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REVIEW ARTICLE

Human Performance in Motorcycle Road Racing: A Review of the Literature

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Abstract Performance in motorcycle road racing is typically considered as the summation of interactions between rider, motorcycle, tires, and environment. Despite the substantial investments made towards the development of motorcycle technology and the business interests of manufacturers, published research focusing on the riders is relatively sparse, and a bike-centered mentality tends to dominate the sport. This manuscript reviews the known human performance aspects of motorcycle road racing and suggests directions for future research. In this sport, riders are exposed to a complex interaction of physiological, mechanical, and psychological stresses, alongside the ever-present potential for injury from crashes or localized muscular overload (i.e., chronic exertional forearm compartmental syndrome). The reviewed literature shows that riders involved in competitive road racing should develop proper levels of body composition, cardiovascular fitness, muscular strength, specific flexibility, and heat tolerance in addition to their all-important technical riding skills. Furthermore, specific resistance to inertial stresses, visual acuity, mental and physical resilience, psychological strategies, and behavioral awareness all appear to be meaningful contributors to successful performance. Further work is needed to profile riders according to their level to create evidence-based methodologies that improve performance. Additionally, future research should aim to improve safety for these athletes and deepen the understanding about the magnitude of metabolic, mental, technical, biomechanical, and muscular demands in relation to anthropometric characteristics, sex, categories of competition, and success rate.

Key Points

Published research investigating the human component of performance in motorcycle road racing is lacking. This is most likely because of the commercial interests of private organizations, a motorcycle-focused mentality, and the challenges associated with on-track testing.

High-performance riders are exposed to physiological, mechanical, and psychological stresses and are highly susceptible to potential injury from crashes or specific muscular overload (i.e., chronic exertional forearm compartmental syndrome).

The potential benefits of investing in human development to improve racing performance needs to be considered.

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1 Introduction

1.1 The Sport and Focus

The sport of motorcycling is popular globally, with 113 National Motorcycle Federations across six continental unions currently affiliated with the Fédération Internationale de Motocyclisme (FIM), which has been officially recognized by the International Olympic Committee since the 2000 Olympic Games in Sydney. Competitions in six different disciplines (road racing, motocross, trial, enduro, cross-country rallies, and speedway track racing) are organized at the local, national, and international level. Throughout all categories and disciplines, 59 FIM world championships and prizes are currently held every year around the globe [1].

Road race motorcycling competitions are races wherein competitors riding appropriate motorcycles, after an organized collective start procedure, race simultaneously on asphalt-surfaced tracks and compete to finish a known quantity of laps (time or distance in endurance races) faster than their opponents. Apart from public road events, races are held on purpose-built circuits where strict safety standards are implemented, and appropriate facilities host a multitude of riders, operators, and spectators.

Established as a world-level competition series in 1949, the FIM Road Racing World Championship Grand Prix (GP) is the oldest motorsport championship in the world. Currently, top-level competitions such as GP or Superbike World Championships (i.e., prototype motorcycles or commercial production models, respectively) attract more than 2.4 million people through the gates of the circuits per season, and up to 200,000 spectators gather for the most spectacular events, which are broadcast live in more than 200 countries and territories, reaching a cumulative audience of 460 million viewers and involving more than 13,000 media personnel throughout the season [2–4].

Although competitions are organized in categories and age restrictions are applied, road race motorcycling is one of very few sports where regulations do not segregate male and female athletes.

While the disciplines of motocross, enduro, and trial have official international prizes reserved for female riders, road race motorcycling, apart from a few national series or rare international events, has historically not differentiated the sex of the performer at any level of competition.

1.2 Aim and Methods

The aim of this review is to provide a synthesis of the scientific literature focusing on human performance in motorcycle road racing to provide both a comprehensive understanding of the rider's human performance requirements and directions for future research.

The literature search was performed in December 2015 (and updated in January 2018) on three electronic databases: PubMed, SPORTDiscus, and PsycARTICLES. We applied different combinations of the keywords racing, motorsports, motorcycle, motorcycling, riders, road race, competitions, and performance. We also applied the snowballing technique to overcome the rigidity of the mechanistic search and to identify relevant papers not found during the electronic search.

To be considered for inclusion in this review, studies had to meet the following selection criteria: (1) focus on competitive motorcycle road racing, (2) include licensed riders as participants directly or indirectly (i.e., retrospective statistics, racing performances), (3) be peer-reviewed journal articles, conference proceedings, books, or book chapters, and (4) include at least an abstract written in English.

2 Science on Riders

2.1 The Issues with Research

As common in motorsports, the final performance in road race motorcycling arises from the summation and interaction of three main performing elements: the rider, the motorcycle (i.e., chassis, engine, suspensions, brakes), and the tires, integrating with the environment. The distinct contributions of these parts to performance remain unmeasurable, particularly when the competing motorcycles are not identical, and the influence of the human component in the final outcome is quantitatively unknown. Considering the significant investments made in the development of the motorcycle, the business interests of manufacturers, and the paucity of published research focused on the riders, a bike-centered mentality is prevalent in this sport [5–7].

A vast number of popular publications have been dedicated to racing motorcycles, successful riders, riding techniques, and popular competition series, but literature relating to the analysis of human performance in motorcycle road racing is scarce, and methods focusing on performance development are unpublished. The paucity of published work on the human components of racing is likely attributable to the following factors:

- Measurement devices must not interfere with the safety and the ecology of rider performance.
- In the competitive setting, data collection must conform with strict rules of the organizers (club, national or international federations) or track facilities.

- The unique setting of the competition event means "friendly matches" or proper simulations are problematic. Test riding sessions (i.e., individual practice) can be organized, but race mode is not replicable.
- Laboratory simulations of motorcycle racing cannot exactly recreate the inertial stresses and the hormonal/emotional/cognitive activity of real racing.
- Professional motorsport teams are extremely reluctant to allow the collection of experimental data on their riders, especially given the perception that data that could be advantageous to their opponents will be shared.
- Potential research performed by motorcycle manufacturers, racing equipment companies, racing departments, or right holder organizers remains in the private domain because of the commercial interests and sporting benefits of the conducting body.
- Professional motorsport teams are reluctant to allow "non-experts" to have access or interfere with their work.
- Being a high-risk sport, riders are reluctant to participate in experimental settings, especially when invasive methods are used, or they fear being exposed to something uncomfortable.
- Road race motorcycling, which includes training/testing sessions, is very expensive. Therefore, no time on track can be wasted, and no extra risk for crash/damage/wear is typically allowed.
- Riders report to the track from different geographical sites and are not usually available to travel extensively for laboratory evaluations.

This list is not comprehensive but clearly details the challenges of conducting impactful research in the setting.

2.2 Stressors of Motorcycle Racing

In the competitive setting, the rider is exposed to a complex interaction of external and internal stresses. The inertial forces generated by the abrupt accelerations and decelerations (as well as the management of centrifugal forces), the technical movements and postures of high-speed riding (i.e., braking, cornering, changing direction, aerodynamic penetration, etc.), and the burden of the protective equipment (i.e., helmet, leathersuit, chest and back protectors, boots, gloves, etc.), may combine to produce considerable load to the body of these athletes. In addition, the risks and the costs of motorsports (i.e., crashes, injuries, high-performance mechanical equipment, traveling, tires, fuel, etc.), combined with the usual sporting/competition emotional and mental pressures (i.e., tension, fear, anxiety, etc.), may represent an intricate maze of the mind for the population of two-wheel racers.

Biographies of winning riders such as Agostini, Rossi, Dunlop, Sheene, Lorenzo, and Stoner, among others, provide valuable first-hand insight into the riding demands but not empirical information describing the stresses experienced by top-level competitors. To better understand the human demands of motorcycle racers in a more holistic manner, we collated and discuss the peer-reviewed literature under the following section headings: injuries and sports medicine, and physiological, mechanical, and psychological loads.

2.3 Injuries and Sports Medicine

Riding motorcycles on public roads has been a topic investigated in terms of behavioral patterns [8–10] and road accidents [11–15], but few publications have clarified details of crash-related injuries in modern road racing riders involved in competitions [16–24]. Researchers analyzing data from 278 dry races at the top class of the GP world championship (from 1997 to 2016) reported that, independent of environmental factors and speed of racing, 12–14% of starters experienced a crash during a competition [25]. Furthermore, during the 2013 season, an incidence rate of 9.7 crashes per 100 riding hours was recorded during the three American GPs, and 11.5% of crashes caused significant injuries to riders [24].

Statistical records and classifications of injuries have been of interest to several doctors engaged with medical teams offering service during motorcycle road racing competitions [17–24]. From those records (some including sidecar riders [18, 19]), it seems that skeletal fractures were the most common consequence of crashes [16–19, 21, 24], and the limbs seem to be the most vulnerable site of injury since they are used to break falls and to protect more important parts, such as the head [20]. In particular, the upper limbs [18, 19], with the shoulder, wrist, and hand in primis [16, 23], appeared to be the most frequently injured anatomical region. Chapman and Oni [19] reported that 42% of injuries occurred in the upper limbs, whereas Tomida et al. [16] reported that 68% of injuries were fractures and 40% of total injuries were localized to the upper limb. Similarly, Varley et al. [18] found that 60% of injured riders had bone fractures, 44% of those in the upper limb, and—interestingly—70% of fractured riders experienced multiple fractures. The different methods used to collect these data and the variable events (circuit or open road track) at which they were collected do not allow clarification or comparison of the relationship between participants, riding time, crashing events, and injured riders (i.e., injury incidence range 0.24–7%) [16–24]. Moreover, considering the dates of some of those investigations and the technological and material advancements in protective equipment (i.e., airbag-equipped leathersuits, ergonomic and titanium-shield protections, composite fiber helmets, etc.), the pattern or percentages of crash-related injuries may have changed over time. However, the most detailed and current epidemiologic study reported that serious injuries (i.e., brain, spinal cord, internal chest, and abdomen) at the top level of this sport are rare but quantified an injury rate ranging from 3.8 per 1000 race kilometers in the MotoGP™ class to 16.9 injuries per 1000 race kilometers in the Moto3 class [23].

Several researchers have highlighted the importance of high-quality protective equipment worn by riders to minimize injuries [16, 17, 20, 23, 26] and discuss the improvements that should be made to tracks and rescue systems and to regulations to increase racing safety [18, 26–28]. However, no in-field data measurements have yet corroborated the efficiency of current protective equipment (i.e., suits with vs. without airbags), no analysis has clarified the causes of fatalities in motorcycle racing, and—surprisingly—only two recent papers have mentioned the relevance that preventive behavior such as strength training or crash-skills training could have on reducing overload syndromes and lowering the risk of skeletal injury to riders [7, 23].

Although environmental safety apparatuses such as air-fences, gravel traps, or asphalt run-off areas appear to make circuits safer for riders, the death of Luis Salom at the 2016 Catalunya GP is testament to the unpredictability of crash dynamics, and the lack of literature demonstrating scientific evidence on the efficiency of modern protective systems does not clarify the issue. Indeed, despite the quota of crashes happening per event [7, 24, 25] and the reported concussions [23, 24], no published research has investigated sideline screening and monitoring of head concussions in this sport, especially at national or non-professional levels [29–31].

In addition to the traumas associated with crashes, riders seem to be exposed to some pathologies related to the environmental and physical stresses of racing. McCombe and colleagues [32, 33] investigated noise-induced hearing loss in 44 riders competing at the GP world championship level in 1992 and suggested that the average hearing ability of GP riders (45% of the tested population) was significantly worse (below the 95th percentile) than that of age-matched, non-noise-exposed controls. The motorcycles and helmets currently available to riders differ substantially from those used 26 years ago, and—although earplugs are not mandatory in competitions (but were regularly used by 39% of riders in the McCombe studies)—no data pertaining to hearing loss prevention practice in motorcycle racing are available. In addition to wind noise and the decibels generated by their own motorcycle while riding, athletes are exposed to environmental noise (i.e., pit-lane, garages, paddock) throughout the entire race events (3–4 consecutive days each). However, the current level of noise exposure, the potential magnitude of subsequent pathologies, and the efficacy of hearing loss protection devices in road race motorcycling competitions is unknown.

Another pathology often related to motorcycle racers is chronic exertional compartment syndrome of the forearms, informally known as "arm pump" by some. Maneuvering the handlebars (i.e., steering, counter-steering), counteracting inertial stresses (i.e., accelerations, decelerations), operating the throttle command, frequent and intense use of brake and clutch levers, and a tight protective leathersuit combine to expose racers to unique stress in the upper limbs, generating exceptional tension in the forearm region [7, 34–39]. Although researchers have investigated the neuromuscular patterns of force-fatigue models using laboratory protocols simulating motorcyclist activity (i.e., brake lever pulling), considerable limitations may preclude the application of these findings to competitive riding effort [40–42]. Specifically, no inertial forces were involved in muscular activity in the laboratory setting, steering control was not included, the intermittent fatigue protocol was declared to not replicate the effort patterns of motorcycle racing, and throttle movements were involved only in a study with no riders [40–42]. While the work offers an interesting hypothesis regarding the specific use and co-activation of carpi radialis and flexor digitorum superficialis (to improve the precision and sensibility of braking) [41], these studies neither clarified the potential parameters involved with the compartmental syndrome nor provided information relating to the physiological variables associated with riding performance.

Symptoms of local pain and pressure in the forearm region, muscular tension, loss of strength, and lack of grip control may occur during and after motorcycle riding [34–38]. In pathological conditions, local pain can appear after 2–20 min of motorcycle riding [34, 36, 38]. Authors have suggested that treatment for forearm chronic exertional compartment syndrome is surgical decompression by a fasciotomy of all affected compartments [34–38]. While surgical interventions have proven successful in the treatment of this chronic syndrome (up to 94% of riders-patients satisfied with the outcome) [36], and riders can regain full riding capacities within 1–5 weeks [38], the efficacy of non-operative treatments or preventive methods (i.e., specific muscular strengthening and stretching, regimen of myofascial tissue treatment, or technical adaptations) seem relatively unexplored [7, 43].

2.4 Physiological Load

High-speed racing exposes riders to a variety of stresses that contribute to a complex physiological load. Indeed, apart from endurance events, classic sprint races are fierce competitions wherein a multitude of riders battle and push themselves to their limits to stay in front of their opponents from the start to the end of the race, without pit stops or time breaks of any sort [44]. Sprint races last from 22 to 44 min (national to top level) without interruption, and riders compete wearing full-body protective garments [7, 25, 44, 45]. Consequently, intense neuromuscular activity is required to ride fast and maneuver the motorcycle on the track while counteracting the numerous inertial stresses to which the rider is subjected [7, 44, 46, 47]. This section explores the contributing factors to this physiological load with reference to anthropometry; cardiovascular, metabolic, and hormonal physiology; thermal stress and other performance limitations.

2.4.1 Anthropometry

Racer body mass and size is considered influential to riding performance [5–7]. The final mass of the rider–motorcycle combination affects the engine power-to-weight ratio and consequently the ability to obtain high acceleration (reaching higher top speed before the next turn). Therefore, since motorcycles are weight regulated, a lighter and smaller rider is usually considered favorable to final performance [5–7]. Indeed, a comparison of a cohort of 27 young elite riders (mean age 15.6 years) with a reference group of Spanish physically active adolescents (mean age 16 years) showed that the racers were significantly lighter (− 12.5 kg) and smaller (− 4.7 cm) and had significantly lower values for almost all skinfolds and for all the measured girths, with unclear results in regards to the forearm (i.e., the authors' statement in the abstract contrasted with data and results) [6]. Furthermore, data from a population of 26 female national- and international-level riders (mean age 30.8 years, body mass 56.5 kg, stature 164 cm) placed the group in the 10–15th percentile for body mass and at the 50th percentile for body height [44, 48]. Similarly, analysis of top-level professional male riders (mean age 26.9 years) found they were relatively light (63.9 kg) and in the lower percentile range of stature (172.2 cm) [7, 48]. In contrast, Filaire et al. [47] measured 12 national-level riders (mean age 22.2 years) and showed they were relatively bigger (mass 76.4 kg and stature 178.4 cm).

While a small and light racer might be an advantage in the low- and mid-class categories, where the power-to-weight ratio is more affected by the human portion of the total mass due to limited engine power, further research is required to validate this general assumption when racing larger, heavier, and more powerful motorcycles. Indeed, a rider with longer limbs might be biomechanically advantaged in handling inertial forces associated with abrupt braking and high-speed leaning when cornering (i.e., center of mass displacement) [7]. Furthermore, there may be an ideal range of body mass that supports the efficiency of the tires by properly loading the rubber-to-tarmac area to create the proper conditions to offer the ideal grip for intense accelerations. In conclusion, while logic suggests that generally a lighter rider should be better for performance, the real influence of anthropometry on optimal performance is currently unknown.

2.4.2 Cardiovascular, Metabolic, and Hormonal Physiology

The physiological demands associated with road racing during official competitions have been quantified via the measurement of heart rate, concentration of blood lactate, salivary cortisol, and gastrointestinal temperature [5, 44, 45, 47]. Direct measurements of heart rate and blood lactate concentrations of female and male riders during free practices, qualifying sessions, and races in official national and international circuit motorcycle racing competitions indicate that competitive riding imposes a high cardiovascular load on riders [5, 44, 47].

During competition, heart rates in female riders have been reported at 77 ± 6% of its maximum value (HRmax) at the start, increasing rapidly to 92 ± 6% HRmax within the first 50 s, and remaining at that level until the end of the race (end heart rate: 98 ± 5% HRmax) [44]. Similar trends have been reported in male riders [47], with heart rates almost always reportedly above 90% HRmax (frequency of occurrence in different categories: 125GP class = 92.9 ± 5.3%; 250GP class = 93.6 ± 7.3%; 600 cc class = 93.2 ± 10.2%) [5]. Interestingly, no differences have been shown between male riders who reached the podium at the end of the race (frequency of occurrence of heart rate above 90% HRmax = 92.9 ± 7.7%) and those who did not (heart rate above 90% HRmax = 93.5 ± 8.9%) [5]. Furthermore, a longitudinal case study showed a positive correlation ($r = 0.76$) between the cardiac response (frequency of occurrence HRmax > 90%) and lap performance (mean speed of racing) but not between cardiac load and perceived track difficulty [49].

Heart rate as a sole measure cannot differentiate between mental and physical stressors, therefore the measure of strain in motorsports must account for the specific complexity of each performance setting [44, 50]. Indeed, given the psychoemotional stress associated with high-speed motorcycle racing, additional catecholamine (i.e., adrenaline) release would be expected [47, 51–54]. While some researchers postulated that the physical demands of high-speed riding or driving are a substantial component of the elevated heart rate [5, 44, 47, 49, 55–59], others attributed the prevalence of this elevation to increased sympathetic nervous output and changes in hormone levels due to anxiety and other emotional responses [50].

Moreover, the thermal stress to which riders can be exposed (i.e., hot environment, hot motorcycle, protective garments, etc.) and potential dehydration might represent an additional factor contributing to increased heart rate [60–63]. Hemodynamic analysis (i.e., stroke volume, cardiac output, left ventricular ejection time, etc.) has been used to further the understanding of the cardiovascular responses to off-road riding and the effect of dynamic or static muscular efforts [64]. For example, using this technique, Sanna et al. [64] provided evidence to suggest that muscle activity during a 10-minute enduro training session activates the mechano-metaboreflex, leading to a sympathetic-mediated venous constriction and an enhanced cardiac pre-load (i.e., end diastolic volume). However, it appears that profiling the performance of motorcycle riding in real competitions necessitates a more expansive multi-systemic, discipline-specific approach [44, 47, 52, 55, 56, 59, 65, 66]. Even though literature in other motorsports can offer insights into the cardiovascular load in motorcycle road racing, extrapolating data from car driving or off-road motorcycling to road racing requires careful consideration since athletes are subject to different stresses/forces and environmental conditions, adopt different postural positions, wear different protective equipment, and move their bodies differently to operate and control their respective machines.

Direct metabolic assessment via gas analysis during motorcycle riding could help clarify the energetic demands of racers, but so far only a single case study describing this, with an amateur and a competitive rider, has been publicly presented to the scientific community [67]. Using direct gas analysis while riding on the track during private testing, oxygen consumption was shown to be four and seven times the basal value in an amateur and competitive rider, respectively; the mean speed was 40% higher in the competitive rider under non-competition conditions [67].

Blood lactate concentration values measured after racing have provided evidence of the high metabolic involvement required to control the motorcycle at a high speed [5, 44, 47]. Post-race sampling from international and national male racers (125GP, 250GP, and 600 cc class) and female riders (600 and 1000 cc class) were both very high, ranging from 5.6 to 6 ± 2.1 mmol/l for men to 4.5 ± 1 mmol/l for women [5, 44, 47]. The mean speed of racing in these measured populations ranged from 115 to 144 km h^{-1}, whereas top-level competitions during the same time period recorded a mean racing speed of 161 km h^{-1} [25].

In terms of the hormonal responses to competitions, both the qualifying session and the race have been reported to induce a high level of stress on 12 male riders, characterized by an anticipatory response to the contest. Cortisol concentrations measured on the morning of the race have been shown to be up to three times higher than on a resting day [47]. In fact, there was a significant progressive increase in the cortisol concentrations on the riding day, with values measured 10 min after the race being highest (57.3 ± 4 vs. 13.2 ± 2 and 4.04 ± 2 nmol l^{-1} as basal values). There was also a significant decrease (−48%; $p < 0.01$) in cortisol values 60 min after the race, but the concentration was maintained at a higher level for a longer period; values reported more than 4 h after the end of the race were significantly higher (332%) than those reported at the same time on a resting day [47]. Such manifestations are expected, with cortisol the major stress hormone arising from the hypothalamic–pituitary–adrenal axis, indicative of the arousal state [47].

2.4.3 Thermal Stress and Other Performance Limitations

Worldwide, road race motorcycling competitions are held during the warm months of the year and typically scheduled during the central, brightest hours of the day. Factors such as the physical demands of riding, protective equipment, and environmental conditions of racing (i.e., internal combustion engine between rider's legs, dark asphalt track, etc.) can all contribute to thermal stress and consequently limit the rider's performance [5, 45]. To quantify the physiological responses to heat, the gastrointestinal temperature of four male riders (median age 24.5 years) was measured during a national event held at high ambient temperatures (29.5–30.2 °C) and elevated environmental humidity (64.5–68.7%). Racers' gastrointestinal temperature increased from 37.6 °C in the pre-session at a median rate of 0.035, 0.037, and 0.067 °C/min during practice, qualifying, and race sessions, respectively, again highlighting the considerable physical/metabolic demands of racing [45]. Peak post-session gastrointestinal temperature reached a median value of 38.9, 38.8, and 39.1 °C during practice, qualifying, and race sessions, respectively. Riders' thermal sensation was reported as "very hot" after each riding session, and sweat rates ranged from 1.01 to 0.90 l/h during practice and qualifying sessions [45]. Considering the limited permeability of racers' protective clothing, their inability to use active cooling, and the environmental conditions of the track, riders clearly get hot during competitive riding. However, no investigation of methods limiting the impact of thermal strain on a rider's performance, and the efficacy of pre-cooling or acclimatization strategies, are yet published [45].

Assumptions in regard to the low concentrations of CO_2 (and lowered concentrations of O_2) inside the visor-closed integral helmet, and their effects on cognitive abilities relevant to the control of a motorcycle, have been investigated as potential problems [68]. Nevertheless, when riders were moving at reasonable speed, the CO_2

concentration values inside an integral helmet equaled those associated with normal breathing; indeed, riders rarely experienced breathing discomfort except when standing still, suggesting that normal road speeds are sufficient to ventilate the helmet dead space [68].

Since visual performance could be considered an essential attribute for racers, it has been proposed that athletes competing in high-speed sports require superior dynamic visual acuity [69]. Undeniably, motorsport is a dynamic reactive sport that requires sustained visual performance in the areas of contrast judgement, directional localization, visual resolution, and peripheral and far distance demands [70]. Indeed, motorcycle racers are required to process visual information quickly to rapidly analyze available temporal and spatial information during racing situations to make accurate decisions on technical maneuvers (i.e., braking markers, corner's apex, racing lines, etc.). The only published study measuring gaze stabilization, visual acuity, and perception time in nine male car drivers (mean age 17.6 years) reported that this limited population of motorsport athletes demonstrated superior visual acuity in the horizontal plane compared with controls for all measures [69].

The complexity of systemic requirements articulated previously suggests that professional programming for riders' preparation to racing would be a prerequisite to successful performance; however, very few studies have described the training methods of this population of athletes, and no literature is available in support of specific evidence-based training practice. Indeed, both a worldwide selection of young riders (n = 27, mean age 15.3 years) competing internationally in an entry-level category during the 2009 season and a population of female riders (n = 18, mean age 25.8 years, 2013 season) were reported to have a poor approach to preparation practices [71, 72]. While 88% of international young male racers considered physical training essential to improving their performance during competitions, only 27% of them and 33% of female racers reported using a coach or trainer for programming preparation [71, 72]. In particular, despite the number of hours dedicated to physical training (6.9–8 h per week), the rationale of allocation for endurance (95% of riders run and cycle), flexibility (80% train range of motion), and strength training (74% include strength-training sessions, predominantly weight-training machines, free body load, and free weights) is unclear [71]. The absence of specificity (i.e., instability/proprioceptive exercises, riding skills training, etc.) [71] and mental and tactical training [72], as well as the trivial support of professional guidance to which riders seem to be exposed (in regards to human development) [72], perhaps reflects the cultural setting in motorcycle road racing and/or may be the consequence of the paucity of literature investigating this population of athletes. There is no doubt that a more systematic evaluation of the preparation practices of racers competing at the top level of modern motorcycling is needed. Quantifying their physiological loads and their training regimens would help determine more specific solutions for the systemic component of the human side of this sport.

2.5 Mechanical Load

Riding at high speed on a track with multiple bends and curves, and to record consecutive laps within a range of a few tenths of a second, requires the rider to master precise control of the tri-axial dynamics of the motorcycle (i.e., pitch, roll, and yaw for longitudinal load transfer during speed changes, lateral leaning during cornering, and steering/counter-steering for bike directionality, respectively). The specific actions riders are required to execute, and the inertial forces to which they are subjected while riding, represent the mechanical load for these racers.

A rider attempts to minimize their lap time and finish the race in front of their opponents by operating the engine and the brakes (via the throttle, gearshift, clutch and brake levers), maneuvering the handlebars (i.e., steering, counter-steering), moving the body (i.e., aerodynamically penetrative position, braking posture, different phases of cornering, changing direction, etc.), and shifting their mass on-bike around the center of mass of the motorcycle (i.e., along the seat, from footpeg to footpeg, hanging on tank or pushing on handlebars, etc.) [5, 7, 39, 73–77]. To improve their performance, riders aim to increase their mean speed throughout the lap and therefore desire late braking, early and intense corner exits, and high mid-cornering speed [7, 76]. These maneuvers expose the rider to abrupt postero-anterior and antero-posterior accelerations and centrifugal forces balanced by leaning the motorcycle into corners [5, 7, 76, 77].

Top-level riders (i.e., MotoGP™) are required to perform for about 43 min at mean speeds higher than 160 km.h^{-1} per lap, braking more than 170 times and leaning into the curves more than 370 times per race [7]; however, the forces associated with these actions and the consequent muscular strength involved are currently unknown. What has been quantified at the professional level in recent years (2013–2015), is that over 40% of postero-anterior negative accelerations (braking action) were initiated at a speed higher than 260 km h^{-1}, with 13% of these at over 300 km h^{-1}. It has also been reported that a braking action lasting 4.2 ± 0.6 s was performed every 11.6 ± 4.1 s of racing [7]. Considering the expectation that the decrease of speed is of a non-linear shape, it has been calculated that professional riders using top-level carbon disk brakes experience a mean negative acceleration ranging from 16.5 to 2.7 m s^{-2}, and 25% of those braking actions generated a mean inertial stress > 1 g [7]. While these repetitive braking actions might be considered of lower magnitude in lower categories (i.e., lower mean speed of racing and no use of carbon brake systems), and even though this sport is highly supported by forefront technology at any level, currently no published research has instrumented the motorcycle or the rider with the intent of profiling the physical stresses of competitions to quantify the relative muscular strength requirements of racing.

Only two studies have performed cross-sectional measurements of road racing riders' muscular capacities (i.e., handgrip strength, lumbar isometric strength, and vertical countermovement jump) [6, 44]. Handgrip peak strength was reported to be significantly higher in the right hand (used to operate the brake lever and gas throttle) than in the left hand (used to operate the clutch lever) (307 N vs. 281 N) in female adult riders [44] and, similarly, significantly higher in young elite riders (402 N for the right hand vs. 371 N for the left hand) [6]. Recognizing that hypertrophic forearms seem to be a common characteristic of motorcycle riders [43, 78], and considering that the more specific use of the clutch lever in off-road riding demonstrated a left dominance [56], the load due to hard braking for road racers summed to the frequent full wrist extension to keep the throttle fully open, could explain the stronger right side and the more frequent occurrence of forearm compartmental syndrome on the same limb [38]. Although the evolution of technology has facilitated some technical actions (i.e., clutch-less electronic gearing system, electronically controlled engine brake, electronic "ride-by-wire" throttle system etc.), with the constant improvements of the motorcycle components such as braking systems, tire compounds, suspensions, and electronically controlled engine power, the physical stresses on the rider appear to be increasing in intensity [7, 25, 26].

Engineering manuals [73, 77] and academic papers [74, 79–81] have aimed to analyze and improve the dynamics of the motorcycle and have only indirectly described general rider's actions or riding skills such as the "optimal maneuver method" [82–84]. However, such resources do not explain the real stress on a rider because they use the concept of an ideal rider, that is, a rider who can perform any required optimal-control maneuver, such that the vehicle can follow the best possible trajectory, and the highest performance is achieved in the maneuver. The optimal maneuver method therefore is vehicle specific, determining an optimal control sequence for each vehicle for a specific maneuver [85]. However, these mechanical analyses of motorcycle dynamics and subsequent models of riding performance do not clarify the actual demands of competition riding or the physical demands on the rider.

2.6 Psychological Load

Although riding behavioral patterns and cognitive processes have been studied in relation to public road accidents and urban traffic dynamics [8, 9, 86, 87], psychological factors important to motorcycling competitions have been rarely investigated [88, 89]. Dosil and Garcés de Los Fayos [89] reported that the psychological demands of motorcycle road racing were embedded within the specific characteristics of racing and the technical peculiarities of this high-cost sport.

In particular, control of varying intensities of pre-competition anxiety (depending on the phase and period of competition/season) and self-confidence (also in relation to the risks of this sport) are considered fundamental in a high-speed sport where a mistake can cause severe injury to the athlete or have career repercussions [7, 89]. With regards to experimental research, a program of physical, technical, and tactical training has been implemented previously and appeared to have unclear effects on the psychological status of young elite riders (mean age 15.6 years) [88]. Following 2.5 months of physical conditioning, riding practice, and tactical training, subjective evaluations of technical execution, physical efficiency, and psychological responses to competitions indicated improvements in technical, physical, and psychological status in the experimental group ($n = 16$). This was confirmed by a better index of performance given by results in ranking positions and championship points. While the 10-item Perceived Stress Scale (PSS-10) indicated lower values in the riders following the experimental training program, no significant differences were reported in self-evaluated physical and psychological status; self-esteem (measured with the 10-item Rosenberg scale) also did not differ between the experimental and control groups ($n = 11$) at the end of the intervention program [88].

Racers use several psychological skills, including concentrating on several aspects of the riding performance (such as the front/rear load of the motorcycle, engine revolutions per minute [RPM], gears, leaning angle, opponent lines, among others) and imagery [89], but literature measuring the effects of these skills on racing performance is lacking. Psychological support through interventions consisting of a combination of relaxation techniques, imagery, positive self-talk and affirmations, goal setting, stopping negative thoughts, and cognitive restructuring were reported to be successful (all the 12 self-measured constructs showed positive changes) in a case study with an injured national-level rider [90]. In this intervention program, Jevon and O'Donovan [90] used a variation of "Butler's performance profile" over 12 weekly appointments to monitor the development of psychological factors assessed as important in the recovery of a seriously injured motorcycle racer.

Successful riders are also required to master emotional self-control (to minimize mistakes and risks), decision making (to discriminate decisions and prioritize actions), communication skills (interactions with their team, media, and sponsors), and establish and manage objectives successfully (short-, medium-, and long-term goals in different areas directly or indirectly related to performance) [89]. The personality construct of hardiness, which is a personality characteristic anticipated to explain the differences in mood states among individuals subjected to stress, appears to be an important component in the success of a rider, as it has been found to be significantly higher in professional riders than in club racers [91]. Interestingly, since the effect of physical, technical, and tactical training related to motorcycling has been reported to lower the perceived stress in young elite riders [88], and physical training seems to decrease the strain of human beings during psycho-emotional-concentrative stress situations [50], no information is available in regards to the age, experience, or training loads/habits of the professional riders with a higher hardiness score [91]. Therefore, the interaction between age, performance level, training habits, and the effects of psychological training are yet to be elucidated.

Despite the psychological attributes of a rider being reportedly significantly influential in riding performance [88–91], very few publications have investigated the rider within this context, and only few riders (i.e., higher levels) seem to be regularly supported by a sport psychologist or have a structured approach to improving their mental performance [72, 89–91]. Beside anecdotal references to riders' "mind games" [76, 92–94], the psychological skills and mental strategies used by riders in competitions, qualifying, or free practice are seemingly undefined. More importantly, a well-rounded psychological profile of successful motorcycle racers and the effects of an experimental protocol of mental skills training on rider's performance would benefit understanding in this area substantially.

3 Conclusion

The limited work completed to date suggests that human performance in motorcycle circuit racing involves a complex interaction of specific skills and abilities. High-performance riders are exposed to physiological, mechanical, and psychological stresses, in addition to the potential of injuries from crashes or localized muscular overload (i.e., chronic exertional compartmental syndrome of the forearm). The literature recommends that riders involved in competitions possess proper levels of body composition, cardiovascular fitness, muscular strength, specific flexibility, and heat tolerance. Furthermore, specific resistance to inertial stresses, visual acuity, mental and physical resilience, psychological strategies, and behavioral awareness, along with technical riding skills, appear to be meaningful to perform successfully.

3.1 Recommendations

Riders may benefit from specific multidisciplinary training to minimize the effects of fatigue during competition, to prevent the risk of injury, to improve their technical and mental skill set and capacities, and to manage successfully their investment in their racing career. Considering the risks, costs, and specificity of motorcycle circuit racing, both young and adult riders are recommended to be guided and assisted by highly specialized professionals with an holistic approach to improving their performance.

3.2 Future Research

It is evident that further work is needed to profile riders according to their level and to demonstrate how best to prepare them by creating evidence-based methodologies and model-of-performance-based training protocols that improve their performance in competitions.

Undoubtedly, future research should aim to improve safety for these athletes by measuring the effects of technological (such as equipment and facilities) and behavioral (i.e., regulations, crash skills techniques) solutions.

Physiological, psychological, and biomechanical investigations are recommended to deepen our understanding of the magnitude of metabolic, mental, technical, and muscular demands in relation to the anthropometric characteristics, categories of competition, and success rate. The influence of the human component on final performance is currently understudied, and the potential benefits of investing in human aspects to improve racing performance must be considered. Furthermore, the under-representation of, and biased beliefs around, female involvement and racing ability (in a male-dominated sport) needs exploration [95]. Future research is needed to evolve the cultural resistance prevalent in motorcycle racing and to invest in riders by providing evidence-based applications that improve rider performance. This information should not be viewed in isolation but rather in tandem with current experience-based practices.

Compliance with Ethical Standards

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