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Physical conditioning in land-based motorsports:

A scoping review of the scientific literature

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Porto, 2025

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A scoping review of the scientific literature

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Abstract

This dissertation investigated the current state of knowledge on physical conditioning in land-based motorsports. The primary objective was to conduct a systematic scoping review to map the existing evidence, identify key research gaps, and provide a comprehensive understanding of the physical demands and conditioning practices for drivers across various vehicle categories. To contextualize and demonstrate the pertinence of this main objective, an introductory narrative review established the context of land-based motorsports and underscored the necessity of targeted physical conditioning to prepare athletes for the unique physiological demands of driving a racing vehicle. The narrative review revealed an understanding of the impact on driver performance caused by the environmental stressors and physical demands of a land-based vehicle. The core of this work is a scoping review article guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. Following abstract and full-text screening, was performed a search of reference lists and a snowball citation search. Based on this process, supplemented by recommendations from external experts, a total of six studies were ultimately included for analysis. The scoping review highlighted significant gaps in the scientific literature. A primary finding is the small number of experimental studies designed to test the efficacy of specific training interventions, the biggest prevalence research focuses on profiling athlete characteristics or identifying the physical demands of the vehicle. Notably, the scoping review found a complete absence of experimental research on neck-strengthening interventions, indicating that current neck reinforcement programs are likely based on empirical practice rather than scientific evidence. Thereby, it highlighted an urgent need for experimental research that assesses the direct impact of structured training interventions on driver performance, emphasizing the importance of developing and validating evidence-based training protocols, particularly for neck reinforcement to enhance the safety and performance of motorsport athletes. This dissertation underscores the necessity of a research agenda that evaluates the combined effects of racing-specific stressors under real competition conditions and tailored training programs.

Keywords: Motorsports; Motor racing; Racing driver; Training; Conditioning.

Resumo

Esta dissertação investigou o estado atual do conhecimento sobre o condicionamento físico no automobilismo. O objetivo principal foi conduzir uma revisão sistemática de escopo para mapear as evidências existentes, identificar as principais lacunas de pesquisa e fornecer uma compreensão abrangente das demandas físicas e práticas de condicionamento para pilotos em diversas categorias de veículos. Para contextualizar e demonstrar a pertinência deste objetivo principal, uma revisão narrativa introdutória estabeleceu o contexto do automobilismo e ressaltou a necessidade de um condicionamento físico direcionado para preparar os atletas para as demandas fisiológicas ao guiar um veículo. A revisão narrativa revela uma compreensão do impacto no desempenho do piloto causado pelo ambiente e pela demanda física de um veículo de competição. O estudo central deste trabalho é um artigo de revisão de escopo, guiado pelas diretrizes do *Preferred Reporting Items for Systematic Reviews and Meta-Analyses* (PRISMA) 2020. Após a análise de resumos e textos completos, foi realizada uma busca nas listas de referências e uma busca por citação em cascata. Com base nesse processo, complementado por recomendações de especialistas externos, um total de seis estudos foi incluído para análise. A revisão de escopo, destaca lacunas significativas na literatura científica. Um achado principal é o pequeno número de estudos experimentais desenhados para testar a eficácia de intervenções de treino específicas A maior parte da pesquisa foca em traçar o perfil do atleta ou em identificar as exigências físicas do veículo. A revisão encontrou uma ausência de pesquisa experimental sobre intervenções para fortalecimento do pescoço, indicando que os programas atuais de reforço cervical são baseados na prática empírica, em vez de evidências científicas. Dessa forma, este estudo destaca a necessidade de pesquisas que avaliem o impacto de intervenções de treino estruturadas no desempenho do piloto, enfatizando a importância de desenvolver e validar protocolos de treino baseados em evidências, particularmente para o reforço do pescoço, a fim de aumentar a segurança e a performance dos atletas. Esta dissertação ressalta a necessidade de uma agenda que avalie os fatores de stress fisiológico específicos das corridas, em competição, e programas de treino personalizados.

Palavras-chave: Automobilismo; Corrida de automóveis; Piloto de corrida; Treino; Condicionamento físico.

List of abbreviations

CO - Carbon Monoxide

COD - Change of Direction

EGM – Evidence Gap Map

FIA - Fédération Internationale De L'automobile

G-FORCES - Gravitacional Forces

HG - Hand Grip

HIIT - High-Intensity Interval Training

HR – Heart Rate

LL - Lower-Limb

OSF - Open Science Framework

PCF – Participant Classification Framework

PRISMA - Preferred Reporting Items For Systematic Reviews And Meta-Analyses

VTS - Vienna Test System

Chapter 1

General Introduction

1.1 Rationale

The high-end world of land-based motorsports represents a multifaceted interaction between cutting-edge technology and human capability, encompassing disciplines from the strategic precision of Formula Racing and the arduous endurance of rally driving to the intense demands of motocross and the tactical prowess required in sports car racing and the foundational competitive demands (Del Rosso et al., 2015; Gobbi et al., 2005; Owen et al., 2015; Zarębski et al., 2025). Within this complex adaptive system, engineering provides the competitive platform but the human element – i.e., the driver – is the central subject to performance (Ferguson, 2019). Historically, the emphasis in motorsports rested predominantly on vehicle mechanics and engineering, addressing drivers as operators rather than elite athletes (Lighthall et al., 1994; Potkanowicz & Mendel, 2013). However, recent decades have witnessed a paradigm shift, recognizing the driver as a highly trained athlete whose physical and physiological capabilities are paramount to optimize vehicle performance and achieve competitive success (Ebben & Suchomel, 2012). The driver's ability to consistently operate at the physiological and cognitive limits, adapting to dynamic race conditions and extracting maximum performance from the machine, is the ultimate determinant of success (Potkanowicz et al., 2021). This critical interdependence between human and machine requires a profound understanding of driver physiology and its optimization, meaning that structured physical conditioning is no longer ancillary but a fundamental prerequisite for drivers to fully exploit the vehicle's capabilities and achieve the peak of competitive performance (Ferguson & Myers, 2018; Holland et al., 2025).

The environment of land-based motorsports imposes unique stresses on the driver, unparalleled in most other athletic environment (Reid, 2022). Drivers are routinely subjected to sustained gravitational forces (G-forces), particularly during extreme acceleration, braking, and cornering, which can exceed 5G (McKnight & Noonan, 2022). These forces place immense and prolonged musculoskeletal loads, especially on the neck, core musculature, and limbs (McKnight et al., 2019). Beyond this mechanical stress, thermal regulation presents a major challenge. Cockpit temperatures frequently surpass 50°C, leading to extreme heat stress and dehydration (Brearley & Finn, 2007). This combination of high G-forces and heat elevates cardiovascular strain, with heart rates

often sustained at over 85% of their maximum for the duration of a race (Reid & Lightfoot, 2019).

Concurrently, motorsports demand exceptional cognitive processing and neuromuscular control (Di Credico et al., 2024; Lappi, 2018). Drivers must interpret vast amounts of sensory information, make split-second decisions, and execute precise and complex motor skills under extreme physical and psychological pressure (Baur et al., 2006). The physiological stressors, including heat and sustained G-forces, are compounded by intense psychological stress, all of which contribute to physical and mental fatigue. This decline in executive function and reaction time can directly impact performance and safety (Ebben & Suchomel, 2012; Watkins, 2006). This unique constellation of physiological and cognitive demands underscores the necessity for targeted physical preparation that transcends general athletic training to ensure drivers can deal with these extreme conditions (Jacobs et al., 2002).

Given the nature and high-level demands of motorsport, sport-specific physical conditioning is not merely supplementary but fundamental to optimizing driver performance, enhancing safety, and promoting career longevity. Comprehensively, physical conditioning training programs needs to be meticulously designed to augment strength, particularly in the cervical spine and trunk to mitigate G-force-induced fatigue and injury risk, with specific attention to isometric and dynamic neck strength (Beaumont et al., 2022). Similarly, cardiovascular fitness must be considered to enhance oxygen delivery to working muscles and the brain, thereby delaying fatigue and preserving cognitive acuity during prolonged events (McKnight et al., 2019).

Despite the well-established needs of physical conditioning in land-based motorsports, the current body of literature is characterized by relevant inconsistencies and recognizable gaps. Therefore, the lack of optimal and standardized conditioning protocols tailored to specific motorsport categories is highlighted and addressed by profiling and understanding the physiological demands of racing drivers, evidencing the absence of empirically validated training methodologies consistently adopted across different vehicle types, motorsport series, or even within professional motorsport teams (Beaumont et al., 2024; Tornaghi et al., 2023). Consequently, racing drivers and their trainers have often tried to replicate the race environment without quantifiable data on the demands placed on the driver (Potkanowicz & Mendel, 2013). Additionally, even consultants and

specific laboratories working with racing drivers have not found a way to make these conditioning programs available to the public (Reid & Lightfoot, 2019). In most cases, trainers rely on their own experience or on general fitness literature to develop physical conditioning training programs for racing drivers. This point is corroborated by Tomás et al. (2016), who highlighted the need for tailored training programs that address the specific muscular requirements of different motorsport disciplines. Furthermore, minimal literature is available on appropriate training programs designed to offset the physiological challenges of auto-racing, emphasizing the urgent need for more extensive research in this domain (Reid & Lightfoot, 2019; Tornaghi et al., 2023).

We thus aimed to explore how physical conditioning is approached within land-based motorsport. We engaged in a narrative review with the aim of providing insights into the context and research landscape in this field. Additionally, we identified gaps by mapping the existing literature on physical conditioning interventions within land-based motorsports through a scoping review and the development of an evidence gap map (EGM). From a scientific perspective, this dissertation pinpoints the literature around physical condition in land-based motorsports, highlights its methodological inconsistencies, and delineates avenues for future investigation. From a performance standpoint, we provide an overview of the development through the years and current practices of physical conditioning in land-based motorsports. We further identify specific strengths and weaknesses of the literature, highlighting gaps in the published research.

1.2 Research aims

Our aim was to develop an understanding of the impact on driver performance caused by the physical demands of land-based vehicles. This is presented through a narrative review and a scoping review that highlight how the current body of literature has addressed physical conditioning within land-based motorsports. Specifically, it explores the types of training interventions employed, their contextual applications, and the adaptations made for different motorsport disciplines.

The main research question guiding this dissertation was: "Among racing categories, how are physical conditioning training programs structured for athletes in land-based motorsports?

The specific objectives were:

1. To provide a narrative review of the existing body of literature related to the physical conditioning of racing drivers across various types of land-based motorsport.
2. To conduct a scoping review categorizing the training interventions implemented within each land-based motorsport category.
3. To identify key characteristics of the scientific literature, focusing on participant and contextual variables such as motorsport type, age, sex, application context, and competitive tier.
4. To develop an EGM that offers a structured visualization of gaps in the current literature concerning the physical conditioning practices in land-based motorsports.

1.3 Thesis structure

This thesis was prepared according to the norms and guidelines of the Faculty of Sport of the University of Porto (FADEUP, 2024). It is structured using the Scandinavian model, which was chosen to enable the creation of a manuscript (i.e., scoping review) suitable for publication in a high-impact academic journal, thereby promoting wider dissemination of the research and raising the scientific level in the field. To achieve these goals, the thesis is divided into three distinct chapters.

Chapter One provides a general introduction to the content and scope of the thesis. It emphasizes the importance of the research question and thesis statement in guiding the overall direction of the dissertation. Additionally, this chapter features a dedicated subsection that articulates the primary research question and specific objectives.

Chapter Two offers a comprehensive narrative literature review, crucial for understanding the current state of physical conditioning for land-based motorsports. This chapter delves into four main aspects essential for gaining insights into the context and research landscape of this dissertation. Firstly, it analyzes the evolution of conditioning in motorsport, detailing how the subject has been addressed throughout the years and highlighting the significance of physical conditioning in motorsport. This analysis provides a comprehension of the impact on driver performance caused by the

environmental stressors and physical demands of a land-based vehicle. By understanding these aspects, the narrative review establishes a foundation and pertinence for the scoping review next presented.

Chapter Three presents the scoping review with an EGM. This review aims to understand the published research related to physical preparation for drivers across various types of land-based vehicles and their unique requirements. Specifically, the scoping review was designed to understand how physical conditioning training programs are designed and applied within different land-based motorsport contexts. Both the scoping review and the EGM were employed to provide a comprehensive understanding of the objectives outlined as the research aims.

Finally, Chapter Four presents the general discussion, main conclusions, limitations of the thesis, future research directions.

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Chapter 2

Narrative review

Not yet submitted to publication

The role of physical preparation in motorsport for different type of vehicles: A narrative review

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Abstract

Background: Despite motorsports' widespread appeal, there is a notable paradox in the role of the racing drivers as athletes. Early performance models did not view the driver as an athlete, and even drivers themselves often struggled with being recognized as such. This has historically led to their exclusion from scientific research focused on athletic performance. **Objective:** The aim was to provide a comprehensive overview of the evolution of physical conditioning in land-based motorsports. We investigated the physical demands that a land-based vehicle imposes on a racing driver, drawing from all types of sources, whether empirically validated or not, to examine the physical profiles required to cope with such demands. **Methods:** A narrative review of the literature was conducted to address historical misconceptions and synthesize what is required for a racing driver to handle different vehicle types, taking into consideration diverse sources such as, online material, opinion articles and practical reports, in order to understand the status quo of the evolution of physical preparation, the physiological demands of racing, and the corresponding training programs in motorsport. **Findings:** The evolution of driver training has progressed from being focused solely on safety concerns to a more holistic training perspective, moving away from the initial idea of not considering the driver as an athlete at all. The physical demands are unique and severe, varying significantly by the type of vehicle: Closed-wheel, Open-wheel and Two-wheel. Each type of vehicle has specific training recommendations based on studies that have profiled the drivers. For closed-wheel vehicle drivers, full-body exercises and multi-joint lower limb [LL] exercises are recommended. Open-wheel vehicle drivers are advised to focus on LL and neck strength, while two-wheel vehicle riders are suggested to concentrate on hand grip [HG] strength training. **Conclusion:** Tailored conditioning programs that cater to the unique physiological demands of each motorsport category are fundamentally linked to both performance and safety. Therefore, it is crucial to verify, in a concrete and systematic manner, whether physical conditioning programs in motorsport are being empirically investigated, to improve the ecological validity of training recommendations, driver performance and safety.

Keywords: Motorsport; Motor racing; Racing driver; Training; Physical preparation; Motorsport training.

1 Introduction

Even though millions of people watching and being often involved in racing events, a great paradox lies at the core of motorsports (Wood & Burkhalter, 2023). There is a distinct gap between how the public views racing drivers and the reality of their profession (Ferguson et al., 2015). The image of a driver merely sitting and steering a high-tech machine is powerful, but it is also deeply misleading. The physical demands of controlling a racing vehicle are extreme, but this reality remains invisible to most of the public. Drivers are seldom seen as athletes, and for a long time, they did not even recognize themselves as athletes (Potkanowicz & Mendel, 2013). The understanding of the racing driver as an athlete is paramount, and the body of literature has changed the research approach on the subject (Jutley, 2003; Owen et al., 2015).

The word “athlete” derives from the Greek term “athlos”, which means “achievement” or “contest,” and reflects a deeper understanding of the concept, encompassing some of the greatest virtues of human existence (Campa & Coratella, 2021). The term “athlete” can be defined from various perspectives. For instance, the Cambridge Dictionary defines an athlete as “a person who is very good at sports or physical exercise, especially one who competes in organized events” (Brown et al., 2013). From that point of view, racing drivers are completely included in the athlete characterization. Although motorsport athletes do not perform traditional athletic movements like running or jumping during competition, they suffer from similar demands found in traditional sports. These demands, involving significant physiological, psychological, and emotional stress, are often what characterize someone as an athlete (Backman et al., 2005; Baur et al., 2006; Del Rosso et al., 2016).

In any category of motorsport, drivers must manage high speeds and multitasking demands of driving (e.g., braking, steering), sustained and continuous performance periods lasting 2-3 hours, persistent thermal stress, and the stress imposed by all these factors. Moreover, there is an ever-present risk of injury or even death (Altmann et al., 2011; Ferguson, 2019; Potkanowicz & Mendel, 2013). Thus, it is critical to comprehend these variables and the specific factors that auto racing imposes on drivers to provide targeted interventions for training (Beaumont et al., 2023). As Hoffman (2002) emphasized, physical training in motorsports should be relevant and appropriate to the athlete's sport to achieve the desired training effect. Recent research has investigated the

impact of being prepared and trained for these variables and their subsequent influence on drivers' performance (Barthel & Ferguson, 2021; McKnight et al., 2019).

Over the years, both the scientific literature and the athletes and teams themselves have come to acknowledge the critical role of physical conditioning and its subsequent impact on competitive performance in the context of motorsports (McKnight et al., 2019). For drivers of closed-wheel vehicles, the challenges include withstanding cockpit temperatures that can reach 82°C and exposure to high levels of carbon monoxide due to the enclosed cabin. Conversely, drivers of open-wheel vehicles must contend with significant gravitational forces (G-forces), which can reach up to 5-G on certain circuits (Potkanowicz & Mendel, 2013; Reid & Lightfoot, 2019). Given these evolving demands, several questions arise: How has physical conditioning evolved over the years to adapt to the challenges presented by faster and more demanding vehicles? Is there a specific physical conditioning program tailored to these needs? And how are physical conditioning training programs designed to address the unique demands of this sport?

To answer these questions, this narrative review aimed to provide a comprehensive overview of the evolution of physical conditioning in the land-based motorsports. Specifically, it explored the physical demands that a land-based vehicle imposes on a racing driver, drawing from all types of sources, such as, online material, opinion articles and practical reports whether empirically validated or not, to examine the physical profiles required to cope with such demands. It becomes crucial to highlight the physical conditioning training programs designed for racing drivers and expose their specificities and differences. By addressing historical misconceptions and highlighting recent research, this narrative review aims to expose the contrast between physical conditioning and land-based motorsports.

2 Evolution of Physical Conditioning in Motorsport

A key role of a physical conditioning program is to enhance an athlete’s capacities, with the aim of improving competitiveness and overall sports performance (Jeffreys & Moody, 2021). However, motorsport has traditionally been defined by the challenge of determining which combination of vehicle and driver can complete a course in the shortest time (Brown et al., 2019). Between 1966 and 2019, only 46 reports

addressed the physiology of auto racing athletes, with the majority published after 2000. Before the 1980s, in the sport's foundational era, performance was driven almost entirely by advances in mechanical engineering, and variables such as engine output, chassis design, and braking power were considered the primary determinants of victory (Potkanowicz & Mendel, 2013). The driver, though indispensable, was often viewed as a human component integrated into the machinery, an operator who gather innate skill and tactical sharpness. However, their physical condition remained largely absent from the performance equation. This vehicle centered mentality fostered a culture that relegated the human factor to a supporting role and ensured that the driver was rarely seen as an athlete (Reid & Lightfoot, 2019).

Even the drivers, over the years, often dismissed the idea of viewing themselves as athletes (Ferguson, 2019). Their focus remained aligned with the pursuit of the car that brought together the best combination of technical factors to achieve greater speed (Potkanowicz & Mendel, 2013). It was only after Nelson Piquet collapsed on the podium following a Formula 1 Grand Prix in 1982 that the Fédération Internationale de l'Automobile (FIA) began to show some concern for the physical condition of drivers. However, this concern was not initially rooted in optimizing performance but rather emerged from a growing safety risk concern (Jutley, 2003). One of the first to highlight the importance of physical fitness and the impact on the performance of a race car, was the three-time Formula 1 World Champion Ayrton Senna, who stated in an interview:

"You can drive a Grand Prix car whether you are fit or unfit but for how long you can drive, how precise, how consistent you can drive under stress, under high temperature, the difficult conditions during race is another thing. You know that's gonna be tough, you know you gonna feel tired, gonna have some pain, you gonna lose a lot of liquids. But you know you can do it as good as anybody if not better if you are well trained, well fit. So, if you are not fit your concentration just tends to go gradually away during a race" (Senna, 1992).

At this time, the main issue was that the scientific community did not produce studies to validate physical training for racing drivers, largely because until quite recently, they were not even regarded as athletes (Beaune et al., 2010). Early concerns regarding drivers' physical condition were primarily related to safety while operating the vehicle, rather than performance optimization. As a result, racing drivers and their trainers were

left without formal guidance, each relying on empirical assumptions to develop training routines they believed were needed (Lighthall et al., 1994; Potkanowicz & Mendel, 2013).

Automobile racing is a physical demanding sport (Holland et al., 2025). Refined neuromuscular control translates directly into precise and fast vehicle handling promoting accurate responses to changing track conditions (Backman et al., 2005). Moreover, bespoke training modalities, such as grip strength exercises are crucial for maintaining control, while rigorous heat acclimation protocols, directly prepare drivers for the unique environmental stressors of racing, facilitating superior thermoregulation and sustained performance in extreme conditions (Walker, Dawson, et al., 2001). Such integrated physical preparation allows for a higher adaptive reserve, enabling any athlete to focus more acutely on strategic elements rather than succumbing to physiological limitations, thereby directly influencing performance consistency (Alhumaid et al., 2022).

Each racing category is defined either by the type of vehicle or the context of competition. Open-wheel vehicles feature cars with open cockpits and engines positioned behind the driver. Such configuration influences the driver's exposure to heat, noise, and carbon monoxide (CO) (Walker et al., 2001). Closed-wheel vehicles with front engines, rear-wheel drive, and enclosed cockpits exacerbate these stressors due to the confined design of the cabin (Reid & Lightfoot, 2019). Additionally, two-wheel vehicles with large engine sizes (e.g., 600cc, 1000cc) and high-speed environments, combined with minimal rider protection, introducing a constant risk of falling (D'Artibale et al., 2007).

The evolution of physical conditioning in motorsport has been shaped by several critical turning points. The episode involving Nelson Piquet in 1982 underscored the importance of safety-related aspects of physical preparation, drawing attention to the role of fitness in mitigating health risks under extreme racing conditions (Jutley, 2003). Subsequently, the focus shifted toward the relationship between physical fitness and performance, driven by the premise that improved athletic capacity translates into enhanced on-track results. This progression has culminated in a contemporary, holistic training paradigm. Modern motorsport conditioning now extends beyond traditional strength and endurance training, like many other sports, and increasingly incorporates agility training, structured psychological support, and advanced cognitive training interventions (Scanlan et al., 2014). These approaches are designed to optimize mental

acuity, decision-making, and precision in high-stress competitive environments (Oliver & Meyers, 2009).

3 Physical Demands Profile of a Racing Driver

As motorsport training methodologies have advanced, scientific research has progressively shifted toward characterizing the unique physiological, biomechanical, and cognitive demands imposed on drivers by the competitive environment (Carlson et al., 2014; Ferguson & Myers, 2018; (Potkanowicz & Mendel, 2013). Contemporary research emphasizes that these demands are shaped by a range of contextual factors, including circuit configuration (e.g., oval, road circuits), race duration, vehicle characteristics, and competitive format (e.g., single-seater, team-based events) (Beaumont et al., 2023). Each of these variables imposes distinct stressors on the athlete, influencing cardiovascular load, neuromuscular fatigue, thermoregulatory strain, and cognitive workload throughout competition (Reid & Lightfoot, 2019). As a result, conditioning programs have progressively evolved to replicate these stressors. However, a key limitation in the scientific literature is that research has focused on studying individual stressors experienced by racing drivers (e.g., Konttinen et al. (2008); Lappi (2018)), often evaluated during the off-season using instruments and protocols that are not feasible to use during actual competition. While such studies provide valuable insights, their findings may lack full ecological validity, limiting their applicability to real race conditions (Beaumont et al., 2023; Jacobs & Olvey, 2000; Jacobs et al., 2002; Schwaberger, 1987; Walker, Ackland, et al., 2001).

By examining the physical demands imposed by vehicle stressors, the scientific literature has increasingly sought to characterize the physiological profiles and performance requirements of racing drivers (Raschner et al., 2013). With the concomitant development of vehicle technology over the years resulting in faster cars, increased downforce, greater G-force exposure, and heavier braking loads influences the physical demands imposed on racing drivers (Ferguson, 2019). These technological advancements have, in turn, influenced the physiological profiles and performance requirements of racing drivers, requiring continuous adaptation in the physical conditioning training programs. The most common demands identified by the drivers are upper body strength,

cardiovascular endurance and heat tolerance (Ebben & Suchomel, 2012). Racing drivers demonstrated greater isometric strength, faster perceptual processing, and shorter reaction times compared to physically active control subjects (Backman et al., 2005; Baur et al., 2010; Rosalie & Malone, 2018).

Physical profiling of racing drivers begins with a rigorous understanding of sport-specific demands and the identification of each athlete's physiological and physical characteristics within their competitive category. Accordingly, segmentation by vehicle type is essential to provide a coherent framework a state-of the-art overview of the physical profiles required of drivers across different classes of motorsport.

3.1 Four Open wheel

Drivers of open-wheel vehicles, such as Formula 1 and IndyCar, experience sustained lateral G-forces often exceeding 4–5 G during high-speed cornering, coupled with intense braking loads, requiring exceptional isometric neck and core strength, forces comparable to those experienced in some fighter aircraft maneuvers. Managing such extreme loads demands exceptional isometric neck and core strength to stabilize the head and torso, alongside superior aerobic capacity to support both cardiovascular and muscular endurance (Reid & Lightfoot, 2019). The cardiovascular demand is directly influenced by the impact of these stressors on the body. In the fastest open-wheel vehicle, the Formula 1 car, the mean HR recorded during a Grand Prix was 146 bpm, with peak values observed at the start of the race and lower levels during safety car periods (Tornaghi et al., 2023; Turner & Richards, 2015).

3.2 Four Closed wheel

In closed-wheel disciplines, including endurance racing, touring cars, and GT series, peak G-forces are comparatively lower, but prolonged driving stints in elevated cockpit temperatures impose significant cardiovascular and thermoregulatory strain, demanding fatigue resistance, consistent upper-body and trunk endurance, and effective heat management strategies (Barthel & Ferguson, 2021; Carlson et al., 2014). Carbon monoxide [CO] exposure is particularly significant in vehicle types where air quality is compromised by exhaust fumes from race cars and the electrical generators used in

garages and pit areas (Reid & Lightfoot, 2019). In general, CO exposure increases with the number of cars on track, vehicle proximity, and race duration. On oval circuits, where large numbers of closed-wheel vehicles compete, CO concentrations are even higher (Gwin et al., 2005). Elevated CO levels can increase the circulating carboxyhemoglobin concentration in motorsport athletes, potentially leading to moderate CO poisoning, which may cause symptoms such as headache, lethargy, and fatigue (Smollin & Olson, 2010).

3.3 Two wheel

Two-wheel motorsports, such as MotoGP and motocross, present additional challenges, including dynamic balance, asymmetric load handling, and postural adjustments, emphasizing core stability, limb strength, and fast reaction times to manage unpredictable track surfaces (D'Artibale et al., 2007; Marina et al., 2011; Martin et al., 2019). Finally, four-wheel off-road disciplines, such as rally and rally-raid, expose drivers to irregular terrains and changing environmental conditions, requiring dynamic trunk stabilization, cognitive adaptability, decision-making, and endurance to tolerate vibration, impacts, and thermal stress across long stages (Backman et al., 2005b; Del Rosso et al., 2016). In two-wheel motorsport, rapid accelerations, abrupt decelerations, and extreme lean angles during cornering impose substantial physical and neuromuscular demands on riders. Effective control of the motorcycle requires precise body-weight distribution and continuous postural adjustments to maintain stability under these dynamic conditions. Consequently, riders must strategically regulate their physical exertion across the race weekend, balancing training intensity and recovery to prevent fatigue from impairing performance in early sessions while ensuring optimal physical readiness for qualifying and race events (D'Artibale et al., 2007; Gobbi et al., 2005).

4 Tailored Training programs for Different Motorsports

Physical strength plays a critical role in preventing injuries in automobile racing. Previous research has shown that injuries such as those affecting the back, neck, shoulders, hands, knees, and certain muscle strains can be reduced through the implementation of effective strength and conditioning programs. These programs not only

help to reduce the risk of injuries but also enhance the overall physical resilience and stability of the drivers (Ebben & Suchomel, 2012b; Hanna, 1963). Strength forms the foundation upon which all other physical performance qualities, such as power, speed, and agility, are built. In order to optimize these qualities, it is essential to develop proper strength (Lorenz & Morrison, 2015). Drivers require sufficient strength, particularly under fatiguing conditions, to achieve the high pedal forces needed for braking (approximately 600–700 N in Gran touring sports car racing) and to stabilize the body and extremities against the high mediolateral and anterior-posterior G-forces generated during races (Jacobs et al., 2002; Mansfield & Marshall, 2001; Walker-Bone & Cooper, 2005).

A tailored training program for motorsport athletes should reflect the distinct physical demands imposed by each vehicle category (Potkanowicz & Mendel, 2013). In open-wheel racing, where drivers experience greater G-forces, athletes exhibit superior strength in neck extension, flexion, and lateral flexion compared to those in closed-wheel vehicles, emphasizing the need for targeted strength and power development in the neck lateral flexors and knee extensors (Ferguson, 2019). Such training should prioritize low-repetition, high-intensity resistance programs to maximize strength while minimizing undesirable increases in body mass due to strict weight regulations (Beaumont et al., 2023). Conversely, VO_2max values show minimal variation between open- and closed-wheel drivers, likely reflecting similar cardiovascular demands. For riders of two-wheel vehicles, research has primarily focused on HG strength and cardiovascular parameters, with consistently higher HG values observed in the right hand due to throttle use, and off-road riders demonstrating greater VO_2max levels than on-road riders (D'Artibale et al., 2007; Mansfield & Marshall, 2001). These findings highlight the importance of both resistance training for HG strength and cardiovascular conditioning for all two-wheel vehicle athletes, particularly in disciplines such as motocross where aerobic capacity plays a critical role.

4.1 Four Closed wheel

Athletes competing in closed-wheel vehicles exhibit greater ankle plantarflexion and shoulder strength compared to those in open-wheel vehicles, largely due to differences in cockpit design. In closed-wheel vehicles, drivers are seated with increased

hip and knee flexion degrees, which places greater mechanical demand on the ankle plantar flexors. Similarly, shoulder flexion strength is elevated in these athletes because closed-wheel vehicles allow greater freedom of movement in the steering wheel, requiring increased upper-limb engagement compared to the more constrained steering positions typical of open-wheel vehicles (Beaumont et al., 2023). Accordingly, conditioning programs for closed-wheel drivers should prioritize the development of LL strength and power, while also incorporating targeted training to improve both shoulder strength and neuromuscular control. Such an approach aims not only to enhance on-track performance but also to reduce the risk of musculoskeletal injuries associated with the unique postural and mechanical demands of these vehicles (Salles et al., 2015; Smilios et al., 2013).

For closed-wheel vehicle athletes, a comprehensive full-body muscular endurance program is recommended (Ebben, 2010). Additionally, multi-joint LL strength exercises, such as squats and lunges, should be supplemented with selected open kinetic chain movements, as pedal transitions between the brake and accelerator occur in an open kinetic chain. The seated leg press offers biomechanical specificity to the driving position, and when initiated with a visual stimulus and the foot starting off the platform, it can simultaneously train LL strength and braking reaction time (Ebben & Suchomel, 2012). In categories with comparable vehicle configurations, such as GT endurance racing, prolonged physical stress combined with cumulative fatigue needs targeted cognitive training to maintain focus and decision-making capacity during extended events lasting up to 24 hours (Ferguson, 2019).

4.2 Four Open wheel

Athletes competing in open-wheel vehicles experience greater G-forces and consequently demonstrate superior strength in neck extension, flexion, and lateral flexion compared to their counterparts in closed-wheel categories. In contrast, VO_2max values show minimal variation between the two groups, likely reflecting comparable cardiovascular demands imposed by both forms of racing. (Backman et al., 2005; McKnight et al., 2019). The primary recommendation for athletes competing in open-wheel vehicles is to address the specific physical demands imposed by this category (Beaumont et al., 2023). Training should focus on developing strength and power in the

neck lateral flexors and knee extensors, while carefully monitoring body mass due to strict weight regulations (Crewther et al., 2005). Strength and resistance programs should emphasize low-repetition, high-intensity training aimed at maximizing strength and power while minimizing undesirable changes in body composition (Schoenfeld et al., 2016).

An important component of the training program for open-wheel athletes is long-duration endurance training, as drivers can experience HR reaching up to 80% of their maximum during races, making cardiorespiratory fitness essential (Ferguson, 2019). Regarding neck training, the manufacturer of a specialized training device recommends that programs should: first, target the major neck movements (e.g., extension, flexion, and rotation), second, employ lower loads initially to develop a foundation of muscular endurance, and third, utilize loading patterns that replicate the duration and intensity of peak forces experienced by drivers. The manufacturer also emphasizes that the device provides quantifiable data, giving the opportunity for drivers and their trainers to design individualized, neck training programs (Gatherer et al., 2018).

4.3 Two wheel

Riders of two-wheel vehicles have primarily been assessed for HG strength and HR, with studies reporting higher HG values in the right hand, likely due to the use of the throttle on that side (D'Artibale et al., 2007; Marina et al., 2011; Martin et al., 2019). Within this same classification, off-road riders demonstrate higher VO_2max levels compared to on-road riders, reflecting the greater cardiovascular demands of off-road conditions (Gobbi et al., 2005). General training recommendations for riders of two-wheel vehicles emphasize the development of HG strength through targeted resistance training. Moreover, given that motocross riders typically demonstrate elevated VO_2max levels, these findings highlight the importance of incorporating cardiovascular training into the conditioning programs of all two-wheel vehicle athletes (Beaumont et al., 2023; Owen et al., 2015).

Conditioning program for two-wheeled vehicles must be multifaceted, integrating robust physical and neuromuscular development with advanced cognitive training. The physical foundation is built upon a blend of high-intensity cardiovascular training such as circuit training and High intensity interval training [HIIT] sessions to ensure sustained

aerobic and anaerobic endurance, and a targeted strength program (MotoGP, 2025). Neuromuscular stimuli consist in Upper-body exercises (e.g., pull-ups, rows) improve grip and steering control, core stabilization (e.g., planks, crunches) enhances braking and cornering, and lower-body training (e.g., squats, lunges) supports precise bike manipulation (Konttinen et al., 2008). Cognitive resilience is equally emphasized: expert motor racing skill hinges on refined perceptual-cognitive expertise a product of deliberate practice and top-down processing rather than innate ability (Lappi, 2018).

5 Final thoughts

A paradigm shift can be seen in the evolution of physical conditioning in motorsport, which has transformed the racing driver from a passive part of high-performance equipment to a specialized athlete acknowledged as a key factor in competitive success. At first, safety concerns were the main motivation behind conditioning efforts, but growing scientific data has shown a direct correlation between physical fitness and athletic performance. A more holistic viewpoint that recognizes the role of the driver's physiological and psychological abilities has gradually replaced the long-standing mechanistic mindset that saw success as the result of technological and engineering breakthroughs. This shift is evidenced by growing research that highlights the unique and demanding physiological stressors experienced by drivers such as thermal load, cardiovascular strain, and neuromuscular fatigue which demand structured, athlete-focused training interventions. Motorsport is a physically demanding sport with a variety of physiological stressors that can have a significant impact on competitive results. It is by no means just a matter of sitting and turning left. The scientific community has responded to drivers and teams growing recognition of these demands by conducting research to pinpoint the precise stressors at play and create customized training plans that maximize efficiency and safety (Altmann et al., 2011; Ferguson, 2019; Ferguson et al., 2015; Potkanowicz & Mendel, 2013).

Open-wheel vehicle drivers must withstand strong G-forces, which frequently exceed 4 to 5 g, especially when braking and cornering. These forces place heavy demands on the head and neck, necessitating very high strength in these areas (McKnight et al., 2019). Closed-wheel competitors, as stock cars, on the other hand, experience

prolonged cardiovascular and thermoregulatory strain. Research has shown significant increases in skin and core temperatures, heart rates that are close to 80% of their maximum, and physiological strain indicators that point to moderate to high levels of physiological stress (Carlson et al., 2014). While motocross athletes exhibit higher aerobic power and muscular strength than other rider categories, motorcycling and off-road disciplines add yet another set of demands, including high intensity braking and leaning maneuvers, which expose them to repetitive inertial stresses (D'Artibale et al., 2007). As a result, training that is one-size-fits-all is not effective. In order to meet their specific physiological and neuromuscular demands, two-wheel athletes require HG strength and aerobic training, closed wheel drivers needs endurance conditioning, and thermal management techniques, while open-wheel drivers require high-intensity, low-repetition range, neck and core strength (Ebben & Suchomel, 2012; Ferguson, 2019; Gobbi et al., 2005).

The physical conditioning required for land-based motorsports has evolved significantly over the years, with growing public understanding of each racing category presents unique physical demands. Whether for safety or performance, this technology driven sport has advanced in identifying the specific needs of drivers and in tailoring training programs accordingly. The physiological demands vary depending on factors such as whether the vehicle has an open or closed cockpit, and whether it is a two or four-wheeled machine. These variables directly impact what the driver experiences on track, making it essential for coaches to first understand the vehicle's characteristics before designing appropriate physical conditioning programs. For example, closed-wheel drivers often focus on LL strength and power, along with targeted shoulder training, while open-wheel drivers require greater neck strength and must carefully monitor body mass due to strict weight regulations. Two-wheel riders, on the other hand, need a combination of sustained aerobic and anaerobic endurance, supported by a targeted strength training program. Ultimately, recognizing and addressing and studying these distinct physical conditioning training programs is crucial improve sport safety and competitive performance.

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Chapter 3

Scoping Review

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What do we know about physical conditioning in land-based motorsports? A scoping review

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Abstract

Land-based motorsport places high physical demands on drivers, yet evidence on conditioning practices is limited. Thereby, this scoping review aimed to map current research, highlighting its key features, gaps, and future directions. Following PRISMA-ScR and PRISMA 2020 guidelines, the search was conducted in PubMed, Scopus, and Web of Science databases on November 15, 2024. Studies of any date or language were included if they assessed physical training in competitive motorsport drivers. Additional sources included reference lists, citation tracking, and recommendations from external specialists. Two authors independently screened all records. The initial search yielded 192,748 records, of which six studies met the inclusion criteria, underscoring a substantial deficit in the evidence base. Most studies involved male drivers in on-road, open-wheel racing and focused on in-vehicle, cognitive, and strength training. Two key gaps emerged: no studies on world-class or national-level drivers, and no interventions targeting neck strength, vital for managing high G-forces. Thus, current literature lacks evidence to support training guidelines for motorsport athletes. Homogeneous study samples and overlooked areas, like neck conditioning, demonstrated a disconnection between research and specific demands. Future studies should focus on targeted interventions and include diverse, elite drivers to inform effective, sport-specific conditioning protocols.

Keywords: Motor racing; Racing driver; Training programs; Physical preparation

1 Introduction

Overall, motorsport includes all types of motorized vehicles competing across diverse terrains, ranging from four-wheeled vehicles, both open and closed, on-road and off-road, to two-wheeled vehicles on similar surfaces. The range of land-based racing within motorsport presents a set of challenges and characteristics, including open-wheel racing like Formula One and IndyCar, as well as rally and stock car racing (Haynes & Robeers, 2020). Racing takes place not only on-road, in street circuits and purpose-built tracks (e.g., Formula One and IndyCar), but also off-road, in environments like mountains, snow, or desert sand (Del Rosso et al., 2016). Closed-wheel racing, like touring car racing, with enclosed wheels, often based on production models, competing on both circuits and street tracks. Additionally, two-wheeled racing, such as Motocross and MotoGP, occurs in both on-road and off-road versions (Gobbi et al., 2005).

Racing drivers face physical challenges, primarily the high gravitational forces [G-forces] present in all competition categories with different intensities within vehicle speed and cornering (Gatherer et al., 2018). To ensure performance and safety, drivers perform constant isometric neck contractions to support the head and a helmet weighing approximately 6.5kg at 1G (Ferguson, 2019). Motorsport competitions are broadly divided into two types (Beaumont et al., 2023). Speed races (e.g., Indianapolis 500-mile race) and Endurance races (e.g., Le Mans 24 Hours) (O'Kane, 2014). Despite their differences, both formats demands physical conditioning and high-level cognitive skills (Klarica, 2001), which are vital for drivers to withstand the combined stressors of extreme G-forces, high temperatures, and potential hypoxia while maintaining precise vehicle control (Hanna, 1963; Miller, 1989; Rausch et al., 2021).

Alternatively, some endurance races are team events (e.g., FIA World Endurance Championship), with two to four drivers sharing the responsibility of covering a set number of hours and solo efforts (e.g., Formula 1) and competing for roughly two hours without leaving their cars. Moreover, endurance drivers, face distinct challenges compared to drivers in individual-based competitions. As noted by Potkanowicz and Mendel (2013), motorsports has historically concentrated on technological advancements in automobiles, often overlooking the drivers and their performance. This raises critical questions about the intersection of vehicle technology and the physical requirements on drivers across various categories. What are the specific requirements for each type of

vehicle? Is the driver training adapted to the unique demands of each category they compete in?

These questions underscore progress in understanding driver performance demands (Tornaghi et al., 2023). According to Klarica (2001), early training programs included yoga or steering wheel resistance exercises to replicate race demands. With the onset of modern technologies and the growth of sports science, programs now focus on meeting the drivers' baseline requirements, considering the needs of the car, the setting, and the racing calendar (Reid & Lightfoot, 2019; Ziv, 2024). Time-efficient programs, such as high-intensity interval training (HIIT), have become a preferred approach (Beaumont et al., 2023).

Profiling racing drivers was a step in scientific research aimed at understanding their physical performance. Early reviews focused on the stressors that influence the driver´s experience, with Potkanowicz and Mendel (2013) study shifting the focus to the drivers themselves. A literature review on racing driver's fatigue found that heart rate [HR], respiration, carbon monoxide levels, hydration, temperature, and whole-body vibration are factors influencing physical and mental fatigue (Owen et al., 2015b). Reid and Lightfoot (2019) further highlighted the physiological stressors affecting drivers and pit crews, emphasizing the need to understand these stressors to improve training programs. Recently, a scoping review conducted by Beaumont et al. (2023) reported the physiological profiles and suggested physical training recommendations for types of motorsports.

Physiological profiles alongside training programs are crucial areas of concern. To date, it is unclear whether the recommendations made by Beaumont et al. (2023) scoping review are being followed or if training programs are being adapted to meet the demands of each vehicle. Therefore, this scoping review aims to map the available literature on physical conditioning for drivers across different levels and types of land-based motorsport categories. The primary objective is to gain a comprehensive understanding of the published research related to physical preparation for drivers in each type of vehicle and its unique requirements.

2 Methods

Full details of the methods are provided in the supplementary material, and a synthesis of this section is presented below.

2.1 Protocol

The methods were based on adaptations of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al., 2021), the PRISMA Extension for Scoping Reviews (PRISMA-ScR) Checklist and Explanation (Tricco et al., 2018), and the Cochrane Handbook for Systematic Reviews of Interventions (Higgins et al., 2022). The review project was registered on the Open Science Framework [OSF] under the following link: (https://osf.io/ahd3k/?view_only=45243c3940d345f7ae0790b4e67c2d60).

2.2 Eligibility criteria

Empirical research in peer-reviewed journals was selected meeting the inclusion criteria, which were defined according to the PICOS (Participants, Interventions, Comparator, Outcome, Study design) structure. No limitations were imposed regarding publication date or language. Any competitive motorsport racing driver from Tier 2 or higher as participants, along with any forms of land-based motorsport and any associated physical training programs. A comparator was not compulsory. The outcomes pertained to any variables related to physical conditioning in motorsports, including, but not limited, to strength, cardiovascular or change of direction [COD].

2.3 Information sources

A systematic search was conducted on PubMed, Scopus, and Web of Science on November 15, 2024, which was supplemented by screen of reference lists, snowball citation tracking and suggestions provided by two external experts.

2.4 Search strategy

The search strategy was conducted using free text terms and Boolean operators on two concepts: motorsport and training, applied to the titles and abstracts. Full search strategies used in each database are presented in supplementary material Table 1.

2.5 Selection process

Post-search, duplicates were identified and removed automatically and through manual processes using EndNote™ 20.4. Afterward, two authors (G.V. and C.A.M) screened all titles and abstracts and conducted independent assessments of the full texts for potentially eligible articles. In case of disagreement, a joint re-screening took place. When necessary, a third author (J.A.) made the final decision together with the main authors.

2.6 Data collection process

An independent, dual-reviewer process was used for data collection, where two authors (G.V. and C.A.M) extracted relevant information into a standardized Microsoft Excel® sheet. Authors of original studies were contacted in the absence of relevant information.

2.7 Data items

Extracted data items consisted of participants' details including sample size, age, sex, competitive level, motorsport details. The intervention and comparator details including type, timing, and dose, outcome measures, and study design. Each study's level of evidence was classified using a color-coded system. An organized compilation of the data was conducted, and the focus was placed on the training programs.

2.8 Synthesis of evidence

A structured synthesis of the selected studies was presented in tables, figures and an EGM. The EGMs were generated using EPPI-Reviewer 4: a Software tool for Research Synthesis that synthesizes evidence across predefined domains. In this review, EPPI-Reviewer was used to categorize and display the distribution of included studies by study design, intervention type, participant characteristics, and measured outcomes (Thomas & Brunton, 2010).

3 Results

3.1 Study selection

A total of 192,748 records were identified through database searches. After the removal of duplicates, 152,167 records remained for title and abstract screening. Of these, 152,132 were excluded for not meeting the eligibility criteria. After initial screening, 35 full-text articles were assessed for eligibility, of which 29 were excluded based on the predefined PICOS criteria. An additional 13 studies were identified through reference list searches, and 7 studies were retrieved via snowball citation tracking. Furthermore, 6 studies were suggested by two external experts. However, none of the studies identified through these additional methods met the PICOS criteria. In total, 6 studies met the criteria and were included in the final scoping review (Beaune & Durand, 2011; Ferguson & Myers, 2018; Horváth et al., 2022; Mosley et al., 2022; Rodríguez-Pérez et al., 2019; Simões et al., 2016). Full details of the screening process and exclusion decisions can be found in the supplementary material available on OSF (https://osf.io/jcbhu).

Figure 1 presents the PRISMA 2020 flow diagram, which provides an overview of the study selection process.

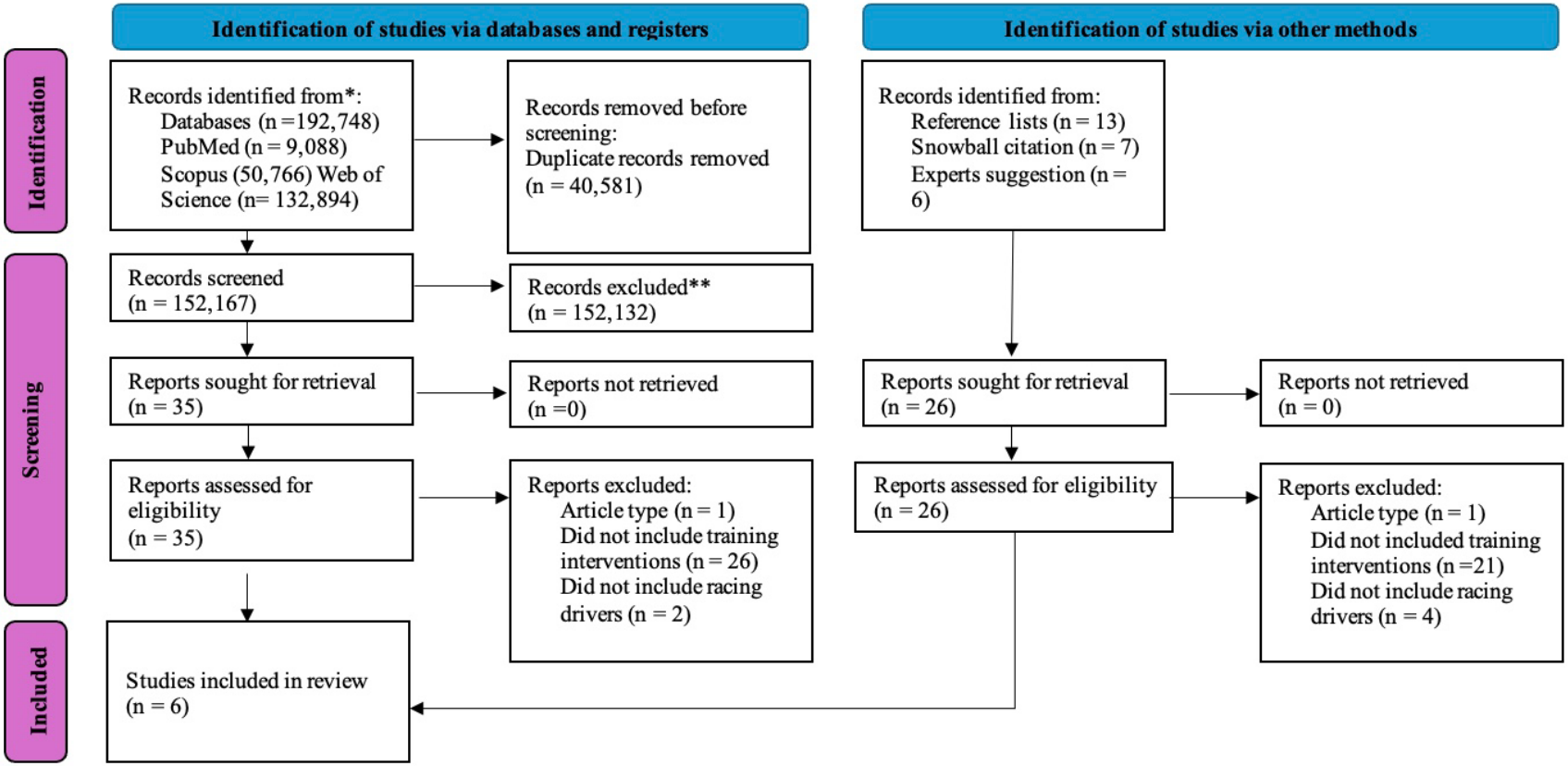


Figure 1. PRISMA 2020 flow diagram illustrating the study selection process, including the number of records identified, screened, excluded, and included at each stage of the review.

3.2 Study Characteristics

Although the search was conducted without restrictions on language or publication date, all articles were published in English between 2011 and 2022. All six studies reported training programs with drivers of open-wheeled vehicles competing in single-seater races, and all involved male participants (Beaune & Durand, 2011; Ferguson & Myers, 2018; Horváth et al., 2022; Mosley et al., 2022; Rodríguez-Pérez et al., 2019; Simões et al., 2016). One study included analyses both team-based and single seater races, open and closed-wheeled vehicles (Horváth et al., 2022). Most studies focused on the physical preparation of racing drivers in on-road racing contexts (Beaune & Durand, 2011; Ferguson & Myers, 2018; Horváth et al., 2022; Mosley et al., 2022; Rodríguez-Pérez et al., 2019), while two studies included off-road contexts (Horváth et al., 2022; Simões et al., 2016). The study designs were evenly distributed by two: case studies (Ferguson & Myers, 2018; Mosley et al., 2022), non-randomized studies (Beaune & Durand, 2011; Simões et al., 2016), randomized trials (Horváth et al., 2022; Rodríguez-Pérez et al., 2019). A breakdown of the individual studies is presented in Table 1.

Table 1. Summary of the main characteristics of the studies included in the review.

Data collected from the included studies Participant related characteristics					
Author	**Sample size**	**Age (Mean ± DP)**	**Motorsport type and context**	**Study design**	**Type of race**
Beaune and Durand (2011)	8 Male drivers	18.75 ± 3.41	Open four-wheel vehicles in on-road context.	Non-randomized	Single seater
Ferguson and Myers (2018c)	1 Male driver	26 to 31	Open four-wheel vehicle in on-road context.	Case study	Single seater
Horváth et al. (2022)	24 Drivers	exp: 24.7 ± 4.4 | con: 25.6 ± 3.3	Open and closed four-wheel vehicles in on-road and off-road contexts.	Randomized	Single seater and team race
Mosley et al. (2022)	1 Male driver	18	Open four-wheel vehicle in on-road context.	Case study	Single seater
Rodríguez-Pérez et al. (2019)	27 Male drivers	15.6 ± 1.1	Open two-wheel vehicles in on-road context.	Randomized	Single seater
Simões et al. (2016)	9 Male driver	22.7 ± 2.8	Open two-wheel vehicles in off-road context.	Non-randomized	Single seater

3.2.1 Intervention-level synthesis

Full details of the interventions are provided in the supplementary material, and a synthesis of the interventions is presented below. Strength training was reported in two studies (Ferguson & Myers, 2018; Rodríguez-Pérez et al., 2019). As previously

mentioned, Ferguson and Myers (2018), implemented a strength development phase during the preseason stage of the training program for the athlete in their case study. However, the authors did not specify which exercises were performed or the anatomical focus of the strength training. To assess the program effects, annual measurements were taken over six years using the Wingate cycle ergometer test, which indicated improvements in power and fatigue reduction (Zupan et al., 2009). In contrast, Rodríguez-Pérez et al. (2019) provided descriptions of their strength training program, and the specific anatomical focus. Although participants did not show significant improvements in physical performance, the results suggest enhanced competitive performance among the experimental group.

In the study by Horváth et al. (2022), the control group performed regular cardiovascular exercises such as walking and/or cycling, while the experimental group engaged exclusively in COD exercises with lights training drills. Rodríguez-Pérez et al. (2019) also incorporated a 90-minute cycling session as the aerobic cardiovascular component of their training program. Similarly, Ferguson and Myers (2018) adjusted their training during the season to focus on long-duration cardiovascular training. The COD training was also used by Mosley et al. (2022) who incorporated visual exercises in which the athlete was required to catch a ball thrown over their shoulder, stimulating peripheral vision.

The studies included in this review reported interventions across three main categories. Two studies focused on in-vehicle training involving Tier 2 participants, with outcomes related to physiological or performance responses (Beaune & Durand, 2011; Simões et al., 2016). Two studies addressed COD training with a cognitive performance focus (Horváth et al., 2022; Mosley et al., 2022). The remaining two studies targeted aerobic and strength-conditioning training, both incorporating resistance training as a core component (Ferguson & Myers, 2018; Rodríguez-Pérez et al., 2019). Only athletes classified as Tier 2 or Tier 4, according to the Participant Classification Framework [PCF] were represented in the included studies (McKay et al., 2022). These classifications, along with contextual and intervention-level details, are summarized in Table 2.

Table 2. Summary of the interventions reported in the included studies, detailing Competitive level, Type of motorsport, Type of training, Dose, Anatomical focus and Activity selection.

Data collected from the included studies **Intervention-Level Information**						
Author	**Competitive level (PCF)**	**Type of motorsport**	**Type of training**	**Dose**	**Anatomical focus**	**Activity selection**
Beaune and Durand (2011)	Tier 2 (Trained/Developmental)	Four wheel	In vehicle training	30 Min Driving session | 5x a day only one day.	Heart rate	Driving sessions
Ferguson and Myers (2018b)	Tier 4 (International level)	Four wheel	Aerobic and Strength-conditioning	Did not specify	Full body	Resistance training
Horváth et al. (2022)	Tier 2 (Trained/Developmental)	Four wheel	Reactivity agility	60 Min Training session | 2x a week for 6 weeks.	Cognitive	Lights training
Mosley et al. (2022)	Tier 4 (International level)	Four wheel	Reactivity agility and Breathing training	180 Min Session | one session per week for 9 weeks.	HRV and Cognitive	Foveal vision exercise
Rodríguez-Pérez et al. (2019)	Tier 4 (International level)	Two wheel	Aerobic and Strength-conditioning	150 Min Session | 2x a day | 4 x week for 4 weeks.	Lower-body muscular power, Hand grip strength, and Lumbar isometric strength	Resistance training and cycling
Simões et al. (2016)	Tier 2 (Trained/Developmental)	Two wheel	In vehicle training	20 Min session | One session.	Hand grip strength, Lactate concentration	Motorcross training session

3.2.2 Outcome-Level Information

Across the included studies, outcomes were primarily related to three domains: strength, cardiovascular, and cognitive function. A commonly reported outcome was handgrip strength, which was evaluated in studies involving strength and conditioning

protocols delivered through in-vehicle training, cycling, and resistance exercises during the competitive season (Rodríguez-Pérez et al., 2019; Simões et al., 2016). Cardiovascular related outcomes, particularly those associated with long-duration endurance training, were also frequently measured, typically within interventions that combined cycling and muscular resistance training at the gym. Outcomes related to interval training were reported but appeared less consistently across studies. Cognitive outcomes were the least represented, with only a few studies assessing COD performance using light's reaction training or foveal vision tasks (Horváth et al., 2022; Mosley et al., 2022).

Studies focusing on COD training reported improvements in cognitive performance, assessed through the Vienna Test System [VTS] (Ong, 2015). Along with enhanced visual function and increased mind–body awareness (Horváth et al., 2022; Mosley et al., 2022). Outcomes of the program were assessed through measures like handgrip strength, lower-body muscular power, lumbar isometric strength, and on-track performance (Rodríguez-Pérez et al., 2019). Aerobic and strength-conditioning studies were associated with gains in overall physical fitness, competitive performance, lower-body muscular power, and handgrip strength (Ferguson & Myers, 2018; Rodríguez-Pérez et al., 2019). One longitudinal case-study reported improvement in peak power and a reduction in fatigue rate over a six-year period (Ferguson & Myers, 2018). Outcomes of in-vehicle training programs reported an elevation in HR as an indicator of physical demand and adaptation. Additionally, results from this type of training indicated a decrease in handgrip strength in both hands (Beaune & Durand, 2011; Simões et al., 2016).

None of the six studies included in this review reported implementing neck-specific training, despite the well-established importance of neck strength in motorsport performance (Ebben & Suchomel, 2012; Ferguson, 2019; McKnight et al., 2019). Two studies acknowledged the significant muscular demands placed on the neck due to G-forces, however, without include or describe any specific training programs aiming this demand (Beaune & Durand, 2011; Ferguson & Myers, 2018). Additionally, several of the studies excluded during full-text screening primarily focused on profiling the physical demands of motorsport and frequently highlighted the relevance of neck strength in their findings (Beaumont et al. 2023; Dawson, 1979; Sánchez-Muñoz et al., 2011).

3.2.3 Evidence Gap Map (EGM)

Figures 2 and 3 synthesise the patterns related to study designs and interventions about the outcomes and gaps identified in the review through EGMs.

The EGM reaffirmed the absence of studies involving drivers from tiers 3 and 5, and the lack of observational studies. It also highlighted that most studies focus on open four-wheel vehicles, within an on-road context, and primarily involving single-seater drivers. Still, EGM illustrated the absence of studies reporting neck training, while showing that most interventions were conducted in-season. Additionally, there is a predominant anatomical focus on handgrip strength and full-body training.



Figure 2. Study designs differentiated by color, illustrating their prevalence across various motorsport categories. Green for randomized, Yellow for Non-randomized, Orange for Observational and Red for Case study.



Figure 3. Distribution of activity selection (e.g., resistance, cycling, cognitive, in-vehicle) across reported outcomes such as Interval training, long endurance, Neck reinforcement, Hand grip strength, and COD. Bubble color indicates activity type; bubble size reflects the number of studies reporting each activity

4 Discussion

The main goal of this scoping review was to systematically map and synthesize the available evidence on physical conditioning programs implemented for land-based motorsport athletes across various vehicle categories. Through an EGM, we provided a structured synthesis of the available evidence on physical conditioning for land-based motorsport athletes, identifying which training programs have been empirically applied and where the gaps are. The review identified a total of six eligible studies (Beaune & Durand, 2011; Ferguson & Myers, 2018; Horváth et al., 2022; Mosley et al., 2022; Rodríguez-Pérez et al., 2019; Simões et al., 2016), denoting a scarce body of motorsport research. The existing evidence predominantly features male drivers competing in open four-wheel, single-seater vehicles, primarily in on-road settings. Importantly, no studies included drivers from Tier 3 or Tier 5, revealing a research gap in developmental and elite-level athletes.

4.1 Evidence and gaps in the landscape: What do we know?

Although a growing body of research has explored the physical demands, physiological characteristics, and proposed training recommendations for drivers across various motorsports and competitive levels, the number of studies reporting empirically validated physical training programs remains notably limited (Beaumont et al., 2023; Owen et al., 2015; Potkanowicz & Mendel, 2013; Reid & Lightfoot, 2019). A recent scoping review from Beaumont et al. (2023), provided guidance for motorsport-specific physical conditioning, organizing driver's needs considering the demands of different vehicle types. Unlike previous reviews (e.g., Beaumont et al., 2023), which outlined theoretical training recommendations based on drivers' physical profiles, the present review employed inclusion criteria specifically designed to capture studies reporting predefined and implemented training protocols.

Ebben and Suchomel (2012) identified upper body strength as a primary physical requirement for stock car drivers, emphasizing its importance in managing the physical strain of competition. In contrast, Owen et al. (2015) observed that coaches and sport

scientists often attempt to replicate race conditions during training. However, these practices are frequently guided by subjective observations rather than grounded on measurable data. This finding aligns with the current review, which found a disconnection between evidence-based recommendations in the literature Beaumont et al. (2023); Ebben and Suchomel (2012); Owen et al. (2015) and the implementation of structured training programs within motorsport populations.

Indeed, only one study involving four-wheel open-wheel drivers reported the use of interval training with the purpose of maintaining VO_2max. However, this adjustment was a response to travel scheduling constraints and limited access to equipment, rather than part of the original program design of Ferguson and Myers (2018). One study included drivers of four-wheel closed-wheel vehicles, but the intervention focused specifically on COD exercises using light-based stimuli (Horváth et al., 2022). Among the included studies, only one involving two-wheel on-road riders applied a training program that closely matched the recommendations of Beaumont et al. (2023), incorporating core training, stretching routines, motocross-specific drills, and on-track speed training (Rodríguez-Pérez et al., 2019). Finally, a single study reported an intervention involving two-wheel off-road riders, which consisted of in-vehicle training aimed improving handgrip strength (Simões et al., 2016).

This review highlighted another gap in empirical research involving participants from two competitive levels, despite their significance within the competitive structure of motorsport. These findings emphasized both conceptual and empirical gaps in the current literature recommendations and underscored the need for future research systematically examines structured, category-specific, and multidimensional training interventions for racing drivers across all competitive levels.

4.2 How are training programs implemented?

Earlier studies have provided general recommendations regarding physical conditioning in motorsport, emphasizing the need for sport-specific physical development to the driving demands (Baur et al., 2006). Afterwards, Raschner et al. (2013) suggested

that fitness training for drivers should include general and vehicle-specific strength training, as well as sensorimotor function, coordination, and long-endurance training.

Based on the training programs reported in the literature, athletes in land-based motorsport, both two-wheeled and four-wheeled vehicles, follow distinct conditioning approaches to the physical and cognitive demands of their respective sports. Two-wheeled vehicle riders, such as motocross athletes, typically engage in motocross-specific sessions, muscular resistance training, and cycling (Rodríguez-Pérez et al., 2019; Simões et al., 2016). In contrast, four-wheeled vehicle drivers tend to follow programs including muscular resistance training, driving practice sessions, and light-based cognitive training (Beaune & Durand, 2011; Ferguson & Myers, 2018; Horváth et al., 2022; Mosley et al., 2022).

Motocross sessions are primarily intended to improve handgrip strength and upper body muscular endurance, given the sustained forces and vibrations transmitted through the handlebars (Simões et al., 2016). Training in this group commonly incorporates aerobic work, interval training, and targeted grip-strength development. The cognitive training is designed to enhance perceptual cognitive skills like reaction time, attentional control, and visual processing, essential elements for maintaining performance under high-speed and pressure conditions (Horváth et al., 2022; Mosley et al., 2022). However, given the lack of standardized intervention protocols and inconsistent reporting across studies limits the ability to draw conclusions regarding training efficacy in both groups.

In this scoping review, none of the included studies implemented interventions that systematically aligned training with the type of vehicle or environment in a structured and targeted way. Only one study reported adjustments to the training program in response to evolving car design and performance demands (Ferguson & Myers, 2018), while another study implemented an intervention focused on enhancing handgrip strength through in-vehicle training (Simões et al., 2016). These isolated examples underscore the overall lack of context-specific training strategies in the current literature. Furthermore, even with numerous studies highlighting the need of a specific training program who combined strength, conditioning and cognitive aspects, designed based on the car's type, context of application and physical demands for the driver (e.g., Gobbi et al., 2005; McKnight et al., 2019; Potkanowicz & Mendel, 2013; Raschner et al., 2013), none of the studies included in this review had interventions with such characteristics.

4.3 Are there any gaps in neck-specific training interventions?

The importance of cervical strength in motorsport performance and safety is well supported by the demands placed on drivers (Hoyes & Collins, 2018; McKnight et al., 2019). During high-speed cornering and braking, racing drivers are subjected to G-forces often exceeding 4–6 G, which impose substantial inertial loads on the cervical spine (Ito et al., 2005). For example, a helmeted head weighing approximately 6.4 kg may generate forces surpassing 250 N at 4 G, placing considerable stress on neck musculature (Reid & Lightfoot, 2019). Adequate neck strength is essential for maintaining stability, visual tracking, and neuromuscular control, with each additional pound of cervical strength reducing head acceleration upon impact and lowering concussion risk by approximately 5% (Collins et al., 2014).

A study by Backman et al. (2005) surveyed trainers and drivers to evaluate the perceived importance of fitness components in driving performance. The results indicated that most open-wheel drivers highly valued neck and upper body strength as critical for optimal performance. Head stability and central positioning within the cockpit are fundamental for tasks involving head–eye coordination and proprioceptive demands, like spatial perception on track (Ferguson, 2019). During driving, it is well recognized that the only structures supporting the head under G-forces are the cervical spine and its associated soft tissues (Gatherer et al., 2018). Despite two of the studies included in this review have mentioned the importance of cervical musculature, neither implemented or tested a neck-specific intervention. For example, Beaune and Durand (2011), noted that the cervical musculature must counteract cockpit vibrations and support helmet weight to maintain posture and mitigate G-forces effects on the neck. Similarly, Ferguson and Myers (2018) recommended the inclusion of isometric neck exercises in driver conditioning routines to address muscle fatigue resulting from sustained G-forces.

4.4 Limitations and future avenues

The small number of eligible studies restricted the depth of analysis regarding physical conditioning strategies in land-based motorsport, limited our understanding of

how training interventions are applied to enhance driver strength and fitness in response to the motorsport's physiological demands. Additionally, the focus on land-based motorsport may represent a potential limitation, as a broader scope including other racing modalities could provide more diverse training insights and enrich the scientific perspective.

This scoping review underlined a lack of complementary study designs that could contribute meaningfully to this field. Particularly, field-based investigations that explore how coaches plan and implement physical conditioning programs could diminish the gap between research and the real world. While the need for research into neck-specific training programs tailored to drivers is evident, the broader literature also reveals a lack of consistency in training program design and sport-specificity across studies. As a result, the current body of evidence offers only a partial view of how physical preparation is approached within motorsport disciplines. For example, several studies were excluded due to a sole focus on performance testing or athlete profiling without any applied intervention. Even among included studies, such as Beaune and Durand (2011) Ferguson and Myers (2018), details regarding training dosage and specificity on exercise planning were insufficiently reported. This lack of methodological uniformity underscores the need for more homogeneous and transparent training research. Improved protocol clarity and standardization could enhance both the scientific value of future studies and the practical utility of findings for athletes and coaching staff across different motorsport categories.

5 Conclusion

Despite motorsport physical demands including high G-forces, elevated temperatures, and prolonged muscular strain, few studies have empirically tested training programs. Most available research centers on male drivers in open-wheel categories, with limited representation from other vehicle types, competitive tiers, or female athletes. Notably, no included studies implemented or evaluated neck-specific strength programs, despite the well-documented role of cervical stability in mitigating G-force exposure and injury risk. Additionally, the review highlighted inconsistency and a lack of sport-specificity in the training programs described, revealing a disconnection between existing recommendations and practice. Thereby, it reveals urgent the need for robust, structured

investigations that assess targeted physical training programs tailored to the specific demands of each motorsport disciplines.

Training approaches in motorsport remain inconsistent, with significant gaps in empirical evidence. For two-wheeled riders, motocross-specific practice, resistance training, and cycling are commonly used to develop grip strength and upper-body endurance. Four-wheeled drivers, by contrast, benefit from resistance work, driving drills, and cognitive tasks designed to enhance reaction time and visual processing. The absence of neck-specific interventions is particularly concerning, given the critical role of cervical strength in managing G-forces and reducing injury risk. Current programs largely reflect general training principles and the profiled demands of racing rather than experimentally validated methods. A central challenge, therefore, is the prescription of effective training programs in the context of such limited research on physical conditioning for racing drivers.

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Disclosure statement

The authors report there are no competing interests to declare.

Data availability statement

The review protocol and data extraction details are available on the OSF under the following link: (https://osf.io/jcbhu).

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Chapter 4

Final Synthesis

6.1 General Discussion

Through the years the role of the racing driver has changed considerably in motorsports. Traditionally, performance was thought mostly from the mechanical engineering viewpoint, racing drivers were seen as an extra human component rather than a real athlete even by the racing drivers themselves (Potkanowicz & Mendel, 2013). This focus on vehicles created a paradox: drivers were largely ignored in scientific research, even though they competed in a sport that was known all over the world. Initially, this shift in thinking was caused by concerns about safety. Later, it was catalyzed by mounting proof that a driver's physical fitness is directly linked to their ability to perform well in a race (Jutley, 2003). In the end, this evolution led to the modern, holistic training approach that places the driver, not just the vehicle, at the center of performance.

6.1.1 Narrative review findings

There are clear suggestions in the research about how to make physical conditioning training programs for motorsport athletes. Two-wheel athletes need to work on their HG strength and aerobic conditioning. Closed-wheel drivers can benefit from endurance training and thermal management. Open-wheel drivers, in turns, require high-intensity, low-repetition range, neck and core strength (Ebben & Suchomel, 2012; Ferguson, 2019; Gobbi et al., 2005). There are still important gaps in these recommendations, even though they consider the physical profiles and vehicle-specific needs for each category. In particular, it is still not clear how the different physiological stressors work together during training or competition, or how tailored training programs would affect athletes' ability to handle the combined demands of motorsport environments.

6.1.2 Scoping review findings

Even though it is becoming more widely known that drivers are athletes, from 192,748 records identified through database searches only six studies met the criteria for testing a training program. This very small number showed a big gap in the literature, pinpointing the lack of guidance for racing drivers of open-wheeled vehicles competing in single-seater races, as well as for male participants, due to the current focus of the scientific literature. Therefore, other racing categories have their athletes' physical

conditioning programs designed based on how trainers perceive the demands of the vehicle, rather than on tested, empirical, evidence-based training protocols. (Ferguson, 2019). A lot of the research that has already been done has been describing the physical, and biomechanical, and physiological profile of drivers or the demands of the sport, rather than thoroughly testing the effects of physical conditioning training programs.

The few documented training programs are structured around distinct modalities. The scoping review identified interventions into three main categories: in-vehicle training, cognitive training, and strength and conditioning. Specific interventions included strength training, cardiovascular exercise such as walking or cycling, and COD exercises. In-vehicle training was used to measure physiological responses and adaptations, such as elevated heart rates and decreases in handgrip strength during driving sessions. Aerobic and strength-conditioning studies were associated with gains in overall physical fitness, competitive performance, lower-body muscular power, and handgrip strength (Ferguson & Myers, 2018; Rodríguez-Pérez et al., 2019). Additionally, cognitive outcomes were the least represented, with only a few studies assessing COD performance using light's reaction training or foveal vision tasks (Horváth et al., 2022; Mosley et al., 2022).

6.1.3 Contribution of this dissertation

A critical finding of this dissertation is the identification of significant gaps within the literature in the little research that has been done on physical conditioning in land-based motorsports. However, the narrative review highlighted the importance of profiling both the demands of the vehicles and the physiological characteristics of racing drivers in order to understand the specific physical requirements of each vehicle type. Therefore, it clearly emphasizes what should be implemented in physical training programs for this population. The scoping review revealed that the existing evidence is homogenous, with studies mostly looking at male drivers competing in on-road, open-wheel racing categories. This narrow focus means there is a lack of research on female athletes and other key disciplines like closed-wheel, two-wheel, and off-road racing. The EGM presented on the scoping review also showed that there were no intervention studies with world-class (Tier 5) or national-level (Tier 3) drivers. This is a big knowledge gap for both elite and developmental athletes. The lack of any experimental research on neck-

strengthening interventions may be the most important gap that has been missed. Despite the well-documented importance of cervical strength for managing extreme G-forces and mitigating injury risk, no included studies empirically tested a neck-specific training program suggesting that coaches and trainers are relying on general training principles to design neck reinforcement programs rather than using empirically validated protocols.

Finally, this dissertation highlights a disconnection between theoretical training recommendations and empirically validated practices in motorsport. While literature reviews have proposed training guidelines from profiling the sport's physiological and biomechanical demands, the findings of this dissertation through the scoping review reveals that the few available intervention studies do not systematically align with the recommendations made by the scientific literature. In practice, coaches and sport scientists frequently attempt to replicate race conditions; however, these efforts are often informed by subjective observations and empirical assumptions rather than by scientific tested, evidence-based protocols. As a result, despite a growing understanding of the physical and cognitive demands imposed on drivers, there are a critical lack of scientifically validated physical conditioning training programs tailored to these specific requirements from land-based motorsports.

6.2 Practical applications

We provide practical applications for coaches, athletes, and researchers in motorsports. Initially it does give a picture of what is known currently. It shows how physical conditioning in sports has changed over time and how it works presently. The physical profile of racing drivers is already well documented in the scientific literature, particularly regarding the stressors that influence performance and training recommendations based on those profiles to meet the demands of the sport. This clearly helps practitioners in designing appropriate training programs and provides valuable guidance in the sense of understanding the specific needs and physical demands placed on racing drivers. Therefore, it potentially paves the way for further scientific investigations into training prescription and the application of physical conditioning training programs for such a specialized population.

This dissertation underscored the urgent need for evidence-based training approaches in motorsport, where athletes are often subject to generalized conditioning

programs despite the highly specific physical and cognitive demands in the sport. In the elite environment of professional racing, training practices remain inconsistent, with no standardized guidelines addressing critical aspects such as pre-race preparation, post-race recovery, or even the design of neck training protocols despite the well-established importance in open-wheel disciplines. This lack of clarity reflects an imbalance in research priorities, as motorsport devote significant resources to engineering innovation while the scientific study of drivers' physical conditioning remains comparatively underdeveloped.

Historically, the physical fitness, health, and performance capacities of racing drivers have been acknowledged as essential. However, this recognition has not been matched by the development of empirically validated physical conditioning training programs. The current absence of rigorously tested interventions leaves coaches and athletes without reliable, evidence-based frameworks to guide performance optimization or injury prevention. Addressing this gap requires a systematic research agenda that evaluates the combined effects of racing-specific stressors such as G-forces, thermal strain, and cognitive load under real competition conditions while assessing the efficacy of tailored training programs designed to mitigate these demands.

6.3 Limitations

The primary limitation is the small number of eligible studies identified by the systematic scoping review, which ultimately included only six articles. This scarcity of empirical research restricted the depth of the analysis and limits the conclusions regarding effective physical conditioning strategies across land-based motorsports. Another limitation is the defined scope of the research, which was intentionally focused on land-based disciplines. Thus, a broader inclusion of other racing modalities might have provided more diverse insights into training practices. Furthermore, the dissertation is constrained by the limitations of the existing literature itself. This includes a lack of complementary research designs, such as field-based investigations exploring how coaches actually plan and implement training, which creates a gap between academic findings and real-world application. Lastly, the included studies often lacked sufficient detail regarding training dosage, exercise planning, and specificity, a methodological

inconsistency that hinders robust comparisons and underscores the need for more transparent and standardized research protocols in the future.

6.4 Future research avenues

Bridging the gap between theoretical recommendations and empirically validated training efficacy emerges as a central challenge underscored by the findings of this dissertation. The development and testing of physical conditioning training programs that align with the recommendations derived from systematic reviews particularly those considering the physiological demands and physical profiles of racing drivers are essential for providing evidence-based guidelines to coaches and athletes in the sport. Empirical research is urgently needed to establish standardized protocols for neck training, given its critical role in meeting the extreme physical demands experienced by open-wheel drivers. Furthermore, future investigations should focus on assessing the combined impact of multiple racing stressors such as G-forces, thermal load, and cognitive fatigue on driver performance under real competition conditions. Equally important is the evaluation of how tailored training interventions targeting these stressors could enhance both physical resilience and competitive outcomes.

6.5 Conclusions

In land-based motorsports, drivers must possess sufficient physical strength and resilience to withstand the multiple stressors imposed by the vehicle during competition. While current physical conditioning training programs are often designed around the documented physiological demands of various racing disciplines, thereby creating a physical profile of the driver population, they are not grounded in empirically tested physical conditioning training programs specific to this sport. Despite the recognized importance of physical conditioning, particularly in high-impact areas such as neck strength for open-wheel racing, no studies to date have evaluated the effectiveness of targeted neck reinforcement programs within the scientific literature. Additionally, most of the research is focused on male drivers in open-wheel categories, with limited representation from other vehicle types, competitive tiers, or female athletes. This dissertation highlights a common ground in physical conditioning for land-based

motorsports, where coaches attempt to replicate the stressors experienced in various vehicles, continually developing new approaches to training racing drivers throughout the season. It demonstrates that practice is evolving rapidly keeping pace with vehicle development while scientific research is still striving to catch up.

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Appended Work

Article Supplements: “What do we know about physical conditioning in land-based motorsports? A scoping review”

1 Appendix A: Detailed description of the methods

1.1 Eligibility criteria

Empirical research in peer-reviewed journals was selected meeting the inclusion criteria, which were defined according to the PICOS (Participants, Interventions, Comparator, Outcome, Study design) structure. No limitations were imposed regarding publication date or language.

Participants: Any competitive racing driver (Tier 2 or above of the Participant Classification Framework [PCF] (McKay et al., 2022), participating in land-based motorsports (e.g., Kart, Drift) without restrictions regarding age, sex, or health status.

Interventions: Any type of training with the aim to deal with the demands of the vehicle (e.g., aerobic, strength) applied at any moment of the season (e.g., pre-season, competitive phase), with or without co-interventions or recovery time after a race and before a training session.

Comparator: Not compulsory.

Outcomes: Any variables related to physical conditioning in motorsports, including, but not limited, to strength (e.g., weightlifting, neck reinforcement), cardiovascular fitness (e.g., aerobic, anaerobic), or change of direction (e.g., lights training drills, ladder drills).

Study design: empirical studies, including experimental and observational studies, as well as case studies and case series.

1.2 Information sources

The following databases was searched on November 15, 2024: PubMed, Scopus, and Web of Science (Core Collection). Additional searches: (i) reference lists of included studies; (ii) snowball citation tracking in Web of Science (in case the study was not indexed in Web of Science, PubMed was consulted); (iii) suggestions provided by two external experts (authors with published research on the topic in peer-reviewed journals). When available, registered protocols and supplementary materials were retrieved for the selected studies. Finally, we searched for errata or retractions of the selected manuscripts.

1.3 Search strategy

The general search strategy used was a two-code line with free text terms and Boolean Operators applied to the Title/Abstract:

(Automobile) OR ("Close wheel*") OR (Drift*) OR (Kart) OR (Motorsport*) OR (Motorbike*) OR (Motorcycle*) OR ("Open wheel*") OR ("Race car") OR (Racing) OR (Rally*)*

AND

(Aerobic) OR (Anaerobic) OR (Agility) OR (Conditioning) OR (Cardiovascular) OR (Endurance) OR (Fitness) OR (Neuromuscular) OR ("Physical preparation") OR (React) OR (Strength) OR (Training)*.

Full search strategies used in each database are presented in the supplementary table 1 available on appendix B.

1.4 Selection process

Initially, using EndNote™ 20.4 for MacOS, an automated removal of duplicates was performed. Further duplicates were removed manually. Then, two authors (G.V. and C.A.M) independently screened the retrieved records (titles and abstracts). Afterwards, the authors analyzed the full texts that passed the screening stage to decide on their inclusion. In case of disagreement, a joint re-screening took place. When necessary, a third author (J.A.) made the final decision together with the main authors.

1.5 Data collection process

Data was extracted independently by two authors (G.V. and C.A.M). Disagreements resulted in a joint re-analysis, and a third author (J.A.). Using Microsoft Excel®, a data sheet was created to extract all relevant information (available as supplementary material). In the absence of relevant information, the main authors and correspondents of the original studies were contacted via email and/or ResearchGate.

1.6 Data items

- *Participant-related information:* sample size, age, sex, and competitive level [PCF].
- *Motorsport-related information:* type of motorsport (e.g., two-wheel, four-wheel), context of the application (e.g., on-road, off–road), type of vehicle (e.g., closed wheel, open wheel) or type of race (e.g., single-seater, team race).
- *Intervention-related information:* type of training (e.g., endurance, strength), season timing (e.g., pre-season, competitive phase), anatomical focus (e.g., neck, core), dose (e.g., duration, intensity), co-interventions (e.g., strength training combined with yoga) and recovery time after a race to be back on training.
- *Comparator-related information*: same variables as for the interventions.
- *Outcomes*: Strength (e.g., weightlifting, neck reinforcement), Cardiovascular (e.g., long endurance, interval sprints), Activity selection (e.g., running, cycling, swimming, rowing), Change of direction (lights training drills, ladder drills).
- *Study design-based evidence-level*: a color coding was used to Randomized (green), Non-randomized (yellow), Observational (orange), and Case studies (red).
- *Additional data*: funding details, competing interests.

1.7 Synthesis of evidence

A structured synthesis of the selected studies was performed, focusing on the various training programs developed for drivers. The findings were presented in tables and figures, displaying the most prevalent training methods for each type of vehicle or motorsport category in a clear and concise manner. Thereafter, an EGM provided a simple visualization of the existing knowledge gaps. The objective was to pinpoint areas that require additional evidence, evaluate existing study collections, enhance the discoverability and accessibility of studies, and ultimately, demonstrate the evidence collected from the systematic review (White et al., 2020). This method supported transparent reporting of evidence and facilitated identification of research concentrations and gaps, in accordance with established scoping review guidelines (Campbell et al., 2024). In all maps, circle size is proportional within each cell, and individual studies may be represented in multiple categories or outcomes.

2 Appendix B: Search strategy for each database

Supplementary Table 1. Full search strategy for each database.

Database	Search strategy
PubMed	((Automobile[Title/Abstract]) OR ("Close* wheel*"[Title/Abstract]) OR (Drift*[Title/Abstract]) OR (Kart[Title/Abstract]) OR (Motorsport*[Title/Abstract]) OR (Motorbike*[Title/Abstract]) OR (Motorcycl*[Title/Abstract]) OR ("Open wheel*"[Title/Abstract]) OR ("Race car"[Title/Abstract]) OR (Racing[Title/Abstract]) OR (Rally*[Title/Abstract])) AND ((Aerobic[Title/Abstract]) OR (Anaerobic[Title/Abstract]) OR (Agility[Title/Abstract]) OR (Conditioning[Title/Abstract]) OR (Cardiovascular[Title/Abstract]) OR (Endurance[Title/Abstract]) OR (Fitness[Title/Abstract]) OR (Neuromuscular[Title/Abstract]) OR ("Physical preparation"[Title/Abstract]) OR (React*[Title/Abstract]) OR (Strength[Title/Abstract]) OR (Training[Title/Abstract]))
Scopus	TITLE-ABS (automobile) OR TITLE-ABS ("Close* wheel*") OR TITLE-ABS (drift*) OR TITLE-ABS (kart) OR TITLE-ABS (motorsport*) OR TITLE-ABS (motorbike*) OR TITLE-ABS (motorcycl*) OR TITLE-ABS ("Open wheel*") OR TITLE-ABS ("Race car") OR TITLE-ABS (racing) OR TITLE-ABS (rally*) AND TITLE-ABS (aerobic) OR TITLE-ABS (anaerobic) OR TITLE-ABS (agility) OR TITLE-ABS (conditioning) OR TITLE-ABS (cardiovascular) OR TITLE-ABS (endurance) OR TITLE-ABS (fitness) OR TITLE-ABS (neuromuscular) OR TITLE-ABS ("Physical preparation") OR TITLE-ABS (react*) OR TITLE-ABS (strength) OR TITLE-ABS (training)
Web of Science	TS=((Automobile) OR ("Close* wheel*") OR (Drift*) OR (Kart) OR (Motorsport*) OR (Motorbike*) OR (Motorcycl*) OR ("Open

	wheel*") OR ("Race car") OR (Racing) OR (Rally*)) AND TS=((Aerobic) OR (Anaerobic) OR (Agility) OR (Conditioning) OR (Cardiovascular) OR (Endurance) OR (Fitness) OR (Neuromuscular) OR ("Physical preparation") OR (React*) OR (Strength) OR (Training))

3 Appendix C: Detailed description of the results

3.1 Studies interventions - detailed description

3.1.1 Change of direction training

Two studies reported training interventions involving change of direction (COD) aimed at improving the cognitive performance of drivers, both involving four-wheel vehicles (Horváth et al., 2022; Mosley et al., 2022). Both interventions assessed cognitive outcomes using the Vienna Test System (VTS) (Ong, 2015). The longest intervention duration among the studies reporting COD training in this review was implemented by Mosley et al. (2022). In this case study, three professionals participated in monthly three-hour sessions over a nine-month period, which included psychological interviews, vision training, and slow-paced breathing exercises. The training intervention followed a structured sequence, beginning with cognitive assessment using the VTS, followed by a series of vision and cognitive load exercises. These included a foveal vision task, a mobile phone–based cognitive exercise, and a physical response task targeting peripheral vision such as catching a ball thrown over the athlete's shoulder. The session then returned to the VTS for post-training assessment and concluded with slow-paced breathing practice to enhance mind-body awareness and recovery. Heart rate variability data confirmed the effectiveness of the breathing sessions, and the authors highlighted improvements in mind–body awareness and enhanced visual functions.

The competitive levels of the drivers in these studies corresponded to Tier 2 and Tier 4, respectively. Of particular note, Horváth et al. (2022) implemented COD training sessions and tests using lights training drills in a darkened environment. The intervention consisted of 60-minute training sessions, performed twice a week over a six-week period. Each session began with a 10-minute warm-up that included 2 minutes of walking at 5 km/h and 3 minutes of jogging at 8 km/h on a treadmill, followed by 5 minutes of dynamic stretching combined with core exercises. Subsequently, participants engaged in reactivity training using FitLight devices. The study reported improvements in cognitive performance and positive changes in peak heart rate, gas exchange threshold, ventilation, and relative VO_2max during a maximal cardiorespiratory test.

3.1.2 Aerobic and Strength-conditioning

Two studies reported strength and conditioning interventions for drivers, one involving a two-wheeled vehicle (Rodríguez-Pérez et al., 2019) and the other a four-wheeled vehicle (Ferguson & Myers, 2018). Both studies analyzed drivers competing at the international level, classified as Tier 4. The latter conducted a longitudinal case study over six years, from 2011 to 2016, with a driver diagnosed with type 1 diabetes, aiming to investigate the role of physical fitness and blood glucose in racing performance. While the exact training dose was not detailed, the authors described a periodized training based on the driver needs and demands during the year. From September to November (early off-season), the focus was on skeletal muscle hypertrophy, followed by strength development from December to January. In February, training shifted toward endurance to prepare drivers to compete at 45–80% of their VO_2max. During the competitive season (March to September), the program emphasized aerobic conditioning, largely influenced

by travel demands. However, changes in car structure over the years required in-season adaptations, including sprint work, interval training, and weightlifting to meet evolving physical demands. Over the six-year study period, combined improvements in peak and minimum power reflected a 12.9% reduction in fatigue rate. Additionally, a decrease in VO_2max and an increase in body fat percentage were observed, which is consistent with the natural aging process.

Rodríguez-Pérez et al. (2019) conducted an experimental study to assess physical fitness in elite young road-race motorcyclists. The findings demonstrated improvements in the physical performance of the experimental group, with notable gains in overall fitness and, more clearly, in competition outcomes. The training program was delivered in two daily sessions over four consecutive days each week, across a four-week period. It was structured into four stages and included aerobic and strength-conditioning exercises, core training, stretching routines, motocross-specific drills, and on-track speed training. Each session began with dynamic flexibility exercises targeting the major joints, followed by resistance training for large muscle groups (three sets of 10 repetitions at 60% of one-repetition maximum, with three-minute rest intervals between sets). Core exercises included both isometric and dynamic movements performed on unstable surfaces (three sets per exercise). The sessions concluded with static stretching of the major muscle groups, with each position held for 20–25 seconds across two sets. The study concluded that the specific training program was effective in enhancing rider´s performance.

3.1.3 In-vehicle training

Two studies examined how in-vehicle training during on-track practice sessions influenced in driving performance and physical outcomes (Beaune & Durand, 2011;

Simões et al., 2016). Both non-randomized studies focused on drivers competing at a developmental level, classified as Tier 2. The physiological responses of young drivers during open four-wheel, on-road driving sessions were explored in a study that evaluated heart rate (HR) as an indicator of physical demand and adaptation (Beaune & Durand, 2011). Eight participants from a driver development academy completed five consecutive 30-minute driving sessions over a single day. The first two sessions were held in the morning with a one-hour rest interval, while the remaining three sessions took place in the afternoon with two-hour rest periods. Of note, the temperature change occurred throughout the day, rising from 10°C in the morning to 16°C in the afternoon. The study reported a mean HR elevation of up to 143 beats per minute during the sessions, highlighting HR monitoring as a simple and reliable tool for evaluating driver adaptation during training.

To investigate ways to improve the competitive performance of amateur motocross riders, a study assessed neuromuscular responses and blood lactate concentrations following a motocross training session (Simões et al., 2016). Nine male participants underwent pre-test assessments, including handgrip strength, horizontal jump performance, and blood lactate analysis to establish baseline parameters. After completing three warm-up laps for track and obstacle familiarization, the training session included 20 minutes of continuous riding on a 1.6 km track at each rider's maximal individual speed. Post-session results indicated a decrease in handgrip strength in both hands, while horizontal jump performance remained unchanged. Additionally, the study highlighted a significant demand on anaerobic metabolism, as evidenced by peak blood lactate concentrations immediately following the session.

4 Appendix D: References of the appended material

4.1 References

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