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MEASUREMENTS IN CYCLING

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CHAPTER 1. INTRODUCTION TO CYCLING

1.1 Cycling: A General Overview

Cycling is one of the most practiced and followed sports in the world, with a long history dating back to the 19th century. This sport has evolved over time, adapting to the needs of athletes and technological innovations. What began as a simple means of transportation has transformed into a highly specialized and competitive sport, encompassing various disciplines, each requiring distinct physical and technical skills.

The evolution of cycling has been driven by technological advancements, strategic innovations, and a growing understanding of human physiology. From the early wooden bicycles without pedals to modern aerodynamic carbon fiber bicycles, cycling has undergone radical transformations that have made competitions increasingly fast and strategic. The introduction of lighter materials, more efficient gearing systems, and advanced aerodynamics has significantly improved both speed and endurance capabilities, allowing cyclists to push the limits of human performance [1].

In particular, the development of carbon fiber frames has revolutionized cycling, allowing for a perfect balance between stiffness, lightness, and shock absorption. Aerodynamic studies have led to the optimization of bicycle geometry and component design, reducing air resistance and improving energy efficiency [2]. Modern gear systems, including electronic shifting, enable smoother and faster transitions between different levels of resistance, optimizing effort distribution during races. The integration of power meters and biomechanical analysis tools has further refined training methodologies, allowing athletes to monitor and adjust their performances with unprecedented precision [3].

Beyond its role in professional sports, cycling remains a crucial element in promoting health and well-being. Regular cycling enhances cardiovascular fitness, strengthens muscles, and improves mental well-being by reducing stress and increasing endorphin production [4]. Additionally, cycling is an environmentally sustainable mode of transport, reducing carbon emissions and fostering a healthier lifestyle.

As a form of physical activity, cycling offers a range of benefits for individuals of all ages. It serves as an excellent low-impact workout, making it accessible to people recovering from injuries or suffering from joint issues. The repetitive pedaling motion helps build muscular endurance and balance while minimizing strain on the joints compared to high-impact activities like running. Studies have also highlighted the positive impact of cycling on cognitive function, showing that regular cycling can enhance memory, concentration, and overall brain health by increasing oxygen flow to the brain.

Cycling is practiced worldwide, both at amateur and professional levels, and includes a wide range of disciplines, each with its own specific characteristics. From road racing to mountain biking, track cycling, cyclocross, and BMX, each discipline presents unique challenges that test different aspects of a cyclist’s physical and technical abilities. The continued popularity of cycling is reflected in major global events such as the Tour de France, the Giro d’Italia, and the Vuelta a España, which attract millions of spectators and inspire new generations of athletes.

1.2 History of Cycling

The history of cycling as a sport is deeply intertwined with the evolution of the bicycle itself, which began in the early 19th century. The first significant milestone was the invention of the draisine by Karl von Drais in 1817, a two-wheeled vehicle propelled by pushing off the ground with one's feet. This innovation laid the groundwork for subsequent developments, including the addition of pedals by Kirkpatrick Macmillan in 1839, marking the transition to a mechanically powered bicycle [5]. As bicycles evolved into practical and efficient machines, they gained popularity not only as a mode of transportation but also as a tool for recreation and competition.

The first documented cycling race took place on May 31, 1868, at Saint-Cloud Park near Paris. This 1,200-meter event was won by James Moore, an expatriate Englishman riding a bicycle with solid rubber tires [6]. This race marked the beginning of organized competitive cycling. Shortly thereafter, city-to-city races emerged, with Moore also winning the first such event between Paris and Rouen in November 1869. Covering 135 kilometers in over ten hours, this race showcased the endurance and determination required for long-distance cycling.

Cycling quickly gained traction as a competitive sport in Europe during the late 19th century. The improvement of road conditions facilitated the rise of iconic one-day races such as Paris-Roubaix, established in 1896 [7]. By 1903, cycling had reached new heights with the inauguration of the Tour de France, a grueling multi-stage race that remains one of the most prestigious events in professional cycling today. Other major races like the

Giro d'Italia (1909) and Vuelta a España (1935) further solidified cycling's status as a cornerstone of European sports culture.

In parallel, track cycling flourished in countries like England and the United States, where road conditions were less favorable. By the 1890s, hundreds of velodromes hosted races across major American cities, attracting large crowds and professional athletes [8]. Events like six-day races became particularly popular, combining endurance and strategy in competitions lasting up to 142 hours.

Cycling's development extended beyond competition to influence broader social dynamics. The advent of affordable bicycles democratized mobility and played a pivotal role in women's liberation during the late 19th century. The "safety bicycle," introduced in the 1880s, allowed women to ride more comfortably and safely, challenging societal norms regarding gender roles [9]. Advocacy for dedicated cycling infrastructure began around this time, with countries like the Netherlands pioneering separate paths for cyclists to promote safety and accessibility.

Today, cycling continues to thrive as both a competitive sport and a recreational activity. Its rich history reflects not only technological advancements but also profound cultural and social shifts that have shaped its enduring legacy.

1.3 Physical Benefits of Cycling

Cycling is a highly beneficial activity for physical health, offering improvements across cardiovascular, muscular, and metabolic systems. As an aerobic exercise, cycling strengthens the heart, lungs, and blood vessels while enhancing overall cardiovascular fitness. Studies have shown that regular cycling reduces the risk of cardiovascular diseases by improving heart rate efficiency, lowering blood pressure, and reducing cholesterol levels. For example, individuals who cycle regularly have been found to experience a 15% reduction in heart attack risk compared to non-cyclists [10].

From a muscular perspective, cycling engages major muscle groups such as the quadriceps, hamstrings, glutes, and calves. It promotes muscle strength and endurance while improving flexibility and joint mobility. Unlike high-impact activities such as running, cycling is gentle on the joints, making it an ideal exercise for individuals with arthritis or those recovering from injuries [11]. Additionally, cycling enhances balance and coordination by requiring the rider to maintain stability on two wheels, which is particularly beneficial for older adults [12].

Cycling also supports weight management by burning calories efficiently. Depending on intensity and duration, a one-hour cycling session can burn between 400 and 1,000 calories [13]. This contributes to fat loss and helps prevent obesity-related conditions such as type 2 diabetes. Furthermore, regular cycling has been linked to improved mental health outcomes. It reduces stress levels, alleviates symptoms of anxiety and depression, and boosts overall mood by releasing endorphins during physical activity [14].

1.4 The Importance of Cycling for Prevention

Cycling is widely recognized as a beneficial activity for both physical and mental health, offering numerous preventive benefits against various diseases. By incorporating cycling into one's lifestyle, individuals can significantly reduce the risk of chronic conditions while enhancing overall well-being. Below is a detailed exploration of the preventive aspects of cycling.

1.4.1 Cardiovascular Health

Cycling is an aerobic exercise that strengthens the heart and improves cardiovascular function. Regular cycling:

Reduces the Risk of Heart Disease: Studies have shown that cycling can lower the risk of heart attacks, strokes, and other cardiovascular diseases by improving blood circulation and reducing blood pressure [15].

Improves Blood Lipid Profiles: Cycling helps maintain healthy cholesterol levels by increasing high-density lipoprotein (HDL) and reducing low-density lipoprotein (LDL) [16].

Enhances Vascular Health: Regular cycling improves the elasticity of blood vessels, reducing the risk of hypertension and related complications [17].

1.4.2 Metabolic Health

Cycling plays a crucial role in maintaining metabolic health by:

Regulating Blood Sugar Levels: Regular aerobic exercise like cycling helps control blood glucose levels, reducing the risk of developing type 2 diabetes [18].

Promoting Weight Management: Cycling aids in maintaining a healthy weight by burning calories and enhancing metabolic efficiency [19].

Improving Insulin Sensitivity: This reduces the risk of metabolic syndrome and associated conditions [20].

1.4.3 Mental Health and Stress Reduction

Cycling is not only beneficial for physical health but also has a positive impact on mental well-being:

Reduces Stress and Anxiety: The physical activity involved in cycling releases endorphins, which help alleviate symptoms of stress and anxiety [21].

Improves Mood: Regular cycling can enhance overall mood and reduce the risk of depression [22].

Promotes Social Interaction: Cycling can be a social activity, encouraging interaction with others and fostering a sense of community [23].

1.4.4 Musculoskeletal Health

Cycling is a low-impact activity that supports musculoskeletal health by:

Strengthening Muscles: It particularly strengthens the muscles of the legs without putting excessive strain on the joints [24].

Improving Bone Density: Regular cycling can help maintain or improve bone density, reducing the risk of osteoporosis [25].

Reducing Joint Pain: Cycling is often recommended for individuals with joint issues as it is gentle on the joints compared to high-impact activities [26].

1.5 Environmental and Social Benefits

Beyond personal health benefits, cycling also offers broader advantages:

Environmental Sustainability: Cycling is a zero-emission mode of transportation, contributing to cleaner air and reduced greenhouse gas emissions [27].

Social Benefits: It promotes a sense of community and can support local economies through cycling tourism [28].

1.5.1 Environmental Benefits of Cycling

Beyond its physical advantages, cycling plays a pivotal role in addressing environmental challenges such as climate change and urban pollution. As a zero-emission mode of transportation, bicycles produce significantly less carbon dioxide compared to motor vehicles. For instance, cycling has a carbon footprint of only 21 grams of CO_2 per kilometer—less than walking or taking public transportation—and represents less than one-tenth of the emissions generated by driving a car [29]. If more people replaced short car trips with cycling, global CO_2 emissions could be reduced substantially.

Cycling also improves air quality by reducing vehicle emissions that contribute to smog and respiratory illnesses. In Europe alone, the reduction in air pollution due to cycling is valued at approximately €435 million annually [30]. Additionally, cycling reduces noise pollution in urban areas since bicycles operate silently compared to motorized vehicles. This contributes to quieter cities and a better quality of life for residents [31].

Another significant environmental benefit is fuel conservation. Cycling saves over 3 billion liters of fuel annually in the European Union alone, equating to nearly €4 billion in savings [32]. This reduction in fuel consumption not only decreases greenhouse gas emissions but also lessens dependence on finite fossil fuel resources.

Moreover, bicycles are space-efficient compared to cars. They require less infrastructure for parking and roads, which helps combat urban sprawl and preserves green spaces. Cargo bikes are emerging as sustainable alternatives for urban logistics; they could replace up to 25% of commercial deliveries in cities and reduce traffic congestion while lowering emissions [33].

1.6 Cycling Disciplines

Cycling is a multifaceted sport that encompasses a wide range of disciplines, each with unique characteristics, challenges, and equipment requirements. These disciplines cater to different terrains, skillsets, and competitive formats, making cycling one of the most versatile sports globally. Below is an in-depth exploration of the major cycling disciplines [35-40].

1.6.1 Road Cycling

Road cycling is perhaps the most recognized and widely practiced discipline in the world. It involves riding on paved roads and is known for its emphasis on endurance, strategy, and speed. Events in road cycling can be categorized into several formats:

Road Races: These are mass-start events where riders compete over long distances, often exceeding 200 kilometers in professional races. Iconic examples include the Tour de France, Giro d'Italia, and Liège-Bastogne-Liège.

Time Trials: Known as "the race of truth," time trials involve individual or team efforts against the clock over a set distance. Aerodynamics and pacing are critical in this format.

Criteriums: Short circuit races typically held on urban streets. These are high-intensity events with frequent accelerations and tight corners.

Stage Races: Multi-day events combining various race formats (road races, time trials) across different terrains.

Road cyclists use lightweight bikes with narrow tires and drop handlebars for maximum efficiency and aerodynamics. The discipline demands high levels of cardiovascular fitness, tactical acumen, and teamwork.

1.6.2 Track Cycling

Track cycling takes place in velodromes—oval-shaped tracks with steeply banked curves. This discipline focuses on speed, precision, and strategy within a controlled environment. Track cycling events include:

Sprint: A short-distance race emphasizing explosive power and tactics.

Keirin: Riders follow a motorized pacer before sprinting to the finish over the final laps.

Team Pursuit: Teams of four riders compete to cover a set distance as quickly as possible.

Omnium: A multi-event competition testing versatility across endurance and sprint formats.

Track bicycles are fixed-gear machines without brakes, designed for simplicity and speed. Riders often use drafting techniques to conserve energy and maximize efficiency.

1.6.3 Cyclocross

Cyclocross blends elements of road cycling and mountain biking, creating a dynamic off-road racing experience. Races take place on short circuits featuring diverse terrains such as grass, mud, sand, and pavement. Obstacles like barriers or steep hills require riders to dismount, carry their bikes, and remount seamlessly.

Cyclocross bikes resemble road bikes but have wider tires for improved traction and clearance for mud. The sport is particularly popular in Belgium, France, and the Netherlands, with races typically held during autumn and winter .

1.6.4 Mountain Biking

Mountain biking is an off-road discipline that encompasses several subcategories:

Cross-Country (XC): Focuses on endurance racing over varied terrain with climbs and technical descents.

Downhill (DH): A gravity-driven discipline where riders navigate steep, technical trails at high speeds.

Enduro: Combines timed downhill sections with untimed uphill transfers, requiring both technical skill and endurance.

Mountain bikes are equipped with suspension systems (front or full), wide tires for grip, and robust frames to handle rough terrain.

1.6.5 BMX

BMX (Bicycle Motocross) originated as an off-road racing discipline inspired by motocross. It has since evolved into two main formats:

BMX Racing: Short sprints on dirt tracks with jumps, berms, and tight corners.

Freestyle BMX: Focuses on performing tricks in skateparks or urban environments.

BMX bikes are compact with sturdy frames and single-speed drivetrains designed for agility and durability.

1.6.6 Gravel Cycling

Gravel cycling is one of the newest disciplines in the sport, gaining popularity for its adventurous nature. It involves riding on unpaved roads, gravel paths, and mixed terrains that combine elements of road cycling and mountain biking.

Gravel bikes feature wider tires for stability on uneven surfaces and relaxed geometries for comfort during long rides. Events range from endurance races like Unbound Gravel to multi-day bikepacking adventures.

1.6.7 Fat Biking

Fat biking is designed for extreme conditions such as snow, sand, or mud where traditional bicycles struggle to perform. Fat bikes are equipped with oversized tires (3.8–5 inches wide) to provide flotation and traction on low-grip surfaces.

This discipline appeals to adventure seekers who enjoy exploring remote areas under challenging conditions.

1.6.8 E-Mountain Biking (eMTB)

E-mountain biking combines traditional mountain biking with electric-assist technology. eMTBs feature integrated motors that provide pedal assistance, enabling riders to tackle steep climbs or longer distances with reduced physical strain.

This discipline has grown rapidly due to its accessibility for riders of varying fitness levels while maintaining the thrill of off-road exploration.

1.7 Types of Bicycles for Each Discipline

Cycling encompasses a wide array of disciplines, each requiring specific types of bicycles tailored to the unique demands of the terrain, performance needs, and rider preferences. Below is a detailed overview of the bicycle types associated with each major cycling discipline.

- Road Cycling Bicycles

Road bikes are designed for speed and efficiency on paved surfaces. They are characterized by:

Lightweight Frames: Typically made from carbon fiber or high-strength aluminum to minimize weight while maintaining stiffness.

Narrow Tires: Usually 23-28 mm wide, these tires provide low rolling resistance and aerodynamics.

Drop Handlebars: Allow riders to adopt an aerodynamic position, reducing air resistance.

Gearing Systems: Equipped with derailleur systems offering a wide range of gears for varied terrain.

Road bikes are further categorized into subtypes based on their intended use:

Racing Bikes: Optimized for speed and efficiency, often used in professional competitions.

Endurance Bikes: Designed for comfort over long distances, featuring slightly more upright riding positions.

Time Trial Bikes: Specialized for aerodynamics, with features like aero frames, wheels, and handlebars.

- Track Cycling Bicycles

Track bikes are built for speed and simplicity on velodromes. Key features include:

Fixed Gear: No freewheel mechanism, meaning the pedals are always turning when the bike is moving.

No Brakes: Riders control speed by adjusting pedal cadence or using the track's banking.

Aerodynamic Frames: Often made from carbon fiber for minimal weight and maximum stiffness.

Slick Tires: Provide low rolling resistance and high grip on the smooth track surface.

Track bikes are optimized for the unique demands of velodrome racing, emphasizing speed and control.

- Cyclocross Bicycles

Cyclocross bikes combine elements of road and mountain bikes, designed for racing on mixed terrain:

Drop Handlebars: Similar to road bikes, but with a slightly more upright position.

Wide Tires: Typically 30-40 mm wide, offering better traction on grass, mud, and sand.

Cantilever or Disc Brakes: Provide reliable stopping power in wet conditions.

Clearance for Mud: Frames designed to accommodate wider tires and allow for mud clearance.

Cyclocross bikes are versatile, suitable for both racing and commuting in adverse weather conditions.

- Mountain Bicycles

Mountain bikes are built for off-road adventures and come in several subtypes:

Cross-Country (XC) Bikes: Lightweight frames with front suspension (hardtail) or full suspension, designed for efficiency and speed on varied terrain.

Downhill (DH) Bikes: Robust frames with full suspension (travel up to 200 mm), optimized for high-speed descents and technical trails.

Enduro Bikes: Combine elements of XC and DH bikes, offering a balance between climbing efficiency and downhill capability.

Freeride Bikes: Similar to DH bikes but with a focus on aerial stunts and technical features.

Mountain bikes feature wide, knobby tires for traction and robust frames to withstand rough terrain.

- BMX Bicycles

BMX bikes are compact and sturdy, designed for racing and freestyle riding:

Single-Speed Drivetrain: Simple and durable, with no gears to maintain.

20-Inch Wheels: Provide agility and maneuverability.

Strong Frames: Often made from steel or aluminum, designed to withstand impacts and jumps.

Wide Tires: Offer grip and stability on dirt tracks and urban surfaces.

BMX bikes are ideal for short sprints, tricks, and stunts.

6. Gravel/Adventure Bicycles

Gravel bikes are designed for riding on unpaved roads and mixed terrain:

Drop Handlebars: Similar to road bikes but with a more relaxed geometry for comfort.

Wide Tires: Typically 35-45 mm wide, providing stability on gravel and dirt.

Disc Brakes: Reliable stopping power in wet conditions.

Frame Clearance: Allows for larger tires and mud clearance.

Gravel bikes are versatile, suitable for long-distance adventures and commuting.

- Fat Bikes

Fat bikes are specialized for extreme conditions such as snow, sand, or mud:

Oversized Tires: 3.8–5 inches wide, providing flotation and traction in low-grip environments.

Wide Rims: Accommodate the large tires and maintain stability.

Robust Frames: Designed to handle the stresses of oversized tires and rough terrain.

Fat bikes enable riders to explore remote areas inaccessible by traditional bicycles.

- E-Mountain Bikes (eMTBs)

E-mountain bikes combine traditional mountain biking with electric assist:

Integrated Motors: Provide pedal assistance, enhancing climbing ability and reducing fatigue.

Battery and Controls: Integrated systems for managing power output and battery life.

Suspension Systems: Similar to traditional mountain bikes, offering comfort and control on varied terrain.

eMTBs are popular for their accessibility and ability to extend ride distances without increased physical strain.

Characteristics of Racing for Each Cycling Discipline

Cycling competitions are highly diverse, with each discipline presenting unique race formats, strategies, and physical demands. Below is an in-depth exploration of the characteristics of racing across the major cycling disciplines.

- Road Cycling

Road cycling is the most traditional and widely practiced competitive discipline, featuring several race formats [34]:

Road Races: These mass-start events involve large pelotons of riders competing over long distances, typically ranging from 150 to 250 kilometers. Races can be point-to-point or consist of multiple laps on a circuit. Teamwork is crucial, as riders often work together to protect their leader or execute strategic attacks. Climbs, descents, and crosswinds play a significant role in shaping race outcomes.

Time Trials: Known as "the race of truth," time trials are individual or team events where riders compete against the clock rather than directly against each other. Aerodynamics are paramount, with riders using specialized equipment such as aero helmets and carbon disc wheels. Drafting is prohibited, making pacing and positioning critical.

Stage Races: Multi-day competitions like the Tour de France combine road races and time trials across varied terrains. Riders accumulate time over stages, with the lowest aggregate time determining the overall winner. Stage races demand endurance, consistency, and tactical flexibility.

Criteriums: Fast-paced races held on short urban circuits (typically 1-2 km) lasting between one and two hours. These events emphasize bike handling skills, quick accelerations, and sprinting ability. Criteriums often end in mass sprints, favoring explosive riders.

- Track Cycling

Track cycling takes place in velodromes and is characterized by controlled environments and high-speed racing [36]:

Sprint Events: These short-distance races focus on explosive power and tactical positioning. Riders often engage in cat-and-mouse games to gain the best position before launching their sprint.

Endurance Events: Competitions like the points race or madison test riders' stamina over longer distances while requiring strategic collaboration with teammates.

Team Pursuit: Teams of four riders compete to complete a set distance (typically 4 km) in the shortest time possible. Drafting within the team is essential for maintaining speed and conserving energy.

Track cycling emphasizes precision and teamwork, with fixed-gear bicycles designed for maximum efficiency on smooth surfaces.

- Cyclocross

Cyclocross races are held on mixed terrain circuits that include grass, mud, sand, and pavement. Riders must navigate obstacles that often require dismounting and carrying their bikes [38]. Courses are typically 2.5–3.5 km long, with races lasting 30–60 minutes depending on the category.

Key characteristics include:

Frequent accelerations due to sharp turns and obstacles.

Technical skill for navigating slippery or uneven surfaces.

Physical resilience to endure cold weather conditions common during cyclocross season.

Cyclocross rewards versatility and adaptability in both technical riding and running.

- Mountain Biking

Mountain biking competitions vary significantly based on subdiscipline:

Cross-Country (XC) [35]: Races take place on varied terrain with climbs and technical descents. Riders compete over distances ranging from 20 to 50 km in Olympic-style events or longer marathon formats.

Downhill (DH): Gravity-driven races focus on descending steep technical trails as quickly as possible. Courses are typically less than 5 km long but demand exceptional bike handling skills.

Enduro: Combines timed downhill sections with untimed uphill transfers, requiring both technical skill and endurance.

Mountain biking places a premium on strength, bike control, and adaptability to unpredictable terrain.

- BMX

BMX racing involves short sprints on dirt tracks featuring jumps, berms, and tight corners. Races typically last less than a minute but require explosive power and precise bike handling [37].

Freestyle BMX competitions focus on performing tricks in skateparks or urban environments rather than racing against competitors.

Key characteristics include:

High-intensity efforts over short durations.

Emphasis on agility and aerial skills.

Compact courses designed for spectator engagement.

- Gravel Racing

Gravel racing combines elements of road cycling and mountain biking on unpaved roads or mixed terrain courses [39]. Distances can range from 50 km to over 300 km in endurance events like Unbound Gravel.

Characteristics include:

Varied terrain requiring versatile equipment.

Long-distance challenges demanding endurance.

Less emphasis on drafting compared to road racing.

Gravel racing appeals to riders seeking adventure in remote landscapes.

- Fat Bike Racing

Fat bike races take place in extreme conditions such as snow or sand where traditional bicycles struggle to perform. Courses are often shorter but demand strength and balance due to low-grip surfaces.

1.8 Energy Metabolism Across Cycling Disciplines

Cycling is an incredibly versatile sport, with various disciplines requiring unique energy strategies to optimize performance. The three primary metabolic pathways involved are aerobic metabolism, anaerobic glycolysis, and alactic anaerobic metabolism. Each pathway plays a crucial role depending on the intensity and duration of the effort. Here, we explore how these metabolic pathways intersect across different cycling disciplines.

1.8.1 Aerobic Metabolism: Sustained Energy for Endurance

Aerobic metabolism is the dominant energy system in endurance disciplines, such as road cycling and cross-country mountain biking. This system utilizes oxygen to convert carbohydrates, fats, and proteins into ATP, the primary energy currency of cells. The efficiency of aerobic metabolism is crucial for long races, where riders must maintain a steady pace for hours [41].

Mechanism:

Aerobic metabolism occurs in the mitochondria of muscle cells, where glucose or fatty acids are oxidized via the Krebs cycle and electron transport chain.

A single glucose molecule yields over 30 ATP molecules when metabolized aerobically, making this system highly efficient for endurance activities.

Disciplines:

Road Cycling: Long road races and time trials primarily rely on aerobic metabolism to sustain power output at submaximal intensities (Zones 2–4). Riders spend over 90% of their race time in aerobic zones [42].

Mountain Biking: Cross-country races require aerobic metabolism to navigate climbs and technical sections over extended durations [43].

Gravel Racing: Similar to road cycling but on mixed terrain, aerobic metabolism dominates due to the long distances involved.

Advantages:

Aerobic metabolism provides a virtually unlimited supply of ATP when oxygen is available.

It allows for the oxidation of fats as an energy source, which is particularly important during prolonged efforts where glycogen stores are depleted.

1.8.2 Anaerobic Glycolysis: Short-Term High-Intensity Energy

Anaerobic glycolysis provides energy when oxygen availability is insufficient to meet demand, such as during brief bursts of activity. This system breaks down glucose into pyruvate, producing ATP quickly but inefficiently, with lactate as a byproduct.

Mechanism:

Glycolysis occurs in the cytoplasm of muscle cells and yields only 2 ATP molecules per glucose molecule.

Lactate accumulation leads to muscle fatigue and limits performance during sustained high-intensity efforts.

Disciplines:

Cyclocross: Frequent accelerations and transitions between riding and running rely on anaerobic glycolysis for short bursts of power.

Track Cycling: Events like sprints or keirin races depend heavily on anaerobic glycolysis due to their short duration and high intensity.

Mountain Biking (Pro XC): Technical sections requiring explosive power often engage anaerobic glycolysis.

Advantages:

Provides rapid ATP production for short-duration efforts.

Supports high-intensity efforts when aerobic pathways cannot meet energy demands.

Limitations:

Lactate accumulation leads to fatigue, requiring recovery periods to clear lactate from muscles.

1.8.3 Alactic Anaerobic Metabolism: Immediate Energy for Explosive Efforts

The alactic anaerobic system, also known as the phosphagen system, provides immediate energy by utilizing stored ATP and phosphocreatine (PCr) within muscle cells. This system is critical for explosive efforts lasting only a few seconds.

Mechanism:

Phosphocreatine donates a phosphate group to ADP, rapidly regenerating ATP without requiring oxygen.

This system is limited by the small amount of PCr stored in muscles.

Disciplines:

BMX Racing: Short sprints on dirt tracks rely almost entirely on alactic anaerobic metabolism for explosive power.

Track Cycling (Sprint): Events lasting less than 10 seconds are dominated by this energy system.

Road Cycling (Final Sprint): During mass sprints at the end of road races, riders engage this system for peak power output.

Advantages:

Provides immediate energy for maximal efforts.

Does not produce lactate and does not require oxygen.

Limitations:

Energy supply is exhausted within seconds due to limited PCr stores.

Energy System Interactions Across Disciplines

Most cycling disciplines involve a mix of energy systems depending on race intensity and duration:

Road Cycling:

Predominantly aerobic during long stages but transitions to anaerobic glycolysis during climbs or breakaways.

Final sprints engage alactic anaerobic metabolism for peak power output.

Mountain Biking:

Cross-country races are primarily aerobic but require anaerobic bursts for technical sections.

Downhill events rely more heavily on anaerobic systems due to their shorter duration and explosive nature.

Track Cycling:

Sprint events are dominated by alactic anaerobic metabolism.

Longer endurance events like team pursuit engage both aerobic and anaerobic systems.

Cyclocross:

Combines aerobic endurance with frequent anaerobic bursts during transitions and obstacles.

1.9 Physiological Adaptations in Cyclists

Cycling, as a predominantly endurance sport, induces profound physiological adaptations that enhance the performance capacity of athletes. These adaptations occur across multiple systems, including cardiovascular, respiratory, metabolic, and muscular, and are influenced by the type, intensity, and duration of training [44]. Below is a detailed exploration of the key physiological adaptations observed in cyclists.

1.9.1 Cardiovascular Adaptations

One of the most significant changes in trained cyclists is the improvement in cardiovascular efficiency. Regular cycling leads to:

Increased Stroke Volume: The heart becomes more efficient at pumping blood, resulting in a higher stroke volume (the amount of blood ejected per beat). This adaptation allows for greater oxygen delivery to working muscles during prolonged efforts.

Enhanced Cardiac Output: With increased stroke volume and heart rate optimization, cardiac output—the total volume of blood pumped per minute—rises significantly during exercise.

Lower Resting Heart Rate: As a result of improved heart efficiency, trained cyclists exhibit lower resting heart rates, indicating enhanced parasympathetic nervous system activity.

Improved Capillarization: Endurance training promotes the growth of capillaries around muscle fibers, facilitating better oxygen and nutrient exchange.

1.9.2 Respiratory Adaptations

Cycling enhances the respiratory system’s ability to deliver oxygen and remove carbon dioxide efficiently:

Increased Pulmonary Ventilation: Cyclists develop stronger respiratory muscles such as the diaphragm and intercostals, enabling greater lung ventilation during high-intensity efforts.

Improved Oxygen Uptake (VO_2 Max): VO_2 max, a measure of maximal oxygen consumption, is a key determinant of endurance performance. Professional cyclists often exhibit VO_2 max values exceeding 70 ml/kg/min due to their training regimens.

Efficient Gas Exchange: Training improves alveolar-capillary diffusion capacity, allowing for more effective oxygen transfer into the bloodstream.

1.9.3 Metabolic Adaptations

Cycling induces metabolic changes that optimize energy production:

Enhanced Fat Oxidation: Cyclists develop an increased reliance on fat metabolism even at higher intensities. This adaptation conserves glycogen stores for critical moments such as sprints or climbs.

Improved Glycogen Storage: Training increases muscle glycogen content, allowing cyclists to sustain prolonged efforts without premature fatigue.

Lactate Threshold Elevation: The ability to perform at higher percentages of maximal effort without accumulating excessive lactate is a hallmark adaptation. Cyclists exhibit increased lactate clearance rates and tolerance.

1.9.4 Muscular Adaptations

Cycling-specific training induces structural and functional changes in skeletal muscles:

Muscle Fiber Recruitment: Endurance cycling primarily engages slow-twitch (Type I) fibers known for their fatigue resistance. However, sprinting and high-intensity efforts recruit fast-twitch (Type II) fibers as well.

Mitochondrial Biogenesis: Training stimulates mitochondrial growth within muscle cells, enhancing aerobic energy production. Cyclists have higher mitochondrial density compared to untrained individuals.

Capillary Density: Increased capillary networks around muscle fibers improve oxygen delivery and waste removal during exercise.

Neuromuscular Efficiency: Cyclists develop better coordination between motor units, optimizing force production while minimizing energy expenditure.

1.9.5 Skeletal Muscle Oxygen Utilization

Advanced techniques like Near Infrared Spectroscopy (NIRS) have demonstrated improved skeletal muscle oxygen extraction in trained cyclists:

Deoxyhemoglobin Dynamics: Studies show that trained male cyclists exhibit significant increases in oxygen utilization within the vastus lateralis muscle during high-intensity efforts.

Gross Mechanical Efficiency: Training enhances mechanical efficiency by reducing unnecessary energy expenditure during pedaling motions. Cyclists achieve up to 5% improvements in efficiency after targeted training camps.

1.9.6 Hormonal and Endocrine Adaptations

Cycling also influences hormonal responses that regulate energy metabolism and recovery:

Reduced Cortisol Levels: Prolonged endurance training lowers stress hormone levels post-exercise.

Enhanced Insulin Sensitivity: Regular cycling improves glucose uptake by muscles, reducing the risk of insulin resistance.

Testosterone and Growth Hormone Response: High-intensity interval training stimulates anabolic hormones that support muscle repair and growth.

Oxygen Consumption and Heart Rate: Physiological Parameters During Cycling

Cycling is a demanding aerobic activity that requires precise coordination between the cardiovascular and respiratory systems to meet the metabolic demands of working muscles. Oxygen consumption (V˙O2V˙O2) and heart rate (HR) are two critical physiological parameters that define performance during cycling, reflecting the body's ability to deliver oxygen to tissues and sustain prolonged efforts. Below is an in-depth analysis of these parameters and their relationship during cycling.

Oxygen Consumption (V˙O2V˙O2)

Oxygen consumption (V˙O2V˙O2) measures the rate at which oxygen is utilized by the body during exercise. It is a direct indicator of aerobic capacity and is influenced by factors such as cardiac output, pulmonary function, and skeletal muscle oxidative capacity.

Maximal Oxygen Consumption (V˙O2maxV˙O2max):

V˙O2maxV˙O2max represents the upper limit of oxygen uptake during intense exercise and is a key determinant of endurance performance. Elite cyclists often exhibit V˙O2maxV˙O2max values exceeding 70 ml/kg/min, compared to 40–50 ml/kg/min in recreational athletes.

The Fick equation expresses V˙O2maxV˙O2max as a product of cardiac output (CardOut) and arterial-venous oxygen difference (a−vO2a−vO2):

V˙O2=Qcardiac·(CaO2−CvO2)V˙O2=Qcardiac·(CaO2−CvO2)

where QcardiacQcardiac is cardiac output, CaO2CaO2 is arterial oxygen content, and CvO2CvO2 is venous oxygen content.

Submaximal Oxygen Consumption:

During steady-state cycling, oxygen consumption increases linearly with power output until reaching the anaerobic threshold. Beyond this point, lactate accumulation accelerates, impairing muscle efficiency.

Pedaling cadence significantly influences V˙O2V˙O2. Higher cadences increase oxygen demand due to greater muscle activation but may reduce mechanical efficiency.

Muscle Oxygen Extraction:

At maximal exertion, muscle oxygen extraction can reach values of 14–18 ml O22/100 ml blood. This reflects the efficiency of mitochondria in utilizing oxygen for ATP production during high-intensity efforts.

Heart Rate (HR)

Heart rate is a fundamental parameter that reflects cardiovascular workload during cycling. It is closely linked to oxygen consumption and varies with exercise intensity.

Resting Heart Rate:

Trained cyclists often exhibit lower resting HRs due to increased parasympathetic tone and enhanced stroke volume. Values below 60 beats per minute are common in elite athletes.

Heart Rate Response During Exercise:

HR increases linearly with exercise intensity up to the anaerobic threshold. Beyond this point, HR plateaus or rises more gradually due to limitations in cardiac output or peripheral fatigue.

The relationship between HR and V˙O2V˙O2 is not always linear; studies show that individuals with higher fitness levels exhibit a negative curvature in this relationship, reflecting greater efficiency in oxygen delivery and utilization.

Heart Rate Variability (HRV):

HRV decreases during intense cycling due to reduced parasympathetic activity and increased sympathetic dominance. Monitoring HRV can provide insights into recovery status and training adaptation.

Interaction Between V˙O2V˙O2 and HR

The interplay between V˙O2V˙O2 and HR is governed by cardiac output (Qcardiac=HR×SVQcardiac=HR×SV), where stroke volume (SV) represents the amount of blood ejected per heartbeat.

Cardiac Output:

Cardiac output increases linearly with exercise intensity until maximal QcardiacQcardiac is reached. In trained cyclists, maximal cardiac output can exceed 30 liters per minute.

As exercise intensity rises, stroke volume plateaus while HR continues to increase, emphasizing the role of HR in sustaining high cardiac outputs.

Efficiency at Maximal Effort:

At maximal exertion, limitations in cardiac output or pulmonary function may reduce arterial oxygen saturation (SaO2SaO2), affecting tissue oxygen delivery.

Maximal Oxygen Consumption (VO2 Max) Testing: Methodology and Interpretation

Maximal oxygen consumption, or VO2 max, is a critical physiological parameter that reflects an individual's aerobic capacity. It is defined as the highest rate at which oxygen is utilized by the body during intense exercise and is a key determinant of endurance performance. VO2 max testing is widely used in sports medicine and exercise physiology to assess cardiovascular fitness, monitor training effects, and predict performance potential. Below is a detailed overview of the methodology and interpretation of VO2 max testing.

Methodology

VO2 max tests are typically conducted using a treadmill or stationary bicycle ergometer. The choice of equipment depends on the individual's familiarity with the device and the specific goals of the test.

Preparation:

Warm-Up: A brief warm-up (5–10 minutes) is essential to prepare the cardiovascular system and muscles for intense exercise.

Equipment Calibration: Ensure that the ergometer and gas exchange analyzer are properly calibrated to provide accurate measurements.

Subject Preparation: Participants should avoid strenuous exercise and caffeine for at least 24 hours prior to testing.

Protocol:

Incremental Exercise Protocol: The test involves an incremental increase in workload until exhaustion. For cycling, this might involve starting at a low power output (e.g., 50 watts) and increasing by 25–50 watts every minute until the participant cannot maintain the required cadence.

Treadmill Protocol: For running, the incline and speed are gradually increased to achieve maximal effort.

Measurement Techniques:

Gas Exchange Analysis: A mask or mouthpiece is used to collect expired gases, which are analyzed for oxygen and carbon dioxide concentrations using a metabolic cart. This allows for the calculation of VO2, VCO2, and respiratory exchange ratio (RER).

Heart Rate Monitoring: Continuous heart rate monitoring provides additional data on cardiovascular stress and recovery.

Interpretation

VO2 max is calculated as the highest rate of oxygen consumption achieved during the test, typically expressed in milliliters per kilogram per minute (ml/kg/min). Interpretation involves understanding the physiological significance of the measured value and its implications for performance.

VO2 Max Values:

Elite Athletes: Values above 70 ml/kg/min are common in elite endurance athletes, such as professional cyclists or distance runners.

Recreational Athletes: Average values range from 30 to 50 ml/kg/min, depending on fitness level and age.

General Population: Sedentary individuals may have VO2 max values below 20 ml/kg/min.

Physiological Significance:

Cardiovascular Efficiency: Higher VO2 max indicates better cardiovascular function, including increased cardiac output and enhanced oxygen delivery to tissues.

Muscle Oxygen Utilization: Reflects the efficiency of skeletal muscle in extracting oxygen from the bloodstream for energy production.

Performance Prediction:

Endurance Performance: VO2 max is a strong predictor of performance in endurance events like marathons or long-distance cycling races.

Training Effectiveness: Changes in VO2 max over time can indicate the effectiveness of a training program in improving aerobic capacity.

Limitations and Considerations

While VO2 max testing provides valuable insights into aerobic fitness, there are limitations and considerations:

Test Reliability: Results can vary based on the specific protocol used and the individual's motivation during the test.

Equipment Accuracy: Calibration of the ergometer and gas exchange analyzer is crucial for accurate measurements.

Individual Variability: Genetic factors influence VO2 max, and some individuals may have naturally higher or lower aerobic capacities regardless of training.

Lactate Testing: Determination of the Anaerobic Threshold

Lactate testing is a widely used method in exercise physiology to assess an individual's anaerobic threshold, which is the intensity at which lactic acid begins to accumulate in the blood. This threshold marks the transition from aerobic to anaerobic metabolism and is a critical determinant of endurance performance. Below is a detailed explanation of lactate testing and its role in determining the anaerobic threshold.

Methodology

Lactate testing typically involves an incremental exercise protocol where blood lactate levels are measured at various intensities.

Exercise Protocol:

Incremental Intensity: Participants perform exercise on a stationary bike or treadmill with incremental increases in workload (e.g., power output or speed).

Blood Sampling: Capillary blood samples are taken from the earlobe or finger at regular intervals (e.g., every 2–3 minutes) to measure lactate concentration.

Lactate Measurement:

Portable Analyzers: Blood lactate levels are measured using portable lactate analyzers, which provide rapid results.

Venous Blood Sampling: In some cases, venous blood may be used for more precise measurements, though this is less common due to the invasiveness of the procedure.

Data Analysis:

Lactate Curve: Plotting lactate concentration against exercise intensity reveals a characteristic curve. Initially, lactate levels remain low as exercise is primarily aerobic. As intensity increases, lactate begins to rise more sharply, indicating the anaerobic threshold.

Threshold Determination: The anaerobic threshold is often identified as the point where lactate concentration increases by 1 mmol/L above baseline or where the rate of increase accelerates.

Interpretation

The anaerobic threshold, as determined by lactate testing, is a critical parameter for endurance athletes. It reflects the highest intensity at which an athlete can sustain exercise without accumulating excessive lactic acid, which impairs muscle function.

Performance Implications:

Endurance Capacity: Athletes with a higher anaerobic threshold can perform at higher intensities for longer durations without fatigue.

Training Zones: The anaerobic threshold helps define training zones, allowing athletes to optimize their workouts for specific goals (e.g., endurance, speed).

Physiological Significance:

Metabolic Shift: The anaerobic threshold marks a shift from aerobic to anaerobic metabolism, where energy production becomes less efficient and leads to fatigue.

Muscle Fatigue: Accumulation of lactic acid contributes to muscle fatigue and decreased performance.

Training Adaptations:

Threshold Training: Specific training programs can improve the anaerobic threshold by enhancing muscle buffering capacity and increasing mitochondrial density.

Periodization: Training is often periodized to focus on different intensities and volumes to optimize adaptations around the anaerobic threshold.

Limitations and Considerations

While lactate testing is valuable for determining the anaerobic threshold, there are limitations and considerations:

Individual Variability: Baseline lactate levels and the rate of increase can vary significantly among individuals, affecting threshold determination.

Methodological Variability: Different protocols and analyzers may yield slightly different results, emphasizing the need for standardized procedures.

Environmental Factors: Environmental conditions such as temperature and humidity can influence lactate accumulation and thus the measured threshold.

Electric Bicycle Technology: Components and Functionality

Electric bicycles, also known as e-bikes, have become increasingly popular due to their versatility, convenience, and environmental benefits. These vehicles combine traditional cycling with electric assistance, making them an attractive option for commuting, recreation, and fitness. The technology behind e-bikes involves several key components that work together to provide a seamless riding experience.

1. Main Components of Electric Bicycles

E-bikes consist of several essential components that enable their operation:

Electric Motor:

Types: E-bikes typically use one of two motor types: hub motors (located in the front or rear wheel) or mid-drive motors (positioned near the pedals).

Functionality: Motors provide power assistance to the rider, enhancing speed and reducing physical effort. Hub motors are simpler and more common, while mid-drive motors offer better efficiency and control.

Battery:

Types: Most e-bikes use lithium-ion batteries due to their high energy density, lightweight design, and long lifespan.

Capacity: Battery capacity is measured in watt-hours (Wh) and determines how far an e-bike can travel on a single charge. Common capacities range from 300 to 700 Wh.

Controller:

Function: The controller acts as the brain of the e-bike, managing the flow of electrical energy from the battery to the motor. It ensures safe operation by regulating power output and monitoring system performance.

Features: Modern controllers often include features like regenerative braking, which captures kinetic energy and converts it back into electrical energy to recharge the battery.

Display and Controls:

Display: Provides essential information such as speed, distance, battery level, and assist mode.

Controls: Include buttons or levers for adjusting assist levels, turning the system on/off, and accessing additional features like lights or GPS connectivity.

2. How Electric Bicycles Work

The operation of an e-bike involves a coordinated interaction between its components:

Power Assistance:

Pedal Assist System (PAS): Most e-bikes use a PAS, which provides power assistance when the rider pedals. The amount of assistance can be adjusted through different modes (e.g., eco, normal, sport).

Throttle: Some e-bikes include a throttle, allowing riders to propel the bike without pedaling.

Energy Flow:

Battery to Motor: The battery supplies electrical energy to the motor via the controller. The motor then converts this energy into mechanical power to assist the rider.

Regenerative Braking: In some models, when the brakes are applied or the bike is coasting downhill, the motor acts as a generator, capturing kinetic energy and feeding it back to the battery.

Cut-Off Systems: Automatic cut-off when the bike reaches a certain speed (e.g., 25 km/h) to comply with regulations.

Overcharge Protection: Controllers prevent overcharging to prolong battery lifespan.

3. Types of Electric Bicycles

E-bikes are categorized based on their design and functionality:

Commuter E-Bikes:

Designed for urban use, these bikes often feature practical accessories like fenders, lights, and cargo racks.

Mountain E-Bikes:

Built for off-road adventures, these bikes have robust frames, wide tires, and powerful motors to tackle challenging terrains.

Hybrid E-Bikes:

Combine elements of road and mountain bikes, offering versatility for both paved and unpaved paths.

Environmental and Social Impact: Benefits and Limitations of Electric Bicycles

Electric bicycles have gained popularity as a sustainable mode of transportation, offering numerous environmental and social benefits. However, like any technology, they also present some limitations and challenges. Below is a detailed analysis of the benefits and limitations of e-bikes from both environmental and social perspectives.

Environmental Benefits

E-bikes contribute positively to the environment in several ways:

Reduced Greenhouse Gas Emissions:

Zero Tailpipe Emissions: E-bikes produce no direct emissions during operation, reducing air pollution in urban areas.

Lower Carbon Footprint: Compared to cars, e-bikes significantly decrease carbon emissions, especially when powered by renewable energy sources.

Energy Efficiency:

Low Energy Consumption: E-bikes require much less energy than cars, with typical consumption rates of about 1–2 kWh per 100 km.

Regenerative Braking: Some e-bikes capture kinetic energy through regenerative braking, further enhancing efficiency.

Conservation of Resources:

Reduced Material Use: E-bikes generally require fewer materials than cars, contributing to less resource depletion.

Less Infrastructure Demand: E-bikes can utilize existing bike paths and roads, reducing the need for new infrastructure.

While e-bikes offer many environmental advantages, there are also some limitations:

Battery Production Impact:

Resource Extraction: The production of lithium-ion batteries requires mining for lithium, cobalt, and other metals, which can have environmental and social impacts.

Waste Management: The disposal of spent batteries poses challenges, though recycling technologies are improving.

Energy Source:

Dependence on Electricity: E-bikes rely on electricity for charging, which may be generated from non-renewable sources depending on the energy mix of the region.

Carbon Footprint of Production: The manufacturing process for e-bikes, including battery production, contributes to greenhouse gas emissions.

Social Benefits

E-bikes also have significant social benefits:

Accessibility and Inclusivity:

Increased Mobility: E-bikes provide mobility options for those who may struggle with traditional cycling due to age, health, or fitness level.

Reduced Traffic Congestion: By offering an alternative to cars, e-bikes can help alleviate urban traffic congestion.

Health and Fitness:

Encourages Physical Activity: While e-bikes reduce physical effort, they still promote some level of exercise and outdoor activity.

Mental Health Benefits: Cycling, even with electric assistance, can improve mental well-being by reducing stress and promoting a sense of freedom.

Economic Benefits:

Cost-Effective Transportation: E-bikes are generally cheaper to purchase and maintain than cars, offering a cost-effective transportation solution.

Job Creation: The e-bike industry supports employment in manufacturing, sales, and maintenance.

Social Limitations

Despite the benefits, there are also social limitations to consider:

Infrastructure Challenges:

Lack of Dedicated Paths: In many areas, e-bikes must share roads with cars, which can be unsafe and discouraging for riders.

Charging Infrastructure: Limited availability of public charging points can hinder long-distance travel.

Regulatory Frameworks:

Varied Regulations: Different countries and regions have varying laws regarding e-bike use, which can create confusion and barriers to adoption.

Safety Standards: Ensuring safety standards for e-bikes, such as speed limits and helmet requirements, is essential but can vary widely.

CHAPTER 2. SPORT PERFORMANCE

Athletes' success in competing in sports is measured by their sport performance [1]. Sport performance, in particular, refers to a complex fusion of multiple aspects that impact the competition's outcome, and objectively assessing it is vital, particularly for elite athletes [2].

Over the years, a great deal of research has been done on the effects of psychological and physiological variables on athletic performance. For example, various study groups have examined various recovery strategies in relation to the physiological parameters [3]. In a similar vein, different periodization techniques have been assessed to determine how they affect improving performance in both individual and team sports [4]. Additionally, among the various factors investigated to improve performance, studies have looked at the impact of supplements on enhancing athletic performance [5]. In terms of the psychological aspects, a number of research teams looked at athletes' fear of failing as well as the link between performance and psychological stress and burnout [6]. Similarly, it has been demonstrated that athletes who participate in sports suffer from anxiety disorders [7]. These tenets demonstrate the strong connection between sport and the pursuit of peak performance. To get the best outcomes in sports, however, one must have a thorough awareness of the elements of performance and be able to measure it.

2.1 Components of sport performance

The performance in sports is impacted by a blend of the athlete's qualities, which consist of physical features, technical skills, tactical expertise, and psychological and social factors [8].

It is important to recognize that one dimension could be more prominent than another, with physical elements being crucial in certain sports, while technical and tactical skills are prioritized in different sports [8].

For instance, in activities like sprinting or running long distances, success is closely linked to the physical aspect, whereas in team sports involving a ball, mastering technical and tactical abilities is crucial for achieving victory [8]. Furthermore, in terms of the physical realm, certain sports necessitate a higher level of input from one element as opposed to another [9]. Take sprinting or throwing, for instance, as they heavily rely on anaerobic power, while marathon running or rowing primarily require aerobic endurance [9-11].

In the same way, sport-specific technical and tactical expertise, much like the physical aspect, are contingent on the athletes' skill level [12,13]. Moreover, the training regimen comprises drills that focus primarily on the sport-specific element, while engaging all of them collectively in a broad manner [14,15].

Endurance, strength, skill, and recovery are all essential physical elements for excelling in sports [9]. In detail, these dimensions can be described as follows: the ability to engage in exercise for an extended period; the capacity to generate high power in a single movement; the skill to execute a sport-specific motor skill; the capability to return to pre-performance physiological levels after training sessions or competitive events [8,16].

The best performance outcomes are tied to the development of specific physical components, which is intricately connected to training and the functioning of the respiratory, cardiovascular, musculoskeletal, and nervous systems [8]. Additionally, the utilization of equipment or methods is becoming more prevalent among athletes to enhance their abilities. It is indispensable to report that in order to establish any improvement in physical components during training or in performance during competitions, these must be appropriately measured.

2.2 Measurements of sport performance

The measurement of sport performance is crucial for determining its success. The assessment of athletic performance serves the dual function of objectively tracking performance in training sessions and primarily, evaluating performance in competitive events [1]. Therefore, evaluating athletic performance, particularly in top athletes, implies striving for excellence and success, elevating the standard of performance.

As stated by Raysmith and colleagues, excelling in performance not only leads to reaching the final stages of competitions or securing victories but also attracts financial support from sponsors and funding [1]. Scientific research has thoroughly examined the factors that impact sport performance outcomes for these reasons [1].

Achieving high performance in sports relies on a combination of elements from sports science, like training plans, performance tracking devices, and performance-enhancing equipment [17-21].

Regarding the initial domain, Doherty and colleagues explored the correlation between various training regimens and marathon results [20]. In the same vein, a recent systematic review was carried out with the goal of determining the key aspects of resistance training in relation to training intensity distribution, training volume, and periodization models among swimmers [21].

Regarding the devices employed, technological progress has enabled the quantitative assessment of factors like motion, exertion levels, and biological indicators to enhance athletic performance [17-19]. Performance analysis in sports is a sub-discipline of sports science that utilizes various technologies known for their high validity and reliability, including local positioning systems, global positioning systems, pedometers, accelerometers, video tracking and analysis systems, and physiological sensors [17,22].

Athletes, coaches, technical staff, and physicians are continuously seeking the potential benefits of wearable devices to optimize performance and prevent injuries in relation to improving performance equipment [23,24]. For example, Drum and colleagues studied the variances in utilizing personalized or custom-made mouthguards, standard mouthguards, and no mouthguards on overall fitness aspects among seasoned collegiate football players [23].

In a related study, Hülsdünker et al. explored how top-tier badminton players' visuomotor abilities and neural visual functions were influenced by a 4-week training regimen incorporating stroboscopic glasses [24].

The significance of technological advancements in the advancement of biomechanical and neuroscientific equipment in sports is emphasized in the passage, highlighting the growing impact of these fields on enhancing athletic performance.

2.3 Biomechanics in sports

Performance analysis in sports encompasses the evaluation of various aspects such as biomechanics, physiology, psychology, technique, and tactics during both training sessions and competitions [22].

Focusing on biomechanics, it pertains to the area of sports science that examines human motion, specifically the mechanics involved in the human body. It focuses on analyzing human motion through the perspective of the forces impacting the body and initiating motion, as well as examining the forces produced by the body in motion.

The mechanics that are employed on the human body are essentially the mechanics of rigid bodies, which are categorized into three branches: statics, kinetics, and kinematics [25-27]. Statics involves examining the state of mechanical balance and the preservation of an object's immobility, such as investigating postural instability. The study of kinetics focuses on understanding the factors that induce or change the motion of an entity, like the explosive acceleration seen in track athletes as they launch themselves forward from the starting point. Kinematics involves analyzing the movement of an object without taking into account the forces influencing or altering the motion. This field of study takes into account factors like space and time, along with the resulting quantities like velocity and acceleration, as seen in the movement of a tennis ball during a serve.

In sports biomechanics, incorporating technology is indispensable for evaluating and monitoring statics, kinetics, and kinematics variables, and for enhancing performance while reducing the risk of injuries [28-31]. In order to precisely achieve these aims, the investigation has also emphasized the impact of biomechanical equipment such as footwear, insoles, orthoses, external joint supports, strapping, mouthguards, and occlusal splints [32-44].

CHAPTER 3. CYCLING BIOMECHANICS: ENHANCING PERFORMANCE AND SAFETY

Cycling biomechanics is a fascinating field that delves into the intricate relationship between the cyclist, the bicycle, and the forces that govern movement. By understanding how these elements interact, cyclists can optimize their performance, reduce injury risks, and enhance their overall cycling experience. This chapter explores the critical role biomechanics plays in cycling, from optimizing pedaling efficiency to preventing common injuries [1].

3.1 The Importance of Biomechanics in Cycling

Cycling performance is influenced by a complex interplay of human, mechanical, and environmental factors. Traditionally, engineers have focused on improving bicycle design to minimize aerodynamic drag, while kinesiologists have studied the human aspect of cycling performance, such as posture and muscle activation [2]. However, bridging these two perspectives through interdisciplinary research is essential for achieving optimal results.

Biomechanics allows cyclists to understand how different variables—such as body position, seat height, pedal alignment, and cadence—affect joint angles, muscle lengths, and force production. These factors collectively influence power output, energy efficiency, and comfort during cycling. For instance, adjustments in posture can significantly alter joint mechanics and muscle activation patterns. A more aerodynamic position may improve speed but could also increase strain on the lower back or neck if not correctly balanced [3].

Moreover, seat height is a critical factor in ensuring efficient knee extension at the bottom dead center (BDC) of the pedal stroke. Deviations from optimal seat height can lead to increased oxygen consumption or knee pain, highlighting the importance of precise adjustments for both performance and comfort [4].

3.1.2 Optimizing Performance Through Biomechanics

One of the primary objectives of cycling biomechanics is maximizing power output while minimizing wasted energy. This involves directing force effectively at the pedals during each phase of the pedal stroke:

Power Phase: From 12 o'clock (top dead center) to 6 o'clock (bottom dead center), most of the force is generated. Hip extensors (gluteus maximus) initiate this phase, followed by knee extensors (vastus lateralis and vastus medialis) for peak power production. Proper alignment and muscle activation are crucial for optimizing force transfer and reducing strain on joints [5].

Recovery Phase: From 6 o'clock back to 12 o'clock, muscles like hip flexors (iliopsoas) reposition the leg for the next power phase with minimal energy expenditure. Efficient recovery is essential for maintaining high cadences and reducing fatigue [6].

Proper force application depends on aligning foot position with pedal mechanics. Ideally, pressure should be concentrated under the balls of the feet to avoid rotational forces that reduce efficiency [7]. Additionally, equipment plays a crucial role in optimizing biomechanics:

Crank Arm Length: Shorter crank arms may benefit riders with smaller anthropometry by reducing joint strain during high cadences.

Saddle Pressure Mapping: Dynamic assessments at race-level intensities provide insights into how saddle pressure affects comfort and performance over long durations.

3.1.3 Biomechanics for Injury Prevention

Repetitive motion in cycling can lead to overuse injuries if biomechanical principles are not properly applied. Common injuries include:

Patellar Pain: Often caused by incorrect knee angles due to improper seat height or pedal alignment [8].

Lower Back Strain: Excessive forward lean or poor handlebar positioning can increase stress on spinal stabilizers [9].

Numbness or Paresthesia: Tight-fitting shoes designed for high power output may cause discomfort over long rides if not properly adjusted [10].

Dynamic bike fitting methods that account for workload intensity are increasingly recommended to prevent compensatory movements that exacerbate injury risks during high-power outputs [11].

Emerging technologies are revolutionizing how biomechanics is applied in cycling:

3D Motion Capture Systems: These systems provide detailed analyses of joint angles and muscle activation patterns during pedaling, enabling precise adjustments to optimize efficiency [12].

Wearable Sensors: Devices measuring pedal forces and cadence offer real-time feedback for refining technique and monitoring symmetry between legs [13].

Dynamic Bike Fitting: Moving beyond static methods, dynamic fitting evaluates kinematics under race-like conditions to ensure optimal configuration at varying intensities [14].

Interdisciplinary research remains vital for bridging gaps between engineering advancements and human physiology. By integrating biomechanics into training programs and equipment design, cyclists can achieve better results while minimizing injury risks.

3.1.4 Kinematic Analysis

Kinematic analysis is a fundamental branch of biomechanics that studies human movement without considering the forces that generate it. This type of analysis focuses on the geometric description of movements, such as the trajectory and velocity of the limbs and the body as a whole. In practice, kinematic analysis provides a quantitative representation of movement, focusing on parameters such as position, velocity, and acceleration [15,16].

Imagine observing an athlete performing a jump. Kinematic analysis helps understand how different parts of the body move through space, describing the trajectory and speed of the motion without considering the muscular or gravitational forces that generate it. This type of analysis is essential for optimizing sports performance and preventing injuries.

Kinematics is the study of movement and aims to describe it without addressing the causes that produce it. The parameters considered are space and time, and their relative relationship. This type of analysis is useful for understanding the distance covered at different speeds, changes in acceleration, and the positions in space and relative motion of specific body points considered in the analysis.

Kinematics is based on several fundamental principles:

Position and Orientation: Position refers to the location of an object or a body point in space, while orientation describes the rotation of a body segment relative to a reference system. These parameters are essential for understanding how different body parts move relative to a reference point.

Velocity and Acceleration: Velocity describes how fast an object moves, while acceleration represents the change in velocity over time. These parameters are crucial for understanding movement dynamics and identifying inefficiencies or dysfunctions.

The kinematic analysis of human movement can be performed using various methods:

Stereophotogrammetric Systems: These systems use special cameras to reconstruct the three-dimensional position of markers placed on specific anatomical reference points. The markers, typically spherical or semi-spherical, are applied to the subject being analyzed, and the infrared light they reflect appears as a bright point in the scene. This system combines two-dimensional images from multiple cameras to generate a three-dimensional image of the movement [17].

Wearable Sensors: Magneto-inertial sensors are an example of technology used to monitor spatial positions and the orientation of body segments. These sensors allow the kinematics of a joint to be described without the need for external cameras [18].

Small-Scale Photogrammetry: This technique uses video recordings of a subject in motion to analyze their movement. Any technique that allows the visualization and tracking of a subject's motion over time falls under "small-scale photogrammetry."

Kinematic analysis has applications in several fields:

Sports and Physical Activity: In sports, kinematic analysis is used to optimize athletes' techniques and improve performance. For example, in studying swimming technique or javelin throwing, kinematic analysis helps identify areas for improvement in movement trajectory and speed.

Clinical and Rehabilitation Fields: In clinical settings, kinematic analysis is essential for assessing and diagnosing conditions such as spasticity and coordination disorders. This type of analysis helps understand movement mechanisms and design personalized rehabilitation programs.

Ergonomics and Industry: In ergonomics and industry, kinematic analysis is useful for optimizing workers' movements, reducing muscle strain, improving productivity, and preventing repetitive strain injuries.

Kinematic parameters include:

Position: The location of an object or a body point in space. It is fundamental for describing movement and understanding how different body parts move relative to a reference system.

Velocity: The speed at which an object moves. This is a crucial parameter for understanding movement dynamics and identifying inefficiencies or dysfunctions.

Acceleration: The rate of change of velocity over time. This parameter is essential for understanding how movement changes over time and identifying coordination or motor control issues.

In kinematic analysis, it is essential to define local anatomical reference systems for each body segment. These systems originate from estimated joint centers (e.g., hip, knee, and ankle) and allow for describing the orientation of anatomical segments in relation to their proximal segment.

Kinematic analysis presents some limitations and challenges. One of the main challenges is the need for a controlled environment for data collection, especially when using motion capture systems. Additionally, data accuracy can be influenced by the quality of markers and camera resolution. Advanced technologies are revolutionizing kinematic analysis. For example, the integration of Artificial Intelligence (AI) and Machine Learning (ML) can improve the analysis of kinematic data, enabling the identification of patterns and trends that may not be immediately visible. Additionally, augmented reality (AR) and virtual reality (VR) technologies are becoming increasingly important for visualizing and analyzing kinematic data in a more interactive and immersive way.

One example of kinematic analysis application is the study of upper limb kinematics. This type of analysis is essential in rehabilitation and ergonomics to understand how different joints work together to produce smooth and efficient movements. In clinical settings, upper limb kinematic analysis helps assess and monitor conditions such as stroke or Parkinson's disease, supporting the development of personalized rehabilitation plans [20,21].

3.1.5 Dynamic Analysis

Dynamic analysis is a fundamental branch of biomechanics that studies human movement by considering the forces that generate it. This type of analysis focuses on the interaction between internal and external forces acting on the body, such as muscle forces, gravity, and air resistance, to understand how they influence movement [22].

Imagine observing an athlete performing a jump. Dynamic analysis helps to understand how muscle forces and gravity interact to generate movement and absorb impact upon landing. This type of analysis is essential for optimizing sports performance and preventing injuries. Dynamics is based on Newton's principles, which describe the relationships between a body's motion and the forces that alter it. These principles are fundamental to understanding how forces act on bodies and how they respond to such forces.

First Law (Law of Inertia): A body remains at rest or in uniform linear motion unless acted upon by an external force. This principle is crucial to understanding how external forces influence body movement [23].

Second Law (Force and Acceleration): The net force acting on a body is related to its mass and acceleration. This principle is essential for calculating the force required to produce a specific movement [24].

Third Law (Action and Reaction): Every action has an equal and opposite reaction. This principle is fundamental for understanding how forces interact between different bodies [25].

The dynamic analysis of human movement can be carried out through various methods:

Dynamic Models: These models use mathematical equations to describe how forces act on the body and how they influence movement. Dynamic models can be used to simulate the behavior of complex biomechanical systems [26].

Force Measurement Systems: Systems such as force platforms measure the forces acting on the body during movement. This information is fundamental for understanding how external forces affect movement and for optimizing sports performance [27].

Dynamic Simulators: These tools use advanced software to simulate the body's dynamic behavior under different load and movement conditions. Dynamic simulators are essential for designing optimized medical devices and sports equipment [28].

Dynamic analysis is applied in various fields:

Sports and Physical Activity: In sports, dynamic analysis is used to optimize athletes' performance and prevent injuries. For example, in the study of javelin throwing technique, dynamic analysis helps to understand how muscle forces and gravity influence the javelin's motion [29].

Clinical and Rehabilitation Fields: In clinical settings, dynamic analysis is crucial for evaluating and diagnosing conditions such as spasticity and motor coordination disorders.

This type of analysis helps understand movement mechanisms and design personalized rehabilitation programs [30].

Ergonomics and Industry: In ergonomics and industry, dynamic analysis is useful for optimizing workers' movements and reducing muscle strain, improving productivity, and preventing repetitive strain injuries [31].

Dynamic parameters include:

Forces: Forces are the primary causes of movement. They include both internal forces, such as those generated by muscles, and external forces, such as gravity or air resistance.

Moments: Moments represent the rotation of forces around a reference point. They are crucial for understanding how forces influence joint movement.

Energy and Work: Energy and work are fundamental for understanding movement efficiency. Energy represents the capacity to perform work, while work is the effect of forces acting on a body [32].

Dynamic analysis presents several limitations and challenges. One of the main challenges is the complexity of dynamic models, which require precise data and a deep understanding of the interactions between different forces [33]. Additionally, force measurement can be influenced by the quality of instruments and environmental conditions.

Advanced technologies are revolutionizing dynamic analysis. For example, the integration of Artificial Intelligence (AI) and Machine Learning (ML) can improve the analysis of dynamic data, enabling the identification of patterns and trends that may not be immediately visible. Additionally, augmented reality (AR) and virtual reality (VR) technologies are becoming increasingly important for visualizing and analyzing dynamic data in a more interactive and immersive way.

One example of dynamic analysis application is the study of upper limb kinematics. This type of analysis is fundamental in rehabilitation and ergonomics to understand how different joints work together to produce smooth and efficient movements [34]. In clinical settings, upper limb dynamic analysis helps assess and monitor conditions such as stroke or Parkinson's disease, supporting the development of personalized rehabilitation plans [35].

Another example is the analysis of swimming technique [36]. By studying the forces acting on the body during swimming, coaches can identify areas for improvement in technique, helping athletes reduce water resistance and enhance performance.

Dynamic biomechanics continues to evolve, with new technologies and methods constantly being developed. One of the most promising areas is the integration of biomechanics with Artificial Intelligence (AI) and Machine Learning (ML). These technologies can improve dynamic data analysis, allowing for the identification of patterns and trends that may not be immediately visible [37]. Additionally, AI can be used to develop predictive models that help prevent injuries or optimize sports performance [38].

Another rapidly growing research area is the biomechanics of biological tissues at the cellular and molecular level. This field studies how mechanical forces influence the behavior of cells and tissues, helping to better understand the mechanisms of tissue regeneration and repair [39]. These discoveries could lead to new strategies for treating injuries and regenerating damaged tissues [40].

Furthermore, augmented reality (AR) and virtual reality (VR) technologies are becoming increasingly important for visualizing and analyzing dynamic data interactively and immersively. These technologies can improve movement understanding and develop more effective and engaging rehabilitation and training strategies [41].

Advanced technologies, such as motion capture systems and wearable sensors, are revolutionizing dynamic analysis. These tools allow for the precise collection of movement data and the forces acting on the body, enabling the optimization of sports performance and improving rehabilitation.

Additionally, the integration of Artificial Intelligence (AI) and Machine Learning (ML) can enhance dynamic data analysis, allowing for the identification of patterns and trends that may not be immediately visible. This approach can be used to develop predictive models that help prevent injuries or optimize sports performance [42].

Dynamic analysis has important clinical and sports implications. In clinical settings, it helps to evaluate and diagnose conditions such as spasticity and motor coordination disorders, supporting the creation of personalized rehabilitation programs [43]. In sports, dynamic analysis is crucial for optimizing athletes' performance and preventing injuries, improving movement execution techniques, and reducing the risk of injury [44].

Clinical biomechanics focuses on applying biomechanical principles to improve the diagnosis and treatment of musculoskeletal conditions. Dynamic analysis is fundamental in this context, as it helps to understand how forces act on the body and how they influence movement [45]. This type of analysis is crucial for developing personalized rehabilitation programs and improving sports performance [46].

Furthermore, clinical biomechanics utilizes advanced technologies such as Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) to visualize anatomical structures and assess tissue conditions [47]. These technologies, integrated with dynamic analysis, enable a better understanding of movement mechanisms and the development of more effective therapeutic strategies [48].

In ergonomics, dynamic analysis is essential for optimizing workers' movements and reducing muscle strain. This type of analysis helps understand how forces act on the body during work activities and how they influence workers' health. By integrating dynamic analysis with advanced technologies, it is possible to design more ergonomic work environments and reduce the risk of repetitive strain injuries [49].

Additionally, dynamic analysis can be used to assess the effectiveness of ergonomic interventions and improve worker productivity. This approach can help reduce costs associated with workplace injuries and improve workers' quality of life.

3.1.6 Statics

Statics is the study of the equilibrium conditions of a body or system. In biomechanics, statics is essential for understanding how the body maintains balance during daily or sports activities. This type of analysis focuses on the forces acting on a body in a state of rest or slow movement, such as body weight and the muscle forces that support it.

Fundamental Principles of Statics

Equilibrium: A body is in equilibrium when the forces acting on it are perfectly balanced. This means that the sum of the forces and moments acting on a body is zero.

Forces and Moments: Forces are the primary causes of equilibrium, while moments represent the rotation of forces around a reference point. In statics, it is essential to calculate forces and moments to determine whether a body is in equilibrium.

Statics has various applications in biomechanics:

Posture and Balance: Statics helps to understand how the body maintains balance during daily activities, such as standing or sitting. This is particularly important for preventing falls and improving posture.

Design of Medical Devices: Statics is crucial in designing medical devices such as prostheses and orthoses, which must be able to support body weight and maintain balance.

3.2 Kinematic Analysis in Cycling

Kinematic analysis in cycling is a fundamental technique for evaluating and optimizing pedaling technique and the cyclist's position on the saddle. This type of analysis focuses on the quantitative and qualitative description of the movement of individual body segments during pedaling, regardless of the causes that generate it.

Kinematic analysis in cycling describes the trajectories and angles of body segments, such as legs, arms, and torso, during movement. This type of analysis is essential for understanding how the cyclist's body interacts with the bicycle and for identifying potential inefficiencies or dysfunctions in movement.

Kinematic analysis in cycling can be carried out through various methods:

Video Analysis Systems: These systems use cameras to record the cyclist's movement from different angles. The images are then analyzed to evaluate pedaling technique and saddle position.

Optoelectronic Technologies: These technologies, such as motion capture systems, use markers or sensors to track the movement of body segments. This approach provides precise data on movement trajectory and speed.

Inertial Sensors: Inertial sensors can be used to measure the orientation and movement of body segments during pedaling, providing detailed information on movement kinematics.

3.2.1 Applications of Kinematic Analysis in Cycling

Kinematic analysis has several applications in cycling:

Optimization of Pedaling Technique: This type of analysis helps identify dysfunctions in pedaling technique, such as incorrect foot position on the pedal or inefficient load distribution on the legs. By correcting these aspects, cyclists can improve pedaling efficiency and reduce the risk of injuries.

Bike Fitting: Kinematic analysis is crucial in bike fitting as it helps adjust the bicycle according to the cyclist's specific needs. This includes adjustments to the saddle, handlebars, and cleats to ensure an optimal position and reduce discomfort and injuries.

Injury Prevention: By identifying movement dysfunctions, kinematic analysis can help prevent common cycling injuries, such as back pain or knee problems.

Kinematic parameters include:

Position and Orientation: The position and orientation of body segments are essential for evaluating pedaling technique and saddle position.

Speed and Acceleration: The speed and acceleration of movements are crucial for understanding pedaling efficiency and identifying inefficiencies.

Joint Angles: Joint angles, such as those of the knee and hip, are important for assessing pedaling technique correctness.

3.2.2 Motion Capture Systems

Motion capture systems are advanced technologies used to record and analyze human movement in various contexts, such as film, medicine, sports, and rehabilitation. These systems allow for precise evaluation of movement biomechanics, helping optimize sports performance, prevent injuries, and improve rehabilitation.

There are different types of motion capture systems, each with specific characteristics and applications:

Optical Systems: These systems use cameras to track markers placed on the subject's body. Examples include the Vicon system, which uses reflective markers to capture 3D movement. Optical systems are particularly precise and are often used in film and sports applications.

Inertial Systems: These systems use inertial sensors such as accelerometers and gyroscopes to measure body movement. They are especially useful for movement analysis in various environments due to their portability and accuracy. Inertial systems are ideal for applications that require freedom of movement, such as cycling or dance.

3D Motion Capture Systems: These systems combine multiple cameras to create a three-dimensional model of movement. They are essential for assessing the subject’s dynamic position and obtaining more relevant data than static methods [50].

Examples of Motion Capture Systems

Vicon: This system uses 3D motion capture technology to measure every degree of movement and millimeter of distance with precision, providing detailed data on movement biomechanics. Vicon is widely used in film and sports to create realistic animated characters and optimize athletic performance.

Xsens: These systems allow movement digitization in various environments, offering maximum freedom of movement for the subject. Xsens is particularly useful for applications requiring portability, such as cycling or rehabilitation.

OptiTrack: This system uses infrared cameras to track markers and capture movement in 3D, making it ideal for sports and film applications. OptiTrack is known for its high precision and fast data acquisition.

3.2.3 Markers in Motion Capture Systems

Markers are fundamental elements in motion capture systems as they allow precise tracking of body segment movements. These markers can be of different types and are strategically placed on the subject’s body to capture movement data [50].

There are different types of markers used in motion capture systems:

Reflective Markers: These markers reflect infrared light emitted by cameras, allowing 3D movement tracking. They are commonly used in optical motion capture systems.

Active Markers: These markers emit electronic signals detected by cameras, offering greater accuracy and stability than reflective markers.

Passive Markers: These markers do not emit signals and rely on light reflection for tracking. They are more cost-effective and easier to use than active markers.

Marker placement is crucial for obtaining accurate data. Markers are generally placed on specific anatomical points, such as joints or body segments to be analyzed. Their position must be consistent with the reference system used to ensure correct movement reconstruction.

Marker placement in cycling is a key aspect of movement biomechanics analysis. Markers are used in motion capture systems to track the movement of the cyclist's body segments during pedaling, providing crucial data to optimize saddle position and improve performance.

Markers are typically placed on specific anatomical points of the cyclist’s body. These points include:

Wrist: Helps evaluate arm position and movement, crucial for maintaining optimal balance during pedaling.

Elbow: Essential for analyzing arm flexion angles, which influence posture and comfort.

Shoulder: Useful for assessing torso posture and movement, crucial for evenly distributing weight and reducing muscle strain.

Pelvis: Helps determine body position and stability during pedaling, directly influencing pedaling efficiency.

Femur: Placed on the thigh to assess lower limb movement, fundamental for optimizing power and efficiency.

Knee: Crucial for analyzing flexion angles and lower limb alignment, helping prevent knee injuries.

Ankle: Helps evaluate foot position and leg movement, influencing pedaling technique and comfort.

Foot: Essential for analyzing foot position and movement on the pedal, crucial for optimizing power transmission and reducing injury risk.

Markers are essential for obtaining precise data on cycling biomechanics. They allow for evaluating joint angles, load distribution, and other biomechanical parameters during pedaling. These data are crucial for optimizing the cyclist’s position on the saddle, improving pedaling efficiency, and reducing injury risks.

For example, by analyzing knee and ankle positions, coaches can identify movement dysfunctions that could lead to knee or foot problems. Correcting these dysfunctions allows cyclists to improve their pedaling technique and reduce the risk of injuries.

Advanced technologies, such as the Retül system, use markers placed on eight anatomical points to collect real-time data on the cyclist's position and movement. These data are then processed by specialized software to optimize saddle position and improve performance.

Additionally, systems like Idmatch do not use markers but rely on biomechanics and ergonomics principles to optimize the cyclist's positioning on the bike. These systems are particularly useful for cyclists who do not have access to advanced motion capture technologies.

3.3 Cyclist Dynamics and Torque

Cyclist dynamics is a fundamental aspect of biomechanics applied to cycling. This field studies the movement of cyclist and the forces influencing them during pedalling, with the goal of optimizing sports performance and preventing injuries. A crucial parameter in this context is torque, which represents the rotational force applied to the pedals.

Pedaling can be divided into different phases, each with specific dynamic characteristics:

Phase 1: Initial Push: This is the most important phase in terms of propulsion, where most of the force generated is transmitted to the pedal. It is crucial to keep the pedal horizontal throughout this phase, adjusting the cleat position and knee advancement through saddle height and setback.

Phase 2: Load Transfer: In this phase, the load shifts from the right lower limb to the left, preparing the cyclist for the next push.

Phase 3: Dynamic Recovery: Also known as traction, this phase involves the calf in foot extension. The power used is relatively low but is crucial for recovery and preparation for the next push.

Torque is a fundamental parameter in cycling dynamics, as it represents the rotational force applied to the pedals. It is measured in Newton meters (Nm) and directly influences the power output of the cyclist. Power is, in fact, the product of torque and pedaling cadence [27].

The Torque Test is a method used to assess a cyclist's maximum torque at different pedaling cadences, typically between 40 and 110 rpm. This test helps identify the optimal cadence to maximize power output and improve pedaling technique.

Dynamic parameters include:

Forces and Moments: Muscular and mechanical forces act on the pedal and the cyclist's body, influencing pedaling technique and movement efficiency.

Speed and Acceleration: The speed and acceleration of movements are crucial to understanding pedaling efficiency and identifying inefficiencies.

Joint Angles: Knee and hip flexion angles are important for evaluating the correctness of pedaling technique and preventing injuries.

3.3.1 Power Meters in Cycling

Power meters are essential devices for measuring the power output of a cyclist during pedaling. These tools have become indispensable for both professionals and enthusiasts, thanks to their ability to provide precise data on physical performance [16].

Power meters use electronic sensors called strain gauges, placed in specific areas such as the pedals, crank arms, chainring, or bottom bracket. These sensors detect minute deformations in the material (invisible to the naked eye) and calculate power output, converting this information into an electrical signal that is sent to a processor.

The processor converts the signal into watts, and the data is then transmitted to a bike computer, smartphone, or other display devices for real-time monitoring. This allows cyclists to continuously track their performance and adjust their training intensity accordingly.Different types of power meters exist, each with specific advantages and disadvantages:

Pedal-Based Power Meters: These devices are directly placed on the pedals and provide an accurate measurement of power exerted by each foot. They are easy to install and can detect movement asymmetries. Popular models include the Garmin Rally RS200 and Favero Assioma.

Crank-Based Power Meters: These devices are integrated into the crankset and offer an accurate measurement of total power output. They are generally more compact and less intrusive than pedal-based meters but require a more complex installation. SRAM is one of the brands offering this solution.

Hub-Based Power Meters: Positioned in the rear wheel hub, these meters measure total power output. Although less common than other types, they provide precise total power measurement.

3.3.2 Applications of Power Meters

Power meters are used in various aspects of cycling:

Optimized Training: They allow monitoring of power output during training, enabling optimization of intensity and duration for better performance.

Performance Management: They help cyclists manage their efforts during races, maintaining a consistent and optimal performance—crucial in long competitions where fatigue management is key.

Post-Race Analysis: The collected data can be used to analyze performance during races, helping to identify areas for improvement and optimize training strategies.

3.4 Bike Fitting: The Art of Optimizing Cyclist Position

Bike fitting is a crucial process in cycling that involves adjusting the bike to match the physical and functional needs of the cyclist. This approach is essential for improving performance, preventing injuries, and ensuring optimal comfort during pedaling [14].

Bike fitting is a physical evaluation of the cyclist, followed by adjustments to the bike based on their anatomical characteristics [4]. This process includes saddle height, handlebar position, and cleat alignment to ensure a correct and efficient posture. Bike fitting offers several benefits:

Greater Comfort: A correct position reduces stress on joints and muscles, improving comfort during long rides.

Improved Performance: Optimizing the cyclist's position can enhance pedaling efficiency and sports performance.

Injury Prevention: Incorrect positioning can cause excessive stress on muscles and joints, leading to injuries. Bike fitting helps prevent common issues such as knee pain, lower back pain, and Achilles tendonitis.

3.4.1 Bike Fitting Process

The bike fitting process includes several stages:

Physical Evaluation: An assessment of the cyclist's flexibility, strength, and body asymmetries is conducted [3]. This step is crucial for understanding specific needs and adapting the bike accordingly.

Bike Adjustments: Parameters such as saddle height, handlebar position, and cleat alignment are adjusted to fit the cyclist's needs. Precision is required to ensure an optimal position.

Test Ride: After adjustments, a test ride is performed to verify that the position is comfortable and efficient. This step ensures that modifications are effective and do not cause issues during pedaling.

3.5 Common Cycling Injuries

Cycling, like any other sport, carries the risk of injuries [51]. These may be caused by incorrect posture, muscle overload, or accidents while riding. Below is an overview of common injuries and how to prevent them:

Anterior Knee Pain: Often caused by a saddle that is too low or excessive knee stress. Patellar chondromalacia is a feared condition where cartilage protecting the kneecap wears down, causing intense pain.

Patellar Tendinitis: Due to excessive stress on the patellar tendon, often caused by a low saddle or improper pedaling technique.

Lower Back Pain: One of the most common injuries, often caused by poor posture or muscle overload.

Neck Pain: Caused by improper posture while riding, leading to muscle tension and discomfort.

Achilles Tendinitis: Inflammation of the Achilles tendon, often caused by overly forward-positioned cleats or a high saddle.

Carpal Tunnel Syndrome: Due to excessive pressure on the median nerve, often caused by poor posture or muscle overload.

Extensor Tenosynovitis: Inflammation of forearm tendons, often caused by muscle overload on uneven surfaces.

Mechanical adjustments can help prevent pain and discomfort while cycling:

Saddle Height: A correct saddle height ensures the knee remains slightly bent at the bottom of the pedal stroke, preventing excessive joint stress.

Handlebar Position: Adjusting the handlebar distance can prevent lower back and neck pain by maintaining proper posture.

Cleats and Shoes: Proper cleat positioning ensures natural foot movement, preventing foot and ankle pain.

Bike fitting and power measurement technology continue to evolve, providing cyclists with more advanced tools to optimize their performance, prevent injuries, and improve riding comfort.

3.6 Saddle Pressure Analysis

Saddle pressure analysis is crucial for optimizing comfort and improving performance [52,53]. This process uses advanced technology to measure weight distribution on the saddle during pedaling. Here’s a detailed overview of how it works and its benefits:

Pressure Sensors: Devices such as those from Bici Lab, IdMatch, and Velometrik are equipped with sensor arrays that measure saddle pressure in real time. For example, the Velometrik system uses 348 high-precision sensors, while IdMatch employs 68 sensors.

Pressure Mapping: These sensors create a detailed map of high and low-pressure areas on the saddle. IdMatch's Pressure Map, for instance, visualizes pressure zones using a color-coded representation.

Support Area: Measures the surface of the saddle used by the cyclist.

Pressure Distribution: Should be optimized to avoid perineal issues, with approximately 75% of the pressure on the rear and 25% on the front.

Real Ischial Distance: Evaluates whether the saddle width matches the cyclist's pelvis.

Contact Intermittency: Examines how road vibrations affect pressure and comfort.

Performance Improvement: A proper setup allows muscles to work more efficiently, enhancing pedaling effectiveness.

Injury Prevention: Analyzing pressure distribution helps identify and correct imbalances that could cause knee, pelvic, or lower back pain.

Comfort Optimization: Balanced pressure distribution reduces discomfort and the risk of numbness, especially on long rides.

Choosing the Ideal Saddle: Tools like the Pressure Map assist in selecting the most suitable saddle, reducing the chances of choosing the wrong one.

Selecting the right saddle is essential for both comfort and performance. Here are some key factors to consider:

Ischial Bone Width:

Measuring the distance between the ischial tuberosities helps determine the ideal saddle width. This is crucial for properly distributing weight and preventing discomfort.

Pelvic Flexibility:

A cyclist with low flexibility should opt for a saddle with a rounded cross-section, which supports natural pelvic rotation and prevents lower back issues.

A more flexible cyclist may prefer a flat saddle, ideal for aerodynamic positions.

Cycling Discipline:

Road Cycling: Flat and lightweight saddles for aggressive positions.

Mountain Biking: More curved and wider saddles for comfort on rough terrain.

Endurance: Slightly curved saddles for more upright positions.

Perineal Cutout and Pressure Relief: A cutout can help reduce pressure on the perineal area, particularly useful for cyclists with lower flexibility.

Padding and Materials: Minimal but dense padding is preferable for relieving pressure without compromising the necessary rigidity.

CHAPTER 4. WEBSITE CREATION AND SCIENTIFIC ARTICLES PRODUCTION

4.1 Website creation for saddle choice: www.inbici.eu

The website www.inbici.eu was conceived and developed by Giuseppe Alamia, Domenico Savio Salvatore Vicari, Valerio Giustino, Antonino Patti, Antonino Bianco. The website was created with the purpose of indicating to the cyclist the most suitable saddle to use based on his/her body characteristics. The cyclist, by providing the body information requested on the site, will receive the indication on the most appropriate saddle.

Figure. Homepage of the website www.inbici.eu

4.2 Articles on measurements in cycling

4.2.1 Saddle Pressures Factors in Road and Off-Road Cyclists of Both Genders: A Narrative Review

Domenico Savio Salvatore Vicari, Antonino Patti, Valerio Giustino, Flavia Figlioli, Giuseppe Alamia, Antonio Palma and Antonino Bianco

Abstract: The contact point of the pelvis with the saddle of the bicycle could generate abnormal pressure, which could lead to injuries to the perineum in cyclists. The aim of this review was to summarize in a narrative way the current literature on the saddle pressures and to present the factors that influence saddle pressures in order to prevent injury risk in road and off-road cyclists of both genders. We searched the PubMed database to identify English-language sources, using the following terms: “saddle pressures”, “pressure mapping”, “saddle design” AND “cycling”. We also searched the bibliographies of the retrieved articles. Saddle pressures are influenced by factors such as sitting time on the bike, pedaling intensity, pedaling frequency, trunk and hand position, handlebars position, saddle design, saddle height, padded shorts, and gender. The jolts of the perineum on the saddle, especially on mountain bikes, generate intermittent pressures, which represent a risk factor for various pathologies of the urogenital system. This review highlights the importance of considering these factors that influence saddle pressures in order to prevent urogenital system injuries in cyclists.

Keywords: biomechanics; bicycle; cyclists; saddle pressure; perineal pressure; urogenital system

1. Introduction

Cycling is one of the most popular sports in the world and plays an important role in promoting public health, even for those who practice it as an amateur [1,2]. Indeed, cycling, in all its forms and in all its disciplines, is a sport that involves many participants, both at an amateur and professional level.

Cycling is practiced not only on the road, but also off-road and on the track. Four cycling disciplines are part of the Olympics: road cycling, mountain biking, track cycling, and BMX. Road cycling is probably the most widespread and followed discipline of cycling. The races can be one day or in stages. Cross country is the only Olympic discipline of mountain biking. The races take place on undulating mixed circuits with technical descents, forest roads, rock gardens, and obstacles (even artificial) from 4 to 6 km, and the route is repeated several times, depending on the travel time per lap, for a total time race of

≈120 min [3]. Track cycling features several races held within a velodrome, consisting of two straights and two steep curves. BMX is a cycling discipline that uses a small and resistant bike suitable for performing various stunts.

Very often, young people approach the bicycle with a mountain bike, attracted by the sense of freedom and escape from the daily chaos that derives from its use. In fact, the mountain bike, having wider and knobby tires and suspensions, offers the possibility of pedaling on uneven dirt paths and in close contact with nature.

It is important to note that a suitable position on the bike guarantees a good joint dynamic balance, correct breathing, excellent aerodynamics, and adequate weight distribu- tion, favoring maximum muscle work without compromising the optimal balance of the physiology of the entire musculoskeletal system [4,5]. Bicycle fitting is the adjustment of the bicycle to the physical and performance requirements of the cyclist in order to meet the cyclist's goals and needs. An adequate bicycle fitting, performed by the bicycle fitter, can positively influence performance and the perception of comfort and reduce the risk of injury [4,6].

Indeed, regular cycling has an effect on the prevention of many chronic diseases (e.g., cardiovascular disease, diabetes, cancer, hypertension, obesity, depression, and osteoporosis) [2,7,8]. However, cycling can lead to injuries, most of which affect the urogenital system, causing genital numbness, erectile dysfunction (ED), priapism, infertility, and hematuria and affecting serum prostate-specific antigen (PSA) levels [9].

The man–bicycle combination is achieved through five points of contact, such as the two hands on the handlebars, the two feet on the pedals, and the pelvis on the saddle. Pressures are generated at these points of contact given by the distribution of the cyclist's weight. Saddle pressures are generated when the cyclist is seated, and, of course, no perineal pressure is generated when pedaling in standing position. In fact, the study by Sommer et al. (2001) [10] confirmed that pedaling in an upright position does not cause any alteration of the penile blood supply. As a matter of fact, the constant pressure exerted on the bicycle saddle could be the cause of non-traumatic injuries [11], ranging from saddle sores to more serious disorders related to the urogenital system [12].

Perineal discomfort or pain is very common on a bicycle and can be caused by various factors that can affect the normal distribution of pressure in the saddle. As a matter of fact, the saddle is recognized as the major extrinsic risk factor in the development of seat discomfort and perineal pathologies during cycling [13].

Analyzing the pressures in the saddle and controlling the factors that influence it can limit the risk of injury. In the last decade, the measurement of pressures in the saddle and the related compression on the perineum has been investigated [14]. A survey of 2,774 cyclists and 1,158 non-cyclists revealed that cycling is associated with a significantly higher risk of perineal numbness and urethral stricture development [12]. Up to 91% of cyclists experienced perineal numbness. The incidence of erectile dysfunction, especially in long-distance cyclists, was found to be 13%, which is significantly higher than in the general population [15]. Overall, 19% of cyclists who had a weekly distance of more than 400 km complained of erectile dysfunction. Moreover, perineal numbness was reported by 61% of cyclists.

In several sports, the analysis of the pressures in the different points of contact between the athlete and a surface is now widespread. For example, in running athletes, given the increasing attention to the relationship between shoes and running biomechanics [16,17], insole-based sensors that record pressures represent a methodology used to study foot–shoe interactions [18]. Similarly, other studies have investigated the pressure exerted on the saddle on horses and the correlation with back pain in riding horses [19]. Similarly, other studies investigated the differences in plantar pressure distribution between athletes of different sports [20] and between different technical gestures in athletes who practice the same sport [21], and the effects of training or technique [22].

Hence, the need to study saddle pressures in cyclists is of fundamental importance. This review aimed to summarize in a narrative way the current literature on the saddle pressures and the factors that influence saddle pressures in road and off-road cyclists of both genders.

2. Methods

For this review, we searched the PubMed database to identify English-language sources using the following terms: "saddle pressures", "pressure mapping", "saddle design" AND "cycling". We also searched the bibliographies of the retrieved articles. We have included only English-language articles, with no publication time limit.

3. Saddle Pressures Measurement

With technological progress, new instruments have been developed to optimize bicycle fitting. The measurement of pressures distribution in the saddle is essential because it analyzes the points of contact of the pelvis, where there are very delicate biological tissues, on the saddle. Saddle pressures are measured using an instrument applied directly to the saddle and equipped with sensors. The instrument allows the evaluation of the contact area, the distribution of the contact pressures, the distance between the ischial tuberosities, and the intermittence of the contact pressures. In detail, the contact area detects the surface of the saddle covered by the pelvis. The distribution of the contact pressures detects the region with a higher or lower load on the saddle. Among these parameters belong the vertical force (i.e., the integral of the pressure applied to the saddle area frame by frame and normalized to the cyclist's body weight), the mean pressure (i.e., the mean of the pressure values across all mask sensors), and the peak pressure (i.e., the highest value among the pressures recorded) [23]. Once the ischial tuberosities have been detected, the distance between the ischial tuberosities, i.e., how far apart they are from each other, is measured. The intermittence of the contact pressures represents the intermittent pressures exerted by the jerks of the pelvis on the saddle. In fact, the evaluation of the pressures in the saddle can take place in a static or dynamic mode. In static, saddle pressures are recorded with cyclists sitting on the saddle, but without pedaling [24]. In dynamic, the measurement of saddle pressures takes place while the cyclist pedals at a defined pedaling frequency and intensity.

4. High Saddle Pressures and Risk of Injury

In recent years, the scientific literature has focused on the analysis of the mechanical causes of overload injuries affecting the urogenital system in cyclists [23]. The incidence of bicycle-related urogenital symptoms varies [9]. The onset of some disorders is only occasional [25,26], while others, in particular those associated with perineal compression, are more frequent [9]. Sommer et al. (2001) reported an incidence of genital numbness of 61% and erectile dysfunction of 24% in male cyclists whose weekly training exceeded 400 km [10]. Few studies have analyzed the incidence of genital and pelvic floor symptoms in female cyclists [27]. Nonetheless, there is evidence that female cyclists suffer from similar problems as male cyclists, ranging from minor skin lesions to serious conditions, such as pain and neuropathies [27]. The cause of both genital numbness and erectile dysfunction appears to be compression of the pudendal nerve during pedaling [23]. Considering that excessive pressures leads to transient hypoxemia of the nerve [28], the duration of these compressions seems to be more relevant than the intensity of the pressure itself [9,29]. Several studies in the literature show that excessive pressures in the anterior region of the saddle are harmful to erectile tissues compared to pressures recorded in the posterior region of the saddle [30,31]. For this reason, reducing the compressive load on soft tissues is the main goal for the development of bicycle saddle geometries [32].

The factors that influence the distribution of pressures in the saddle are analyzed in the following paragraphs and are shown in Table 1.

5. Influence of Sitting Time on the Bike on Saddle Pressures

Cyclists, while pedaling, are not always sitting in the saddle. In fact, very often cyclists pedal standing up, and this factor is given by personal attitudes, the characteristics of the route, and the specialty practiced.

In fact, mountain bikers frequently find themselves in an upright position for very steep and bumpy climbs, where it is necessary to release greater power peaks to tackle them, and for very long descents, where the cyclist is not sitting in the saddle to over- come obstacles.

Conversely, road cyclists spend more time sitting in the saddle due to the regularity of their routes and the lack of obstacles to overcome. Professional road cyclists cover approximately 30,000 to 35,000 km per year between training and competition, and some races, such as the Tour de France, last 21 days (~100 h of racing), during which cyclists cover more than 3500 km [40].

Time spent sitting in the saddle could be a factor influencing saddle pressures and related urogenital pathologies. A few studies in the literature have analyzed saddle pres- sures for a long time in a sitting position. Often, pedaling standing up and taking breaks during the activity are good habits to reduce pressure on the saddle and prevent the onset of urogenital pathologies [39]. In this sense, off-road cyclists have an advantage over road cyclists because the discipline itself often invites them to pedal standing up.

It could be interesting to evaluate the pressure in the saddle over time to know the maximum time window in which it is possible to remain seated in the saddle while pedaling while maintaining comfort.

6. Influence of Pedaling Intensity on Saddle Pressures

Several studies measuring saddle pressures in a dynamic mode confirmed that pedal- ing intensity could be an influencing factor.

Carpes et al. (2009) [33] evaluated the effects of 2 different pedaling intensities (150 W and 300 W) and 2 saddle designs (plain saddle and holed saddle) on saddle pressure in male and female cyclists, showing that with the plain saddle, the mean pressure increased with increasing pedaling intensity in males. Furthermore, using the holed saddle, the mean pressure increased with increasing pedaling intensity, regardless of gender.

The study by Bressel et al. (2005) [34] investigated pressures at different pedaling intensities (118 W and 300 ± 82.4 W) and different hand positions (tops and drops) in male and female cyclists. The authors found decreased pressures over most regions of the saddle at higher pedaling intensities and the drop hand position. This may have occurred due to a partial weight shift from the saddle to the pedals as pedaling intensity is increased.

7. Influence of Pedaling Frequency on Saddle Pressures

Pedaling frequency could vary the pressure distribution in the saddle. A very high pedaling frequency could lead to higher pressure values in the saddle. In this case, it is advisable to change to a higher gear [39].

8. Influence of Trunk Position and Hand Position on Saddle Pressures

The position of the cyclist's trunk and hand could influence the pressure distribution in the saddle. Carpes et al. (2009) [13] analyzed the effects of trunk position on the pressures exerted in two saddles with different designs in recreational cyclists of both genders seated in a bicycle in static position. In the latter study, saddle pressures were measured on two saddle models (i.e., with and without holes) and in two trunk positions (i.e., upright and forward). The results of this study showed no significant differences in saddle pressures between the two trunk positions in females. Instead, a significant difference was found between trunk positions using the saddle with holes in males. In detail, the forward position of the trunk led to lower pressure using the saddle with holes.

In contrast, the study by Potter et al. (2008) [31] that investigated the influence of gender and hand position on saddle pressures showed that when cyclists pedal and move hand position from the tops to drops, the centers of pressure in all regions move forward, the normalized force and maximum pressure on the posterior region decrease, and female cyclists show an increase in normalized force and maximum pressure in the anterior region.

Bressel et al. (2003) [38] showed an undesirable pressure to the anterior perineum when the cyclist leans forward on the handlebar of the bicycle.

In another study by Bressel et al. (2005) [34], the authors found that the drop hand position decreased saddle pressures in most regions. This could have occurred due to a partial shift of the cyclists' weight from the saddle to the handlebars as a result of moving from the top to drop the position of the hands on the handlebars.

However, it has been suggested that body weight bearing on the saddle at the level of the ischial tuberosities is an effective strategy to minimize pressure on the perineum [32].

9. Influence of Handlebars Position on Saddle Pressures

In the study by Partin et al. (2012) [37], it was demonstrated that the position of the handlebars can influence the pressures in the saddle of female cyclists. Three different handlebar-to-saddle heights were evaluated (at saddle level, lower than saddle, or higher than saddle), and low handlebar-to-saddle placement was associated with greater perineal saddle pressure.

10. Influence of Saddle Design on Saddle Pressures

Several studies have investigated the effects of saddle type on saddle pressures. Indeed, the saddle appears to be the main risk factor for urogenital problems. This aspect has contributed to the development of saddles with new designs.

Potter et al. (2008) [31] evaluated the influence of two saddle designs (saddle A, i.e., gender-neutral; saddle B, i.e., female-specific) by adopting two different hand positions in female cyclists. Using saddle B showed a reduction in the normalized maximum anterior pressure with drop hand position compared to saddle A. No significant differences were found between saddles in the maximum pressure with tops hand position or in the posterior region with drop hand position.

The study by Carpes et al. (2009) [33] investigated the influence on pressure in 2 saddles with different designs (plain saddle and holed saddle) at 2 pedaling intensities (150 W and 300 W) in male and female cyclists. The results of this study showed that the saddle design had no effect on pressures, with the only significant difference found when the peak pressure was compared between the holed saddle and the plain saddle during a pedaling intensity of 150 W in females. Higher pressures can be caused by contact with small surfaces on the edge of the saddle hole. On the plain saddle, the pressures were distributed over the entire surface, while on the holed saddle, there were points of higher pressure, which were given by the ischial tuberosities. This last aspect indicates that the contact of the body weight was mainly on the ischial tuberosities, reducing the pressures on the perineal area.

11. Influence of Saddle Height on Saddle Pressures

The optimal saddle height is an important aspect for a functional bike fitting [4]. The effects of changes in saddle height on the influence of perineal pressures and discomfort and pain have not been extensively studied. The study by De Looze et al. (2003) [41] demonstrated that pressure distribution and muscle activation are parameters related to discomfort. Setting an appropriate saddle height is very important to increase comfort, pre- vent injuries, make pedaling more efficient, and improve performance [36,42]. The scientific literature reports different methods to adjust the height of the saddle [42]. Some of these take into account the anthropometric measurements of the cyclist, and others use 2D or 3D kinematic analysis evaluating the range of the joint angle [43]. Christiaans et al. (1998) [5] suggested that the best saddle height for comfort was 106% of the inseam height in men and 107% of the inseam height in women. Another study by Scoz et al. (2022) [43] evaluated subjects with a standardized bicycle fitting procedure based on 3D kinematic data. The results of this study demonstrated that fitting across 15 angular ranges (minimum ankle, maximal ankle, ankle range, ankle angle at bottom, maximum knee flexion, maximum knee extension, knee angle range, knee forward of foot, knee forward of spindle, knee travel tilt, knee lateral tilt, knee lateral travel, hip angle closed, hip angle open, hip angle range, hip lateral travel, back angle, shoulder angle to wrist, shoulder angle to elbow) was sufficient to produce large, long-term effects on pain, fatigue, and comfort. The study by Gamez et al. (2008) investigated the influence of 3 different saddle heights (i.e., 684.1 mm, 709.1 mm, 734.1 mm) on comfort in cyclists. The authors found that the 709.1 mm high saddle was best because the peak pressure distribution and lower-limb muscle activation decreased [35]. The study by Verma et al. (2016) [36] investigated the influence of different saddle positions (neutral, upward, downward, forward, backward) on saddle pressures dis- tribution. The authors found that the discomfort increased with the upward and backward positions compared to neutral. The minimum force became less negative with the forward position compared to the neutral position. The degree of variability of CoP increased in the upward and backward positions.

A recent work by Wang et al. (2020) showed that low saddle height is related to increased knee adduction moments with longer duration in recreational cyclists [44].

Considering that a higher-than-normal saddle height could generate higher pressures, it is very important to adjust the saddle height and the backwardness of the saddle to prevent urogenital pathologies and ensure greater comfort for cyclists.

12. Influence of Padded Shorts on Saddle Pressures

A recent study evaluated the influence of various cycling padded shorts on saddle pressures in order to preserve the perineal region and increase the level of comfort [23].

A total of 3 padded shorts with different densities were evaluated: basic (60 kg/m3),

intermediate (80 kg/m3), and resistance (80 and 120 kg/m3). Saddle pressures were recorded during three trials of twenty minutes each, in which cyclists wore one of the three padded shorts for each trial. The authors found that the vertical force and the mean pressure on the saddle significantly decreased using the basic and endurance padded shorts. Moreover, the peak pressure on the corresponding perineal area of cyclists was significantly increased only with the use of the basic padded shorts. Further, the increase in the length of the center of pressure of the 3 padded shorts at the end of the test suggested that the basic material was starting to lose its elastic properties due to its low foam density (60 kg/m3). This study, in line with others in the literature, suggests that it is important to consider cyclists' padded shorts as a factor influencing saddle pressures [23,45].

13. Muscle Activity and Saddle Pressures

Several studies in the literature have evaluated muscle activity to improve pedaling economy and efficiency [46–50]. The major muscles typically studied were the gluteus maximus (GM), rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF, long head), medial gastrocnemius (MG), and tibialis anterior (TA) [48]. The study by McDonald et al. (2021) [51] evaluated the muscle activity of these muscles and the changes in the saddle pressure mapping indexes with alteration of the effective seat tube angle (ESTA). To vary the latter, the handlebars and the saddle were moved forwards or backwards simultaneously by 3 cm. The main finding concerns the muscle activity of the BF, GM, and MG, which increased progressively from the forwards to the backwards position. In contrast, the muscle activity of TA decreased progressively from the forwards to the backwards position. No changes were found in the muscle activity of VM, VL, and RF across the different positions. Regarding saddle pressures, a decrease in the percentage of frontal versus rear pressure was found when participants moved from the backwards to the forwards saddle position. A decrease in the mean pubic pressure was also found from the backwards to the forwards position. The results of this study suggest that cyclists in the back position had greater pelvic rotation, therefore increasing perineal pressure and anterior/posterior pressure distribution to compensate. The results were opposite when the saddle was moved forward.

14. Gender Differences on Saddle Pressures

The scientific literature shows several studies that have investigated the difference between male and female cyclists in different aspects. The difference in pelvic geometry, power output, and bike fit can influence saddle pressures. For example, the greater width between the ischial tuberosities in female cyclists could reduce the load on the posterior bone structures and increase the load on the perineal region [31].

The study by Potter et al. (2008) [31] analyzed gender differences in the distribution of pressures in the saddle. The main aim was to investigate the influence of gender, power, and hand position on saddle pressure distribution. The results confirmed a gender difference in saddle pressures. In detail, with the hand in drop position, only female cyclists showed an increase in the normalized force and maximum pressure in the anterior region.

Similarly, Carpes et al. (2009) also found significant differences between genders with the same workload.

Bressel et al. (2005) [34] showed that females, compared with males, did not show lower peak total, posterior, left, and right pressures in the drop position.

An interesting paper by Hermans et al. (2016) [52] explored the prevalence and duration of urogenital overuse injuries and sexual dysfunctions in female cyclists, showing that after at least 2 h of cycling, dysuria (8.8%), stranguria (22.2%), genital numbness (34.9%), and vulvar discomfort (40.0%) were found.

Coutant-Foulc et al. (2014) [53] reported that female cyclists cycling long distances each week resulted in unilateral swelling of the labium majus.

These findings suggest that it is essential to take into account the gender of cyclists in changes in saddle pressures to prevent perineal injuries.

15. Road vs. Off-Road Cyclists: Difference in Saddle Pressures

Between the road bike and the mountain bike, there are substantial differences, both structural and related to the sport, that involve a difference in the variation of saddle pressures. The mountain bike does not allow different grips, such as with the road bike. For this reason, saddle pressures in mountain bike cyclists cannot be influenced by different grips. However, the off-road rough trails cause percussions in the cyclist’s perineum. Genital numbness and erectile dysfunction can result from repeated perineal impacts on the bicycle saddle (micro-trauma).

Sanford et al. (2018) [24] evaluated the relationship between oscillation forces and perineal pressures among cyclists in a simulated laboratory setting by demonstrating a strong linear relationship between oscillation magnitude and perineal pressure during pedaling, mitigated by a saddle post shock absorber.

Studies in the scientific literature report that mountain bikers have a high frequency of extra-testicular and testicular disorders, associated with clinical symptoms in half of the bikers. These may be associated with a high rate of repeated micro-traumas of the scrotal contents [54]. Indeed, mountain bikers are at a higher risk of scrotal disorders than road cyclists [55]. Indeed, a prospective cohort study by Dettori et al. (2004) [56], aimed at exploring the occurrence of erectile dysfunction when using a mountain bicycle/road bicycle after a long-distance cycling event, showed that riding a mountain bicycle increases the risk of erectile dysfunction compared to a road bicycle on a long-distance ride.

Mitterberger et al. (2008) [55] investigated the risk of scrotal disorders in mountain bikers and on-road cyclists. The results showed that 94% of mountain bikers and 48% of on-road cyclists presented with abnormal findings on a scrotal ultrasound.

To the best of our knowledge, there are very few studies that have analyzed saddle pressures during outdoor mountain biking. In mountain biking, there are many factors that can influence the pressure in the saddle. Factors such as tire pressure, shock pressure, shock type, number of shock absorbers, terrain, climbing, and saddle contact time must be considered. Some of these factors are difficult to evaluate in the laboratory on cycle simulators, which is why it is interesting to evaluate the evolution of pressure in the saddle during outdoor pedaling on a mountain bike.

Few studies have so far analyzed the correlation between pressures in the different contact points, and knowing the pressures on the handlebars, in the saddle, and in the soles of the shoes could give us the possibility to identify postural anomalies of the cyclist and inadequate or inefficient pedaling techniques and to develop protocols to make man–bicycle interactions efficient and comfortable.

16. Conclusions

The analysis of saddle pressures is of fundamental importance to prevent the onset of urogenital pathologies in cyclists and to guarantee them a greater perception of comfort. The pressures under the perineal area of cyclists are harmful, and the main objective of bike fitting is to limit them as much as possible. This review suggests the importance of knowing the different factors that can influence the distribution of pressures in the saddle. Among these, technicians should be taking into account the influence of (a) pedaling intensity and frequency, (b) trunk position and hand position, (c) handlebars position, (d) saddle design and saddle height during a bike fit for each cyclist. These factors are individual and depend, among others, on gender, anthropometric measurements, and the type of bike. Moreover, they should recommend the most suitable type of padded shorts to use and give advice, such as getting up from the saddle while pedaling in the case of long periods of sitting time.

Considering which factors influence pressure in the saddle is useful for cycling practitioners. In particular, the use of devices capable of recording pressure in the saddle by technicians could make pedaling more efficient and comfortable. In fact, limiting pressure in the pubic region is the main objective to ensure adequate comfort for cyclists.

All the variables that can influence pressure in the saddle analyzed in this review represent risk factors for urogenital pathologies in cyclists. When fitting a cyclist's bike, these factors should be analyzed, taking into consideration other parameters, such as the weight, age, and level of the cyclist.

Professional bike fitters, cyclists, and trainers can use these findings to improve pedaling [43].

Table 1. Factors influencing saddle pressure distributions.

First Author	Year	Measurements	Main Results
Influence of pedaling on saddle pressures			
Carpes, F.P. [33]	2009	Influence of 2 different pedaling intensities (150 W and 300 W) on saddle pressures in male and female cyclists.	The mean pressure increased with increasing pedaling intensity in males. Furthermore, using the holed saddle, the mean pressure increased with increasing pedaling intensity, regardless of gender.
Bressel, E. [34]	2005	Influence of different pedaling intensities (118 W and 300 ± 82.4 W) with different hand position (tops and drops) on saddle pressures in male and female cyclists.	The pressures decreased over most regions of the saddle at higher pedaling intensities and drop hand position.
Influence of saddle on saddle pressures			
Potter, J.J. [31]	2008	Influence of two saddle designs (gender-neutral and female-specific) with two different hand positions in female cyclists.	Using the female-specific saddle, the normalized maximum anterior pressure with drop hand position decreased compared to the gender-neutral saddle. No significant differences were found between saddles in the maximum pressure with tops hand position or in the posterior region with drop hand position.
Carpes, F.P. [33]	2009	Influence of 2 saddle designs (plain saddle and holed saddle) at 2 pedaling intensities (150 W and 300 W) in male and female cyclists.	The saddle design had no effect on pressures, with the only significant difference found when the peak pressure was compared between the holed saddle and the plain saddle during a pedaling intensity of 150 W in females.
Gámez, J. [35]	2008	Influence of three different saddle heights on comfort in cyclists (measuring saddle pressures).	The best level of comfort was the intermediate one; with this height, the peak pressure distribution and activation of lower limb muscles decreased.
Verma, R. [36]	2016	Influence of five different saddle positions (neutral, upward, downward, forward, and backward) on comfort in cyclists (measuring saddle pressures).	The discomfort increased with upward and backward positions compared to neutral. The minimum force became less negative with forward position compared to neutral position. The degree of variability of CoP increased in the upward and backward position.

Influence of handlebars on saddle pressures			
Partin, S.N. [37]	2012	Influence of three different handlebar-to-saddle heights (at saddle level, lower than saddle, or higher than saddle) on saddle pressures.	Low handlebar-to-saddle placement was associated with greater perineal saddle pressure.
Influence of trunk position and hand position on saddle pressures			
Carpes, F.P. [13]	2009	Effects of two trunk positions (upright and forward) on the pressures exerted in two saddles with different designs.	No significant differences in saddles pressures between the two trunk positions in females. The forward position of the trunk led to lower pressures using the saddle with holes in males.
Potter, J.J. [31]	2008	Influence of two hand positions (tops and drops) on saddle pressures.	From tops to drops hand position, the CoP moved forward, the normalized force and maximum pressure on the posterior region decreased. Only female cyclists showed an increased normalized force and maximum pressure in the anterior region.
Bressel, E. [38]	2003	Influence of hand position (tops and drops) on saddle pressures.	With the cyclist forward on the handlebars (drops position), there was an undesirable anterior pressure at the perineum.
Bressel, E. [34]	2005	Influence of hand position (tops and drops) on saddle pressures.	The drops hand position decreased saddle pressures in most regions.
Influence of padded shorts on saddle pressures			
Marcolin, G. [23]	2015	Influence of three padded shorts with different densities (basic, intermediate, resistance) on saddle pressures.	The vertical force and mean pressure on the saddle significantly decreased using the basic and endurance padded shorts. The peak pressure on the perineal area significantly increased only using the basic padded shorts.
Influence of sitting time on the bike on saddle pressures			
Bond, R.E. [39]	1975	Influence of sitting time or standing up on pedals on saddle pressures.	Often, pedaling standing up and taking breaks during pedaling are good habits to reduce saddle pressures and prevent the onset of urogenital pathologies.

Legend: W, Watt; CoP, Centre of Pressure.

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4.2.2 Hamstring and lower back muscles flexibility as predictor of saddle pressures in young off-road cyclists

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Abstract

Introduction: While pedaling, cyclists rest their pelvis on the saddle, generating pressures on it. The pressures generated on the saddle are influenced by several factors. This study aimed to evaluate whether the flexibility of hamstring and lower back muscles could be considered a predictor of pressures in the anterior region (PAR) on the saddle.

Methods: For this study, 15 young off-road Italian cyclists (11m, 4f) aged 13–16 (Italian Federation categories: ES1, ES2, AL1, AL2) were recruited. Each participant was administered the V sit-and-reach (VSR) to measure the hamstring and lower back muscles flexibility. Subsequently, after performing a bike fitting, the saddle pressures during pedaling at three different intensities (100, 140, 180 W), with participants on their own bike installed on specific bike roller, were recorded. The parameters considered for statistical analysis were front pressure (%) and back pressure (%).

Results: The hamstring and lower back muscles flexibility, as result of the VSR test, was a predictor of saddle PAR at 100 W ($R2 = 0.362$, $p = 0.018$), at 140 W ($R2 = 0.291$, $p = 0.038$), and at 180 W ($R2 = 0.349$, $p = 0.020$) of pedaling intensity.

Conclusion: Higher values of the VSR could predict lower values of the pressures exerted in the front region of the saddle. The hamstring and lower back muscles flexibility may be considered a predictor of PAR on the saddle.

KEYWORDS

biomechanics, cycling, bicycle, bike, pelvic tilt, uro-genital pathologies

1. Introduction

Recreational and competitive cycling is constantly expanding and evolving around the world (1, 2). In Italy, in the last decade, off-road cycling has experienced an exponential growth in popularity, thanks also to the contribution of cycling schools sponsored by the Italian Cycling Federation which promote this sport among young people.

Cycling, due to the peculiar position in which athletes must remain for prolonged periods with the trunk leaning forward and maintaining the lumbar flexion to reach the handlebars with the hands, can lead to alterations in the morphology of the spine and pelvis (3). The spine adaptations on the sagittal plane could also be different based on the discipline practiced. In fact, Muyer et al. (2016) found that road cyclists show greater thoracic kyphosis than cross-country cyclists

(4). These findings could also depend on the different postures that cyclists adopt on bikes with different geometries. The handlebars of the road bike allow for different grips: low, with greater trunk flexion to be more aerodynamic, and high, with less forward trunk flexion to be more comfortable. The mountain bike, on the other hand, has a handlebar with a single grip and the trunk flexion is influenced only by the bike fitting (5).

In this sport, due to the continuous stresses that occur at the three points of contact between the cyclist and the bike (i.e., saddle, handlebars, and pedals) (6), dysfunctions such as the numbness of the hands, feet, or pubic region can arise (5).

Cross-country, the most popular mountain biking event, is a mass start endurance competition characterized by off-road circuits with continuous climbs and descents on uneven terrains and field trails (7, 8). The higher energy expenditure of off-road cyclists compared to on-road cyclists could also be due to the intense and repeated isometric muscle contractions of upper and lower limbs, necessary to absorb shocks and vibrations caused by uneven terrain. Similarly, athletes require higher levels of energy expenditure to stabilize the bicycle when crossing obstacles and to manage descents and climbs (2, 8). The vibrations caused by the uneven terrain, in addition to causing an increase in energy expenditure, could cause impacts to the cyclist's perineum on the saddle and it would seem that uro-genital pathologies could derive precisely from the repeated microtraumas caused by these continuous impacts (5). As a matter of fact, off-road cyclists usually use bicycles with front or full suspension in order to reduce muscle stress on upper and lower limbs and to absorb shocks on the saddle (7).

While pedaling, cyclists rest their pelvis on the saddle, generating pressures on it. However, abnormal pressures, especially in the anterior region, could cause acute and chronic uro-genital pathologies. The pressures generated on the saddle are influenced by several factors as analyzed in a recent review

(5). These factors include the intensity and frequency of pedaling, the cycling discipline, the position of the trunk, and the different anatomical conformation of the pelvis.

As regards the different conformation of the pelvis, related to the athletes' gender, it has already been extensively described in the scientific literature (9, 10). However, it is also necessary to consider the position of the pelvis in relation to the sagittal plane, which can vary from athlete to another (11). In fact, the pelvis can rotate around the femoral heads, following the bi- coxofemoral axis (12). This anteroposterior rotation represents the pelvic tilt (PT), which is the angle between the vertical line and the line drawn from the center of the femoral heads to the center of the upper sacral endplate (11, 13). When the pelvis rotates backwards (retroversion) the PT increases, while when the pelvis rotates forwards (anteversion) the PT decreases (12, 14). The anteroposterior orientation of the pelvis influences the sagittal curves of the spine. Moreover, reduced flexibility of the

hamstring muscles affects pelvic posture and, consequently, the sagittal curves of the spine. Previous studies have shown the effects of reduced hamstring flexibility on PT (15, 16). A study by McEvoy et al. (2007) examined the comparison of mean angles of the anterior PT and the variability of this parameter in elite cyclists and non-cyclists (17). The findings of this study underlined that the mean angles of the anterior PT of elite cyclists were significantly greater and had significantly less variability in non-cyclists when tested in prolonged sitting positions. The study by Muyor et al. (2016), which investigated hamstring flexibility in cross-country cyclists and road cyclists, showed that the latter had greater hamstring flexibility than the former (4). The same research group, in a further study, investigated any correlations between hamstring flexibility and spinal curves and pelvic tilt (18). Their results showed that the hamstring muscles flexibility influence the thoracic and pelvis postures when maximal trunk flexion with knees extended was achieved.

Considering that the hamstring muscles insert at the level of the ischial tuberosity, these can influence the pressures on the saddle (19). That is, these pelvis movements on the sagittal plane (i.e., retroversion and anteversion) could influence the distribution of saddle pressures.

Thus, since saddle pressures can depend on several known and unknown factors, the aim of this study was to evaluate whether the flexibility of hamstring and lower back muscles could be considered a predictor of pressures in the anterior region on the saddle (PAR).

Our hypothesis was that PAR on the saddle decreases as the degree of flexibility of the hamstring and lower back muscles increases, which in fact influences the PT.

2. Materials and methods

- Study design

This is a cross-sectional study in which we evaluated the influence of hamstring and lower back muscles flexibility on saddle pressures in young off-road cyclists of both sexes.

- Participants

Fifteen young Italian cyclists (11m, 4f) aged 13 to 16 (Italian Federation categories: ES1, ES2, AL1, AL2) were recruited from local cycling clubs. A member of the Sicilian regional technical research and development committee of the Italian Cycling Federation invited the potential participants who were shown the objectives of the research. To be eligible for the study, the following inclusion criteria had to be met: (a) be aged between 13 and 16 years; (b) practicing mountain biking for at least 2 years; (c) practicing mountain biking at least 3 h/week. The exclusion criteria were the following: (a) no history of saddle sores; (b) no history of skin irritations in the perineal area, perineal nodules, or perineal numbness; (c) no musculoskeletal injuries in the previous 6 months. The participation of the cyclists was voluntary and, as minors, the research was also presented to their parents who, by completing and signing the informed consent, agreed to include their children in the study. The study, in accordance with the principles of the Declaration of Helsinki for the use of people in research, was approved by the Bioethics Committee of the University of Palermo, Italy (n. 132/2023).

- Procedure

Each participant was administered the V sit-and-reach (VSR) to measure the hamstring and lower back muscles flexibility and, moreover, the saddle pressures during pedaling at three different intensities (100, 140, 180 W) were recorded.

The test session took place in the laboratory from 3:00 to 6:00 PM during the winter preparation, a period in which there is no competition.

For the VSR test, each participant was seated on the floor with the lower limbs extended, feet spaced 30 cm apart, and the plantar surface of each foot touching a box to keep the ankle joints in a neutral position, forming a V-shape leg position (20, 21). Then, each participant was asked to keep their upper limbs extended, flex their trunk, and reach as far as possible sliding the hands along the floor. Three trials were performed, and the distance reached (cm) in the third trial was measured. Between trials, the participants rested for 1 min.

Subsequently, the saddle pressures during pedaling at three different intensities (100, 140, 180 W) were recorded. In detail, each participant was evaluated on their own bike installed on specific bike roller (MagneticDays; Foiano della Chiana, Arezzo, Italy) after performing a bike fitting (22–25). The bike fitting was performed with the aim of optimizing the posture and joint functions of each participant (26). Hence, each participant was asked to warm-up for 10-min at a self-selected pedaling cadence and intensity. Then, a flexible mat, composed of resistive sensors capable of recording saddle pressures (W-Saddle Pro, LetSense Group; Castel Maggiore, Bologna, Italy), was placed on a sex- neutral saddle (saddle A, Selle Italia S1; Casella d'Asolo, Treviso, Italia). The resistive sensors of the flexible mat are divided into three regions: pubic region (anterior), left back region, and right back region (Figure 1). Saddle pressures were recorded at 3 different pedaling intensities (100, 140, 180 W) with a pedalling cadence of 90 rpm. Each trial lasted 30 s and a 3-min rest between trials was scheduled. The trials at the different pedaling intensities were carried out in the following block order: (I) 100 W; (II) 140 W; (III) 180 W. The parameters considered for statistical analysis were front pressure (%) and back pressure (%).

- Statistical analysis

A descriptive analysis of all variables (means and standard deviations) was performed. Then, the Shapiro-Wilk's test was carried out to check data distribution.

Given the normal distribution of data, a predictive model was constructed using a linear regression analysis with the PAR on the saddle (100, 140, 180 W) as dependent variable and the muscles flexibility scoring as independent variable.

Statistical significance level was set at $p < 0.05$. All statistical analyses were performed using Jamovi software package (version 2.3.28) (27)

3. Results

The characteristics of the participants are shown in Table 1. Table 2 shows the scores of muscles flexibility of the VSR test, and the values of saddle PAR recorded at the 3 different pedaling intensities (100, 140, 180 W). The linear regression analysis showed that muscles flexibility was predictive of saddle PAR at 100 W (R2 = 0.362, p = 0.018), at 140 W (R2 = 0.291, p = 0.038),

and at 180 W (R2 = 0.349, p = 0.020) of pedaling intensity, as shown in Figures 2–4 respectively.

FIGURE 1

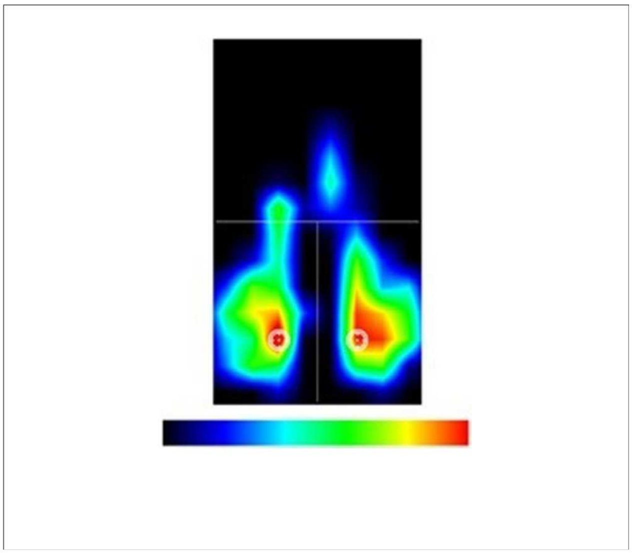

TABLE 1 Characteristics of the participants.

	Male	Female
n	11	4
Age (years)	13.5 ± 1.1	14.5 ± 0.5
Height (cm)	160.3 ± 11.1	162.3 ± 4.11
Weight (kg)	52.6 ± 12.6	53.2 ± 3.58
Body fat (%)	21.36 ± 6.82	25.6 ± 0.79

Values are reported as mean ± SD.

TABLE 2 Descriptive analysis of the performances of muscle flexibility and front pressure on the saddle.

VSR test (cm)	-4.93 ± 15.0
PAR (%) at 100 W	27.2 ± 14.2
PAR (%) at 140 W	27.2 ± 16.2
PAR (%) at 180 W	30.6 ± 24.1

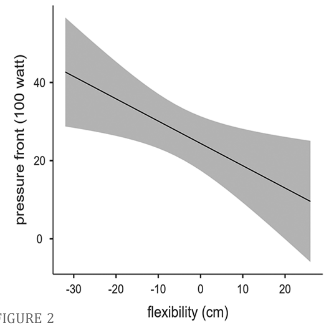

FIGURE 2

Linear regression between muscles flexibility and saddle PAR at 100 W of pedaling intensity.

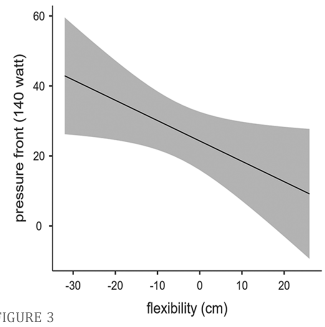

FIGURE 3

Linear regression between muscles flexibility and saddle PAR at 140 W of pedaling intensity.

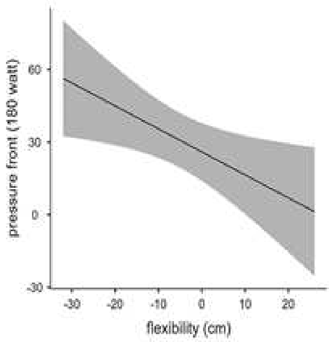

FIGURE 4

Linear regression between muscles flexibility and saddle PAR at 180 W of pedaling intensity.

4. Discussion

The aim of this study was to evaluate whether the flexibility of hamstring and lower back muscles could be considered a predictor of PAR on the saddle. Our hypothesis was a decrease in PAR on the saddle as the degree of flexibility of hamstring and lower back muscles increases. Our results confirmed our hypothesis, in fact, as the level of muscles flexibility increases, lower pressures were recorded in the anterior region of the saddle.

Studies on biomechanics are of crucial importance for preventing injuries (28), and due to the nature of cross-country races, that take place on uneven terrain, vibrations and impacts on the saddle could lead to repeated microtraumas with consequent uro-genital pathologies. Knowing the attributes related to saddle pressures could prevent the onset of these pathologies. Indeed, the practice of one discipline rather than another can lead, over time, to different adaptations in the cyclist's posture (4).

A recent study analysed the effects of practicing road and cross- country discipline on sagittal spine curves, on pelvic tilt, and trunk tilt showing that road cyclists have a greater thoracic kyphosis and a greater forward torso tilt than cross-country cyclists (4). These adaptations could be due to the different posture adopted. In fact, road cyclists have a greater saddle-handlebar height difference than cross-country cyclists. The same research group investigated the difference of road and cross-country cyclists on the extensibility of the hamstring muscles. Authors detected that road cyclists have a greater hamstring extensibility than cross- country cyclists (4). These findings could be explained by the different trunk position in these disciplines in which a greater trunk flexion is required in road cyclists. Previous studies have confirmed the relationship between the degree of muscle flexibility and pelvic position in the sagittal plane.

A study by Muyor et al. (2012) reported that the pelvis rotates forward after hamstring stretching (16). Similarly, Feland et al.(2001) confirmed that pelvic mobility in the sagittal plane increases after hamstring stretching in elderly people (29). Indeed, previous research groups showed that a greater hamstring muscle flexibility allow to reach a higher anterior PT than cyclists with a lower hamstring muscle flexibility (4, 30).

These studies are in line with our results, underlining that the pelvic position plays a key role in the distribution of pressures on the saddle. The present study showed that off-road cyclists who had a greater flexibility of hamstring and lower back muscles reported a lower saddle pressure in the anterior region.

These findings seem to be in contrast with most of the existing literature. Moreover, in cross-country cycling, to promote forward movement on the saddle especially on steep climbs and to avoid lower back pain, the saddle is positioned with the nose tilted down few degrees, this would allow the pelvis to rotate forward. The latter, together with the greater capacity to extend the hamstring muscles, would promote the anterior PT with a greater possibility of PAR on the saddle. However, our interpretation for the results found are in line with the abovementioned studies as these could be explained by the fact that these cyclists are better able to manage PT on the saddle compared to those with less muscles flexibility.

A recent review describes the factors that influence saddle pressures in order to prevent the related pathologies (5). As a matter of fact, some studies in the scientific literature have analysed the relationship between the use of different saddles and PT. The study by Bressel et al. (2003) examined the PT, trunk angle, and electromyography in 20 female cyclists (10 experienced and 10 novice) while pedaling on stationary cycle ergometers on three different saddles (without cutout, with partial cutout, with a complete cutout) (31). The authors' results showed that saddles with cutout in the front promote a forward PT.

Promoting a forward PT and trunk may help distribute a greater percentage of body weight over the handlebars, reducing the load on the saddle and spine (32). Indeed, it seems that the anterior tilt of the pelvis and trunk can reduce the incidence of low back pain (33). However, there are further studies that agree with our findings confirming that a forward PT increases the pressure exerted on the anterior perineum (31). The study by McEvoy et al. (2007) found greater anterior PT in elite cyclists than non-cyclists when sitting on the floor with knees extended

(17). This difference could be related to greater hamstring flexibility in cyclists. Furthermore, authors stated that an increased anterior PT facilitates the aerodynamics of competitive road cyclists. Therefore, greater flexibility of the hamstring and lower back muscles could increase the anterior PT and, consequently, facilitate the aerodynamic position of the cyclists.

Based on our results, the flexibility of the hamstring and lower back muscles could be a factor that can influence the distribution of pressures in the saddle. It should be noted that excessive pressure on the anterior region of the saddle can lead to hypoxia of the nerve, especially if this pressure is prolonged over time. Previous studies showed that an excessive pressure in the anterior region of the saddle is detrimental to the erectile tissues (9, 34). For this reason, reducing the compressive load on soft tissues is the main objective of bike fitting in order to prevent these pathologies.

5. Conclusions

The flexibility of hamstring and lower back muscles could be considered a predictor of pressure on the anterior region of the saddle. In particular, lower values from the VSR test could be indicative of higher values of PAR on the saddle. Coaches and cyclists should consider assessing the flexibility of hamstrings and lower back muscles to manage PAR. This assessment could be useful to optimise cyclist's position and, eventually, to plan a stretching training program.

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4.3 Other articles

4.3.1 Injuries in padel players: What is known? A scoping review

Valerio Giustino, Flavia Figlioli, Antonino Patti, Domenico Savio Salvatore Vicari, Giuseppe Alamia, Antonio Palma, Castillo-Lozano Romualdo, Ewan Thomas and Antonino Bianco

Abstract

Background: Padel has spread rapidly in several countries around the world. Although this racket sport seems to have several health benefits, the number of scientific papers on this sport is still very few. This scoping review aimed to sys- tematically map the evidence regarding injuries in Padel players by identifying, synthesizing, and assessing the studies cur- rently existing in the scientific literature.

Methods: This scoping review was conducted following the guidelines provided by the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews and the Population, Concept, Context framework was adopted. Articles were collected from PubMed, Web of Science, and Scopus.

Results: A total of seven studies were included in this review. The most frequent injury location is in the elbow, followed by shoulder, and low back. As for lower limbs, knee represents the most affected body region. Although not all the studies included described the type of injuries, tendon, joint, and muscle are the body structure most injured.

Conclusion: This scoping review can aid in a better comprehension of the location and type of injuries that occur in Padel players. However, it is worth noting that all the studies existing concerns nonprofessional athletes. Hence, these findings could be useful to

coaches as they add knowledge on the risk of injury in padel that can allow the planning of suitable training programs for amateur and recreational players in order to prevent injuries.

Keywords

Elbow, musculoskeletal, paddle tennis, racket sport, shoulder

Introduction

Padel, initially called Paddle or Paddle Tennis, is a racket sport born in Mexico in 1962.1 This sport has spread rapidly in Spain over the last few decades and is now becoming one of the most popular sports in several countries around the world.2 As a matter of fact, currently more than 60 federations have been founded and recognized all over the world.3 The growing interest in this sport is also accentuated by the great popularity that national and international circuits for professional athletes are gaining (first of all the World Padel Tour). Padel is played in doubles on a court with size of 20 m in length and 10 m in width and on a ground surface that can be composed of artificial grass, synthetic material, or cement. The court is enclosed by metal fences on the sides and glass walls at the end and at the corners of the court. The rules are almost the same as tennis with the difference that it is possible to play the ball after it bounces off fences or walls. Additionally, in padel is used a shorter racket with an unstrung but flat head perforated by cylindrical holes and made of foam, fiberglass, or carbon fiber and of different shape (i.e., diamond, drop, and round).

Padel is a high-intensity intermittent sport which combines high-frequency and low-intensity athletic actions and requires specific physical demands, similar to tennis, as well as related technical–tactical characteristics to obtain the highest performance possible and to prevent the risk of injury.5–8 However, compared to tennis as neither high physical fitness level nor high technical–tactical skills are required to start playing padel. A recent narrative review reported that the physiological demands to which Padel players are subjected during a match are lower than tennis players showing a mean oxygen consumption (VO2) of approximately 40–50% of the VO2 max and a mean heart rate (HR) of between 140 and 160 beats/min (70–80% of the HR max). However, the authors pointed out that different intensity patterns may exist depending on the level of players.9 Moreover, the long length of rallies makes the practice of padel enjoyable.10,11 As a result, this racket sport is widely practiced also in amateur and recreational form, and it seems to have several health benefits.12–14 For example, middle-aged adult women who practice padel regularly show greater physical fitness conditions than sedentary and better physical characteristics such as lower waist and hip circumferences and a lower thigh skinfold.12 However, the risk of injury is, per se, intrinsic to sports practice at any level and it is influenced by several factors such as physical fitness and the level of practitioners. As a consequence, the risk of injury can be higher in recreational contexts among amateur players, especially with a low experience of practice. In itself, the repetition of unilateral gestures, typical of padel, could lead to asymmetries or overuse injuries.9 Moreover, it seems that there is a higher incidence of injuries in those amateur players who do not perform joint mobility exercises, stretching, or specific strength exercises.15 A recent overview of the literature, which summarized some aspects of padel, suggested that in Padel players most injuries affect the lower limbs (ankle sprains are the most common injuries) followed by upper limb injuries (shoulder and elbow are the most affected regions with rotator cuff syndrome, subacromial impingement, bursitis, and epicondylitis as the most common injuries).5 Of interest, the association between some risk factors such as the use of padel-specific footwear or the type of racket and the risk of injury is not well understood.16,17 The growing interest in padel has led some research groups to conduct studies in order to better understand different aspects of this sport including performance,8,18 injury,16,17 biomechanics,19 match analysis,11,20 and physical, physiological, and psychological profile of players.14,21,22 Since this sport has become very popular first in Spain, to date most of the research has been developed in this country and some of these studies are in Spanish language.23–25 However, the number of scientific papers on this sport science area is still very few, and based on these premises, the following research question was formulated: what are the scientific knowledge on injuries in Padel players? Hence, this scoping review aimed to systematically map the evidence regarding injuries (location and type) in Padel players by identifying, synthesizing, and assessing the studies currently existing in the scientific literature. This scoping review could be useful to coaches in order to prevent injury in this emerging racket sport.

Materials and methods

This scoping review was conducted following the guide- lines provided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR).26

Eligibility criteria

The Population, Concept, Context (PCC) framework was adopted to select the studies for this scoping review.27,28 In particular, the following eligibility criteria were used:

(1) Padel players as population; (2) any information on injury in Padel players (incidence/frequency of injury, type of injury, location of injury, risk of factors) as concept; and (3) Padel players of any level/age/gender as context.

Studies were eligible if they were original articles written in English and published from inception to January 2023. Studies were excluded if they were reviews, meta-analyses, conference proceedings, opinion pieces, letters, editorials, commentaries, and books.

Search strategy

The databases searched to identify potentially relevant studies were PubMed, Web of Science, and Scopus using the search field "title" in each database. The search strategy matched the terms "padel" and "paddle tennis" with the term "injur*" using the Boolean operator "AND." In detail, "padel" AND "injur*", "paddle tennis" AND "injur*."

Study selection

The list of studies from each database was exported into EndNote X8 software for removing all duplicate records. Then, two independent investigators worked independently for screening records by title and abstract. Hence, studies were examined by full text to assess their eligibility for inclu- sion. In case of disagreement on study selection between the investigators, a third investigator was involved if needed.

Data extraction

Data regarding "first author and year of publication, aim of the study, sample size, number of males and females, participants' age, participants' level, participants' practice/ week, participants' experience, methods for injury data col- lection, and main outcomes" were extracted by one reviewer and inserted into a Microsoft Excel (Microsoft Corp, Redmond, Washington) spreadsheet. Data extracted were synthesized and presented as a "map" in a table and a descrip- tive narrative synthesis was used to discuss the results.

Results

Study identification

A total of 31 records were identified through searching multiple databases and after duplicates removed a total of 16 records were identified. Based on title and abstract screening, three records were excluded (two of them were reviews and one because it investigates injury in padel coaches). Hence, 13 full-text articles were retrieved and assessed for eligibility. Of these, six were excluded for the following reasons: two were conference proceedings and four were articles in other languages (i.e., three in Spanish and one in Sweden). The remaining seven studies were included in this review (Figure 1).

Study characteristics

Characteristics of the studies included in this review are reported in a table (Table 1). Among the studies identified, n = 5 were epidemiological, observational, descriptive, retrospective crosssectional studies,16,29–32 n = 1 was a cases report,33 and n = 1 adopted an empirical methodology.17

Studies considered represented data from 2150 participants (male = 1690, female = 460) ranging from junior to senior (age range from 15 to 60 years). Across studies, participants' level was amateur/recreational/nonprofessional. In the studies by Castillo-Lozano et al., details about recreational players were provided by specifying that participants included beginner, intermediate, advanced, and professional players.29–31 Participants' practice/week and participants' experience were not reported in all the studies considered. Apart from the study by Catalfamo et al. which was a case report,33 all studies employed the use of questionnaires to collect information about injuries.

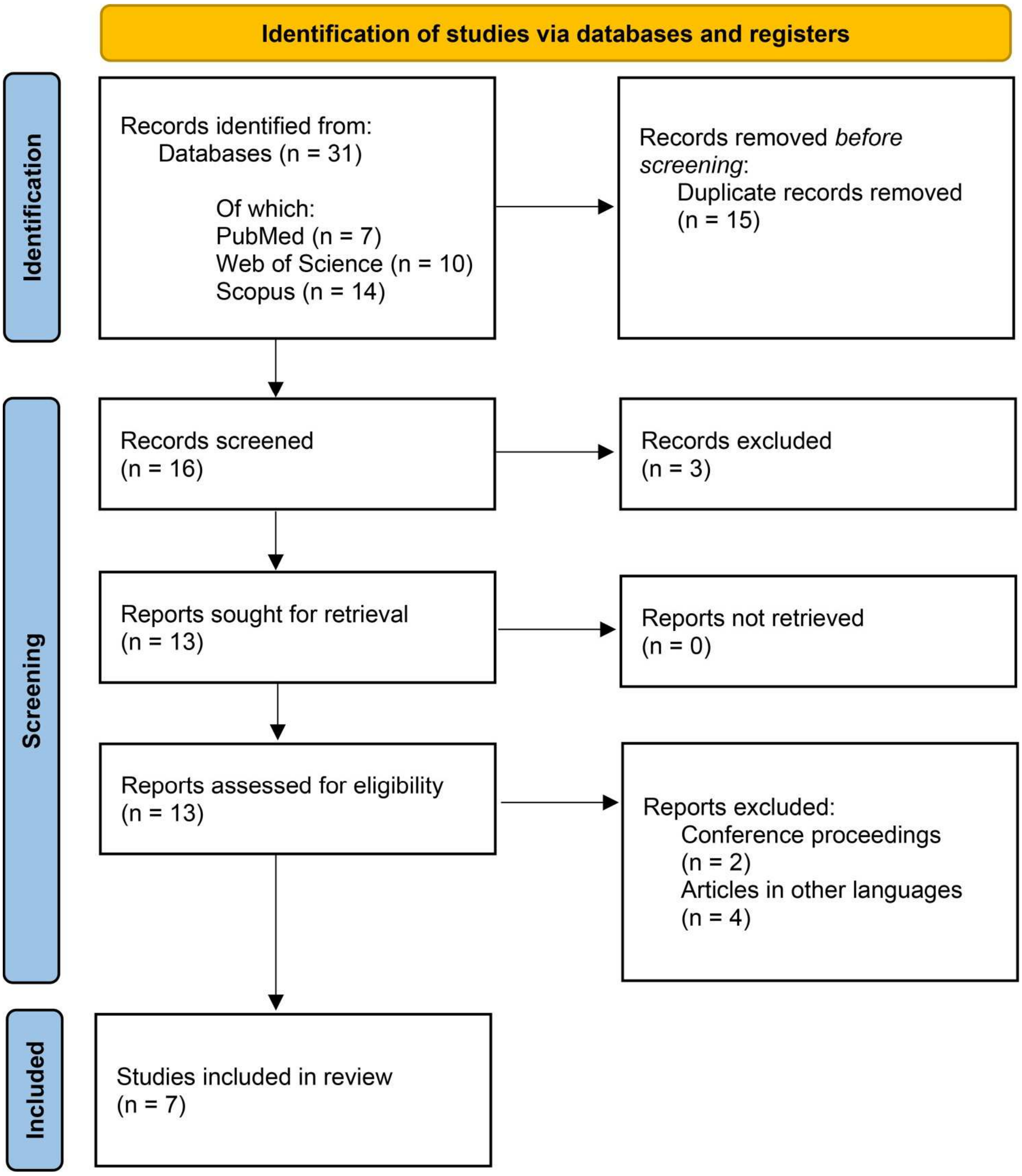

Figure 1. PRISMA 2020 flow diagram for new systematic reviews which included searches of databases and registers only. From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71. For more information, visit: http://www.prisma-statement.org/.

Study outcomes

Injury location. In all, almost all studies suggest that the most frequent injuries were located in the elbow. In detail, the study by Castillo-Lozano et al. showed that injuries fre- quency in the elbow was the 74.4% in a sample of n = 113 Spanish recreational Padel players followed by low back pain (20.2%).31 Similar results were found by the same authors in another research in which the most frequent musculoskeletal injuries in senior recreational Padel players were located in the elbow (29.8%) followed by low back pain (27.5%).30 This trend is confirmed by another work involved senior and junior recreational Padel players in which the authors reported that the most frequent body region injured was the elbow (36.7%), followed by knee sprain (20%), and low back pain (13.3%) in senior players; low back pain (23.3%), followed by elbow injuries (10%), and knee sprain (10%) in junior players.29 Similarly, Munoz et al. found that the frequency of injuries in the elbow has been reported in 35% of male amateur Padel players, representing the most frequent body region injured followed by shoulder injuries (33.8%); the reverse order of location of injury for female amateur Padel players was detected showing shoulder as the most injured body region and elbow as second, although the per- centage difference was almost equivalent (37.3% and 35.6%, respectively).17 Tagliafico et al. reported that the most frequent of injuries were located in upper limb (with the majority of them referred to elbow followed by shoul- der) and lower limb injuries being after with the knee as the most affected body part.32 Contrarily, the only study that found results not in consistent with the previous studies was that of Priego Quesada et al. in which authors found in the lower limbs the highest percentage of injuries followed by those in the upper limbs (53.1% and 37.5%, respectively), although details on upper and lower limbs regions are not reported.16

As for the study by Catalfamo et al., regarding maxillofacial injuries in Padel players, authors reported n = 5 cases of skin wounds and n = 7 par- ticipants with anterior dentoalveolar fractures.33

Injury type. Although not all the studies included described the type of injuries, Munoz et al. reported tendinous and muscular were the most frequent in both male and female players (48.7% and 34% vs. 44.1% and 28.8%, respect- ively).17 Similarly, Priego Quesada et al. found the same results with the joint as another body structure most injured (tendon 43.8%, joint 28.1%, muscle 28.1%).16 Tagliafico et al. reported the epicondylitis as the most fre- quent diagnosis (20.5%).32

Injury factors. Only two studies examined the association between extrinsic and intrinsic risk factors and injuries in Padel players. Priego Quesada et al. found that intrinsic factors such as sex, age, practice/week, and experience were not associated with injury and, among the extrinsic factors, footwear was the only associated with injury.16 Particularly, the authors found the highest frequency of injuries in Padel players wearing padel-specific footwear than those who wore another kind of sports footwear (50% vs. 23.3%, respectively). Moreover, the authors detected that the type of racket used was not a risk factor for injury. This last outcome is in disagreement with the study by Munoz et al. in which authors found differences in frequency of injuries according to racket shape (round 25.1%, tear 39.8%, diamond 35.1%), type of core (soft 41.9%, hard 58.1%), racket weight (<350 g 17%, ≥350 g 83%), number of over grips (none/1 54.6%, 2/more 45.4%), and composition (glass fiber 9.5%, carbon fiber 71.8%, unknown 18.7%).17 Furthermore, the authors deter- mined differences on frequency of injuries according to practice/week (<3 26.8%, 3–6 48.5%, >6 24.7%) and experience (<5 years 60%, ≥5 years 40%).

Discussion

Considering the rapidly growing popularity of padel, the aim of this scoping review was to systematically map the evidence regarding location and type of injuries in players of this sport. In fact, as with other racket sports, padel also seems to have several health benefits.12–14 However, since padel is a relatively recently born sport, there is a need to understand the epidemiology of the type and location of injuries that occur in padel.

The first important evidence to highlight is that there are no studies that have examined the injuries that occur in professional Padel players, and this suggests that it is not possible to have complete knowledge about injuries in this sport.

Moreover, it should be noted that considering all the studies, the percentage of amateur/recreational/nonprofessional female players is much lower than that of males, limiting the possibility of defining specific gender differences on injuries in padel because female players cannot be completely representative.

Other aspects to be noted are that most of the studies are retrospective cross-sectional, one study is a case report, and one study adopted an empirical methodology. This means that no experimental studies have been conducted on Padel players for investigating injury but, to date, only observational studies exist. Furthermore, except for that of Catalfamo et al.,33 all the studies used a questionnaire to collect data about injuries increasing the risk of reporting bias. Indeed, the study by Catalfamo et al. reported case reports on maxillofacial injuries that occurred during padel matches or training.33 The authors indicate that these injuries occurred due to the impact of the racket bouncing against the glass wall of the padel court. Indeed, during the game, the bounce of the racket occurs mainly because the players try to hit the ball close to the glass wall.

In all, evidence suggests that the most frequent injury location is in the elbow (mainly epicondylitis). Results of the present review indicate that also in padel, as with other racket sports, the elbow represents the most affected injury location.34 This finding is in line with several studies conducted in tennis, where it has been found that epicondylitis (or tennis elbow) is the main overuse injury of the upper limbs, due to the repetitive forces, loads, and motions to which the elbow is subjected while playing tennis, particularly in recreational players.35,36 Lateral epi- condylitis (tennis elbow) is seven times more frequent than medial epicondylitis (golfers elbow) and up to 50% of all regular tennis players suffer from this overuse injury.37 This occurs because of, in biomechanical analysis, the elbow plays a central role in the kinetic chain of the strokes in racket sports linking the body with the racket.35 In fact, it allows the transfer of kinetic energy from the body to the racket.35

Subsequently, the other frequent injuries in Padel players are located in the shoulder. In padel, this is particu- larly emphasized in power strokes, which are overhead (e.g., smash and tray).18 The shoulder is particularly involved during the strokes in all the overhead sports such as in tennis.38 Indeed, among the specific tennis injur- ies, the prevalence of shoulder injuries is also common due to repetitive use, as occurs for the elbow injuries.34 As reported in the review by Abrams et al., it seems that shoul- der injuries are related to a subtle instability in younger players while the rotator cuff injuries are more common in older player.34 In a recent review, a research group found that the rotator cuff injuries are caused by micro- trauma and internal impingement in younger players leading to tearing in older players.38

Based on the studies included in this review, other injuries in Padel players are in the low back and, as for the lower limbs, the knee (mainly knee sprain) is the most affected body region. Also, for analyzing these injuries, the tennis' kinetic chains associated with the repetitive strokes should be taken into account. In fact, there are two types of kinetic chains in tennis which, in our opinion, given the similar nature of these two sports, can also be transposed to padel. These are related to the different strategies of body segments coord- ination used according to the strokes.39 In detail, in power strokes and groundstrokes, a higher number of body seg- ments are required to be coordinated in order to produce a high racket speed at impact.39 In particular, this kinetic chain required leg drive and trunk rotations. Contrarily, in precision strokes such as the volley at the net, a lower number of body segments are required.39 Moreover, knee injuries in padel could be explained by the sudden running inversions, rotation, and stopping that occur at a high frequency in this racket sport.16 Moreover, it should be mentioned that the ground surface, which can be composed of artificial grass, syn- thetic material, or cement, can influence on these types of injuries.

Conclusion

This scoping review systematically mapped the evidence regarding injuries in Padel players. Results suggest that the most frequent injuries were located in the elbow fol- lowed by shoulder and low back. As for lower limbs, knee represents the most affected body region. As for the type of injuries, tendons, joints, and muscles seem that are the body structures most injured.

Strengths and limitations

The main strength is that, to the best of our knowledge, this is the first scoping review that systematically mapped the evidence regarding injuries in Padel players.

It is worth noting that all the studies existing and included in this scoping review concern nonprofessional athletes and that the percentage of female players is much lower than that of males. These aspects limit the possibility to analyze in depth and determine specific level and gender differences in injuries in padel. Moreover, it should be noted that most of the studies included are retrospective cross-sectional, one study is a case report, and one study adopted an empirical methodology. Further studies should, therefore, focus on these aspects as the literature is lacking.

Practical implications

Since this racket sport is widely practiced in amateur and recreational form, the results of this scoping review could be useful to coaches as they add knowledge on the risk of injury in padel that can allow the planning of suitable train- ing programs for amateur and recreational players in order to prevent injuries.

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Chapter 1

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