- **Implicit Knowledge**: Skills and tactics that players internalise without conscious awareness. This type of knowledge is preferable for mastering the smash, as it supports automatic execution and reduces the risk of choking under pressure (Yu, 2015).

2.2.3 Focus During Practice

- **External Focus**: Concentrating on the movement's effect on the environment or the goal, such as aiming to hit the ball accurately or targeting a specific spot on the court. This type of focus enhances learning effectiveness and performance.
- **Internal Focus**: Concentrating on the mechanics of the movement and the body parts involved, such as how to swing the arm during a smash. This focus can hinder automaticity and overall performance (Beek, 2011b; Wulf et al., 1999).

2.2.4 Motor Learning Approaches

- Traditional Motor Learning: Focuses on ideal movement techniques that are universally applicable. This approach emphasises standardising techniques.
- **Differential Motor Learning:** Acknowledges and leverages individual differences, promoting variations in execution to facilitate effective learning. This approach supports the idea that there is no single correct way to perform a skill, encouraging personalised learning experiences.

2.2.5 Enhancing Motor Learning Through Self-Control

Allowing athletes to make decisions about feedback and practice schedules enhances motor learning. Self-control promotes active engagement and effective strategy selection, leading to more personalised and effective learning experiences (McNevin et al., 2000; Wulf & Toole, 1999).

By understanding the above mentioned principles that are involved with motor learning, designers can develop methods to accelerate the learning process. For the current study this knowledge will be used to design a product to help individuals quickly and effectively master the motor movement of the smash.

2.3 Coordination

Another important aspect to consider is coordination. Coordination is the movement of multiple effectors that work together to achieve a common goal (Diedrichsen et al., 2010). When coordination is performed effectively and efficiently, it not only minimises the risk of injury, but also accelerates mastery of techniques, improves tactical ability and strengthens mental resilience (Alsaudi, 2020).

In the context of the padel smash, coordination involves several essential aspects: for example, 1) predicting the trajectory of the a lobbed ball, 2) controlling and **timing** the movement of body segments to hit high balls **accurately**, 3) deciding towards which **direction to aim** the ball just before hitting it, based on the situation that is presented and the tactical knowledge the player possesses, 4) processing information about the quality of the performed smash and 5) predicting how the point will continue (Appendix B presents more detailed descriptions about **opponent anticipation, ball anticipation**, prediction ball trajectory and timing).

A lot of the body processes previously described in biomechanics and motor learning come back in coordination. Coordination is the connection between the motor learning of a certain skill and the actual performance of this skill executed by the player. For example when amateur padel players want to learn the smash. In figure 7 a model is presented in which these links are visualised.

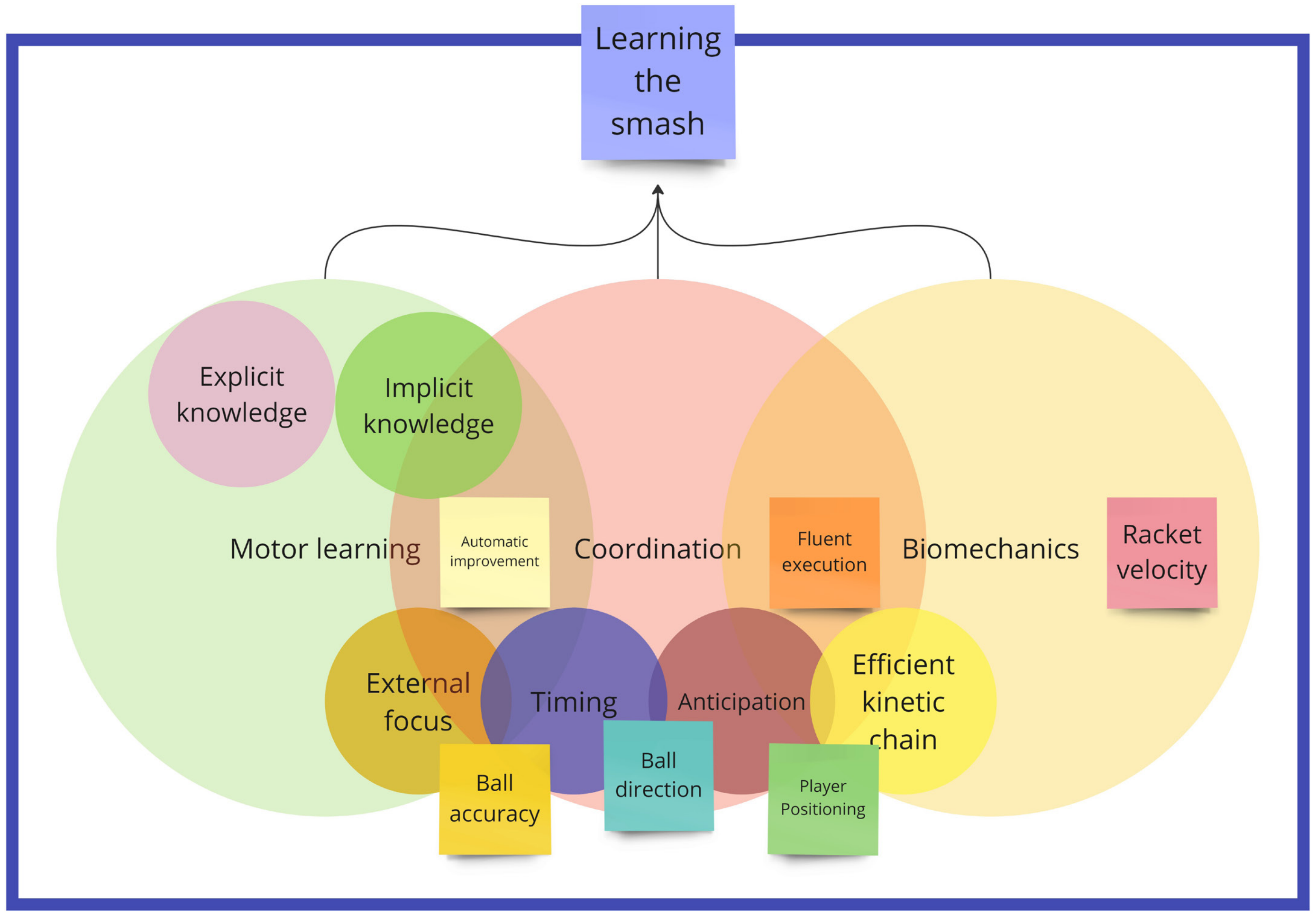


Figure 7: A visualised model of the connections between motor learning, coordination and biomechanics

2.4 Conclusions literature research

Padel amateurs often find themselves in the cognitive or associative phases of motor learning when it comes to executing the smash, because they cannot execute it automatically. The goal is to advance them to higher phases, ultimately reaching the autonomous phase where the smash can be performed effortlessly and consistently.

Initially, players need explicit knowledge about the basic technique and an understanding of the biomechanical movements required to generate racket velocity and maintain fluidity in their swing. However, an overemphasis on explicit knowledge and an internal focus can be counterproductive. This approach is not the most efficient way to learn the smash and can lead to choking under pressure when they have reached the autonomous phase. To improve the learning process, the design should focus on the development of implicit knowledge. This approach reduces the chance of choking under pressure. Emphasising external focus enhances learning effectiveness and performance by directing attention to the effects of the movement on the environment rather than the movement itself.

Furthermore, employing differential learning, which highlights individual variations in execution, is crucial. This method contrasts with traditional learning approaches that promote standardised techniques, which can increase explicit knowledge and hinder performance. Allowing players to have self-control over their learning process also enhances engagement and effectiveness, aligning with the principles of deliberate practice to be more goal-oriented.

Focusing on coordination aspects provides good design directions since coordination integrates biomechanics and motor learning. Emphasising elements such as timing, ball accuracy, ball direction, opponent anticipation, and ball trajectory prediction ensures a comprehensive approach to skill development.

3. Ideation and concepts

In this chapter the ideation phase and (development to) concepts are discussed. Ideas and concepts are chosen based on requirements and wishes.

3.1 List of requirements & wishes

Based on the literature research, a set of criteria has been established for evaluating potential design ideas. Additionally, a list of design wishes, informed by conversations with padel amateurs & trainers, and personal insights, will be used to select the most promising concepts for further development in this project. Table 1 shows this list requirements and wishes.

Table 1: Requirements (based on literature research) and wishes (based on conversations with padel amateurs & trainers, and personal insights)

Requirements The design must...	**Wishes** The design should...
let the player use implicit knowledge	be able to be used on different padel levels
let the player use external focus	allow the player to learn different smashes
support differential learning	not change the padel necessities too much (court, racket, net, player)
integrate self-control	be able to be used on every (type of) court
not increase the risk of any injury	not be too expensive
	be innovative
	allow the player to learn other techniques beside the smash
	be able to be used during practice as well as matches
	be able to be used without trainer

3.2 Ideation

The ideation phase has been a recurring phase since the start of the project. Methods from the book 'Road map for creative problem solving techniques: organizing and facilitating group sessions' by Heijne & Van Der Meer (2019) are used each time literature research illuminates new findings. At the end of every planned ideation session there is a moment in which previous ideas are looked back on so they could be used as inspiration and, if possible, be combined with new ideas. When a burst of inspiration occurs between ideation sessions, or when the topic or ideas are discussed with people in the direct environment, sketches are made so the ideas are not forgotten (see figure 8).

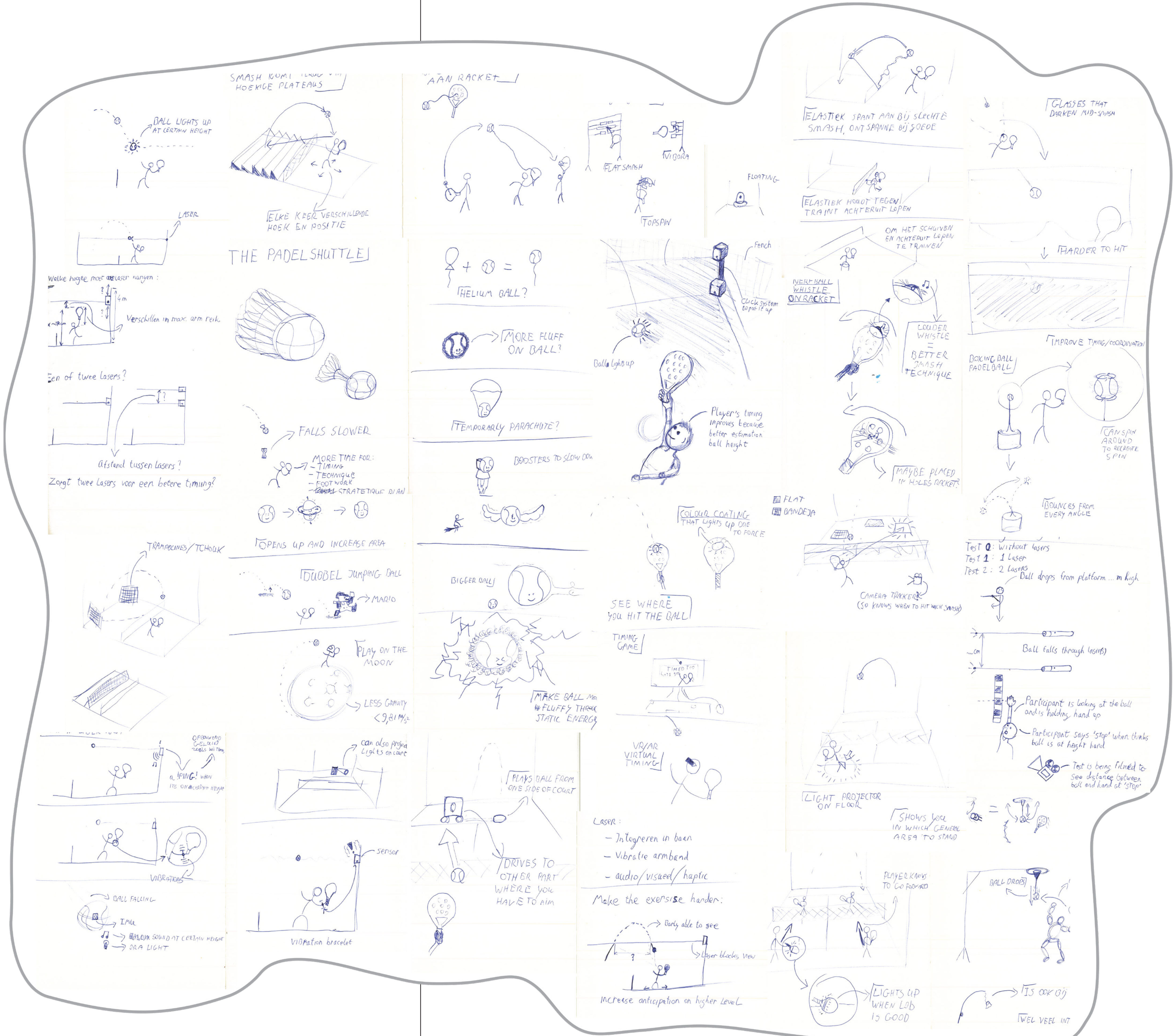


Figure 8: Sketches of the ideation phase

To select ideas that had the potential to become viable concepts, several methods were used. Initially, multiple C-boxes were used to generate and organise ideas, but these did not produce the desired results. Therefore, random clustering was applied, grouping ideas based on patterns and similarities (see figure 9). This approach facilitated the identification of promising clusters and also shows where there is room for further ideas.

Finally, the hits-and-dots technique was used, highlighting the most appealing ideas. The ones with the greatest potential but also the most novel ideas emerged as a result (see figure 9).

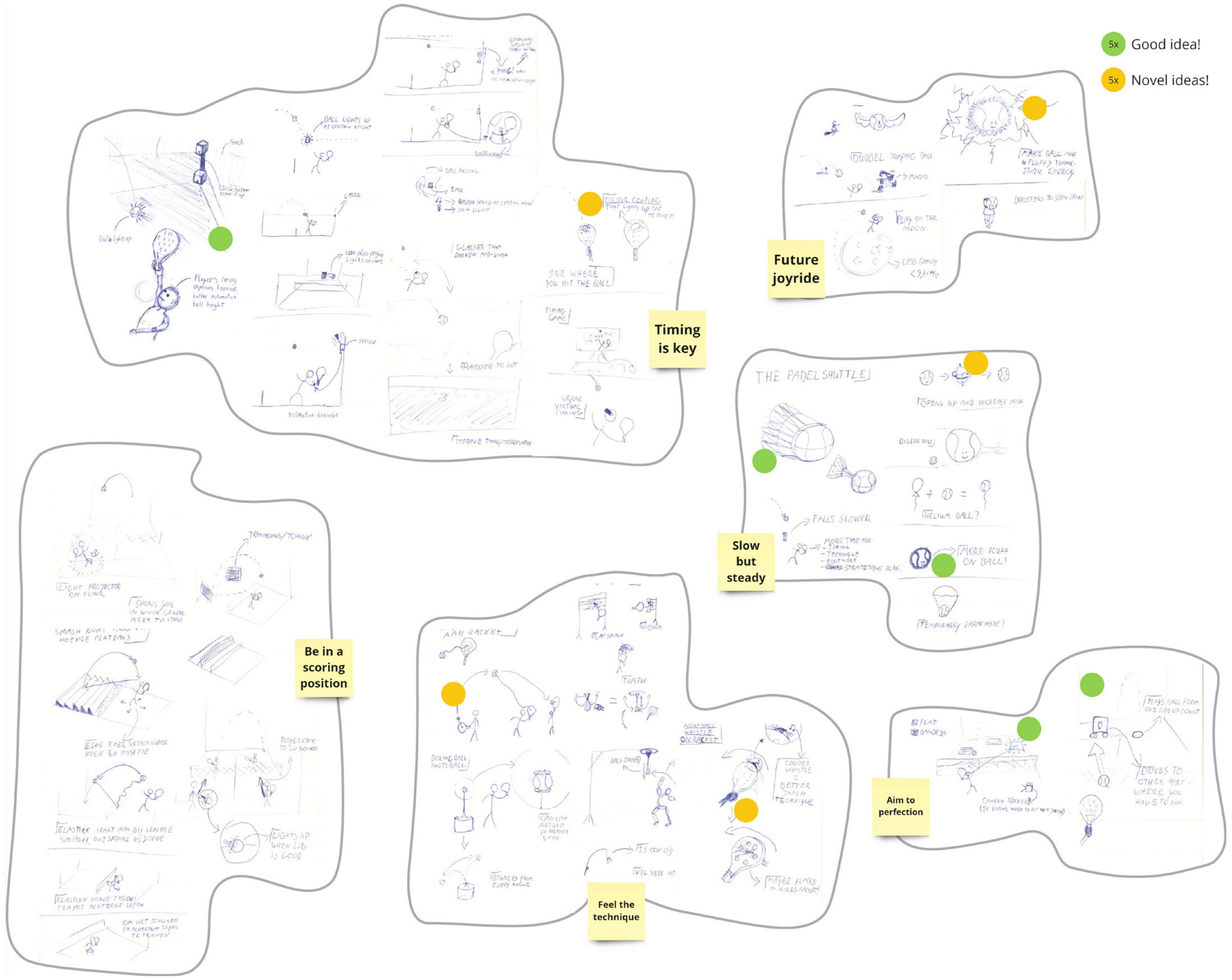


Figure 9: Ideas sketches clustered by using the random clustering method, the hits-and-dots method is used to highlight good and novel ideas

3.3 Concepts

As the ideation phase concluded, the focus transitioned to the further development of the concepts. Using the model in figure 7, four ideas were selected and developed into comprehensive concepts, each with a detailed description and a visual illustration.

3.3.1 Concept 1; Lob, aim, fire

This concept features a driving ball cannon that lobs a ball to the player, who is positioned to perform a smash. As the ball is lobbed, the cannon moves to a different location on the court. The player's objective is to aim their smash at the ball cannon (see figure 10). Players or trainers can select a programmed practice mode to focus on specific smashes or choose a random mode, requiring the player to anticipate the ball's landing spot. An additional function can be that the ball machine can register the player's position on the court, allowing it to adjust the difficulty of the lobs.

Literature keywords that are linked with this concept are; External focus, implicit knowledge, anticipation.

Figure 10: Concept driving ball machine

3.3.2 Concept 2: Aim for the light

Electronic target mats that light up in different colours are used to aid trainers during smash exercises. When the trainer lobs a ball, a sensor detects the lob and activates one of the target mats, which lights up in a specific colour (see figure 11). The player must then aim their smash at the lit target and the colour of the mat indicates the type of smash the player needs to perform. Similar to the driving ball cannon, users can select either a programmed practice mode to focus on specific smashes or a random mode, challenging the player to anticipate both the type of smash and the landing location.

Literature keywords that are linked with this concept are; External focus, implicit knowledge, explicit knowledge, anticipation.

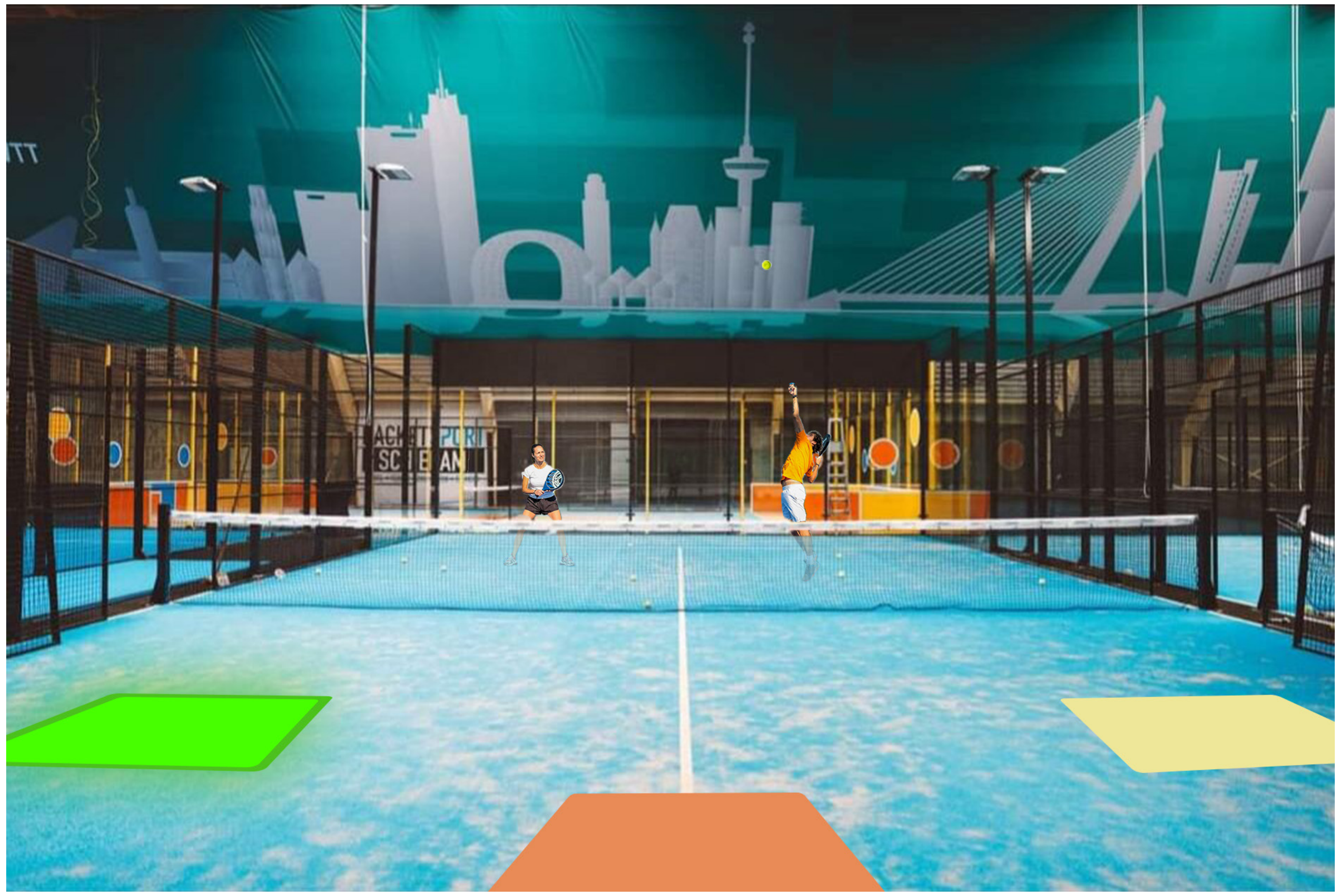


Figure 11: Concept light mats

3.3.3 Concept 3: Roof of falling stars

Beginners often struggle with timing their smashes because the ball is coming directly toward them, making it difficult to predict the exact height and when to start their swing. A device is placed on the fence in the middle of the court, emitting a laser that covers the entire court, creating a light roof. When the opponent lobs the ball, it passes through the laser as it descends. At that moment, the player, positioned under the ball, sees it light up as it passes through the light roof (see figure 12). This laser provides precise height information and additional sensory input. With a bit of practice, the player learns when to begin their swing to execute the smash effectively.

Literature keywords that are linked with this concept are; External focus, implicit knowledge, anticipation, timing, racket velocity.

Figure 12: Laser roof concept

3.3.4 Concept 4: Float like a feather, smash like a hammer

The yellow felt of the padel ball is made fuzzier, which increases the drag letting the ball travel slower through the air (see figure 13). When a lob is played by the opponent, the player receiving it has more time to set up their smash. Instead of performing rushed movements and rushed decision making, the player can focus on their positioning, technique, timing and aiming. Advanced players can also use this ball due to its slower travelling characteristics, which differ from a standard padel ball, improving their timing and anticipation through the differential learning concept discussed earlier in this report.

Literature keywords that are linked with this concept are; External focus, implicit knowledge, anticipation, timing, racket velocity.

Figure 13: Concept fuzzy padel ball

3.3 Concepts

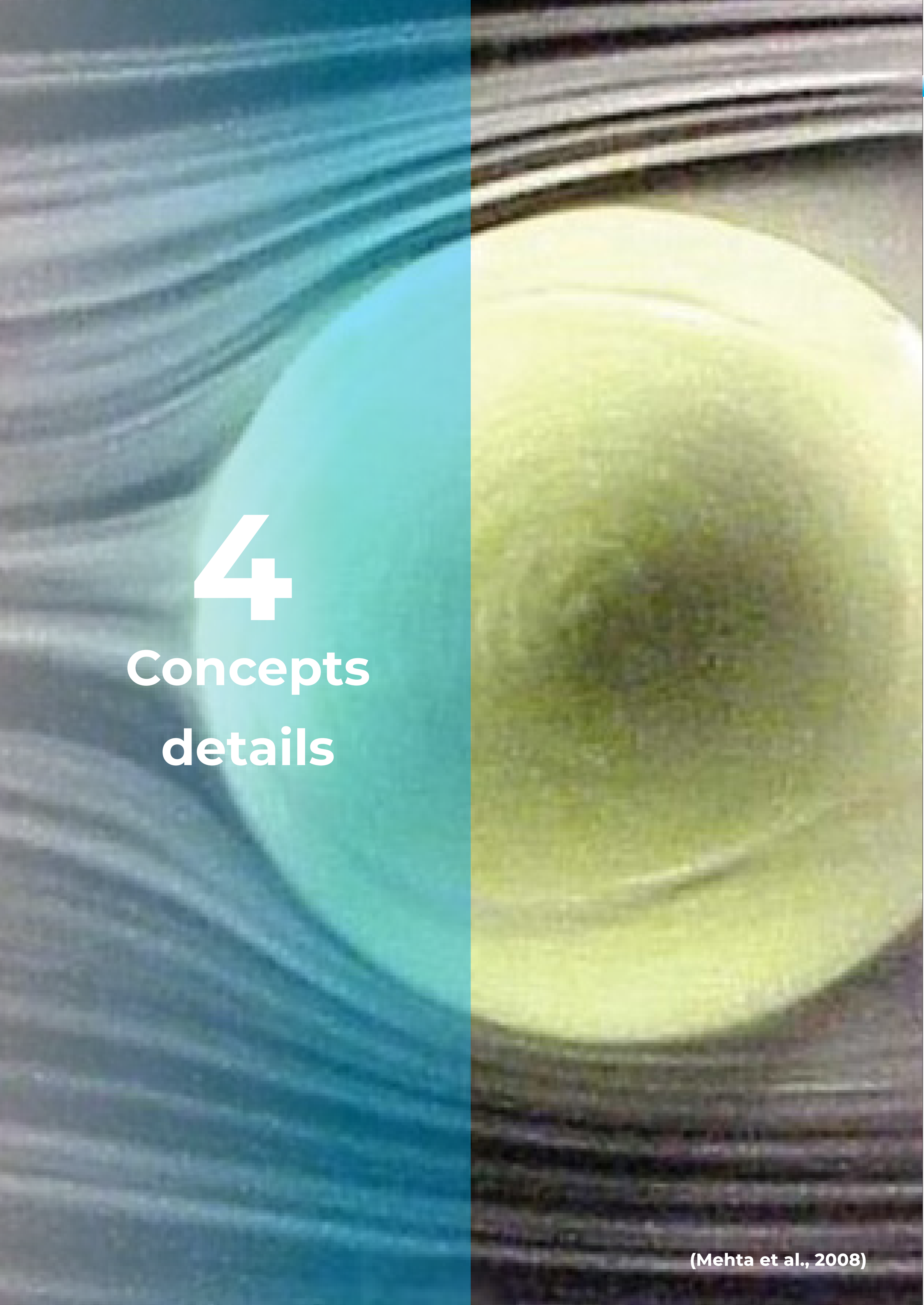
A Harris profile is used to make a choice between concepts based on established wishes presented in table 1 (Van Boeijen et al., 2014). Figure 14 shows the Harris profile. The wishes are listed on the left and the four concepts at the top. The criteria are sorted by importance. The once at the top of the Harris profile are the most important and at the bottom the least important. In this way, the most preferable concept is easy to distinguish.

The concept that stands out the most is concept number 4: the fuzzy padel ball. This concept addresses several good points. 1) It can be used across various padel skill levels and different types of padel courts. 2) The fuzzy padel ball is suitable for learning every padel smash as well as other techniques such as volleys and lobs. 3) Additionally, it is affordable and accessible.

During conversation with trainers about the various concepts, they mentioned using tennis youth balls for beginners learning padel because these balls also travel slower. However, the slower speed of these youth balls is due to their lower air pressure, which causes them to decelerate after bouncing and also to bounce lower. In padel, the bounce is a crucial aspect of the sport since, unlike tennis, the ball can rebound off the walls surrounding the court. Therefore, for fuzzy padel balls to be effective in regular play, they should bounce similarly to standard padel balls.

Appendix C shows quick online research about training balls in different sports. It highlights that many ball sports use specialised training balls that modify certain aspects to make it easier to play with or improve technique learning, except for padel. This gap in the market presents an opportunity to design a training ball specifically for padel.

Figure 14: The Harris profile for choosing the concept



4. Concept details

Since one of the concepts has been selected for further development, it is essential to understand its characteristics. This chapter outlines the production process of standard padel and tennis balls and identifies modifications needed to create a fuzzy ball. Additionally, it explains how increased fuzz affects the ball's aerodynamics, leading to a slower travel speed. Finally, the interactions between the ball, player, field, and racket are analysed to determine the key factors to consider and not to consider while testing the concept in the next chapter.

4.1 Production

In Appendix E is presented how tennis and padel balls are made. Since the concept is about a fuzzy outer layer, it is necessary to look into the felt of the padel ball. WSP Textiles, a company located in Stroud, United Kingdom, manufactures the felt for major tennis and padel ball companies like Wilson, Babolat, and Dunlop. When interviewing a factory employee about their production process provided details how the fuzz on the balls is created. A brief summary of the interview can be found in Appendix E. The employee mentions that mats of felt go through a heating machine with brushes to break the weaving pattern and add more fuzz (see figure 15). This process is repeated several times to meet the specifications of tennis and padel ball companies. The employee explained that the fuzz serves two purposes: to slow down the ball during a bounce and to slow it down in the air. Some companies request the felt to go through the machine multiple times to add more fuzz and make the balls slower.

This process is particularly interesting for the fuzzy padel ball concept because it's easy to increase the fuzz on the ball. The employee mentioned they have not extensively tested pulling the felt through the machine an extreme number of times, suggesting that further research should explore the effects of such an approach.

Figure 15: Machine brushes to give the felt more fuzz (Discovery Nederland, 2023)

4.2 Aerodynamics of the padel ball

The forces acting on a padel ball in the air include gravity & drag (see figure 16). The ball has a certain speed that was caused by contact with the racket. When the ball is in flight, the forces that slow it down are gravity (only when the ball is moving upward, against the gravity vector) and aerodynamic drag (always). To make a ball fly slower, you need to increase the drag. When a ball has spin, it experiences the Magnus effect, which generates a lifting force acting on the ball. For this research, it is assumed that the ball has no spin, allowing this force to be neglected. Consequently, the study will focus on the flat smash, a type of smash that involves no spin. This choice simplifies the analysis by eliminating the need to consider lift. For this reason, the flat smash is used in the smash test later in the report.

4.2.1 Impact of fuzz on the drag coefficient

The formula to calculate aerodynamic drag (*D*):

$$D = \frac{1}{2} \cdot \rho \cdot V^2 \cdot C_D \cdot A$$

And it depends on:

Air density $\rho\ (kg/m^3)$, velocity $V^2\ (m/s)$, drag coefficient C_D, frontal area $A\ (m^2)$ (Sciacchitano et al., 2023)

Research by Shah et al. (2019) and Mehta et al. (2008) demonstrated that the fuzz on the ball can account for 20% to 40% of the total drag. They also discovered that you could increase or decrease the drag coefficient (CD) by 10% by manipulating the fuzziness, either by raising or shaving the fuzz. The fuzziness of a tennis ball primarily impacts the CD, as it is determined by the texture and shape of the object.

Shah et al. (2019) noted that the felt on the tennis balls causes the balls to experience turbulent flow already at low speeds. This would suggest that tennis balls experience less pressure drag and would therefore go faster when hit by a racket compared to the same ball but without the felt. This would not be beneficial for the concept because the goal of creating more fuzz is to slow down the ball. However, the fuzziness of the felt contributes substantially to the drag experienced by the ball due to the fact that each fuzz element experiences pressure drag, which is high enough to counter the decrease of drag the turbulent flow causes. All the individual pressure drag, caused by the fuzz, summed up is called ‘fuzz drag’ (Mehta et al., 2008). Appendix D contains a more detailed explanation about the aerodynamics of a tennis/padel ball.

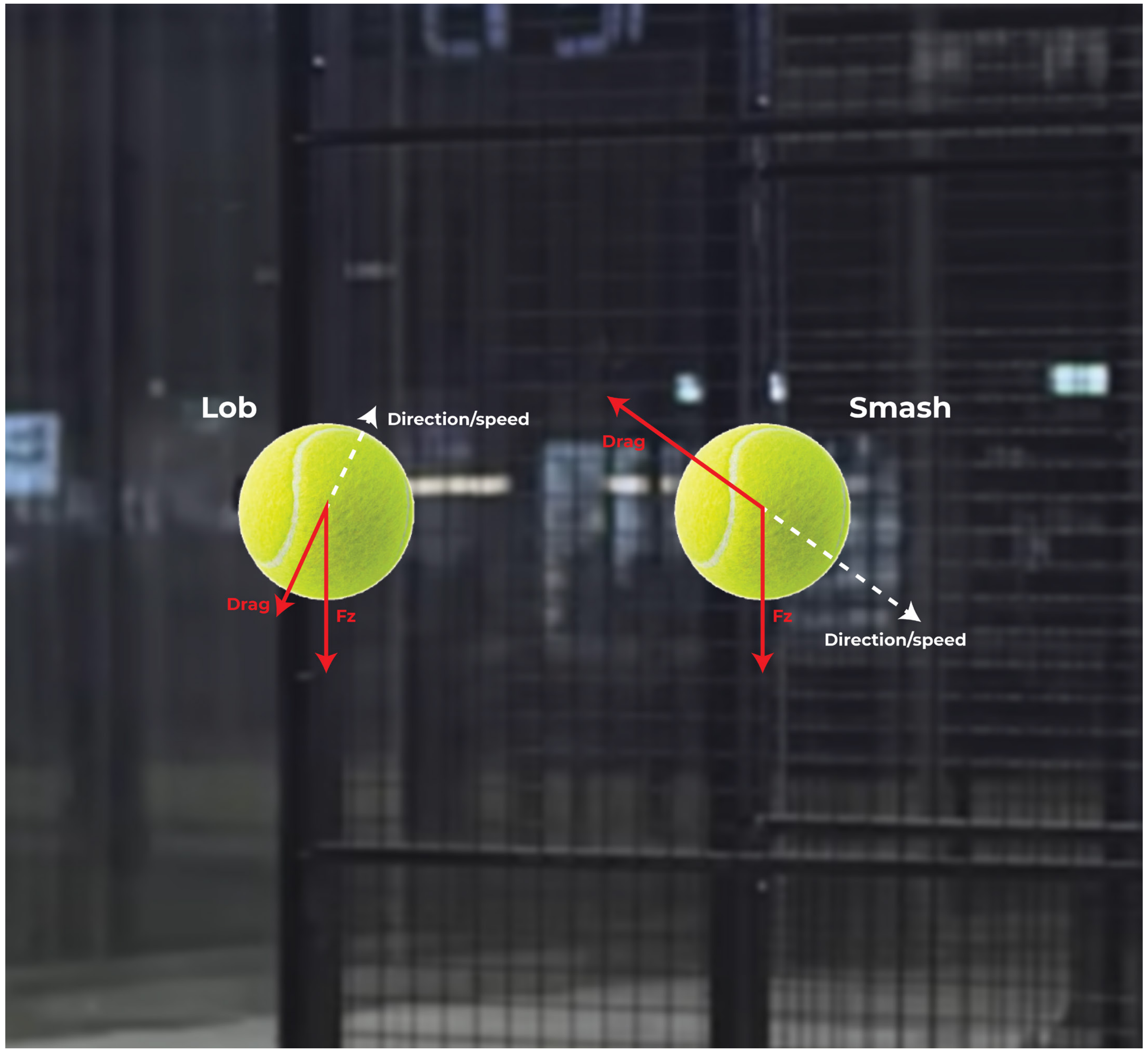


Figure 16: Forces that act on a ball in the air during a lob (left) and smash (right)

5. Experimenting ball characteristics

With a clear understanding of how the fuzzy ball concept works, it is crucial to test its effectiveness. This chapter focuses on the prototypes developed to determine if a fuzzy ball can indeed travel more slowly through the air. Additionally, it examines the prototypes' damping effect and their bounce characteristics compared to standard padel balls. Finally, the chapter explores whether a fuzzy ball genuinely helps amateur padel players in improving their smash performance.

5.1 Prototypes

To slow down the flight of a padel ball, the chosen final concept involves making the felt around the ball fuzzier. Figure 17 shows the prototypes, where cotton and different types of fabric are glued to the balls using textile glue. Table 2 shows the characteristics per ball. Appendix F shows photos of the fabrication of these prototypes. Initially, old tennis balls are used to test if the fabric would stick to the ball properly. In the studies presented later in this chapter, all prototypes are made with new balls to ensure consistent pressure. The next studies use both padel and tennis balls wrapped in fabric felt to observe the differences related to the internal pressure. In these studies, the balls are referred to as Padel-/Tennisball normal, cotton, green, yellow/red and brown. The colours are only for distinguishing the different groups and have no impact on aerodynamics. However, the fuzziness of each group does affect the results. The fuzziness level is measured on a scale from 1 (not fuzzy) to 5 (very fuzzy) and was determined by asking five randomly selected individuals to rank them. The results were unanimous, establishing a clear ranking of fuzziness levels.

Figure 17: Prototype balls

Table 2: Characteristics of each ballgroup prototype

	Weight	Diameter	Fuzziness level (1 - 5)
Padelball normal	57 grams	64 mm	1
Padelball cotton	61 grams	65 mm	2
Padelball green	70 grams	66 mm	3
Padelball yellow/red	72 grams	69 mm	4
Padelball brown	76 grams	71 mm	5
Tennisball normal	57 grams	64 mm	1
Tennisball green	70 grams	67 mm	3
Tennisball yellow/red	72 grams	69 mm	4
Tennisball brown	76 grams	72 mm	5

5.2 Droptest

To test if the prototypes actually have a longer flight time than a normal padel ball, a drop test study is conducted in which prototypes are falling off a certain height.

5.2.1 Pilot

Initially, a pilot study was conducted in which five prototypes were dropped from a height of approximately 6 metres to observe any noticeable differences (see figure 18). The pilot revealed that the ball covered with cotton showed inconsistent fall times and became very stiff due to the glue used, resulting in a complete lack of fuzziness. Therefore, this prototype was excluded from further testing in the actual drop test. Additionally, the pilot indicated that dropping the prototypes from such a height was unnecessary when using slow-motion cameras. It also demonstrated that results are more accurate when each ball is dropped individually, rather than editing the videos side by side as shown in figure 18.

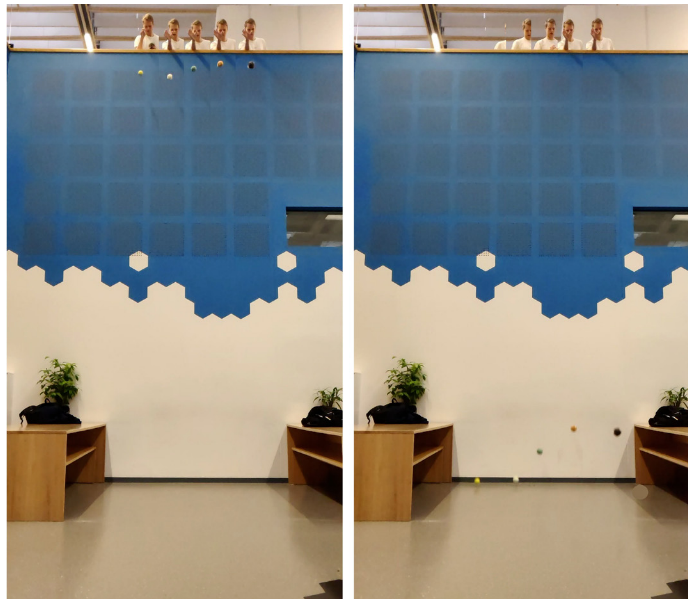


Figure 18: Pilot drop test footage of each ball video edited next to each other

5.2.1 Method

In the actual test, the prototypes are dropped from a height of 1.90 metres using a spring and rod mechanism (see figure 19). Each drop is recorded in 16x slow motion to capture detailed data. To determine the time for the balls to hit the ground a tracker program is used (see figure 20). The research question for this study is: Is there a significant difference in the fall times of padel and tennis balls with different types of felt coverings? Appendix G contains the whole study.

Based on literature, the hypothesis is that prototype balls with fuzzier fabrics experience a higher drag coefficient, resulting in longer fall times.

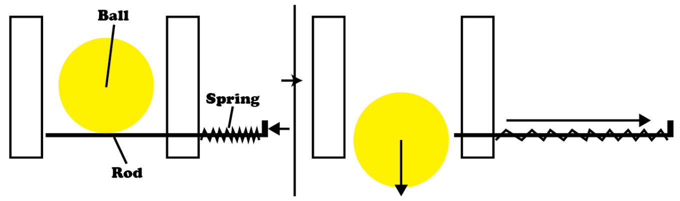


Figure 19: Sketch of the drop mechanism using spring and rod

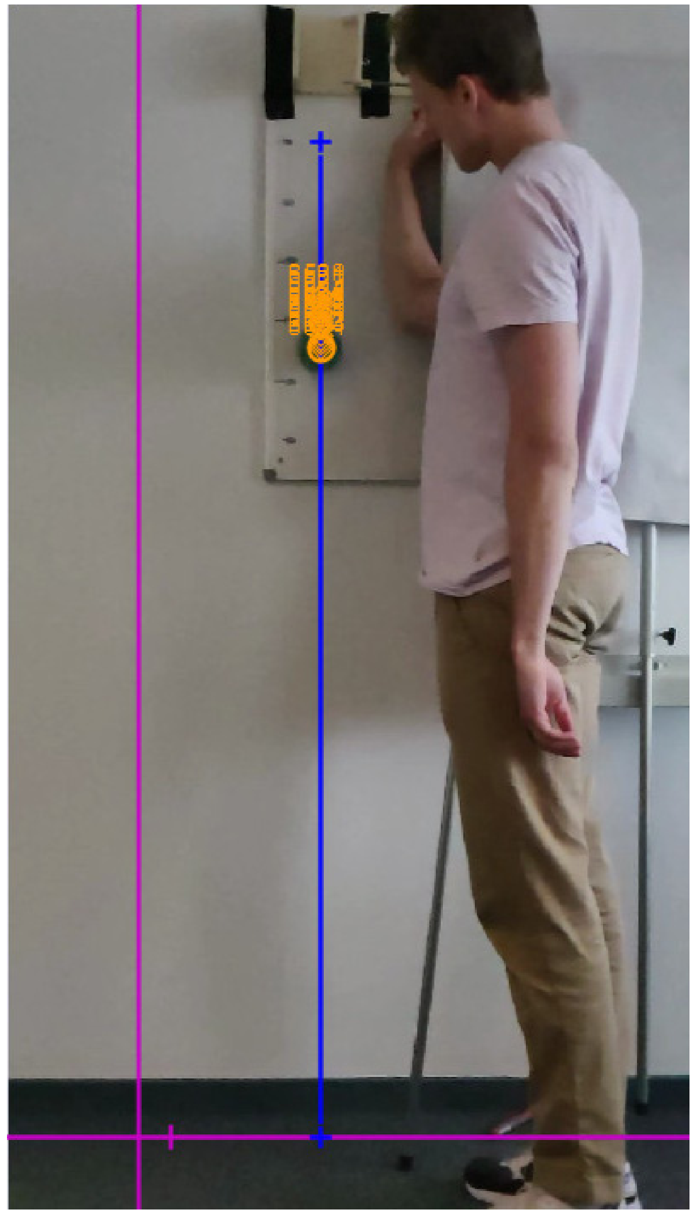


Figure 20: Screenshot Tracker system

5.2.3 Results & discussion

Multiple balls show significant fall time differences compared to normal padel and tennis balls when a one-way ANOVA test is conducted ($F(7,77) = 12{,}88$, $p < .001$). See figure 21 for the boxplot of the results. The Padel-/Tennisball normal are the control groups. These balls reach the ground in 9,40-9,43 slow motion seconds (approximately 0.59 seconds in real-time).

A post hoc pairwise comparison using the Bonferroni correction indicates a significant increase in time for the ball to hit the ground between the Padelball normal ($M = 9.43$) and the Padelball yellow/red ($M = 9.65$, $p < .001$), Padelball brown ($M = 9.61$, $p < .001$) and Tennisball brown ($M = 9.66$, $p < .001$). These balls are the balls to continue with in upcoming tests, scrapping the ones with green fabric felt since they show no significant difference. Returning to the hypothesis, it is partially confirmed. While some balls with increased fuzziness have significantly longer fall times, others do not exhibit this effect despite their fuzziness.

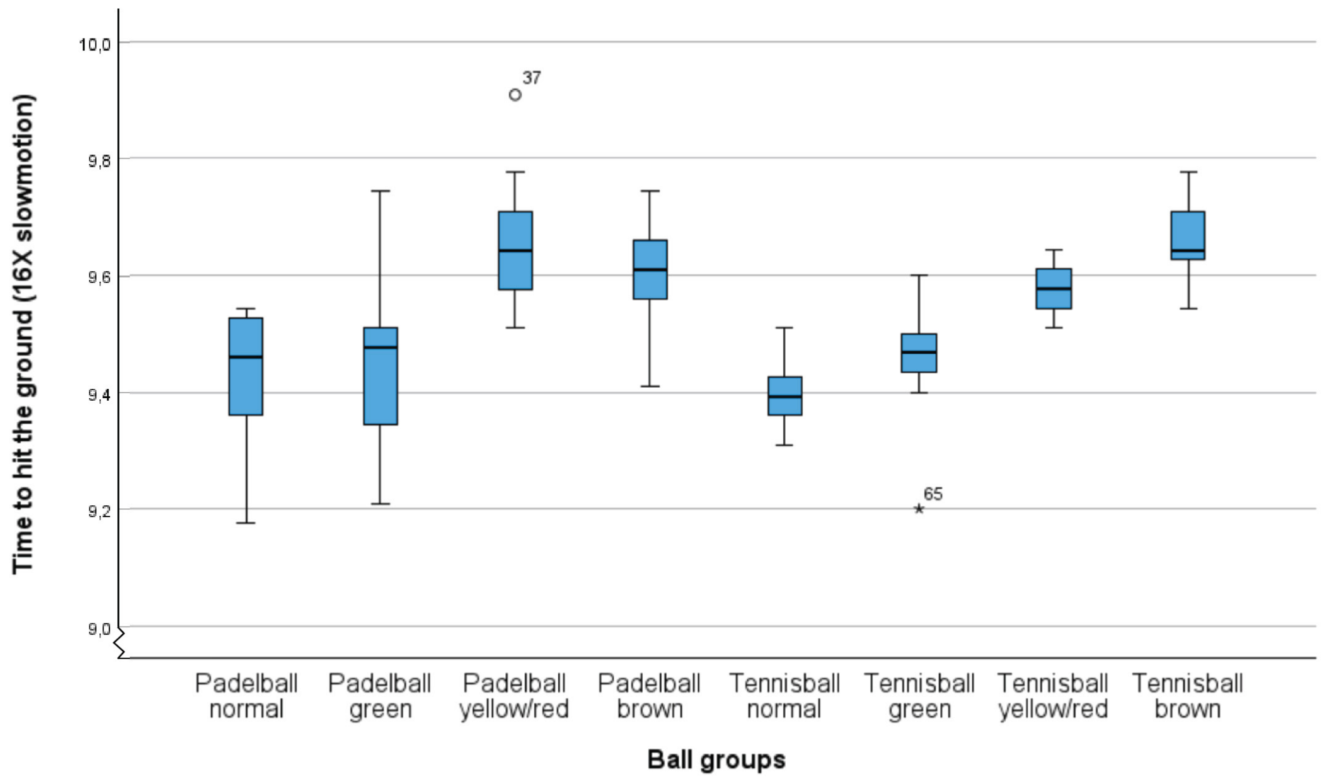


figure 21: Box plot of the ball groups on the x-axis and the time measurements in 16x slow motion seconds for the ball to hit the ground on the y-axis

5.3 Counter damping effect

The drop test is mainly focussing on the fall time of the ball. However, it is also noticeable that the bounce height of the prototypes appear to be lower than the normal padel and tennis balls. The right side of the graphs of the Tracker program in figure 22 shows the bounce height after the ball hits the ground (height of 0 metres). The fabric cover that was stuck on the ball with glue seems to have a damping effect. When a smash is performed the ball gets its speed from the contact of the racket that is swung by the padel player. Ideally, the energy transfer of this bounce should match that of a normal padel ball. However, due to the damping effect, this does not seem to occur. Also if this training ball will be developed further it would be great if it can be used for learning other techniques as well, like when it would bounce off the walls. Therefore a similar bounce as a normal padel ball is desired.

There is an easy way to let a ball bounce higher; increase the internal pressure. The main difference between a padel ball and a tennis ball is its internal pressure. A normal tennis ball has an internal pressure of 0.97 bar while a padel ball has an internal pressure between 0.69 - 0.76 bar. This is an average difference of about 25% (Van T Klooster, 2024). The reason for this is that a padel ball needs to bounce less than a tennis ball. If you play padel with a tennis ball, it will bounce much higher off the ground, walls, and racket, making it a completely different game.

To compensate for the damping effect in this study, the bounce of the prototypes needs to be increased. It is interesting to observe if a tennis ball with a fabric felt cover will bounce more similarly to a normal padel ball. Therefore, a bounce test is conducted.

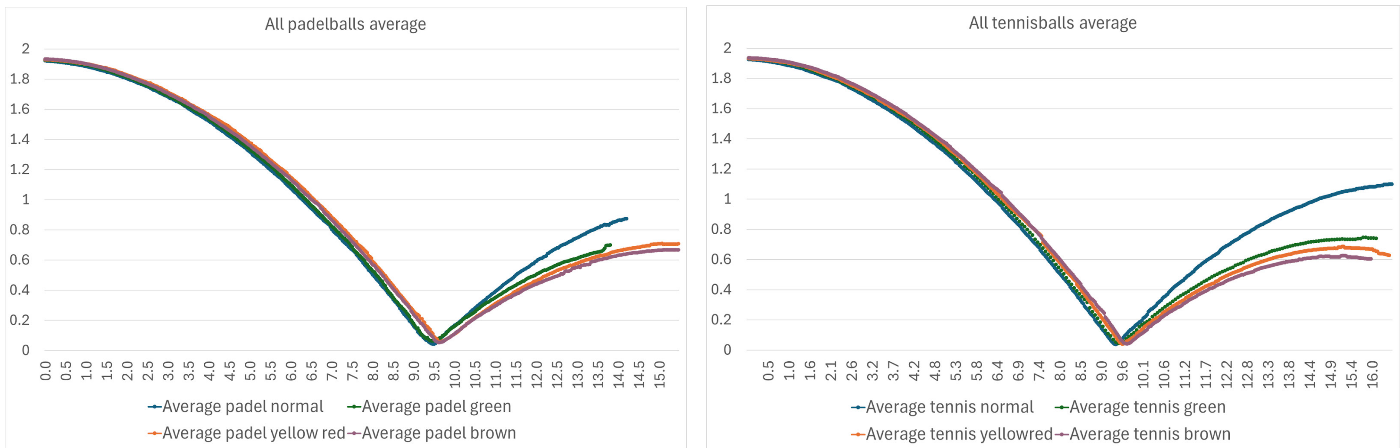


Figure 22: Average fall time padel balls (left) & average fall time tennis balls (right). X-axis shows the time in 16x slow motion second, the y-axis shows the height of the ball in metres

5.4 Bounce test

Repeating the fall test and only observing the bounce height would be inaccurate, since the balls travel through the air at a slower speed and therefore cannot be compared equally. A better method to compare bounce heights is to drop a weight onto stationary balls and measure the return height. The weight should be dropped directly onto the ball, which must remain stationary to ensure consistent deflection. However, the balls ought to have enough room on the sides to compress.

5.4.1 Method

In figure 23, the custom-made weight drop mechanism is shown. In this setup, a hammer is attached to a hinge at the base. The hammer is pulled back until it reaches a wooden block next to the hinge, ensuring that it is released in the same way every time. The hammer then falls onto the ball, which is held just tightly enough under the wooden frame, allowing room on the sides for compression. The head of the hammer bounces back, and the orange dot reaches the highest point of the bounce. A ruler placed behind the orange dot is used to read the height. Weights are placed on the wooden construction to ensure the setup remains stationary. The test is filmed in 8 times slow motion, and the results are determined manually by playing back the video in Adobe Premiere Pro.

The research question for this study is:
Is there a significant difference in the bounce height of padel and tennis balls with different types of felt coverings?

The whole study can be read in Appendix H. Based on the graphs in figure 22 the hypothesis is that the fuzzier the felt of the ball, the lower the bounce return of the hammer.

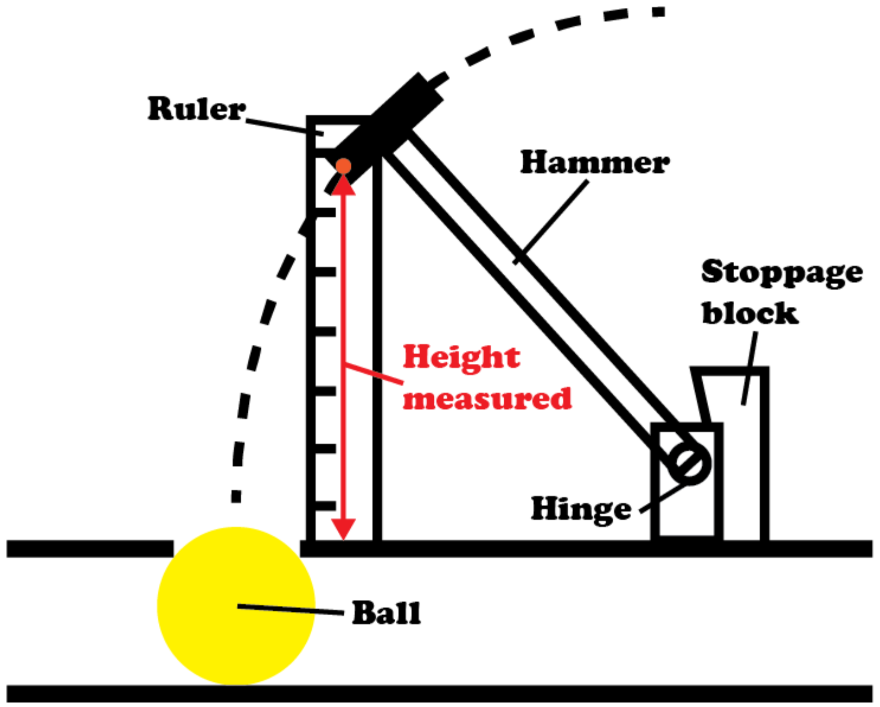


Figure 23: Bounce test set-up

5.4.2 Results & discussion

Examining the results, there is a significant difference between the ball groups, as determined by a one-way ANOVA ($F(5,171) = 8829.134$, $p < .001$). See figure 24 for the boxplot of the results.
A post hoc pairwise comparison using the Bonferroni correction indicates a significant decrease in return height between the Padelball normal ($M = 14.04$) and the Padelball yellow/red ($M = 9.66$, $p < .001$), Tennisball yellow/red ($M = 11.89$, $p < .001$) Padelball brown ($M = 11.81$, $p < .001$) and Tennisball brown ($M = 12.49$, $p < .001$)

However, the hypothesis that a fuzzier ball will bounce lower is not supported. The fuzzier brown ball experiences a significantly higher return height, when the same padel or tennis ball was used, than the less fuzzy yellow/red balls.

The prototypes have less bounce than the normal padel ball. Therefore, the prototypes are not suited for regular play in padel in which it bounces on the ground and off the walls. However, they still have a slower speed through the air so they are still suitable to test if having more time increases the outcome of a smash. It should be kept in mind that these prototypes will bounce less when it makes contact with the racket.

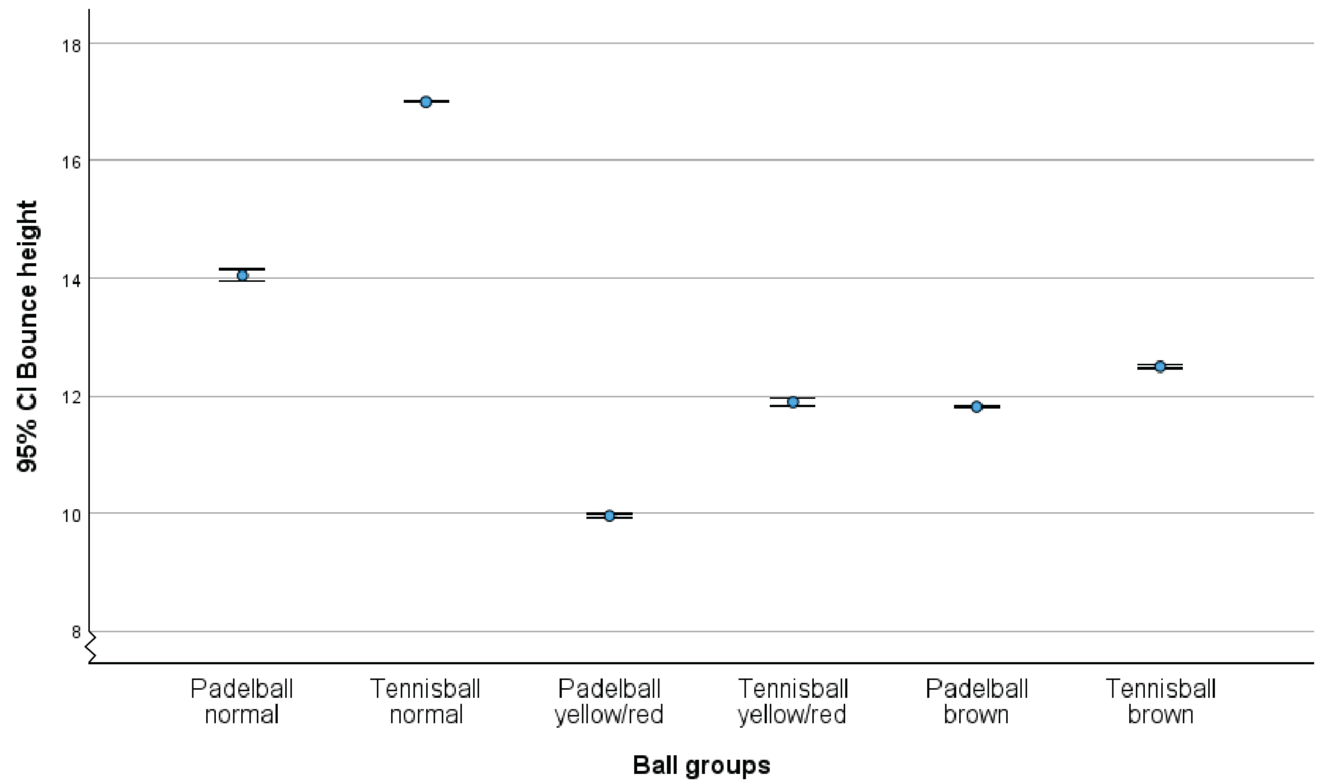
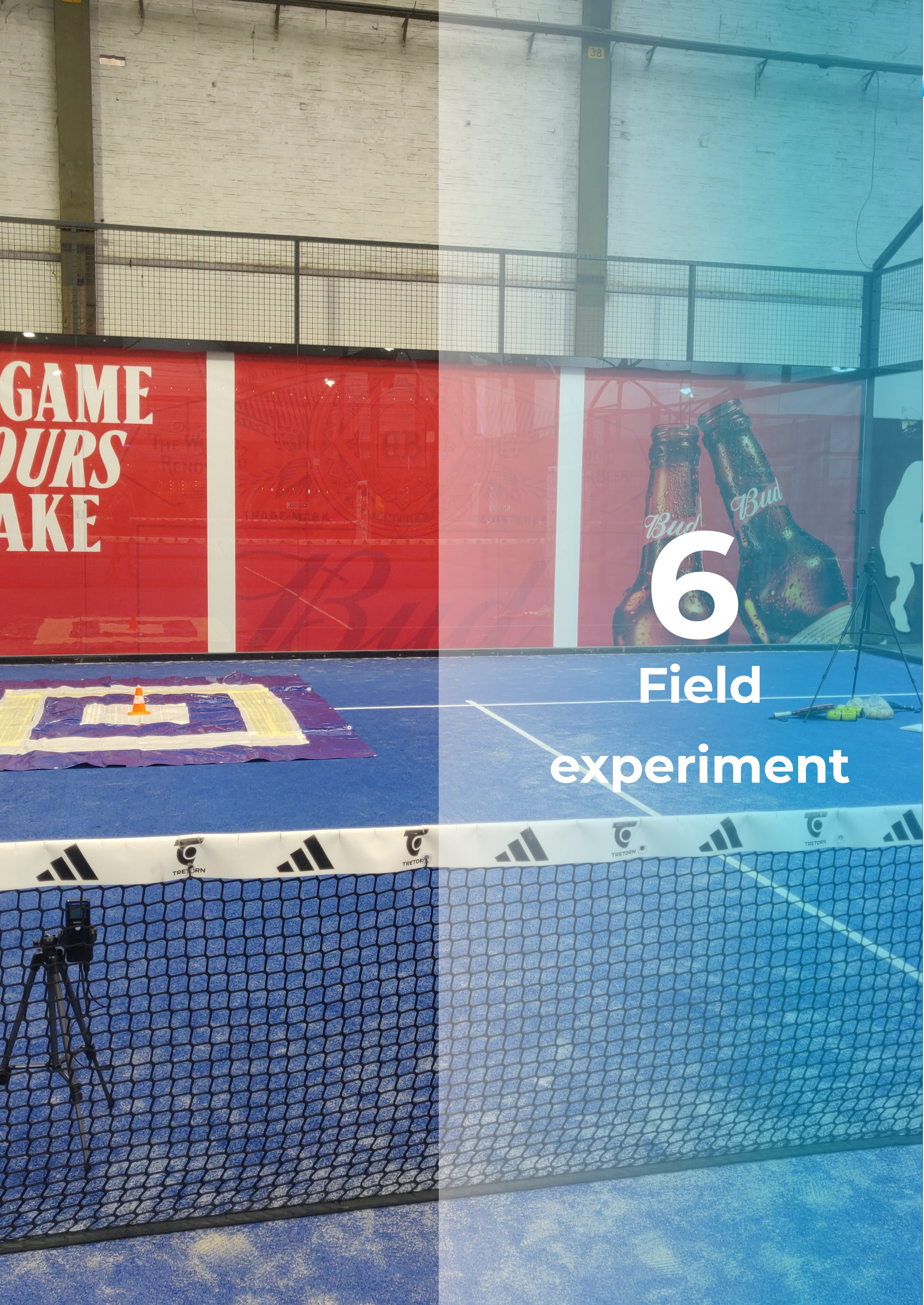


Figure 24: Box plot of the ball groups (x-axis) and the bounce height of the hammer in centimetres (y-axis) after contact with the different balls



6. Field experiment

To see how padel amateurs learn the smash faster using the padel ball with fuzzy felt it is important to look into what kind of effect the prototypes have on the smash performance of these amateurs. Therefore a smash test is conducted. This chapter goes into the execution of the test and a discussion of the results.

6.1 Smash test

The purpose of this test is to see if participants perform better if they have more time to set up their smash. This test was conducted by playing a lob to nine participants who had a beginner and intermediate padel level with normal padel balls and fuzzy prototype balls. The participants had to aim for a target mat at the other side of the field and were given specific points when they hit the target mat to measure the accuracy of the smash. Another component of the smash is its speed. The higher the speed the better the smash so this was recorded by a speedgun. In figure 25 an illustration of the test set-up is shown. The whole study can be read in Appendix I.

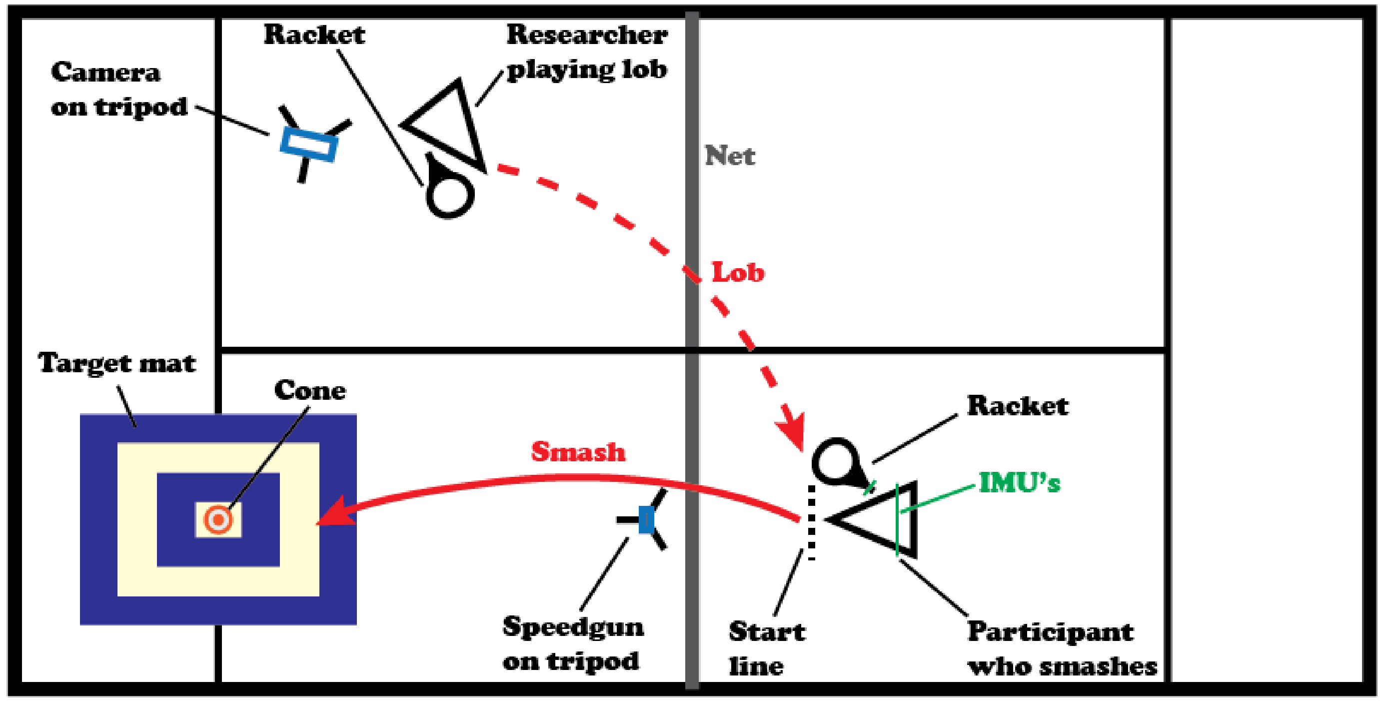


Figure 25: Smash test set-up illustration

6.1.1 Pilot

Prior to the real smash test, a pilot was conducted. The pilot had three changes in comparison to the real test. 1) A ball machine was initially used in the pilot to give consistent lobs. Unfortunately, the ball machine proved to be inconsistent, with balls sometimes over the participant hitting the back wall, and at other times failing to clear the net. Additionally, the prototype balls occasionally got stuck in the machine. For the real test it was decided to give the lobs manually, also simulating a real padel situation more. 2) The prototype balls that were used were the Padelball yellow/red and the Tennisball brown because then the differences between the balls were the biggest since a different ball type and felt type was used. During the pilot it was revealed that the brown felt had a much more damping effect than predicted based on the bounce test. The dark colour of the brown ball was also hard to see and therefore not pleasant to play with. For the real test this ball was replaced by the Tennisball yellow/red. Furthermore, the ball group Tennisball normal is not used in the actual test, as padel is typically not played with tennis balls. Consequently, it does not need to be included in the smash test comparison. 3) In the pilot it was discovered that the blue and white target mat was sometimes blending in with the blue environment. A bright orange cone was therefore placed on the centre for the real test.

6.1.2 Method

The balls that are used in the smash test are; normal padel ball (Pnormal), fuzzy padel ball (Pfuzz) & fuzzy tennis ball (Tfuzz) (see figure 26 and table 3). For each ball group five prototypes are made. For the production process of the prototypes see Appendix F. In the smash test each participant receives 15 lobs per ball group. The order in which they receive the ball groups is randomised. In total they played 45 smashes for which the amount of points by hitting the target was noted and the speed recorded. There are 9 participants (4 beginners & 5 intermediates) who are all playing with the same racket.

Figure 26: The balls used in the smash test; Pnormal (left), Pfuzz (middle), Tfuzz (right)

Table 3: Characteristics of each ball group that are used in the smash test

	Normal padel ball	Fuzzy padel ball	Fuzzy tennis ball
Weight	58 - 59 grams	68 - 70 grams	69 - 71 grams
Ball diameter	64 mm	69 mm	69 mm
Internal pressure	0.69 - 0.76 bar	0.69 - 0.76 bar	0.97 bar

Since amateurs will learn the smash faster if they improve their performance, the research question is: Is there a significant difference in the padel smash performance of amateurs when using balls with varying felt coverings and pressure?

The hypothesis for this research is that when using a ball that travels slower through the air, giving a player more time to set-up a smash, will improve the smash performance of padel amateurs. A second hypothesis is that increasing the pressure in the balls that travel slower through the air, will counter the damping effect and improve the smash performance of padel amateurs.

6.1.3 Results & discussion

The results are mentioned and discussed in four topics; Smash performance, smash speed, smash points & qualitative data.

Smash performance

Smash performance is determined by multiplying the recorded speed of the smashes (km/h) by the amount of points of the corresponding smash, resulting in the smash performance score. Examining the statistical data, no significant results can be concluded between the smash performance scores of the three ball groups. Therefore, both hypotheses are to be rejected. Future research should be conducted to test the hypotheses further.

Smash speed

A repeated-measures ANOVA determined that the mean speed differed significantly between the three ball groups ($F(2, 202) = 7.12$, $p < .001$). A post hoc pairwise comparison using the Bonferroni correction indicates a significant decrease in speed between the Pnormal ($M = 72.64$) and the Pfuzz ($M = 66.99$, $p = .002$).

Five participants mentioned that they felt like the Tfuzz speed was faster when they smashed the ball, which was preferred because it felt more like the Pnormal. However, three participants mentioned that the fuzzy balls felt heavier than the normal balls, which is true because there is a difference of about 11 grams, and that's why they had to give more power into their smash, resulting in a compensation of speed. This can be a reason why three participants mentioned that they preferred the Pnormal because then they did not have to force the power they had to put into the smash.

Smash points

Examining the total number of points each participant has achieved per ball, there is no significant difference between them. As determined by a one-way ANOVA ($F(2,24) = .27$, $p = .768$). See figure 27 for the boxplot of these results. Therefore no conclusions can be taken from this analysis if participants smash better with the fuzzy balls.

An interesting finding regarding the scoring frequency can be observed in Table 4. Specifically, the Pnormal ball landed more 0-point scores and fewer 1-point scores compared to both fuzzy balls.

Three participants mention that the fuzzy balls go to the ground faster so that might be a reason why these fuzzy balls have less 0-point and more 1-point scores than the Pnormal. Less errors were therefore made with the fuzzy balls which can indicate an improvement in smash performance. However since there was no significant difference with the total amount of points between the balls, there is a probability that the Pnormal compensates these bad scores with higher scores.

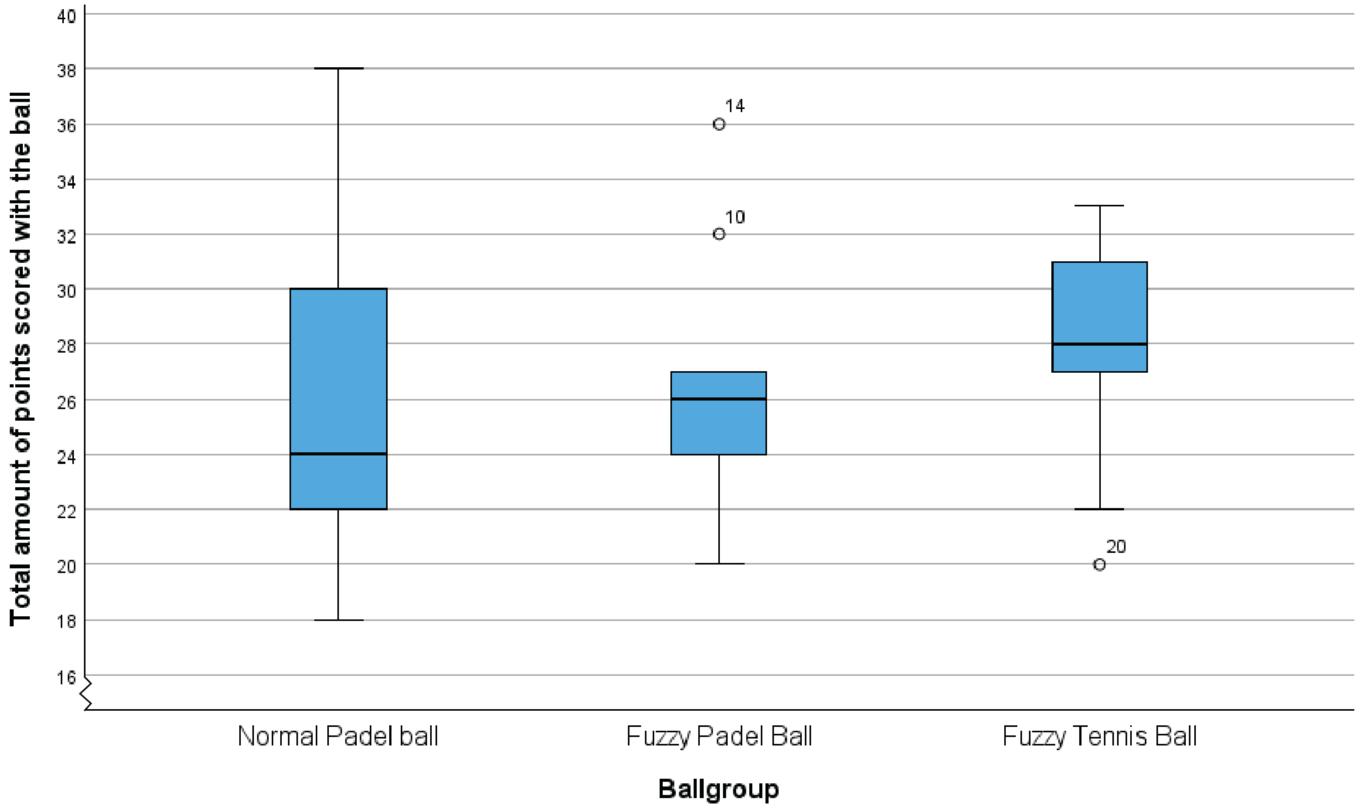


Figure 27: Box plot of the total points scored per participant between the ball groups

Table 4: Frequencies of 0 and 1 point landed per ball

	Pnormal	Pfuzz	Tfuzz
0 points	28	14	12
1 point	43	59	59

Qualitative data

The qualitative results can be found in table 5. Some answers have already been discussed in the previous two points.

Three participants mentioned that they had to adjust to the timing. Two intermediate players expressed confusion when they missed the ball, as they began their smash swing too early due to the slower descent of the fuzzy ball. Their adjustment was quick, and they no longer missed their swings afterward. This observation is particularly interesting as it relates to differential learning discussed in Chapter 2.

Two participants commented on the dampening effect of the fuzzy balls. They either felt it through the racket during a smash or noticed a difference in the sound the fuzzy balls made compared to the Pnormal. One player said he often judges the quality of a smash by the loud banging sound he hears on contact between the ball and the racket. This is very interesting to explore further, as it suggests that manipulating sensory feedback could potentially enhance smash performance.

6.2 Conclusion

While the primary hypotheses were not supported by the data, the study provided valuable insights into the differences in accuracy, speed and feel between normal and fuzzy padel/tennis balls. Future research should further investigate the impact of sensory feedback on smash performance and explore the potential benefits of differential learning with varying ball types.

Table 5: Qualitative results

	Answers	How many participants mentioned it (9 in total)	Beginner (b) /intermediate (i) ratio
1	Prefer/familiar feeling normal ball	3	1b / 2i
2	The ones with fuzz move slower during the lob	5	2b / 3i
3	The ones with fuzz feel heavy	3	0b / 3i
4	There is not much difference between the fuzzy balls	2	2b / 0i
5	The fuzzy tennis ball has more speed during the smash than the fuzzy padel ball	5	2b / 3i
6	The fuzzy balls drop to the ground faster	3	2b / 2i
7	Different timing/adjusting to each ball group	3	1b / 2i
8	Experience dampening feeling (touch or sound)	2	1b / 1i
9	Quality of the lob has influence on the smash	2	1b / 1i

7. Conclusions & recommendations

This chapter integrates the findings from biomechanics, motor learning, and coordination to answer the research question of this thesis. Three core areas are addressed and related to the concept design. After that, detailed recommendations for future research and design development are presented.

7.1 Conclusions

To answer the question, ‘How can padel amateurs learn the smash faster?’ three main categories must be integrated: biomechanics, motor learning, and coordination.

1. Biomechanics involves understanding the different segments of the kinetic chain, which, when executed efficiently from proximal to distal, result in the velocity of the racket during a smash.
2. Motor learning emphasises the use of implicit knowledge, external focus, differential learning and self-control to help amateurs get to the autonomous phase of motor learning.
3. Coordination bridges the gap between learning the smash technique through implicit knowledge and external focus, and actually executing it by using the kinetic chain efficiently to control muscles, based on timing and anticipation.

The concept of the padel ball with fuzzy felt addresses these aspects. By slowing the ball’s travel speed through the air, it provides players with more time to set up their smash. This allows players to gradually improve the efficiency of their kinetic chain without the pressure of performing at the typical high-speed level. An external focus is placed on the ball and the targeted direction, while implicit knowledge is employed as players develop a feeling of having more time and the need to adjust their smash accordingly. The variation in execution, compared to a normal padel ball, supports differential motor learning by improving timing, as players must adjust to the new situation. Through self-control, players can decide when to use the fuzzy ball to improve their smash and when to progress to using normal padel balls.

Aerodynamic research and field tests indicate that it is feasible to produce prototypes with slower flight speeds by increasing the fuzziness of the felt. Although the tests on smash performance among padel amateurs showed no significant improvement or deterioration, the concept remains promising but needs further development. The noticeable significant lower difference in smash speed among the prototypes suggests that the increased internal pressure in balls with fuzzier felt can counter the damping effect that comes with it.

In conclusion, padel amateurs can learn the smash faster by integrating biomechanics, motor learning, and coordination. The fuzzy felt padel ball concept provides a promising tool for achieving this and represents an initial step in innovative product development.

7.2 Recommendations

Recommendations for future research and design development are presented in three categories: ball, concept, and testing.

Ball Recommendations

To enhance prototype development, it is essential to use high quality felt that varies in fuzziness, and also looking into different amounts of internal pressure to counteract the damping effect. The felt should be directly glued onto the rubber balls to improve the quality of the prototypes. Additionally, exploring the impact of ball colour on performance may yield interesting results.

Concept Recommendations

Examining the durability of the prototypes is very important. One innovative idea is to create a fuzzy cover that can be put around existing balls. Furthermore, investigating the psychological aspect of sense hacking, where players perceive improved performance due to louder smashes. And lastly, collaborating with established padel ball manufacturers also provide insights and resources for further development. This partnership could explore the possibility of creating padel balls with gradually increasing levels of fuzziness, resulting in varying degrees of slowness and providing practice opportunities for amateurs at different skill levels.

Test Recommendations

Future prototypes should be tested again for fall time and bounce, with improvements to the smash test setup for more accurate results. Using a round target will allow for better statistical comparisons of smash accuracy, as each ring will have an equal distance to the centre. Engaging a professional padel trainer to deliver lobs can enhance the quality and consistency of the test conditions. Improving filming techniques is also essential; recording the smash and the landing spot within the same frame and using slow motion filming can provide more precise data. Additionally, employing higher-quality cameras with ample storage will prevent data loss. Exploring new tests focused on sense hacking will add a valuable dimension to the research, potentially uncovering how sensory feedback influences player performance.

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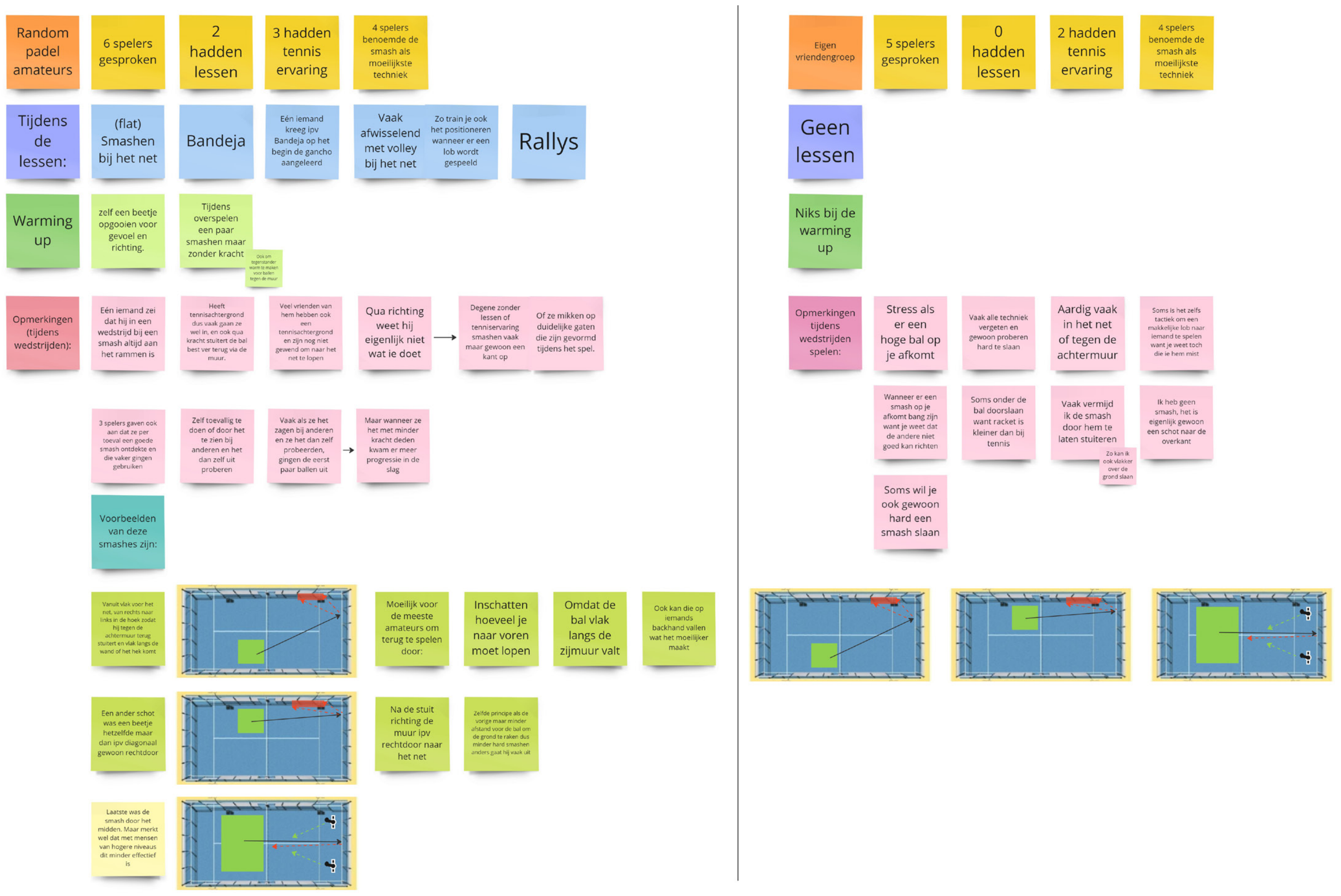
Appendices

Appendix A: Findings interview padel amateurs



Appendix B: The padel smash literature research

Types of smashes

Introduction

Securing dominance at the net in padel is known as a main strategy for scoring points and ultimately winning matches. Yet, this advantageous position is constantly contested by opponents who try to disrupt this attacking location to attain it for themselves, often resorting to high lobs aimed to dislodge the attacking team. However, by receiving balls that soar above the heads of the team that is standing close to the net, lies opportunities for over-head strokes; the smash. This countermove not only neutralises the opponent's lob but also presents a prime chance to seize control of the point. Mastery of this technique appears to be essential for success in padel matches. The effectiveness of the smash as a match-winning shot depends upon multiple factors, such as the area, direction, velocity and accuracy of its execution (Martínez et al., 2020).Types of smashes

In general there are four types of smashes in padel. The Bandeja (tray smash), flat smash, Vibora & topspin smash. However, depending on how, when and where these smashes are executed can lead to variations in the smashes that result in different tactical purposes (Meerpadel.nl, 2023; The Padel School, 2023a). In this chapter the four smashes are presented and explained based on technique, location on the court where to use them and how to recognise which smash the opponent is going to play by looking at their stance.

1. The Bandeja/Tray smash (Basic level)

The Bandeja is a defensive smash employed to regain the net position. Taught as the initial smash technique, it resembles a forehand volley but is executed slightly higher. The swing involves moving the arm from a high to low position (see figure 1). While it may not necessarily result in winning points, it is particularly useful when faced with a high lob (Sánchez-Pay et al., 2023; Techniques- Tennis vs Padel, 2017; The Padel School, 2019, 2021a).

2. Flat smash (Basic level)

The flat smash serves as an attacking smash, often utilised more at lower levels to secure points. Executed with a continental grip (see figure 2) and arm pronation for a flat impact, this smash is effective when opponents are pushed back, creating space in front. Aiming towards the player closest to the back wall is key, and hitting parallel to the wall increases its effectiveness due to a shorter distance and only one bounce against a wall. When used diagonally, the ball may bounce higher as it contacts two walls. The power of this smash comes from the legs and the big swing in which the ball is hit at the highest point (see figure 3) (Sánchez-Pay et al., 2023; OneHowto, 2022; Padel Trainer.com, 2017; The Padel School, 2023a, 2023b).

A variation of this smash is the Gancho. This smash is used more defensively when the ball is lobed over the shoulder of your non-dominant hand further back in the field. You really have to lean backwards and turn your body to reach the ball and hit the ball flat. If you hit this ball too hard it will come back via the back wall to the net, which is an easy ball to finish for your opponent (Redactie, 2023; Techniques- Tennis vs Padel., 2017).

3. Vibora (Intermediate level)

The Vibora is an attacking smash incorporating side spin and a slicing motion. Executed low in the corner, it serves as a finishing move at lower levels and a setup at higher levels where opponents' defence is stronger. The swing involves moving the arm at eye level from the back of the head to the side to generate side spin (see figure 4). Mastering this technique is challenging due to the necessary precision in footwork and positioning (The Padel School, 2021b, 2023a).

4. Topspin smash (High level)

The topspin smash can be employed for both defensive and attacking purposes. To execute it correctly, your body must be positioned directly under the ball. This technique involves brushing over the ball while it is high in the air, which gives the ball topspin. Unlike other techniques in padel, the objective of the topspin Smash is not necessarily to keep the ball low; instead, you want the ball to bounce high. This is because the intention is either to get the ball out of the court or to have it return over the net to your side without the opponent touching it in between, enabling you to win the point. The contact point on the racket is higher, and employing more wrist action enhances the brushing effect (see figure 5). It is crucial to ensure that the ball is positioned behind you when making contact (The Padel School, 2023a).

Figure 1: Basic defensive Bandeja smash generating backspin

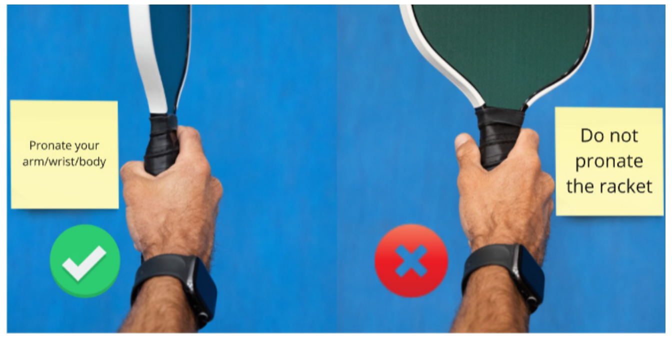


Figure 2: Continental grip (left) vs wrong grip (right) (The Padel School, 2023b) (Justpaddles, 2023)

Figure 3: Basic attacking flat smash generating no spin

Figure 4: Intermediate attacking Vibora smash generating sidespin

Figure 5: Advanced attacking & defensive topspin smash generating topspin

Where on the court would you use which smash?

Each smash is most effective when executed in specific areas of the court. A general rule of thumb is that attacking smashes tend to work best for amateur players when they are close to the net. As the skill level increases, players should be capable of executing smashes from further back in the court. The strategic choice of where to employ each type of smash also varies depending on the player's position on the court (left and right). Figure 6 provides a visual representation of the recommended areas for a right-handed player to use different smashes. It is important to note that exceptions to this exist, influenced by individual player characteristics and personal playing styles (The Padel School, 2019, 2023a).

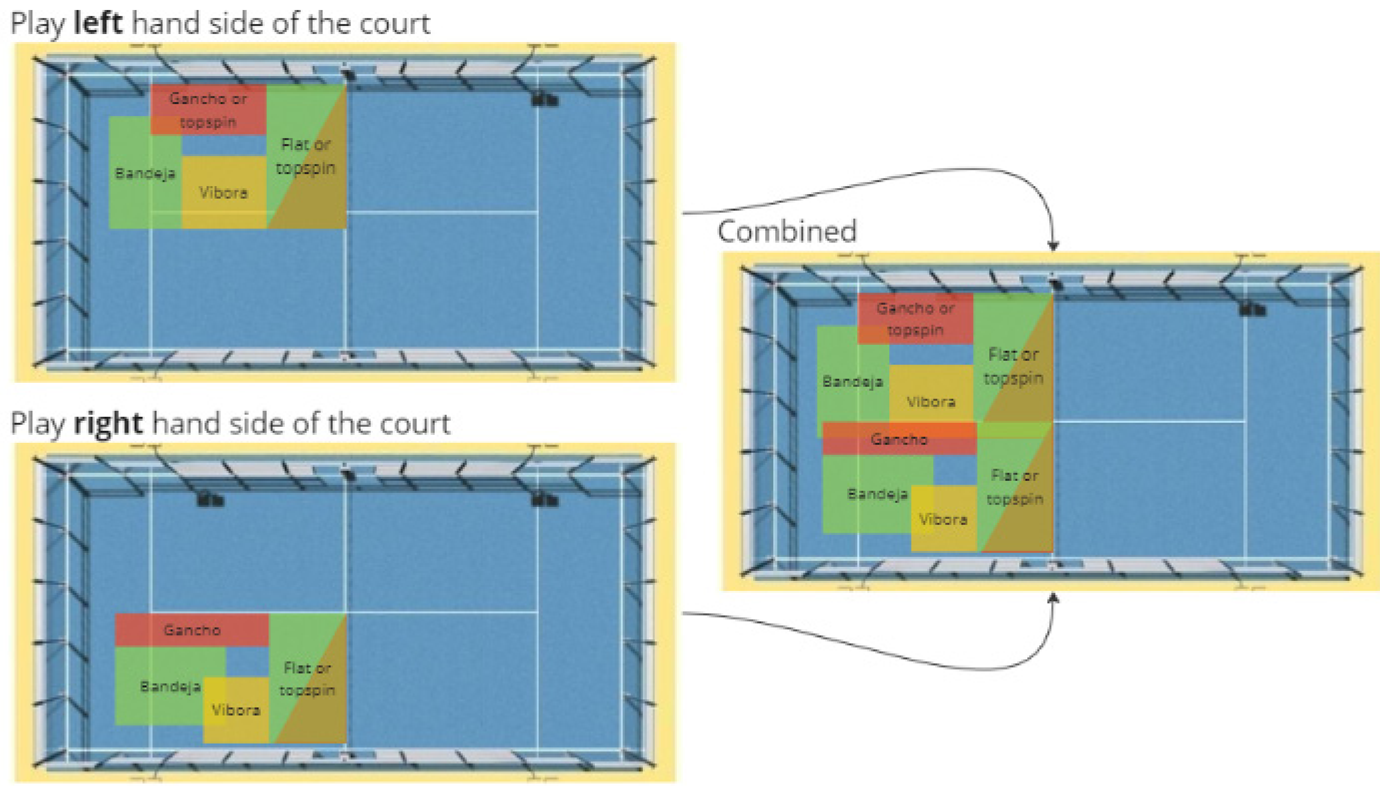


Figure 6: Smash for each area of the field (The Padel School, 2021c)

Line-up stance

Each smash possesses distinct characteristics, and often, the initial stance of the opponent while preparing for the smash can provide clues about the type of smash they intend to execute. In the case of the Bandeja, the arms are held high, and the body is slightly turned, as illustrated in Figure 7a. The Vibora resembles the Bandeja, but with a full body turn, positioning the racket behind the head to give a lot of side spin on the ball, as shown in Figure 7b (The Padel School, 2023c).

Both the flat and topspin smashes share the same setup position, commonly referred to as the trophy pose (coming from its frequent appearance in trophies). In this pose, the racket is positioned behind the head, the non-dominant arm is raised vertically, and the legs are bent in preparation for a jump, as depicted in Figure 7c. Notably, the body is situated directly under the ball, differing from the Bandeja and Vibora where the body is more to the side. Whether it will be a flat or topspin smash depends on various factors, including the player's skill level, personal preference, field position, and the opponents' positions (The Padel School, 2023c).

A bad smash can also be predicted by observing certain indicators. Players who consistently hit the ball far behind them, revealing poor timing and positioning, often struggle to deliver effective smashes. Additionally, when a player's shoulders remain open to the court during the smash, it suggests a lack of proper technique and can lead to compromised shot accuracy (see figure 7d). Another telltale sign of a subpar smash is when the ball makes a curve instead of descending directly to the ground, indicating a lack of control and precision in the execution of the shot (The Padel School, 2023c).

Figure 7. Smash stances for each smash (The Padel School, 2023c)

Conclusion

In conclusion, this chapter has provided a comprehensive overview of the various types of smashes in padel, ranging from the defensive Bandeja to the more complex topspin smash. Each smash type has its unique characteristics, techniques, and tactical applications, highlighting the versatility of this fundamental aspect of the game. The discussion has underscored the importance of understanding when and how to execute each smash effectively, considering factors such as court position, opponent placement, and personal playing style.

Furthermore, the chapter has emphasised the significance of observing opponents' stances and movements to anticipate the type of smash they intend to play, offering valuable insights into reading the game and reacting accordingly. By analysing visual cues and body positioning, players can gain a strategic advantage and make informed decisions on court.

However, it's essential to note that mastering smashes requires not only technical proficiency but also precision, timing, and coordination. As players progress in skill level, they must refine their techniques and adapt their gameplay to suit different situations and opponents.

Biomechanics and coordination

As previously mentioned, the power of a flat smash in padel comes from the energy generated by the legs. Yet an intriguing question arises: how does the energy stored in the legs translate into the high velocity observed in the arm during the execution of a flat smash? This chapter delves into energy transmission throughout the body in a flat smash in padel. Given the absence of specific research on this aspect, a comparative analysis is performed, drawing parallels with the tennis serve, tennis smash, badminton smash and baseball pitch. Despite the different nature of these sports, they share a similarity in their movement patterns, offering valuable insights into the transfer of energy in the context of a padel flat smash.

Kinetic chain

The concept of the kinetic chain originates from engineering principles applied to human movement. It conceptualises the human body as a system composed of rigid, interconnected segments linked by joints, wherein movement at one joint influences movement at another (Ellenbecker & Davies, 2001; Kovacs & Ellenbecker, 2011).
In an open kinetic chain system, such as throwing a ball or swinging a racket, the distal segment moves freely in space. Contrary, in a closed kinetic chain the distal segment is connected to a rigid entity, for example while doing a squad in which the force created by the leg segment is passed through to the rigid ground.
Moreover, open kinetic chain exercises commonly feature multiple segments moving simultaneously, emphasising the dynamic connections between joints and segments within the kinetic chain (Ellenbecker & Davies, 2001).

A lot of sport techniques and motion have a kinetic chain in which the energy comes from larger, heavier, slower central body segments to the smaller, lighter and faster segments. This phenomenon is called proximal-to-distal sequencing (Marshall & Elliott, 2000).

Energy flow in the smash

Kovacs and Ellenbecker (2011) conducted a study on the tennis serve, revealing that 51-55% of the kinetic energy and force directed to the hand originates from the legs and trunk in this open kinetic chain. Next to this, the arm contributes to this energy and force through long axis rotations in the joint, significantly influencing racquet speed. Notably, upper arm rotation and wrist flexion play primary roles, followed by forearm pronation (Marshall & Elliott, 2000). Scarborough et al. (2018) outlined the sequence of motion in overhead baseball pitches which we can compare to the padel smash: pelvis - trunk - arm - hand - forearm. Efficient energy flow through this chain, indicating good technique, results in higher hand velocity. Inefficient energy flow, indicative of poor technique, leads to reduced hand velocity and an elevated risk of injuries due to increased joint loading (Martin et al., 2014; Rusdiana et al., 2021). Fatigue or pressure situations can compromise technique, consequently affecting hand velocity and injury risk (Heirbaut, 2019). Trainers frequently advise their students to maintain a loose swing rather than forcefully muscling the ball (The Padel School, 2022). This guidance stems from the understanding that optimal utilisation of the kinetic chain is hindered when attempting to generate brute force solely through the arm. In essence, a forced swing bypasses the interplay of joints and muscles within the kinetic chain, compromising both power and efficiency in the stroke. By prioritising fluidity and allowing the kinetic chain to function naturally, players can harness the full potential of their body's biomechanics to deliver more effective and controlled shots (Martin et al., 2014).

When comparing padel to other racket sports, there is a notable rise in the occurrence of elbow injuries. This phenomenon can be attributed to several factors unique to padel. Firstly, the sport involves a significant number of overhead shots, imposing considerable strain on the elbow joint. Additionally, unlike traditional racket sports, padel rackets lack stringing. Consequently, when a ball strikes the racket, the tension is directly transmitted to the elbow, potentially aggravating the risk of injury. These distinctive characteristics of padel contribute to the heightened occurrence of observed elbow injuries in comparison to other racket sports (Dahmen et al., 2023).

The kinematic chain does not necessarily influence if a ball goes in or out. The angle in which the ball is hit does have influence, and that is only decided just prior before contact (Whiteside et al., 2013). Aiming where the ball has to go has everything to do with coordination and decision making with the available information present. This has to happen automatically because there is only a very small limited amount of time in which decisions can be processed and made.

Coordination

Coordination is the fusion of multiple movements into a unified and seamless whole. When coordination is performed effectively and efficiently, it not only minimises the risk of injury, but also accelerates mastery of techniques, improves tactical ability and strengthens mental resilience (Alsaudi, 2020). In the context of padel, coordination contains essential aspects such as precise timing in striking high balls, information processing involving observation of both ball trajectory and opponents' body cues.

The ability to anticipate the trajectory of objects depends on predicting both the speed and rhythm the object has, allowing accurate estimates of their path. Objects with perceptual rhythms make it easier to predict their future position, highlighting the importance of perceptual timing in athletic performance. Obtaining information from multiple senses enriches the interaction that we have with the environment and also the estimation of an object's movement (Chang & Jazayeri, 2018).

In sports, experts demonstrate a remarkable ability to anticipate opponents' actions by analysing subtle cues such as body posture. For instance, studies in handball by Cañal-Bruland et al. (2010) have shown that expert players excel in predicting the outcome of penalty shots based on opponents' movements, underscoring the importance of perceptual expertise in sports performance.
In padel, players receiving lobs and preparing to execute a smash primarily focus on the ball trajectory while also attending to opponents' upper body cues. Similar to findings in other sports, high-level padel players exhibit enhanced efficiency in visual processing, directing their attention to the most salient cues for optimal performance (Palma et al, 2023).

Anticipating the landing position of balls is pivotal for padel players when positioning themselves to receive lobs and execute smashes. Research in baseball reveals that fielders begin moving in the correct direction for catching fly balls within 500 milliseconds after the ball's flight begins, suggesting early perceptual cues guiding their actions. Specifically, angular vertical velocity emerges as a critical visual cue for anticipating ball landing positions, highlighting the significance of perceptual expertise in sports anticipation and decision-making to be at the right position at the right time (Brouwer et al, 2006).

Conclusion

In conclusion, this chapter has provided valuable insights into the mechanics and dynamics of energy transmission and coordination in padel, particularly focusing on the execution of a flat smash. While specific research on energy transfer in padel smashes is lacking, comparative analyses with similar sports such as tennis, badminton, and baseball shed light on the importance of the kinetic chain and efficient energy flow through the body. The kinetic chain, originating from engineering principles applied to human movement, underscores the interconnectedness of body segments and joints in generating powerful and efficient movements. Understanding and harnessing the kinetic chain not only enhances performance but also minimises the risk of injuries, as emphasised by trainers' advice to prioritise fluidity over force in swings.

Moreover, coordination emerges as a critical factor in padel performance, encompassing precise timing, perceptual acuity, and decision-making abilities. Expert players demonstrate superior anticipation skills, exploiting subtle cues such as opponents' body posture to predict their actions accurately. Research findings in handball and baseball highlight the importance of perceptual expertise in sports performance, further emphasising the significance of coordination in padel.

The comparison with other racket sports reveals distinctive factors contributing to the prevalence of elbow injuries in padel, underscoring the need for tailored injury prevention strategies. Additionally, insights into perceptual cues and anticipatory skills provide valuable implications for training and enhancing performance in padel.

Motor learning

Understanding the complexity of motor learning is important in optimising athletic performance and skill learning. This article examines key insights that illuminate the diverse nature of motor learning. From deliberate practice to the influence of attentional focus, contextual interference and the emergence of differential learning, this review aims to provide an understanding of the processes involved.

Personalised learning

There is no one-size-fits-all approach to motor learning. The effectiveness of various learning methods, such as operant conditioning, imitation learning, and explicit versus implicit learning, depends on individual factors like motivation, attention, and cognitive orientation. The optimal learning method varies based on the athlete, coach, and contextual factors. The process of motor learning involves understanding what an athlete learns in a training session and its ability to be reproduced in the future. The evaluation of the application of learned skills in different situations relies on transfer tests, gauging the adaptability of acquired knowledge. Complementarily, retention tests determine the lasting impact of learned skills over time.

There is a conventional belief that more training leads to better performance. However there is a way of training that emphasises on purposeful, goal-oriented training to master specific, challenging objectives called deliberate practice (Beek, 2011a). Quality and focus is central and contributes to optimal skill development rather than sheer quantity.
The way complex movement learning unfolds is in three stages: cognitive, associative, and autonomous (Beek, 2011a). The cognitive phase involves understanding the movement, while the associative phase integrates cause-and-effect relationships. The autonomous phase, achieved through intensive repetition, allows for automatic execution. In the autonomous phase, it should be avoided to add more feedback that focuses attention on the now autonomous movement because it leads to disruption of the movement

Where to focus and what to know

Attentional focus plays a crucial role in motor learning. There are two types of focus while learning a new skill; an external focus concentrates on the movement's effect on the environment/purpose/goal, and internal focus which fixates on the mechanics of the movement and the body parts that perform it. Internal focus often hinders automaticity and overall performance when learning a new movement while external focus enhances learning effectiveness probably because of the goal orientated approach (Beek, 2011b; Wulf et al, 1999).

Having knowledge about the skill you want to master is important because it forms the basis on which you build to improve. Motor learning involves building both explicit knowledge (facts and rules we are aware of and can name (verbalise) when asked) and implicit knowledge (things we know without realising it and therefore cannot articulate (tacit knowledge, or silent knowledge)) (Beek, 2011c). Explicit knowledge, gained through deliberate practice, can lead to choking-under-pressure as it interferes with the automatic execution of well-learned movements. Implicit knowledge can prevent this choking under pressure because it is unconscious and automatic (Yu, 2015). Using analogies during training is a form of implicit learning.

Other terms that are used for explicit and implicit knowledge are declarative and non-declarative memory. Declarative memory involves conscious recollection, while non-declarative memory expresses learning through performance. The interplay of these memories determines the adaptation of future behaviour to the environment (Tresilian, 2012).

Practice forms

There are two types of motor learning that are implemented in practices; Traditional and differential motor learning (Beek, 2011e). Traditional motor learning focused on ideal movement techniques universally applicable. In differential learning, the emphasis shifts to acknowledging and leveraging individual differences, with the belief that variations in execution contribute to effective learning.
Concepts like neural self-organisation (the optimal mode of execution is not imposed from outside, but develops autonomously in a way characteristic of the individual) and non-linear phase transitions (a transition accompanied by, and facilitated by, significant fluctuations in execution. These fluctuations are random in nature and provide the information needed to arrive at a new pattern of movement) play a role in this approach (Beek, 2011e).

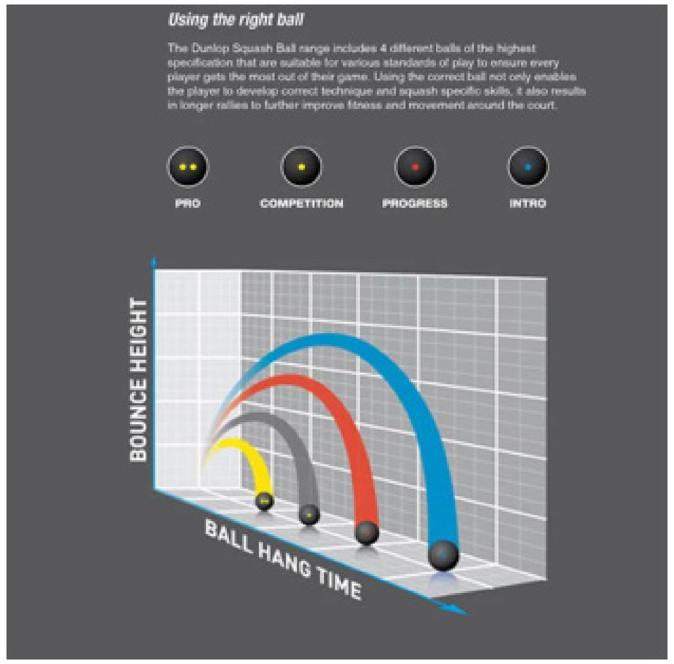
Learning motoric can be enhanced by differences in practice forms. One of them is the contextual interference effect (CI-effect), influenced by the variation in practice conditions, enhances learning, however it is less effective for beginners (Beek, 2011d). The gradual transition from low to high contextual interference in practice schedules is deemed optimal for learning motor skills. Self-control is another way in which motor learning can be enhanced because self-control in learning allows athletes to make decisions about feedback and practice schedules, promoting active engagement and effective strategy selection (McNevin et al., 2000; Wulf & Toole, 1999). Lastly, having practice with a partner combines observational and physical practice, which enhances learning efficiency through partner observation and interaction.This form of practice is called Dyad training (McNevin et al., 2000).

Conclusion

In conclusion, motor learning is a dynamic process influenced by various factors, emphasising individuality, attentional focus, and practice variations. Understanding the nuances of deliberate practice, attentional focus, contextual interference, and differential learning contributes to effective skill acquisition. While evidence for differential learning is emerging, methodological limitations persist. Incorporating self-control and dyad training adds valuable dimensions to the learning process. The interplay of explicit and implicit memories defines the adaptability of learned skills. In essence, navigating the complexities of motor learning requires a nuanced, individualised, and contextually informed approach.

Appendix C: Training balls in different sports

Squash



https://www.squashpoint.nl/blogs/blog/hoe-kies-ik-de-juiste-squashbal/

https://squamata.nl/products/dunlop-progress-squashbal

Different characteristics:
- Size
- Internal pressure

Squash

Different characteristics:
- Material
- Shape

https://khelmart.wordpress.com/2013/12/01/detail-guide-on-nylon-vs-feather-badminton-shuttlecock/

https://www.racquets4u.com/blog/post/which-shuttlecock-should-i-choose-buying-guide/

Tennis

产品参数 PRODUCT INFORMATION

Product	Teloon mascot	Teloon 603	Teloon Rising	Teloon X-ace	Teloon coach
Model	801/mascot	603/[illegible]	Rising/[illegible]	X-ace	coach[illegible]
Material	Nylon	Acrylic	Wool	Wool	Wool
Diameter	63.5-66.7mm	63.5-66.7mm	63.5-66.7mm	63.5-66.7mm	63.5-66.7mm
Weight	56.7-58.5g	56.7-58.5g	56.7-58.5g	56.7-58.5g	56.7-58.5g
Rebounce	125-135cm	130-139cm	140-142cm	140-148cm	140-148cm
Suit	Beginner	Intermediate	Advance	Professional	Robot ball
Feature	Comfortable Easy Control Slow Speed	Abrasion Resistant Suit Hard Court	Competition Level	Competition Level	Pressure keep long time Tennis Robot Ball

Different characteristics:
- Material
- Size
- Internal pressure

https://www.merchantoftennis.com/blogs/junior-tennis/why-junior-sized-tennis-balls-are-important

https://blog.tennisplaza.com/the-life-of-a-tennis-ball/

Football

Different characteristics:
- Weight

https://www.voetbalshop.nl/derbystar-solaris-s-light-voetbal-kids-wit-rood.html

https://www.voetbalshop.nl/derbystar-solaris-light-voetbal-wit-blauw.html

https://www.voetbalshop.nl/derbystar-prof-gold-iii-voetbal-maat-5-wit-roze-goud.html

Handball

Leeftijdscategorie	Balmaat	Balomvang	
Minis	Maat 0 of 00	48 cm	Moet een soft handbal zijn
F-Jeugd	Maat 0 of 00	48 cm	Moet een soft handbal zijn
E-Jeugd	Maat 1	50-52 cm	
D-Jeugd	Maat 1	50-52 cm	
C-Jeugd Meisjes	Maat 1	50-52 cm	
C-Jeugd Jongens	Maat 2	54-56 cm	
B-Jeugd	Maat 2	54-56 cm	
A-Jeugd Dames	Maat 2	54-56 cm	
A-Jeugd Heren	Maat 3	58-60 cm	
Dames Senioren	Maat 2	54-56 cm	
Heren Senioren	Maat 3	58-60 cm	

Different characteristics:
- Size
- Weight

https://www.handbalshop.nl/blog/welke-handbal-is-geschikt-voor-mij

https://nl.wikipedia.org/wiki/Handbal#:~:text=IHF%2Dgrootte%203%3A%20omtrek%2058,(ook%20col%20genoemd)%20gedaan.&text=IHF%2Dgrootte%201%3A%20omtrek%2050,van%208%20tot%2012%20jaar.

https://www.jenisport.nl/merken/kempa-handballen/kempa-training-600-handbal.html

Appendix D: Aerodynamics of a tennis/padel ball

The forces acting on a padel ball in the air include gravity & drag (see figure 1). The ball has a certain speed that was caused by contact with the racket. When the ball is in flight, the forces that slow it down are gravity (only when the ball is moving upward, against the gravity vector) and aerodynamic drag (always). To make a ball fly slower, you need to increase the drag. When a ball has spin, it experiences the Magnus effect, which generates a lifting force acting on the ball. For the purposes of this research, it is assumed that the ball has no spin, allowing this force to be neglected. The smash type used in this study is the flat smash, which involves no spin and will be used later in the smash tests.

The formula to calculate aerodynamic drag (*D*):

$$D = \frac{1}{2} \cdot \rho \cdot V^2 \cdot C_D \cdot A$$

And it depends on:

Air density ρ (kg/m^3), velocity V^2 (m/s), drag coefficient C_D, frontal area A (m^2) (Sciacchitano et al., 2023)

Research by Shah et al. (2019) and Mehta et al. (2008) demonstrated that the fuzz on the ball can account for 20% to 40% of the total drag. They also discovered that you can increase or decrease the drag coefficient (CD) by 10% by manipulating the fuzziness, either by raising or shaving the fuzz. The fuzziness of a tennis ball primarily impacts the CD, as the CD is influenced by the texture and shape of the object. However, with the prototypes, the frontal area (A) also increases because the fabric felt covering the normal padel ball adds thickness.

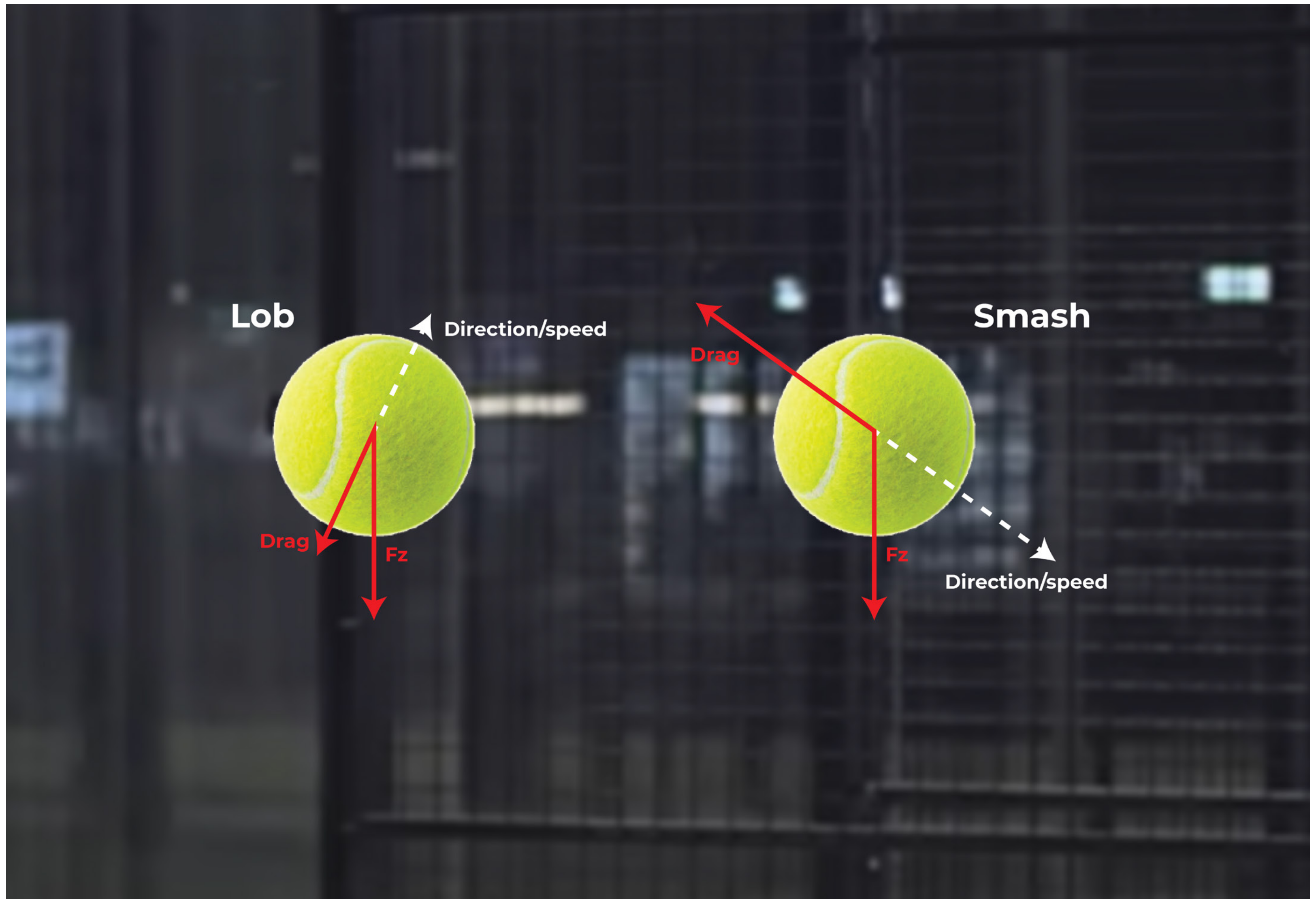


Figure 1: Forces that act on a ball in the air during a lob (left) and smash (right)

Pressure drag

There are two types of drag: friction drag (parallel to the surface) and pressure drag (normal to the surface). Pressure drag is caused by flow separation when air hits an object. The difference between the high pressure at the front of the object and the low pressure at the back creates drag. Pressure drag is influenced by the type of flow around an object. There are two types of flow: laminar flow and turbulent flow. In laminar flow, there is a large area behind the object where the pressure is low (see figure 2). On the other hand, in turbulent flow, the air is disrupted by the ball's surface (e.g., by dimples in golf balls), which helps the air adhere to the boundary layer. This reduces the size of the low-pressure area behind the ball, leading to less drag (Sciacchitano et al., 2023).

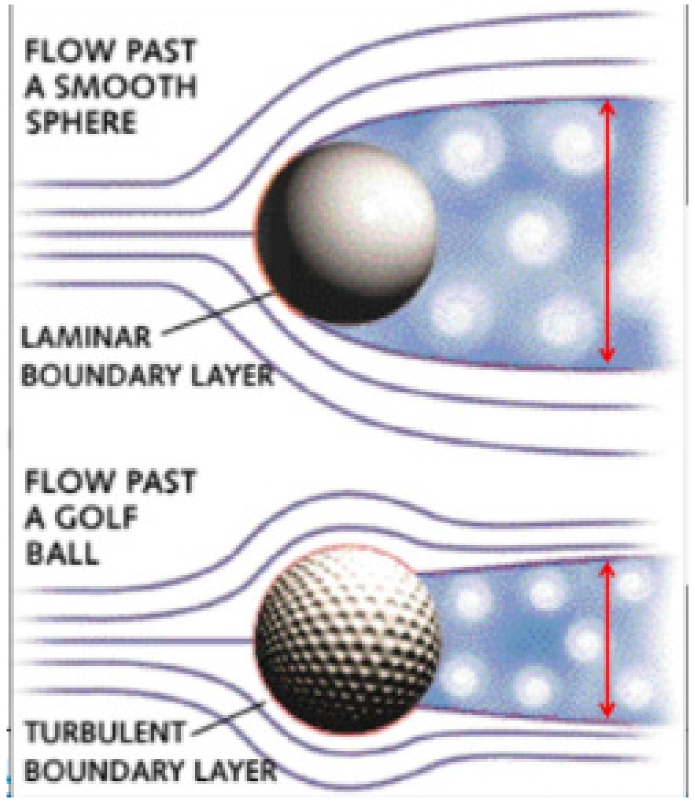
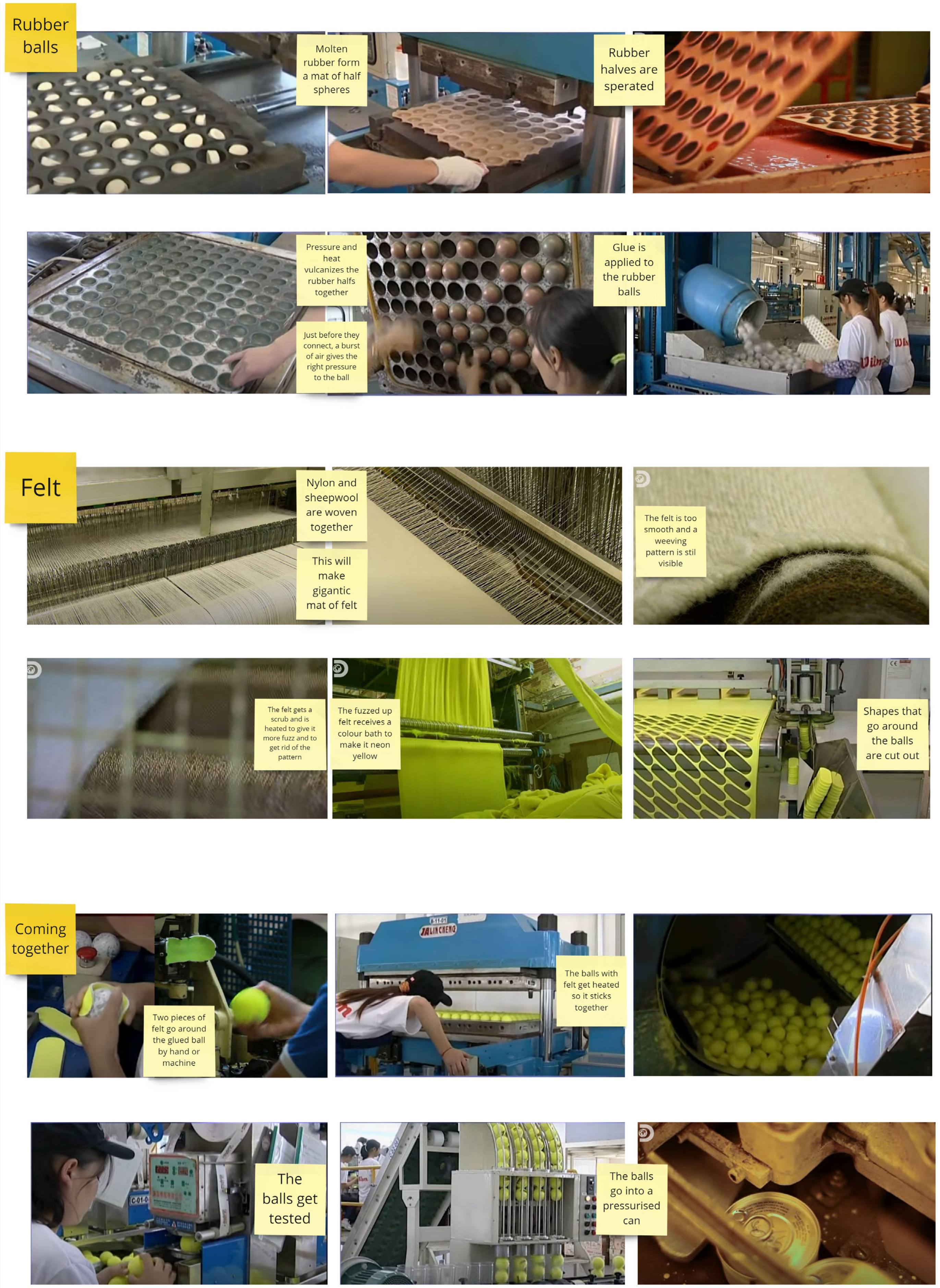


Figure 2: Laminar and turbulent flow examples. The low pressure area behind a smooth sphere (laminar flow) is larger than the area behind a golf ball (disrupted surface) (Sciacchitano et al., 2023)

Objects in a flow always initially experience laminar flow, but as speed increases, the flow transitions to turbulent. To compare different objects and determine when this transition occurs, we use the Reynolds number. The Reynolds number (Re) provides context for an object's flow characteristics and allows for comparison of when objects transition from laminar to turbulent flow. Laminar flow occurs at a low Reynolds number, while higher flow speeds result in a higher Reynolds number. What high and low Reynolds numbers are depends on the specific object in the flow (Sciacchitano et al., 2023).
Shah et al. (2019) noted that the felt on the tennis ball causes the transition of the boundary layer at fairly low Reynolds numbers (Re), therefore the ball experiences turbulent flow for the entire range of Re for which tests were conducted. This would suggest that tennis balls experience less pressure drag and would therefore take less time to hit the ground when dropped from a certain height compared to the same ball but without the felt. However, the fuzziness of the felt contributes substantially to the drag experienced by the ball. Mehta et al. (2008) discovered that each fuzz element experiences pressure drag, which, when summed for all fuzz elements, results in what is termed 'fuzz drag.'

Appendix E: Production process of tennis/padel ball & interview WSP textiles



Brief summary interview WSP textiles factory employee

Niek:
Could you start by telling us a bit about WSP Textiles and its role in the tennis industry?

Employee:
WSP Textiles has been a key player in the textile industry for many years, specialising in high-performance materials. We provide the felt used in tennis balls for various major brands, ensuring quality and performance that meet the standards of professional tennis.

Niek:
Could you start by telling us a bit about the materials used in making the felt for tennis balls?

Employee:
The primary materials are woven sheep wool and nylon, which form a string structure carpet initially.

Niek:
What happens next in the process?

Employee:
The string structure carpet is put through brushes and a heating device, breaking up the string pattern and resulting in an even piece of fabric that becomes more fuzzy.

Niek:
What functions does the felt serve on a tennis ball?

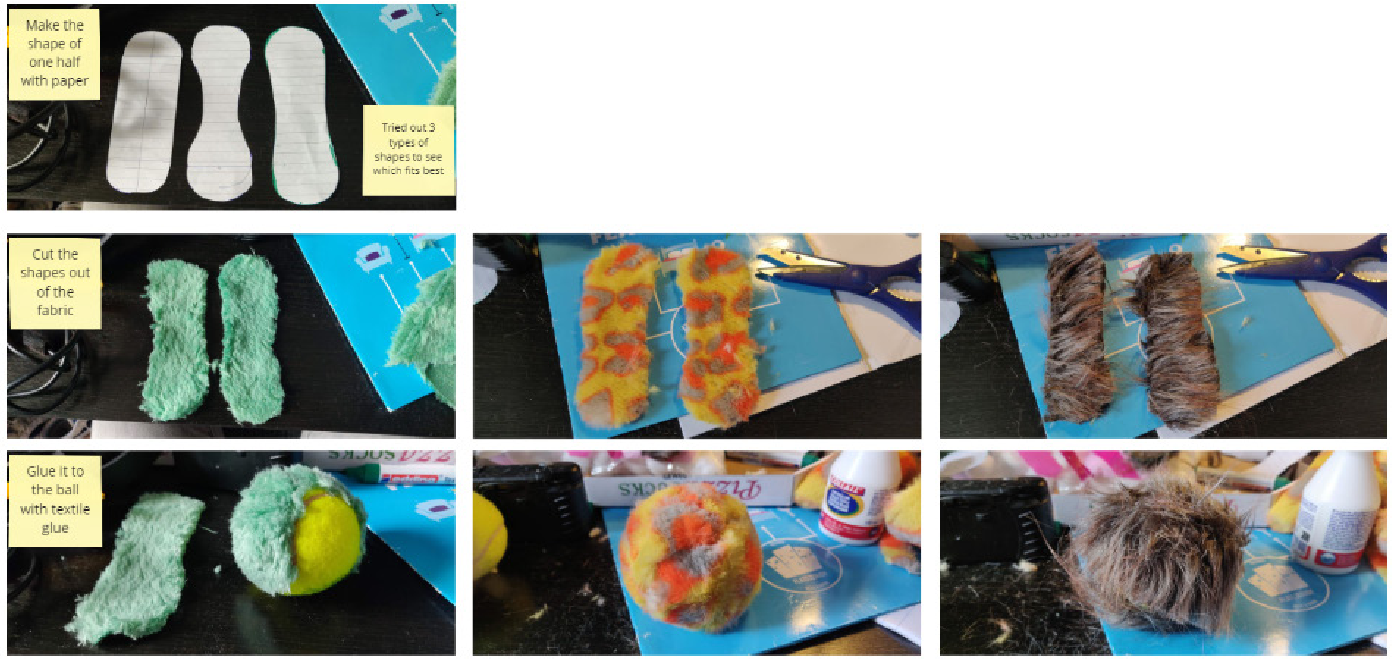
Employee:
The felt slows down the ball when it bounces and reduces its speed as it flies through the air, both of which are crucial for the ball's performance.

Niek:
Can the properties of the felt be adjusted based on specific requirements?

Employee:
Yes, the felt can be put through the brushing and heating machine multiple times to make it thicker and fuzzier, allowing companies to produce slower or faster balls based on their needs. Which already happens.

Appendix F: Fabrication of the prototype balls

Part 1: Fabrication initial prototypes



Part 2: Fabrication prototypes smash test

Appendix G: Aerodynamic Effects of Felt Types on Padel and Tennis Balls: A Drop Test Study

Abstract

This study investigates the impact of felt fuzziness on the fall times of padel and tennis balls. Using a custom-built drop mechanism, 8 balls with different fuzzines were dropped from a height of 190 cm and recorded with a slow-motion camera. The time taken for each ball to hit the ground was analysed using motion tracking software called Tracker. Descriptive statistics and a one-way ANOVA test revealed that balls with fuzzier felt had significantly longer fall times compared to balls with normal felt. The results support the hypothesis that increased fuzziness leads to higher drag and slower fall times. However, the findings are constrained by limitations such as sample size, measurement precision and accuracy, and technical issues. Future research should address these limitations and further explore the aerodynamic effects of felt fuzziness on ball dynamics.

Introduction

The behaviour of padel and tennis balls during free fall can be influenced by several factors, one of which is the texture of the felt covering the ball. Previous studies have highlighted the significant role that the felt plays in the aerodynamics of tennis balls. Shah et al. (2019) noted that the felt on the tennis ball causes the transition of the boundary layer at fairly low Reynolds numbers (Re), therefore the ball experiences turbulent flow for the entire range of Re for which tests were conducted. This would suggest that tennis balls experience less pressure drag and would therefore take less time to hit the ground when dropped from a certain height compared to the same ball but without the felt.

However, the fuzziness of the felt contributes substantially to the drag experienced by the ball. Research by Shah et al. (2019) and Mehta et al. (2008) demonstrated that the fuzz on the ball can account for 20% to 40% of the total drag. Mehta et al. (2008) also described how each fuzz element experiences pressure drag, which, when summed for all fuzz elements, results in what is termed 'fuzz drag.' This additional drag is significant enough that the drag coefficient (CD) of a tennis ball can be increased or decreased by up to 10% by manipulating the fuzziness—either raising or shaving the fuzz.

Therefore the research question for this study is: Is there a significant difference in the fall times of padel and tennis balls with different types of felt coverings?

Based on literature, it is reasonable to hypothesise that when prototype balls with fuzzier fabrics are tested, they will experience a higher drag coefficient, resulting in slower fall times through the air. This study aims to investigate this hypothesis by comparing the fall times of padel and tennis balls with varying types of felt.

Methodology

Materials

Eight new balls are used for this experiment: four padel balls and four tennis balls. These balls are covered with different types of fabric: no cover/normal felt, green fabric, yellow/red fabric, and brown fabric see figure 1 and table 1 for the characteristics of each group. A custom-built drop mechanism, employing a spring and rod to create a trapdoor system, is used to ensure a consistent release of the balls (see figure 2). The drops are recorded with a slow-motion function on a smartphone (Oneplus 6T) capable of capturing 480 frames per second (fps) at 720p resolution. This is 16 times slower than the normal record function. A motion tracking program called Tracker is used to analyse the videos.

Figure 1: Ball groups

Table 1: Characteristics of each ball group

	Weight	Diameter	Fuzziness level (1 - 5)
Padelball normal	57 grams	64 mm	1
Padelball green	70 grams	66 mm	3
Padelball yellow/red	72 grams	69 mm	4
Padelball brown	76 grams	71 mm	5
Tennisball normal	57 grams	64 mm	1
Tennisball green	70 grams	67 mm	3
Tennisball yellow/red	72 grams	69 mm	4
Tennisball brown	76 grams	72 mm	5

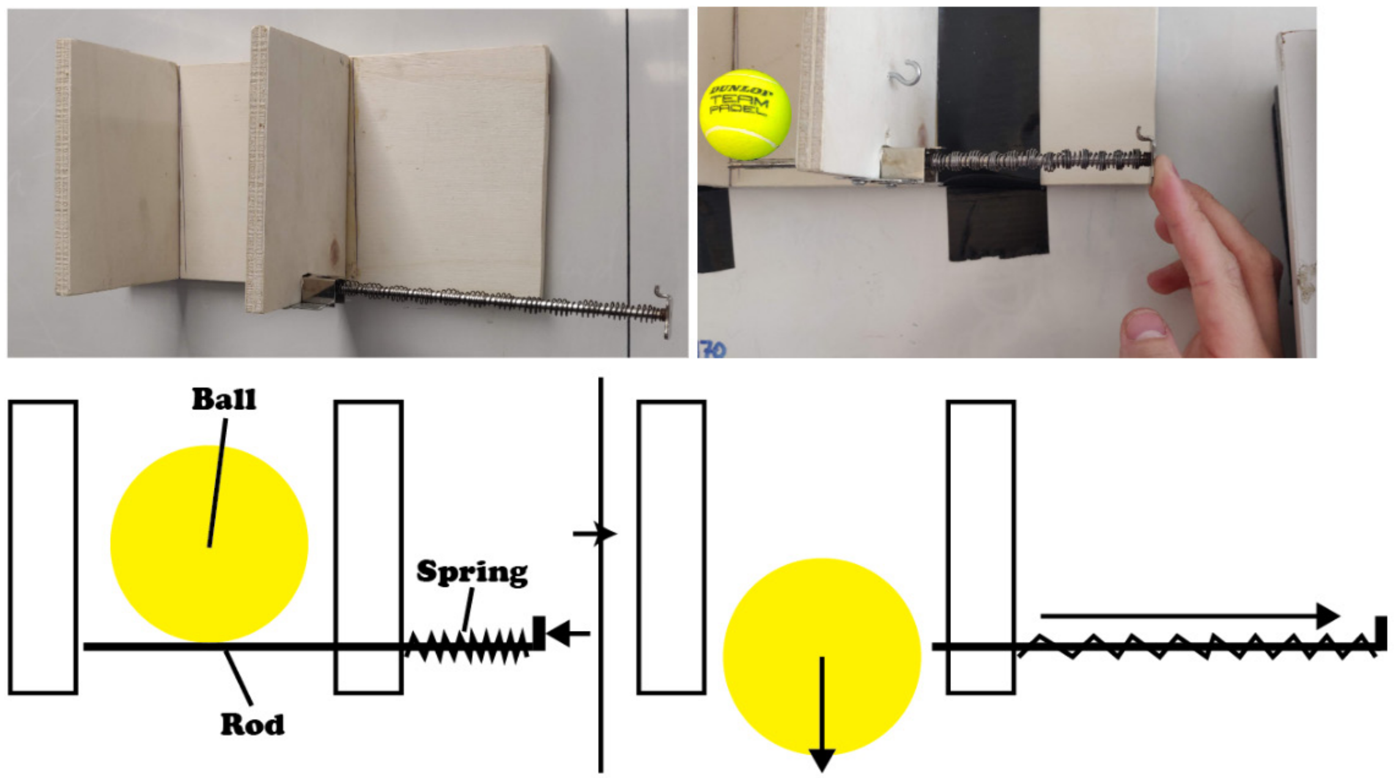


Figure 2: Ball drop mechanism and spring & rod close-up and illustration

Procedure

The custom drop mechanism is designed to ensure each ball is released in a consistent manner. This mechanism involved a spring and rod system that functioned as a trapdoor, shooting out from under the ball and allowing it to fall freely.

Each ball is dropped from a height of 190 cm. The number of drops for each type of (fabric) felt varied between 7 and 16. The slow-motion camera is positioned 290 cm away from the drop point at a height of 120 cm to record the falling balls. The setup of the test is detailed in Figure 3.

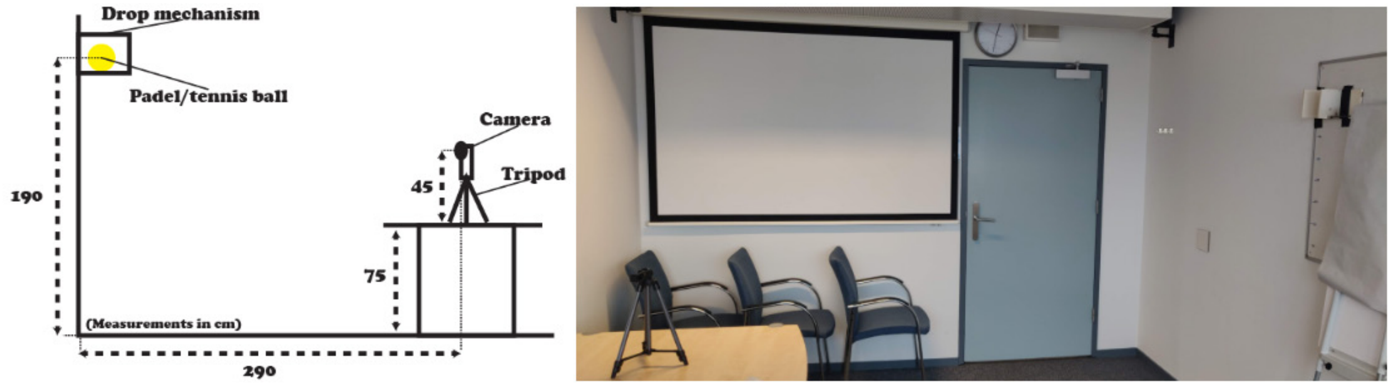


Figure 3: Test set-up drawing (left) and in real life (right)x

For data collection, the videos are analysed using the Tracker motion tracking program. The program tracked the ball from the moment the spring rod is fully extended. A screenshot of the Tracker interface showing the analysis is provided in figure 4. The exact moment the ball hit the ground is recorded for each drop.

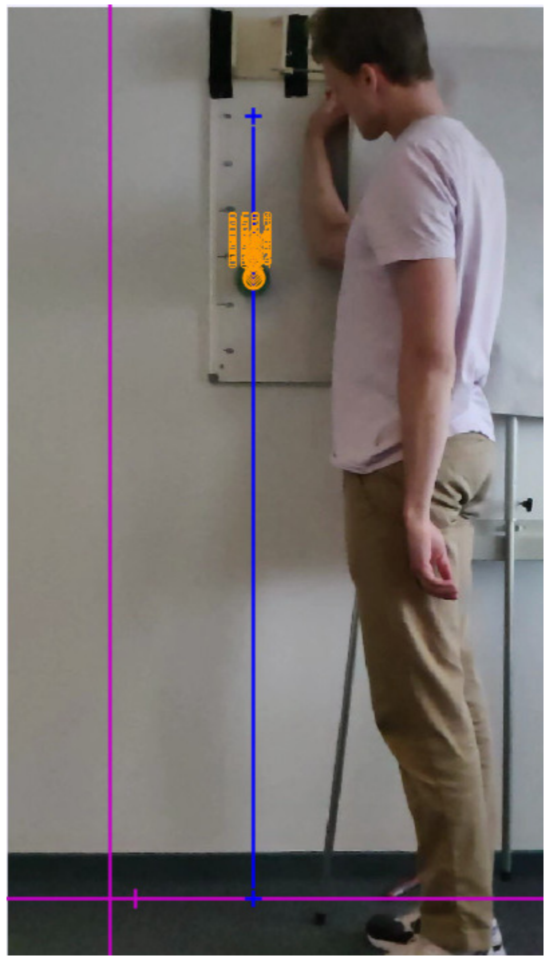


Figure 4: Screenshot of the Tracker interface

Data Analysis

Using the Tracker software, the motion of each ball is tracked, and the time to impact is recorded for each drop. The data is then averaged for each type of felt and compared in SPSS using a one-way ANOVA with ball type as independent variable and time to hit the ground as dependent variable to test the hypotheses. The results are analysed to determine whether the type of felt had a significant impact on the fall time of the balls.

Results

Figure 5 shows the average fall time of each ball. The two graphs are split between all padel balls and all tennis balls. The horizontal axis shows the time in seconds (based on the slow motion footage that is 16 times slower than normal) and the vertical axis shows the height of the ball compared to the ground in metres.

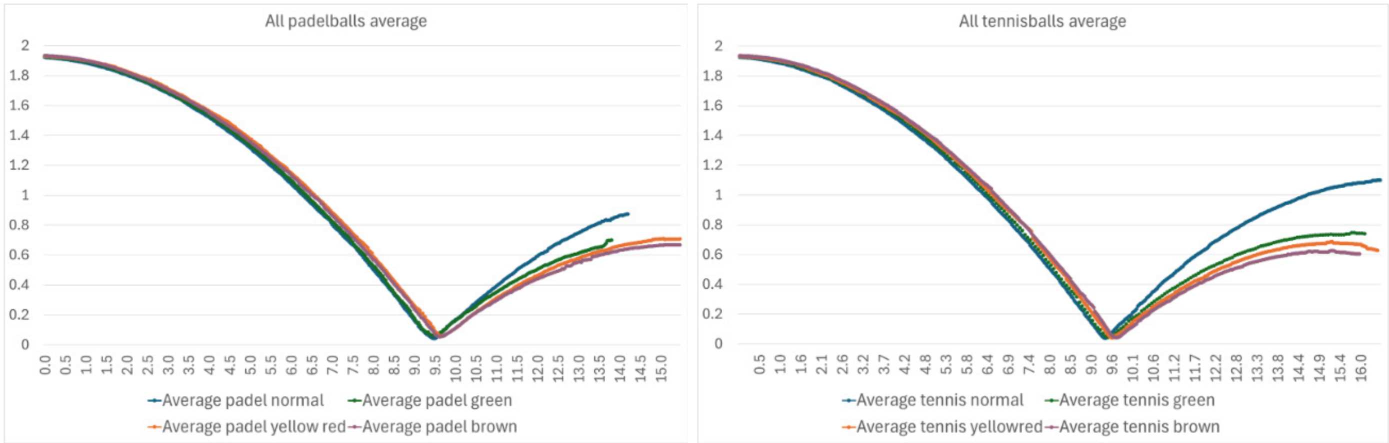


Figure 5: Average fall time padel balls (left) & average fall time tennis balls (right). X-axis shows the time in 16x slow motion second, the y-axis shows the height of the ball in metres

The descriptive statistics table 2 summarises the fall times for each type of ball and felt. The mean fall time for the padel balls and tennis balls varies depending on the type of felt covering the ball.

Table 2: Descriptive statistics table drop test

Time to hit the ground (16X slowmotion)

	N	Mean	Std. Deviation	Std. Error
Padelball normal	16	9,43256	,105911	,026478
Padelball green	11	9,44600	,143415	,043241
Padelball yellow/red	10	9,65230	,119756	,037870
Padelball brown	11	9,60664	,095911	,028918
Tennisball normal	12	9,39542	,054001	,015589
Tennisball green	7	9,44786	,126089	,047657
Tennisball yellow/red	7	9,57657	,047141	,017818
Tennisball brown	11	9,66427	,067049	,020216
Total	85	9,52054	,142049	,015407

A one-way ANOVA test is used to test the hypothesis that fuzzier balls have a longer fall time than less fuzzier balls, with fall time in seconds as the dependent variable and ball group (padel/tennis ball & fuzziness level) as the independent variable. Figure 6 shows the results plotted in a box plot graph.

Compared to the Padelball normal, the Padelball yellow/red & Padelball brown & Tennisball brown are found to be positively correlated F(7,77) = 12,880, p < .001 (see table 2).
Compared to the Tennisball normal, the Padelball yellow/red & Padelball brown & Tennisball brown are found to be positively correlated F(7,77) = 12,880, p < .001 as well as the Tennisball yellow/red p = .009 (see table 3).

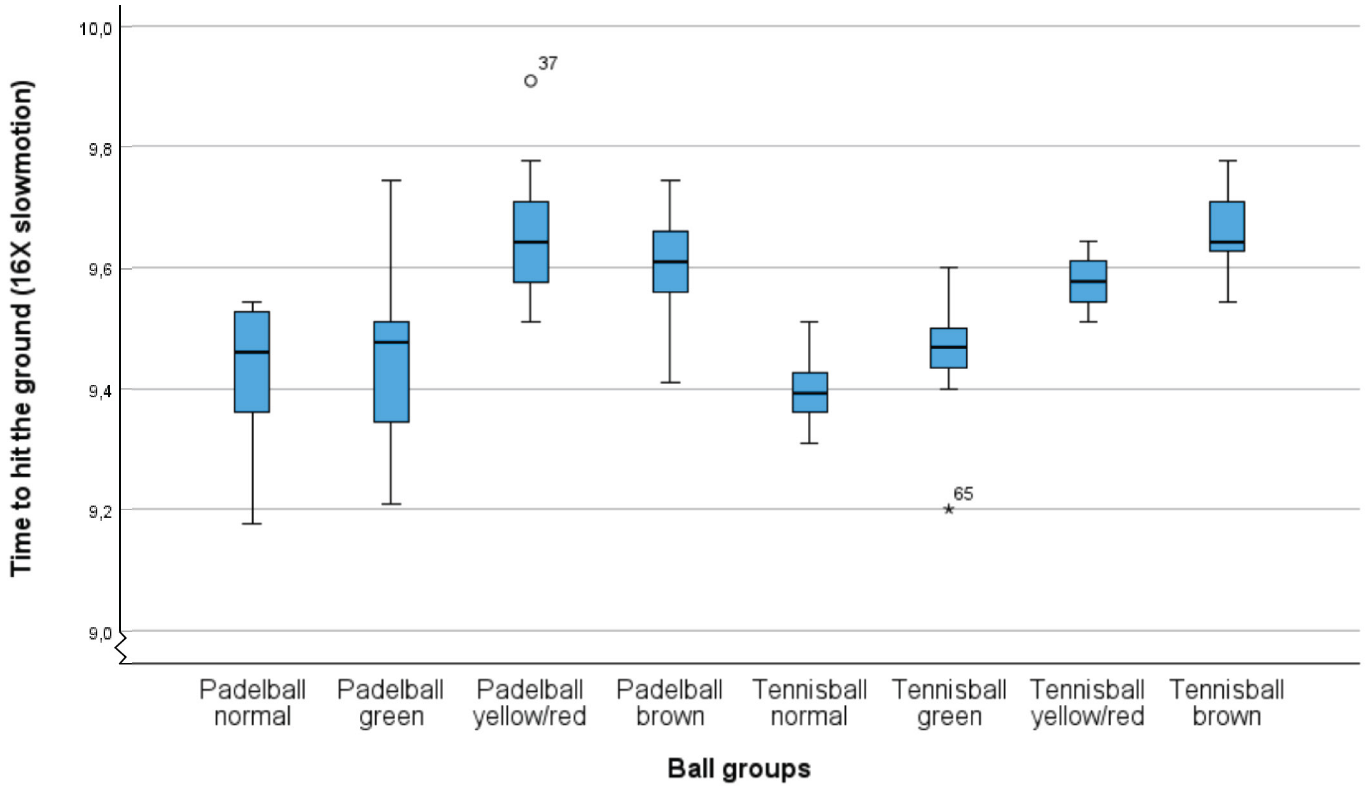


Figure 6: Box plot of the ball groups and the time measurements for the ball to hit the ground

Table 3: Padelball normal statistical comparison to the other balls

(I) Ball groups	(J) Ball groups	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
Padelball normal	Padelball green	-,013438	,039440	1,000	-,14108	,11421
	Padelball yellow/red	-,219738*	,040592	<,001	-,35111	-,08837
	Padelball brown	-,174074*	,039440	<,001	-,30172	-,04643
	Tennisball normal	,037146	,038454	1,000	-,08731	,16160
	Tennisball green	-,015295	,045632	1,000	-,16298	,13239
	Tennisball yellow/red	-,144009	,045632	,064	-,29169	,00367
	Tennisball brown	-,231710*	,039440	<,001	-,35935	-,10407

Table 4: Tennisball normal statistical comparison to the other balls

(I) Ball groups	(J) Ball groups	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
Tennisball normal	Padelball normal	-,037146	,038454	1,000	-,16160	,08731
	Padelball green	-,050583	,042033	1,000	-,18662	,08545
	Padelball yellow/red	-,256883*	,043116	<,001	-,39642	-,11734
	Padelball brown	-,211220*	,042033	<,001	-,34726	-,07518
	Tennisball green	-,052440	,047891	1,000	-,20743	,10255
	Tennisball yellow/red	-,181155*	,047891	,009	-,33615	-,02616
	Tennisball brown	-,268856*	,042033	<,001	-,40489	-,13282

Discussion

The results of this study provide significant insights into the effect of fuzziness on the fall time of padel and tennis balls. The findings align with the hypothesis that fuzzier balls have a longer fall time due to increased air resistance.
The descriptive statistics (see table 2) indicate that the mean fall times for both padel and tennis balls vary with the type of felt covering the ball. Notably, balls with more fuzz, such as the Padelball yellow/red, Padelball brown, and Tennisball brown, show longer fall times compared to balls with less fuzz, such as the padel ball normal and tennis ball normal. This trend is visually represented in the box plot (Figure 6), which shows the distribution and variability of fall times across different ball groups.
The one-way ANOVA test results further support these observations. The significant F-value (F(7,77) = 12.880, p < .001) indicates that there are statistically significant differences in fall times among the different ball groups. Specifically, the post hoc comparisons reveal that the fall times of the Padelball yellow/red, padel ball brown, and Tennisball brown are significantly longer than the Padelball normal and tennis ball normal (see table 3 & 4). Additionally, the Tennisball yellow/red also shows a significantly longer fall time compared to the Tennisball normal (p = .009). It is also important to mention that the Tennisball yellow/red compared to the Padelball normal result in p = .064 which is not far off the significance level of 0.05. The green felt had no significant differences compared to the normal felt.
These findings suggest that the increased drag caused by the fuzziness of the ball's felt contributes to a slower descent. This aligns with existing literature which indicates that the fuzz on tennis balls increases drag by 20%-40% (Shah et al., 2019; Mehta et al., 2008).

Limitations

While the findings of this study are significant, several limitations should be acknowledged:

1. Precision of Measurement: The sample size was relatively small, which may limit the generalizability of the results. Additionally, human factors such as the release of the balls and the timing of the start of tracking in the Tracker program could introduce inconsistencies.
2. Technical Issues: The ball tracker did not always track the ball automatically and therefore manual interventions were needed which could affect accuracy. The camera resolution and lighting conditions were also not the best conditions for tracking, as well as the dark background/floor which sometimes made it harder to see the darker balls.
3. Footage Quality: The slow-motion footage occasionally glitched, leading to the exclusion of some tests which skipped frames at important parts of the fall (during the release of the ball and the moment it would hit the ground) and contributing to the low sample size. Moreover, an issue with the frame rate of the footage for the tennis ball green resulted in only half the frames being recorded.
4. Mechanical Malfunctions: The release mechanism malfunctioned just before testing, potentially causing inconsistent releases during the experiment. This could have impacted the reliability of the fall time measurements.
5. Experimental Setup: The dropping rod would sometimes drag the balls a little bit when released. This sometimes caused the ball to stay longer on the rod and fall down gaining spin. The drops that had a noticeable amount of spin were not included in the analysis.
6. Fuzziness Consistency: The fuzziness of the balls was not consistently uniform. Some balls with the same felt exhibited varying levels of fuzziness, which could have influenced the results. Additionally, the diameter of the balls were also different by 1 mm for the ones with green and brown felt.

Recommendations

Future research should aim to address these limitations by using a larger sample size, improving the precision of measurement techniques, and ensuring consistency in the experimental setup (for example by using a set-up with electromagnets to let the ball drop and electrical sensors that measure the time). Additionally, more professionally manufactured felt types would provide a better understanding of the impact of fuzziness on ball dynamics by also reducing the amount of diameter growth that is now occurring because of the fabric that is glued to a ball that already contains a layer of normal felt.

Appendix H: The Impact of Fuzzy Fabric Felt Covering on the Bounce Height of Padel and Tennis Balls

Abstract

This study investigates the impact of different felt coverings on the bounce height of padel and tennis balls. Previous research showed that felt fabric absorbs shocks and reduces the bounce height, leading to lower bounce heights compared to balls with normal felt. Since bounce is crucial for padel balls during a smash, influencing their reaction off the racket, understanding these differences is valuable. This study aims to quantify these differences using a custom-built mechanism that drops a weight onto stationary balls and measures the bounce height of that weight. Results indicate significant variations in bounce height depending on the type of felt covering, with fuzzier balls exhibiting lower bounce heights compared to balls with normal fuzz. The findings provide insights into the effect of felt types on kinetic energy transference, although limitations such as double damping effects and inconsistencies in pressure application need to be addressed in future studies. Recommendations include using more professionally manufactured ball prototypes and improving the experimental setup to eliminate potential sources of error.

Introduction

Earlier research (Appendix G) highlighted the aerodynamic effects of felt covering on padel and tennis balls when dropped from a height of 1.90 metres. Beside the results of the fall time of each ball, the data also indicated that the felt fabric caused lower bounce heights compared to balls with normal felt coverings, indicating a reduction of the bounce effect. Since bounce is an important feature of padel balls and can influence how the ball reacts off the racket during a smash, it is valuable to gain insights into the differences between the prototype balls.

This study aims to quantify the difference in bounce heights and determine if there is significant data supporting that balls with fabric felt coverings bounce differently compared to those with normal felt. Based on the results of the drop test, both the Padel- and Tennisball green showed no significant difference compared to the Padel- and Tennisball normal; therefore, these two balls are excluded from this test as they are not relevant for further research.

Because there is a significant difference in the fall time of the ball, and thus its fall speed, this influences the bounce height. Therefore, the same setup as the drop test cannot be used. Instead, a different mechanism was built that drops a weight onto a stationary ball to observe the height of the weight's bounce.
The research question for this study is: Is there a significant difference in the bounce height of padel and tennis balls with different types of felt coverings?

Methodology

Materials

Excluding the balls with the green fabric felt, there are 6 new balls that are going to be tested: three padel balls and three tennis balls. These balls are covered with different types of fabric: no cover/normal felt, yellow/red fabric (fuzzy), and brown fabric (very fuzzy/hairy) see figure 1 and table 1. A custom-built bounce mechanism, employing a hammer attached to a hinge, is used to ensure a consistent bounce of the hammer that drops on to the balls (see figure 2). The drops are recorded with a slow-motion function on a smartphone (Oneplus 6T) capable of capturing 240 frames per second (fps) at 1080p resolution. This is 8 times slower than the normal record function. The footage of the bounce height is analysed in Adobe Premiere Pro.

Figure 1: Ball groups

Table 1: Characteristics of each ball group

	Weight	Diameter	Fuzziness level (1 - 5)
Padelball normal	57 grams	64 mm	1
Padelball yellow/red	72 grams	69 mm	4
Padelball brown	76 grams	71 mm	5
Tennisball normal	57 grams	64 mm	1
Tennisball yellow/red	72 grams	69 mm	4
Tennisball brown	76 grams	72 mm	5

Procedure

The custom bounce mechanism is designed to ensure each bounce is recorded in a consistent manner. This mechanism involves a hammer on a hinge that drops on a stationary ball that has been held into place by a piece of wood with a hole but still gives the ball room to expand to the sides when compressed.

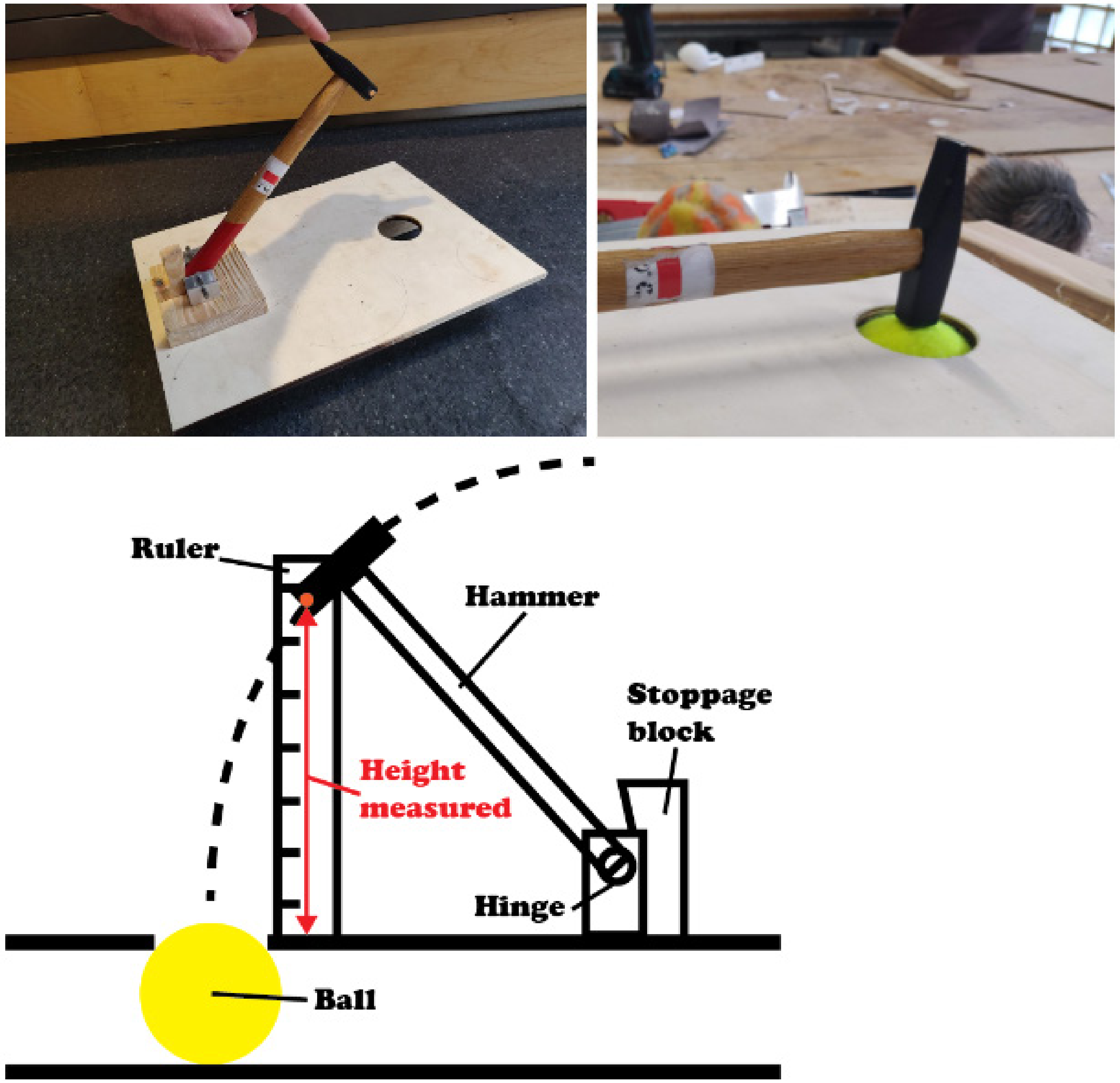


Figure 2: Hammer bounce mechanism with a ball held into place & illustration

The piece of wood at the hinge prevents the hammer from being pulled all the way back (see Figure 3). Manually pulling the hammer back ensures that it always drops from the same height/angle (around 85 degrees).

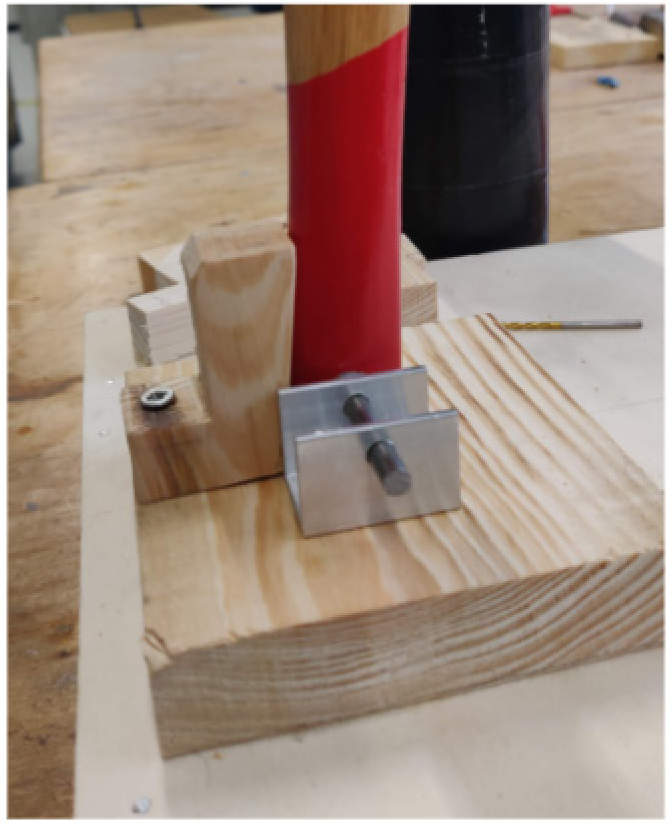


Figure 3: Stopage block

Figure 4: Ruler behind hammerhead

The number of bounces for each type of felt varied between 28 and 30. The slow-motion camera is positioned 24-27 cm away from the bounce mechanism (the bounce of the Tennisball normal was higher than the frame, so the camera was moved back 3 cm to still capture the bounce height). The height from the ground is 95 cm to record the falling hammer. A ruler is placed behind the head of the hammer to show the height after the bounce on the ball (see figure 4). The foundation where the mechanism and balls lie on have to be very hard. In that case most of the kinetic energy will be transferred to the hammer instead of being absorbed by the ground. That is why a table with a 4 centimetre thick concrete tabletop is used. The setup of the test is detailed in figure 5.

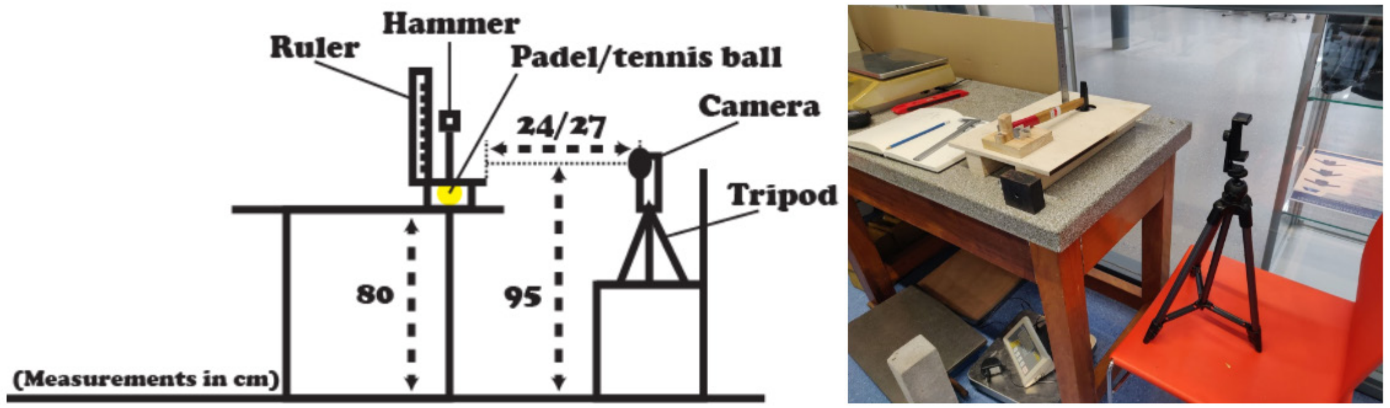


Figure 5: Test set-up drawing (left) and in real life (right)

Because the balls have a different diameter the height to the hole in the board needs to be altered for each ball. Two slats of wood can be screwed at the bottom to compensate for this difference in height (see figure 6). To ensure that the set-up will not move a few weights are distributed on the top. An orange dot meant as a guideline for the analysis is glued to the top of the hammer (see figure 7).

Figure 6: Slats of wood screwed on the bottom

Data Analysis

Using the recordings in Adobe Premiere Pro, the moment the hammer bounces back the highest is viewed. The video is stopped manually and the height is read using the ruler in the background. Guidelines are drawn in the video because the hammer is blocking the stripes on the ruler. The bottom of the orange dot is used as the reference of each height (see figure 8). The data is then averaged for each type of felt and compared in SPSS using a one-way ANOVA with ball type as independent variable and time to hit the ground as dependent variable to test the hypotheses. The results are analysed to determine whether the type of felt had a significant impact on the fall time of the balls.

Figure 7: Weights & orange dot on the mechanism

Figure 8: Close-up of the hammer at the highest point after bouncing (12,0 cm). The white lines are drawn at 11 cm & 12 cm

Results

The descriptive statistics table 2 summarises the bounce height of the hammer for each type of ball and felt. The mean bounce height for the padel balls and tennis balls varies depending on the type of felt covering the ball.

A one-way ANOVA test is used to test the hypothesis that fuzzier balls bounce less high than less fuzzier balls, with bounce height in cm as the dependent variable and ball group (padel/tennis ball & fuzziness level) as the independent variable. Figure 9 shows the results plotted in a box plot graph.

Table 2: Descriptive statistics table drop test

Descriptives

Bounce height

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Padelball normal	29	14,0431	,26883	,04992	13,9408	14,1454	13,75	14,40
Tennisball normal	30	17,0017	,04997	,00912	16,9830	17,0203	16,80	17,10
Padelball yellow/red	30	9,9550	,09317	,01701	9,9202	9,9898	9,60	10,10
Tennisball yellow/red	28	11,8911	,16835	,03182	11,8258	11,9564	11,20	12,10
Padelball brown	30	11,8083	,04749	,00867	11,7906	11,8261	11,75	12,00
Tennisball brown	30	12,4933	,08277	,01511	12,4624	12,5242	12,30	12,60
Total	177	12,8698	2,22999	,16762	12,5390	13,2006	9,60	17,10

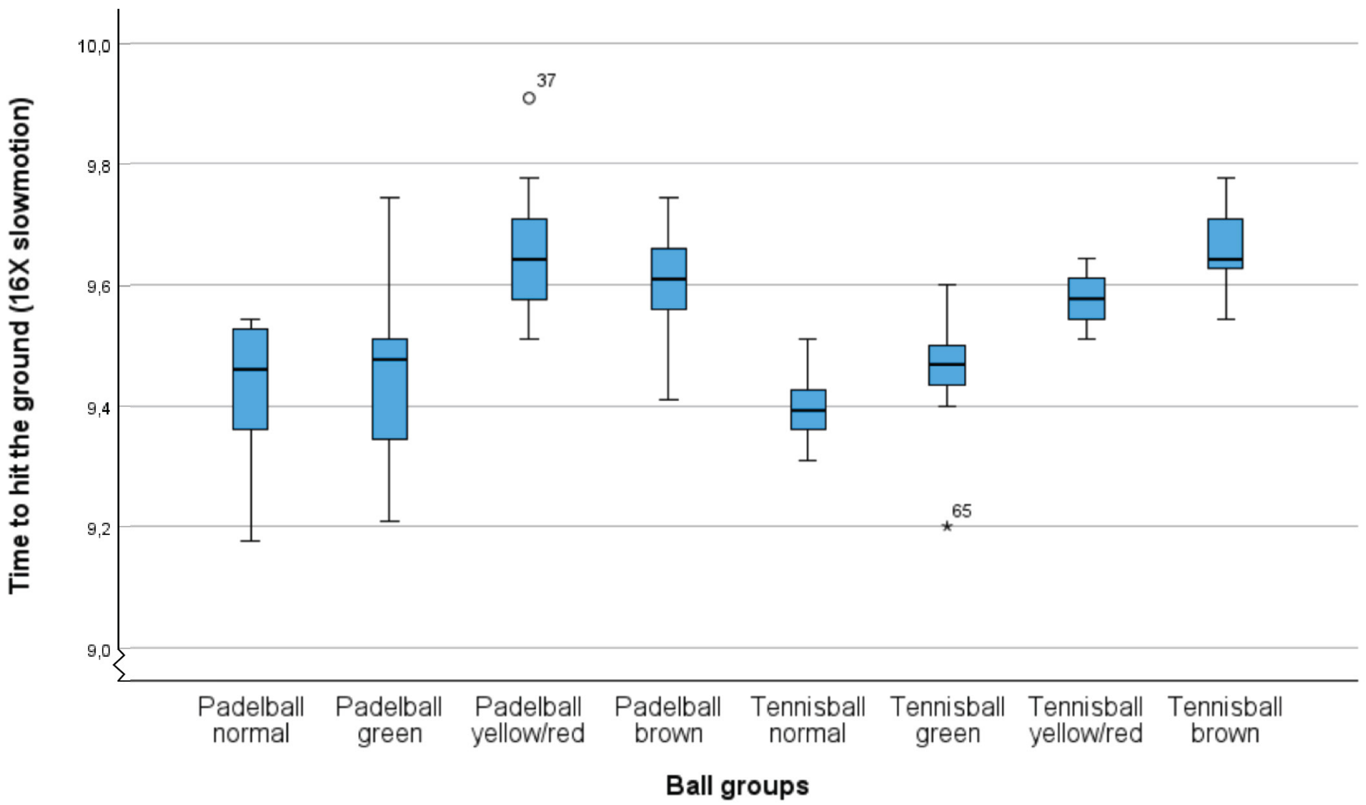


Figure 9: Box plot of the ball groups and the bounce height of the hammer after contact with the different balls

Compared to the Padelball normal, every other ball has a significant difference. F(5,171) = 8829,138, p < .001 (see table 3). The only balls that are not significantly different from each other are the Tennisball yellow/ red & Padelball brown p = .395.

Table 3: Padelball normal statistical comparison to the other balls

Multiple Comparisons

Dependent Variable: Bounce height
Bonferroni

(I) Ball groups	(J) Ball groups	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Padelball normal	Tennisball normal	-2,95856*	,03660	<,001	-3,0675	-2,8496
	Padelball yellow/red	4,08810*	,03660	<,001	3,9792	4,1971
	Tennisball yellow/red	2,15203*	,03723	<,001	2,0412	2,2629
	Padelball brown	2,23477*	,03660	<,001	2,1258	2,3437
	Tennisball brown	1,54977*	,03660	<,001	1,4408	1,6587

Discussion

The results of this study provide significant insights into the effect of fuzziness on bounce height of padel and tennis balls. The findings align with the hypothesis that fuzzier balls have a significantly lower bounce height due to increased damping and thus energy loss.
The descriptive statistics (see Table 2) indicate that the mean bounce height for both padel and tennis balls vary with the type of felt covering the ball. Notably, balls with fuzz show lower bounce heights compared to balls with normal fuzz. This trend is visually represented in the box plot (Figure 9), which shows the distribution and variability of bounce height across different ball groups.

Limitations

While the findings of this study are significant, several limitations should be acknowledged:

1. Double damping effect: The fabric felt on the balls not only damp the contact with the hammer but also with the floor, introducing a double damping effect. This could lead to inconsistencies in the bounce heights recorded. Looking at the smash the ball only has contact with the racket and the air and therefore all kinetic energy will be transferred to the racket and the ball itself.
2. Inconsistent pressure on balls: The balls were held in place by a wooden plate, but the amount of pressure applied by the plate was not the same for each ball since the height needed to be adjusted. Balls that were more tightly held experienced higher bounce heights due to the increased initial pressure.
3. Manual height adjustment: The need to manually adjust the height of the hole in the board for each ball introduces potential for human error and inconsistency in the experimental setup.
4. Potential dead spots: Some balls might have dead spots where the fabric felt and/or the glue leads to less energy transference. These spots could lead to variations in the bounce height that are not accounted for by the type of fabric

felt covering alone.

5. Video analysis limitations: Using Adobe Premiere Pro to manually stop the video and read the height could introduce observer bias and inaccuracies in determining the exact bounce height.
6. Variations in bounce mechanism: The hammer mechanism, while consistent, may still have slight variations in the angle or height of the drop, which could affect the results.
7. Environmental factors: The camera position had to be adjusted for the Tennisball normal which changed the camera perspective. Also the lighting was not optimal for slow motion recording and might have changed during the test, making it harder to observe the exact bounce height.

Recommendations

It is recommended to clamp only the padel and tennis balls because they have the same diameter and will experience the same amount of pressure generated by the wooden plate. The different types of fabric felt can be glued to the end of the hammer to test the bounce height. This approach avoids the double damping effect. Additionally, using more professionally manufactured balls with different felt types would provide a better understanding of the impact of fuzziness on a ball, since now the fabric is applied to a ball that already has a layer of normal felt and therefore has a lot more damping than a ball with normal felt.

Appendix I: The Effect of Fuzzy Prototype Balls on Smash Performance in Amateur Padel Players

Abstract

This study explores the effect of prototype fuzzy padel and tennis balls on the smash performance of amateur padel players. Prior research suggests these prototype balls, designed to fall slower than standard padel balls, can change player perception and reaction during smashes. The primary hypothesis says that slower ball travel improves smash performance by allowing more time to set up the smash, while higher internal pressure on the ball counteracts damping effects so the smash can still be performed similar to a normal padel ball. Nine right-handed amateur players, aged 22 to 62, with beginner or intermediate padel levels and varying racket sport experience, participated in the experiment. Each participant executed smashes using three types of balls (standard padel balls, fuzzy padel balls, and fuzzy tennis balls) aiming at a target mat, with speed and accuracy measured. Results, analysed via repeated-measures ANOVA, indicated significant speed differences between ball types but no significant difference in overall smash performance scores. Qualitative feedback highlighted the perceived slower movement & heaviness of fuzzy balls. There is a need for further research to validate these findings and improve prototype ball designs for skill development in padel.

Introduction

This study investigates the impact of prototype fuzzy padel and tennis balls on the smash performance of padel amateurs. Previous research has indicated that these prototype balls fall slower through the air compared to normal padel balls. This slower descent could potentially influence how players perceive and react to the ball during a smash.

In this experiment, participants are asked to smash the lobbed prototype balls towards a designated target mat on the ground. The external focus on both the unique characteristics of the prototype balls and the target allows for the assessment of instinctive, implicit knowledge in player performance. Participants are not given any specific instructions on technique, relying instead on their natural instincts and prior playing experience.

The research question is as follows: Is there a significant difference in the padel smash performances of amateurs between balls with alternating felt coverings and pressure?

The hypothesis for this research is that when using a ball that travels slower through the air, giving a player more time to set-up a smash, will improve the smash performance of padel amateurs.

A second hypothesis is that increasing the pressure in the balls that travel slower through the air, will counter the damping effect and improve the smash performance of padel amateurs.

This research aims to determine whether the different aerodynamics and internal pressure of the prototype balls enhance or hinder player performance.

Methodology

Participants

In total 9 participants conducted the smash test. These participants consisted of seven men and two women, with an age range between 22 and 31 years old with one outlier who was 62 years old. All participants were right handed and the group had a beginner/ intermediate padel level. They played padel between two times a week and (almost) never (played it five times in his life). There were six participants with tennis experience, three with no other racketsport experience, one with table tennis experience and one with squash experience. A table with all participants can be found in table 1. The motivation of the players to play padel was physical health, mental health, to be with friends, learning a new skill, competition and just for fun.

Table 1: Participant information smash test

	Gender	Height (m)	Weight (kg)	Age	Padel level	Racketsport exp.	How often play padel
1	Male	1.80	86	31	Intermediate	Tennis	2x a week
2	Male	1.80	79	62	Beginner	Tennis	1x a week
3	Male	1.80	72	23	Intermediate	Tennis & squash	2x a month
4	Male	1.80	120	27	Beginner	Tennis	2x a month
5	Male	1.84	105	28	Intermediate	Tennis	1x a month
6	Female	1.78	80	26	Beginner	None	1x a week
7	Male	1.80	65	23	Beginner	None	In total 5 times
8	Male	1.89	99	27	Intermediate	Tennis & table tennis	2x a month
9	Female	1.63	53	22	Intermediate	None	2x a week

Test set-up

Figure 1 and 2 show the test set-up illustrated and in real life

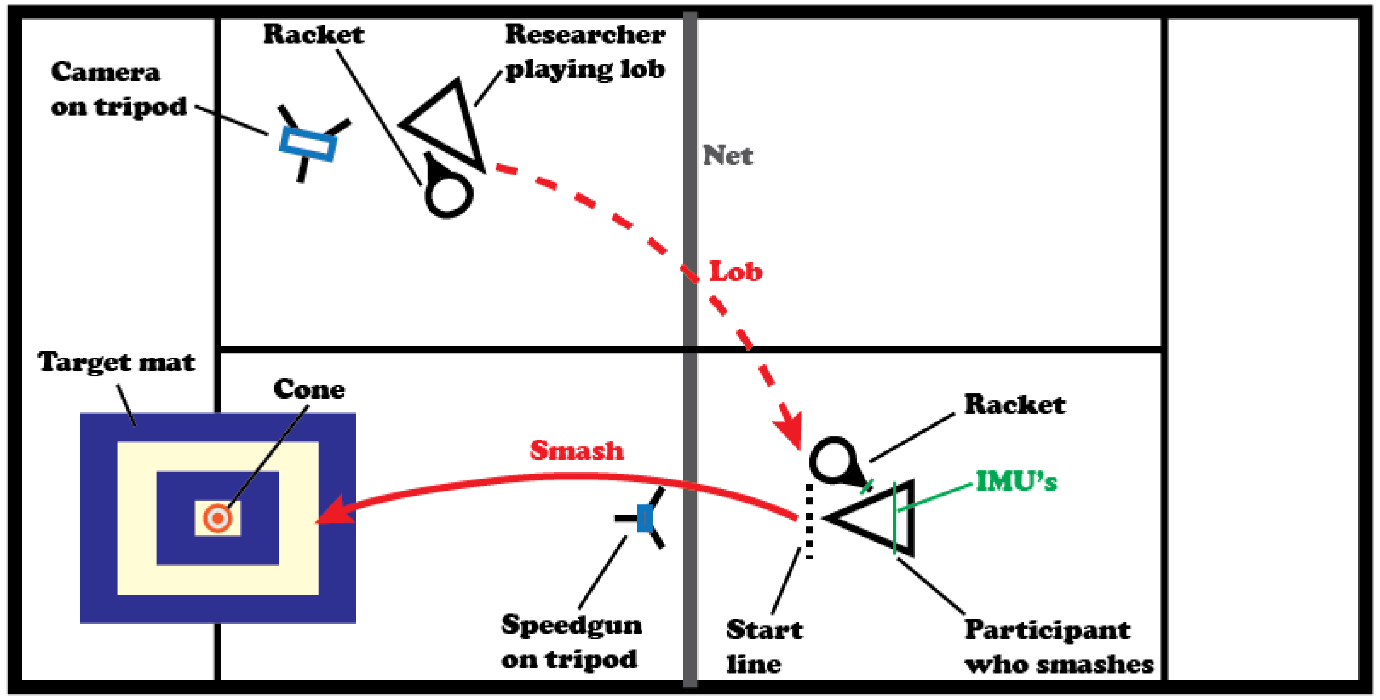


Figure 1: Research set-up smash test illustrated

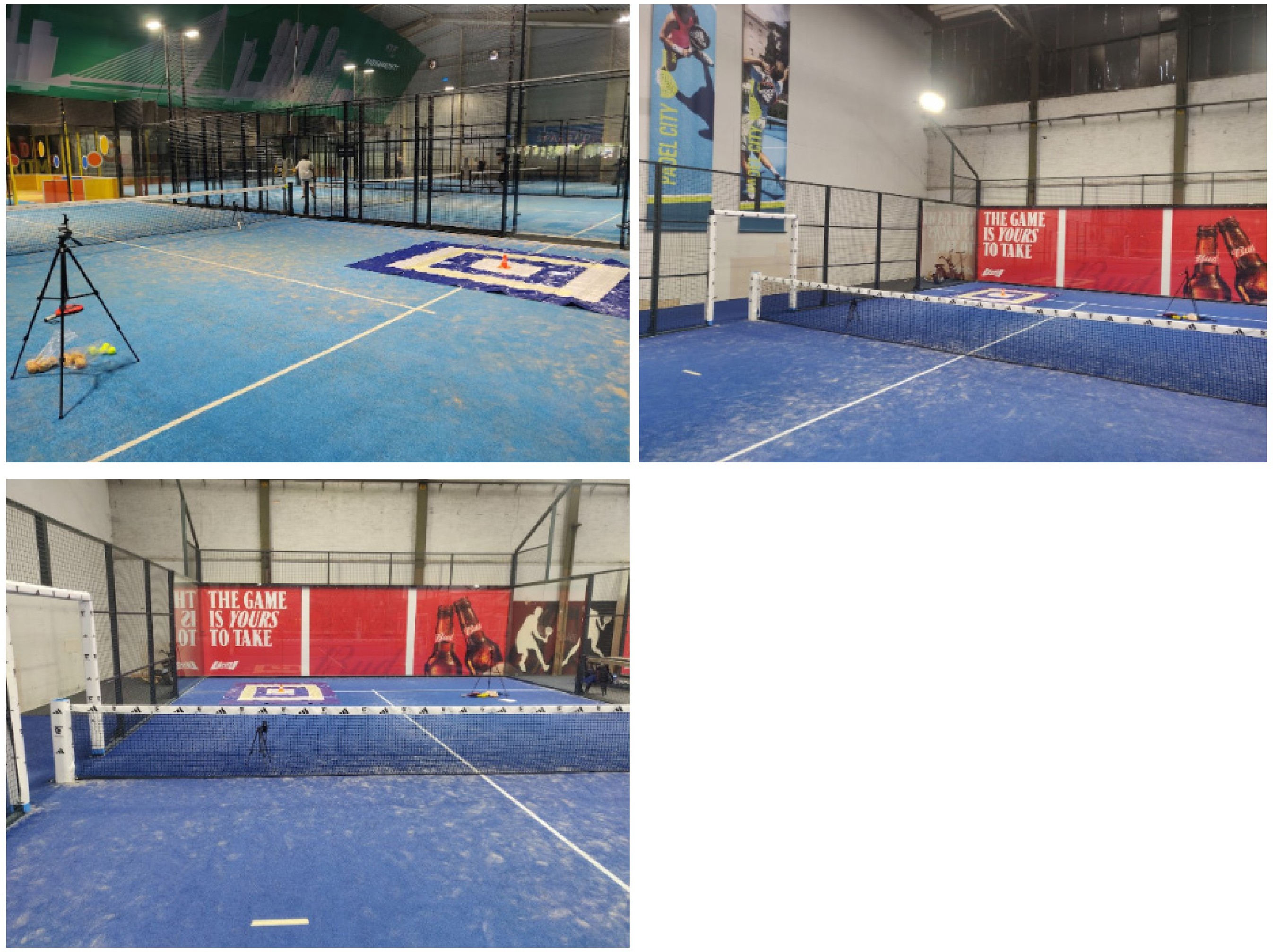


Figure 2: Research set-up smash test in real life

Materials

In this study, three groups of balls are used: Padelball normal, Padelball yellow/red, and Tennisball yellow/red (see figure 1). The target mat measures 2.80x3.80 metres, featuring rings with diameters ranging from 0.7 to 0.95 metres. This mat is placed centrally on the baseline and 108 centimetres from the sidewall & middle line. Participants use a Bullpadel Kitter padel racket, This is a round shaped racket weighing between 360-370 grams, with a thickness of 38 mm, and constructed from polyglass/softeva materials. An additional padel racket is used for playing the lobs.

The study uses a Smart Coach pocket radar, powered by batteries or a power bank, for measuring smash speeds. Two tripods support the recording equipment, one for the pocket radar and one for filming the balls when they hit the target. The recording devices include a smartphone: a Oneplus 6T (for recording the landing of the balls).

Figure 1: The balls used in the smash test; Pnormal (left), Pfuzz (middle), Tfuzz (right)

Table 1: Characteristics of each ball group that are used in the smash test

	Normal padel ball	Fuzzy padel ball	Fuzzy tennis ball
Weight	58 - 59 grams	68 - 70 grams	69 - 71 grams
Ball diameter	64 mm	69 mm	69 mm
Internal pressure	0.69 - 0.76 bar	0.69 - 0.76 bar	0.97 bar

Procedure

Participants begin by signing a consent form, followed by a general explanation of the study. They complete a survey about their padel experience.

Participants warm up by passing the ball over the net with the researcher. They then perform five practice smashes for each ball group (15 in total) to get a feeling for the smash and also the flight speed of each ball group. For every smash in this study the lob is given by the researcher and the participant is asked to start from a projected line on the ground. The speedgun is tested during the five practice smashes.

The test involves 15 smashes per group of balls (45 smashes in total), with participants hitting only five balls in a row before picking them up from the ground. This process is repeated for the other two ball groups. The order in which the ball groups are played is random per participant. Between each group, participants are asked for their thoughts, and observations are noted. Speed recordings are restarted for each group.

During the smashes, the number of points hit is observed and written down by the researcher after every five balls. When all the smashes are performed, the participants can provide post-test remarks. Finally, the speed data that is collected from the speedgun and videos are linked with the written down points.

Between every group of balls questions are asked to the participant what they thought about the ball. The answers were noted in keywords by the researcher.

Data analysis

The smash points are written down during the test and exported to an Excel file where they are combined with the speedgun data.

Smash points are visualised in a bar chart indicating how many times a certain point has been hit by each ball group.

The average speed is compared for each type of ball in SPSS using a repeated-measures ANOVA with ball type as independent variable and speed as dependent variable.

The speed and smash point are multiplied with each other, resulting in a score that is based on the speed and accuracy and shows how well each smash performed (smash performance score). When either the speed or the points were missing in the data, this smash is removed from the data set. If someone smashed the ball out, this results in a score of 0 because the player received 0 smash points. The performance scores are compared for each type of ball group in SPSS using a repeated-measures ANOVA with ball type as independent variable and performance score as dependent variable.

Results

The results are presented into three categories; smash points, smash speed, smash performance score. For each category the most notable results are mentioned here in the results part and discussed in the discussion paragraph.

Smash points

Examining the total number of points each participant has achieved per ball, there is no significant difference between them. As determined by a one-way ANOVA ($F(2,24) = .266$, $p = .768$). See figure 4 for the boxplot of these results. Therefore no conclusions can be taken from this analysis if participants smash better with the fuzzy balls.

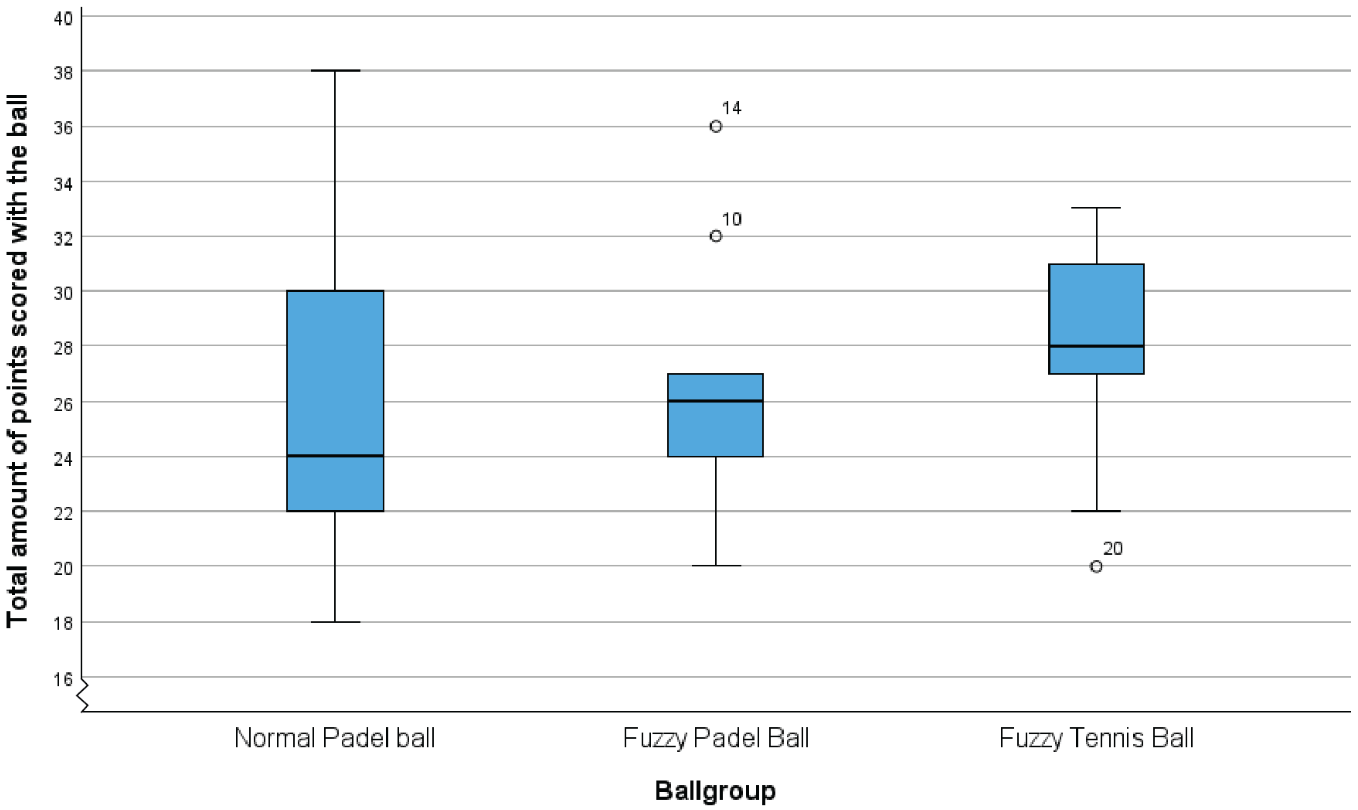


Figure 4: Box plot of the total points scored per participant between the ball groups

Something that can be observed concerning the amount of points occurs when looking at the frequency of the 0 and 1 points scored. Table 3 shows these frequencies. What is interesting is that the Pnormal landed more 0 points and less 1 points compared to both the fuzzy balls. Three participants mention that the fuzzy balls go to the ground faster so that might be a reason why these fuzzy balls have less 0 points and more 1 point than the Pnormal. Less errors were therefore made with the fuzzy balls which can indicate an improvement in smash performance. However since there was no significant difference with the total amount of points between the balls, there is a probability that the Pnormal compensates these bad scores with higher scores.

Table 3: Frequencies of 0 and 1 point landed per ball

	Pnormal	Pfuzz	Tfuzz
0 points	28	14	12
1 point	43	59	59

Smash points

The descriptive statistics table 4 summarises the smash speed of each smash performed per ball group. The mean smash speed for the padel balls and tennis balls varies depending on the type of felt covering the ball.

A repeated-measures ANOVA determined that mean speed differed significantly between the three ball groups ($F(2, 202) = 7.119$, $p = .001$). A post hoc pairwise comparison using the Bonferroni correction indicates a decrease in speed between the Padelball normal and the Tennisball yellow/red (72.64 vs 70.28, respectively), but this was not statistically significant ($p = .309$). However, the decrease in speed reached significance when comparing the Padelball normal and the Tennisball yellow/red (72.64 vs 66.99, $p = .002$) (see table 5). Therefore, we can conclude that the results for the ANOVA indicate a significant effect in speed for padel balls covered with fuzzy fabric.

Table 4: Descriptive statistics smash speed per ball

Descriptive Statistics

	Mean	Std. Deviation	N
SpeedPadelball normal	72,64	17,334	102
SpeedPadelball yellow/red	66,99	14,468	102
SpeedTennisball yellow/red	70,28	15,804	102

Table 5: repeated-measures ANOVA analysis smash speed per ball

Pairwise Comparisons

Measure: MEASURE_1

(I) Balltype	(J) Balltype	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
1 Padelball normal	2 Padelball yellow/red	5,647*	1,639	,002	1,657	9,637
	3 Tennisball yellow/red	2,353	1,429	,309	-1,127	5,833
2 Padelball yellow/red	1 Padelball normal	-5,647*	1,639	,002	-9,637	-1,657
	3 Tennisball yellow/red	-3,294	1,432	,071	-6,781	,193
3 Tennisball yellow/red	1 Padelball normal	-2,353	1,429	,309	-5,833	1,127
	2 Padelball yellow/red	3,294	1,432	,071	-,193	6,781

Based on estimated marginal means

*. The mean difference is significant at the ,05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Smash performance score (speedXpoints)

The descriptive statistics table 6 summarises the smash performance score (speedXpoints) of each smash performed per ball group. The mean smash performance score for the padel balls and tennis balls varies depending on the type of felt covering the ball. When one of the variables (speed or points) were missing from smashes in the data then the score was not included. The tries that were smashed out resulting in a score of 0 points were also not included in this analysis because that says something about the amount of errors made and the performance of the smash.

A repeated-measures ANOVA determined that the mean performance score did not differ significantly between the three ball groups ($F(2, 156) = 1.014$, $p = .365$).

Table 6: Descriptive statistics of the smash performance score (speedXpoints)

Descriptive Statistics

	Mean	Std. Deviation	N
The performance score of Padelball normal	159,09	116,416	79
The performance score of Padelball yellow/red	142,25	91,372	79
The performance score of Tennisball yellow/red	163,29	106,184	79

A post hoc pairwise comparison using the Bonferroni correction indicates a decrease in performance score between the Padelball normal and the Padelball yellow/red (159.09 vs 142.25, respectively), but this was not statistically significant ($p = .88$). The increase in performance score between the Padelball normal and the Tennisball yellow/red comparison also was not significant (159.09 vs 163.29, $p = 1.000$) (see table 7). Therefore, we can conclude that the results for the ANOVA indicate no significant effect in the smash performance score for balls covered with fuzzy fabric.

Table 7: repeated-measures ANOVA analysis smash performance score per ball

Pairwise Comparisons

Measure: MEASURE_1

(I) Balltype	(J) Balltype	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	Upper Bound
1 Padelball normal	2 Padelball yellow/red	16,835	15,913	,880	-22,099	55,770
	3 Tennisball yellow/red	-4,203	16,426	1,000	-44,392	35,987
2 Padelball yellow/red	1 Padelball normal	-16,835	15,913	,880	-55,770	22,099
	3 Tennisball yellow/red	-21,038	14,511	,453	-56,542	14,466
3 Tennisball yellow/red	2 Padelball yellow/red	21,038	14,511	,453	-14,466	56,542
	1 Padelball normal	4,203	16,426	1,000	-35,987	44,392

Based on estimated marginal means

a. Adjustment for multiple comparisons: Bonferroni.

Qualitative data

The main answer to the questions between the smashes of each ball group are shown in table 8. The amount of people that answered with the same answer and the ratio of beginners and intermediates are shown in the most right columns.

Table 5: Qualitative results

	Answers	How many participants mentioned it (9 in total)	Beginner (b) /intermediate (i) ratio
1	Prefer/familiar feeling normal ball	3	1b / 2i
2	The ones with fuzz move slower during the lob	5	2b / 3i
3	The ones with fuzz feel heavy	3	0b / 3i
4	There is not much difference between the fuzzy balls	2	2b / 0i
5	The fuzzy tennis ball has more speed during the smash than the fuzzy padel ball	5	2b / 3i
6	The fuzzy balls drop to the ground faster	3	2b / 2i
7	Different timing/adjusting to each ball group	3	1b / 2i
8	Experience dampening feeling (touch or sound)	2	1b / 1i
9	Quality of the lob has influence on the smash	2	1b / 1i

Discussion

- Points: the data of the points can not really say something definite but it seems like the Padelball normal hits more 0 points but also more 5 points compared to the fuzzy balls. Three participants mentioned that they felt a familiar feeling with the Padelball normal and preferred that ball because they felt like they could aim better. Which can explain the higher amount of 5 points.

Looking at the figure 5 especially beginners hit a lot of 0 points often because they hit the wall at the end of the court. Three participants mention that the fuzzy balls go to the ground faster so that might be a reason why these fuzzy balls have less 0 points and more 1 points than the Padelball normal.

- Speed: the Padelball yellow/red has a significantly slower speed compared to the Padelball normal, and the Tennisball yellow/red does not. Which also comes forward in the comments of the participants. Five participants mentioned that they felt like the Tennisball yellow/red speed was faster when they smashed the ball, which was preferred because it felt more like the Padelball normal. However three participants mentioned that the fuzzy balls felt heavier than the normal balls, which is true because there is a difference of about 11 grams, and that's why they had to give more power into their smash, resulting in a compensation of speed. This can be a reason why three participants mentioned that they preferred the Padelball normal

because then they did not have to force the power they had to put into the smash.
- Smash performance: this score gave no significant result. However it is interesting to see that even though the Tennisball yellow/red had a lower average smash speed than the Padelball normal, it has a higher average performance score. Which means that they had better smash points. Still this is something that really has to be proven to be true in further research.
- Further qualitative research: Three participants mentioned that they had to adjust to the timing. Especially the two intermediate players that mentioned it were very confused when they missed the ball because they already started their smash swinging too early because the fuzzy ball was falling slower. Their adjustment did not take long because after that they did not miss swing anymore. This is very interesting because this relates to differential learning mentioned in chapter 2.
  Two participants commented on the dampening effect of the fuzzy balls. They either felt it through the racket during a smash or noticed a difference in the sound the fuzzy balls made compared to the Pnormal. One player said he often judges the quality of a smash by the loud banging sound he hears on contact between the ball and the racket. This is very interesting to explore further, as it suggests that manipulating sensory feedback could potentially enhance smash performance.

In general the test has a lot of uncertainties however one thing it showed was that increasing the internal pressure (padelball vs tennisball) can compensate for the shock absorption because comparing the speed of the fuzzy balls with the normal padel ball gave a significant difference with the fuzzy padel ball and not with the fuzzy tennis ball. Coming back to the hypotheses; 1) when using a ball that travels slower through the air, giving a player more time to set-up a smash, will improve the smash performance of padel amateurs. 2) increasing the pressure in the balls that travel slower through the air, will counter the damping effect and improve the smash performance of padel amateurs.
There is no significant data that support this difference between the ball groups. However five people mentioned that they felt like they had more time to set up their smash. Further research has to show if it is beneficial to use these slower balls during practice to actually improve learning this skill (faster) by also implementing transfer and retention tests (Beek, 2011a).

Limitations

1. Manual Lob Execution: The lobs were played manually, which could lead to inconsistencies. Variations in the lob's height, speed, and angle might have impacted the smash performance.

2. Fabric Variability: Not all balls had exactly the same fabric felt cover. Differences in the felt and amount of glue could affect the ball's aerodynamics and behaviour upon impact.

3. Dead Spots on Balls: Some balls might have had dead spots because of the glue use, affecting their bounce and overall performance during the test.

4. Ball malfunction: The fabric of one padel ball (yellow/red) came off during the test for participant 6. This ball was excluded from further testing, potentially disrupting the participant's rhythm and performance of this participant, but also other participants since from that point a ball had to be picked up from the ground during every set.

5. Lighting Issues: One participant reported being blinded by one of the lights. This could have affected their visibility and performance during the test.

6. Side Spin Smashes: One participant's smashes had side spin instead of being flat. This should have been noticed earlier because this smash technique could have affected the speed and accuracy of the smash.

7. Injury: One participant was recovering from a knee injury, leading to reduced movement speed and less explosive smashes. This could have impacted their overall performance.

8. Order of Ball Play: Although the order in which the balls were played was randomised, it still influenced performance. Two participants mentioned getting into a better flow with the balls played last compared to those played first.

9. Speed Gun Accuracy: When the ball was not hit in a straight line, the speed gun is more inaccurate when measuring the speed. This could result in incorrect speed data.

10. Unregistered Smash Speeds: Some smashes were not registered by the speed gun, leading to incomplete speed data for those instances.

11. Filming Errors: Some smashes were registered by the speed gun but not filmed due to human error or storage space issues. This made it impossible to verify the points given in post-analysis and might have resulted in incorrect pairing of speeds and points.

12. The colour of the normal balls and the prototypes were different which may have influenced the test results

Recommendations

To improve the accuracy and reliability of future tests, several recommendations are proposed. These suggestions aim to refine the test setup, enhance data collection, and ensure higher quality prototypes, ultimately leading to more reliable and valid results.

1. Improved Test Setup: Usa a round target to measure the distance to the bullseye, allowing for consistent comparisons. With a round target, each ring has an equal distance to the centre, unlike a square target, which can be compared statistically unlike the point system that is now used.

2. Professional Lob Execution: Engage a professional padel trainer to deliver lobs, to ensure higher quality and consistency in the lobs the participants receive.

3. Enhanced Filming Techniques:
   - Film the participant performing the smash and the landing spot of the ball within the same frame so it is easier to combine smashes with the points awarded.
   - Use slow-motion filming to better observe and determine the exact landing spot of the ball.
   - Better Camera Equipment: Use a higher quality camera with enough storage space to avoid data loss issues.

4. Higher Quality Prototypes: Create higher quality prototypes by glueing the fabric felt directly onto the rubber inside the ball rather than on an existing ball. This reduces weight and minimises the damping effect.

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