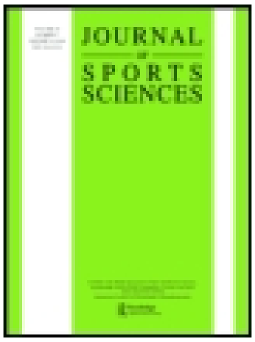

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ABSTRACT

Manoeuvring a motorcycle at high-speed in official competition has been shown to expose riders to substantial and complex physiological and psychological demands, however few studies have analysed the physical load experienced by professional racers. This study aimed to quantify the physical stress experienced by riders and explore relationships between performance related variables (i.e. crashes). Performance and braking data were collected from official race reports from 2013 to 2015 of the top class of the FIM Road Racing Grand Prix World Championship. Top-level riders are exposed to a considerable volume (175 ± 42 brakes and 372 ± 48 leans to corner per race) of high intensity actions (>40% of brakes initiated at speeds higher than 260 km.h^{-1}, and 13.2% over 300 km.h^{-1}), where 1 out of every 4 braking actions generated inertial stresses greater than 10 m.s^{-2}. Furthermore, the mean speed across competitions increased over the years (from 161.7 ± 6 km.h^{-1} to 164.5 ± 6 km.h^{-1}), however no clear relationships between the amount of crashes and competition-related factors were found. Given the findings it would seem that riders could benefit from strength training specifically designed to prepare the body to counteract the repetitive inertial stresses of racing.

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KEYWORDS
Motorcycling; racing; riders; physical load; motorsports

Introduction

Road race motorcycle competitions are performed on asphalt tracks, take place in a wide variety of forms (i.e. on circuit or open roads, sprint or endurance races, classic or modern vehicles, etc.), are usually organized according to engine size and can be held across local club events to world level tournaments. The FIM (Fédération Internationale de Motocyclisme, officially recognised by the International Olympic Committee) established a road-race World Championship in 1949, which currently represents the oldest international motorsport tournament and the highest level of powered two-wheel prototype racing.

Technological advancements in mechanical and electronic engineering, aerodynamics and materials (i.e. tyres, brakes, tarmac) have ensured the evolution of motorcycle performance (Masi, Toffolo, & Antonello, 2010; Tanelli, Corno, & Savaresi, 2014). Furthermore, in a high-risk sport, where crashes affect the performance outcome and potential injuries might influence a rider's career, such innovation can be observed across areas of improved protective gear and safety for the riders (Boubezoul, Espié, Larnaudie, & Bouaziz, 2013; Cossalter, Aguggiaro, Debus, Bellati, & Ambrogi, 2007). Although performance in competition depends upon the characteristics of the motorcycle and the capability of the rider, manufacturers and suppliers seem to invest exclusively in the machines, while human factors in racing may be less investigated (D'Artibale, Tessitore, & Capranica, 2008; Sánchez-Muñoz et al., 2011), and the influence of physiological and psychological components on race outcome is largely unknown (Brearley, Norton, Kingsbury, & Maas, 2014; Dosil & Garcés de Los Fayos, 2006).

The intense neuromuscular activity required to ride fast and manoeuvre the motorcycle on the track (i.e. operational movements on handlebars, footpegs and body positions) while counteracting the numerous accelerations (i.e. anterior, posterior, lateral) to which the rider is subjected (D'Artibale, 2014; Marina, Porta, Vallejo, & Angulo, 2011; Marina, Rios, Torrado, Busquets, & Angulo-Barroso, 2014), alongside the psycho-emotional stress associated with racing (Ascensão et al., 2007; Thomas, Reeves, & Agombar, 2013), imply that motorcycle road racing imposes high mental and physical loads on the riders. The physiological demands associated with road racing during national and international official competitions have been quantified via the direct measurement of heart rate and blood lactate concentration (D'Artibale et al., 2008; D'Artibale, Tessitore, Tiberi, & Capranica, 2007; Filaire, Filaire, & Le Scanff, 2007), salivary cortisol (Filaire et al., 2007) and gastrointestinal temperature (Brearley et al., 2014). In regards to riders' muscular capacities, cross-sectional measurements of female (i.e. handgrip) (D'Artibale et al., 2007) and young riders (i.e. handgrip, lumbar and vertical jump) (Sánchez-Muñoz et al., 2011) have been published, and forearm muscle fatigue has been monitored (Marina et al., 2011, 2014). Furthermore, preparation practices have been investigated within limited populations (Martin, Blasco, Fargueta, Olcina, & Monleon, 2015; Rodríguez Pérez, Casimiro Andújar, Sánchez Muñoz, Mateo March, & Zabala Díaz, 2013); consequently, the mechanical demands of top level performance remain for the most part unstudied.

Top-class circuit racing prototype motorcycles are currently machines of 160 kg, powered by engines generating about 245 bhp, often reaching a track speed above 340 km.h^{-1}. A world level event takes place over three or four consecutive days, with the first two or three days dedicated to practices

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and qualifications, whilst on the last day a warm-up session and a no-pit-stop race are scheduled (FIM, 2015). Repeated movements and high intensity braking actions are technical manoeuvres influencing individual performance and exposing the riders to substantial physical stress (Barrera-Ochoa et al., 2016; Goubier & Saillant, 2003; Marina et al., 2014), however only few studies have analysed the physical load experienced by professional riders and no publications have information pertaining to crashing events in circuit racing motorcycling.

As technology in the sport sciences is rapidly evolving, and riders are encouraged to push themselves and their machines to their limits, further investigation into the technical, physical and tactical aspects of a rider's performance is needed to understand motorcycle racing preparation and performance. The aims of this study were to quantify the physical stress experienced by riders by analysing race results alongside kinematic data from top-class circuit racing motorcycle competitions. Furthermore the relationships between performance-related variables such as crash events, speed of racing and environmental conditions were examined. The ultimate goal of this study was to provide empirically-based foundation knowledge that might be used to assist future rider preparation.

Methods

Methodological approach

In circuit race motorcycling competitions, championships are organized in multiple events, usually performed over several months on different tracks located according to the level of competitions (i.e. club, national or international level). A cross sectional observational research design was used in this study, where performance variables (i.e. time of the fastest racers, values pertaining to braking actions etc.) and event-related data (i.e. track characteristics, weather conditions, etc.) of professional racers (i.e. world championship) were analysed over three consecutive seasons (i.e. 2013–2015). Collating kinematic measurements from official race reports allowed the description of the mechanical stresses experienced by riders during competitions.

Data sample

Data from competitive seasons 2013, 2014 and 2015 of the top class (i.e. MotoGP™) of the FIM Road Racing Grand Prix World Championship (GPWC) were collected and collated for analysis. The research design involved analysis of publicly available sport performance data, and the institutional ethics review board approved the study. Researchers had no professional, social, financial or cultural relationships that might be considered conflict of interest with respect to the collated data.

Data source

Performance and event-related data were retrieved from: a) official documents that included circuit information, Race Direction (RD) reports and rider profiles from the official open-access website of the GPWC (i.e. www.motogp.com); and, b) official race reports (i.e. Brake Circuit Identity Cards) from the open-access website of the leading company manufacturing braking systems for racing prototype motorcycles (i.e. Brembo, Italy).

Performance data

For each competition event (GP), the following quantitative and qualitative variables were selected to quantify the riders' performance: year of event; name of the track where GP was held; length of the track [m]; number of laps needed to complete the GP; race conditions [dry/wet] as declared from RD; air temperature [°C]; humidity [%]; ground temperature [°C]; number of riders crashed during the GP; time needed for the GP-winner rider to complete the race [s]; time needed for the rider finishing in 10th position to complete the race [s]; number of right corners on track; number of left corners on track; longest straight on track [m]; and, number of braking actions per lap. In addition, for each braking action performed in a lap, the following measurements were used to quantify the inertial stress experienced by riders during competitions: speed at the beginning of the braking action [km.h^{-1}]; speed at the end of the braking action [km.h^{-1}]; displacement while braking [m]; duration of the braking action [s]; force peak on front brake lever [kgf]. Braking data were mean values recorded during dry races or dry race on-track simulations (i.e. new track on the seasonal calendar), obtained by data logger systems owned by the racing teams equipped with the Brembo braking systems. Body mass [kg], stature [cm], age [years] and brake brand of the top 10 riders for each season were also recorded.

In a racing tournament, riders collect points according to their final position at each event. Only the first 15 riders crossing the finish line are awarded championship points in an exponentially decreasing order. In competitions, although the leading rider or group of riders are looked upon as the reference performance for setting the pace of the races, the top 10 finishers are usually considered the most competitive athletes in each category or level of competition. Focusing exclusively on the performance of the race winner, especially when a talented rider with a fast bike is synonymous with victory, would restrict the analysis of performances to single machinery-rider binomials, while considering all the finishers, would include the analysis of novice participants or less competitive riders, which would not be representative of the top level of the competition. Therefore in this study, the mean speed and race duration between the first and the 10th rider have been considered for analysis, which are the top two thirds of the finishers being awarded championship points.

From the aforementioned measurements, the following values were calculated: length of the GP [m]; total number of brakes in a GP; total number of corners in a GP; mean speed (MS) between the 1st and 10th position to complete the GP [km.h^{-1}]; GP single lap time (MLT) at MS [s]; mean race duration for the first 10 riders [s]; percentage of time spent braking in a MLT [%]; braking ratio in a MLT [s] which is the number of seconds needed to complete one lap at mean speed divided the number of brakes in one lap; curve ratio in a MLT [s] which is the number of seconds needed to complete one lap at mean speed divided by the sum of left and right corners in one lap; and, negative mean acceleration per each braking action [m.s^{-2}] (i.e. change of speed divided by the duration of braking).

Inclusion criteria

At the GPWC, all races are categorised as either wet or dry by RD before the start of the race. The purpose of this classification is to indicate to riders the varying climatic conditions during a race, which affects their choice of tyres and the overall performance. A white flag being waved at the flag marshal posts during the race indicates that RD has decided to declare a wet race after it was originally declared dry. In this instance riders are allowed to change bikes during the race to those equipped with wet tyres by entering the pit lane and swapping machinery in front of their assigned pit box.

To standardize the fundamental conditions for performance-related data analysis, the following three criteria needed to be satisfied for the competitions to be included in the analysis: (1) the race was declared dry by RD before the start; (2) in case the white flag was waved at any point during the GP, none of the first 10 riders crossing the finish line entered the pit lane during the race; and, (3) the first 10 riders crossing the finish line completed the required original number of laps announced for the event in accordance to the official regulations. The braking-related data referred to measurements in dry settings, therefore they were considered pre-standardized. Circuit-related and rider-related data did not require standardization.

Statistical analysis

Both data gathering and statistical analysis were performed using an open source electronic spread sheet (Open Office 4.1.2). Descriptive statistics (i.e. mean, standard deviation, range) were used to summarise quantitative variables. To estimate the uncertainty of the true mean, 95% confidence limits (CI) for the mean were calculated. Pearson correlation coefficient (r) and its 95% CI using Fisher's z transform was used to explore potential relationships between variables. Trivial, small, moderate and large relationships were considered for r between 0 and 0.1, 0.1 to 0.3, 0.3 to 0.5 and larger than 0.5, respectively.

Results

From a total sample of 54 competitions (18 races per season), 8 races (14.8%) did not satisfy the inclusion criteria (5 wet races, 2 white flags rule applied, 1 race with lap reduction due to exceptional tyre degradation), therefore performance data from a total of 46 competitions (2013 season n = 16, 2014 season n = 15, 2015 season n = 15) in conjunction with the braking data (18 reports per season) were analysed to quantify the riders' load during competition. Twenty-nine out of the thirty (96.7%) riders that ranked in the top 10 positions at the end of the three analysed seasons had their motorcycle equipped with the Brembo braking system, therefore braking data reports were considered relevant and valid information to relate to the race reports.

The youngest rider (all males) was 20 years old, while the oldest was 36. The lightest and smallest rider had a body mass of 51 kg and stature of 160 cm, while the heaviest rider was 77 kg and the tallest was 182 cm. (see Table 1)

In dry conditions, the riders raced for 43:07 ± 1:39 minutes per race, covering a mean distance of 117.2 ± 3.1 km, riding at a speed of 163.2 ± 6.4 km.h^{-1} (maximum MS in the Australia GP in 2015: 177 km.h^{-1}; minimum MS in the Indianapolis GP in 2013: 151 km.h^{-1}). Increases in MS were observed over the three seasons analysed: 1.2% between 2013 and 2014, and 0.6% between 2014 and 2015. In the 19 different circuits included in the GPWC during these three seasons, riders were required to navigate 15 ± 2 corners and 7 ± 1 braking actions per lap, and the longest straight on track measured 827 ± 223 meters. To complete the required distance during actual competitions, they braked 175 ± 42 times and leaned to corner 372 ± 48 times per race (see Figure 1). Maximum values of those technical actions were observed at Assen in the Netherlands, where riders cornered 468 times in the race and at Laguna Seca in the United States, where riders were required to brake 256 times from the beginning to the end of the race. The minimum values were recorded at the Malaysia GP, where riders cornered 300 times and in the Australia GP where only 3 brakes per lap were required for a total of 81 braking actions to complete the race.

In dry conditions, a MLT lasted 1:45.5 ± 00:12.7 minutes, where riders spent 28.6 ± 4.9 seconds braking (27% of their racing time). Matching performance-related data with track-specific braking and cornering requirements indicated riders performed a braking action every 11.6 ± 4.1 seconds of racing (i.e. spent accelerating and not using either the throttle or the brakes) that lasted 4.2 ± 0.6 seconds in duration. The riders were in the middle of negotiating a corner every 7.1 ± 0.8 seconds of riding.

Across the 18 GPs per championship, racers faced 124 different braking actions (i.e. entering 124 different corners) during the 2013 and 2014 seasons and 123 actions during the 2015 season. Over 40% of these braking actions were initiated at a speed higher than 260 km.h^{-1} (see count of brakes in Figure 2). Although during actual racing the decrease of speed is of a non-linear shape (to minimize the time at a lower speed and to optimally manoeuvre the lean of the motorcycle at the end of the braking phase), riders experienced a mean negative acceleration ranging from 16.5 m.s^{-2} to 2.7 m.s^{-2}, and 25% of the aforementioned inertial stresses were greater than 10 m. s^{-2}. The mean peak force applied on the brake lever during those braking actions increased from 5.1 ± 1.2 kgf in 2013 to 5.4 ± 1.6 kgf in 2014 and 2015, with a maximum value reached at the Argentina GP on 2014 where the mean peak force

Table 1. Top ten riders characteristics and performance variables.

	Season 2013 (n = 16)	Season 2014 (n = 15)	Season 2015 (n = 15)	Total Sample (n = 46)
A	27.1 ± 4	26.2 ± 4	27.5 ± 4	26.9 ± 4
BM	63.2 ± 5.3	63.5 ± 5.2	65 ± 6.7	63.9 ± 5.7
S	171.1 ± 6.2	172.8 ± 6.9	172.8 ± 6.9	172.2 ± 6.5
MS	161.7 ± 6	163.6 ± 7	164.5 ± 6	163.2 ± 6
	CI: 158.4–164.9	CI: 159.9–167.3	CI: 160.9–168.1	CI: 161.3–165.1
B > 3	12.9	13.7	13	13.2
Cpr	2.8 ± 2	3.3 ± 2	3.7 ± 2	3.2 ± 2

A: Age (years); BM: Body mass (kg); S: Stature (cm); MS: Mean speed of racing (km·h-1); B > 3: % of braking actions initiated over 300 km·h-1; Cpr: Crash per race.

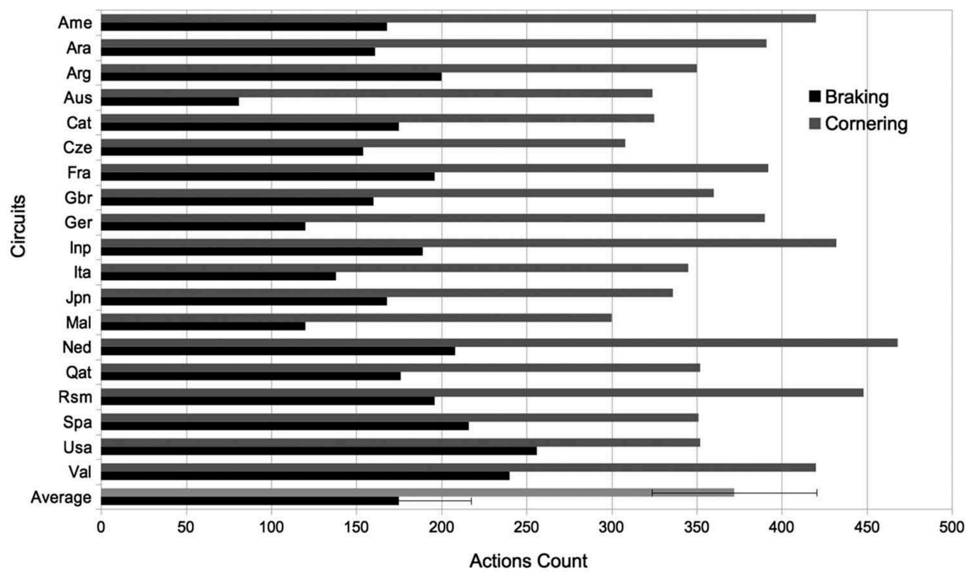

Figure 1. Count of braking and cornering actions performed during competitions across different circuits.
(Ame = Circuit of the Americas, USA; Ara = Motorland Aragon, Spain; Arg = Circuit Termas de Rio Hondo, Argentina; Aus = Phillip Island Circuit, Australia; Cat = Circuito de Catalunya, Spain; Cze = Automotodrom Brno, Czech Republic; Fra = Le Mans Circuit, France; Gbr = Silverstone Circuit, UK; Ger = Sachsenring Circuit, Germany; Inp = Indianapolis Motor Speedway, USA; Ita = Mugello Circuit, Italy; Jpn = Twin Ring Motegi, Japan; Mal = Sepang Circuit, Malaysia; Ned = Assen Circuit, the Netherlands; Qat = Losail International Circuit, Qatar; Rsm = Simoncelli World Circuit, Republic of San Marino; Spa = Circuito de Jerez, Spain; Usa = Laguna Seca Circuit, USA; Val = Ricardo Tormo Circuit, Spain).

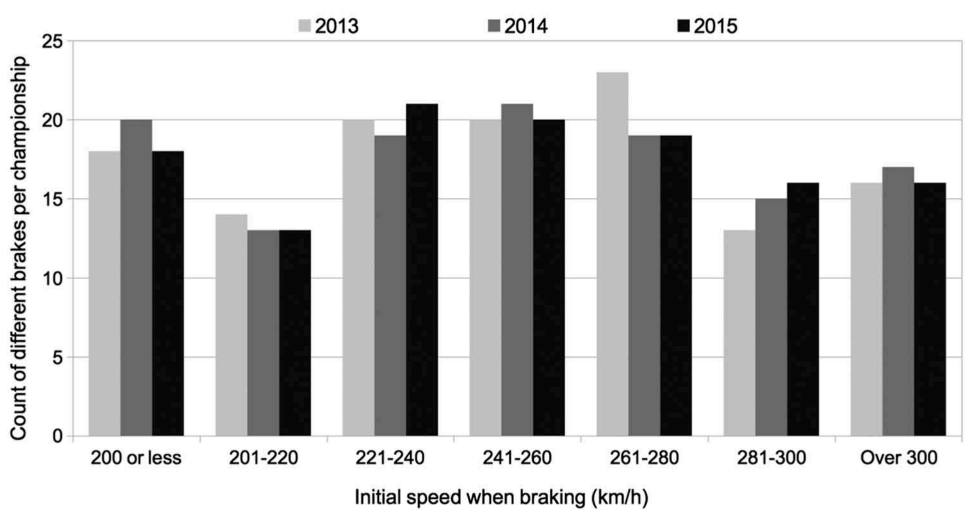

Figure 2. Count of braking actions and their initial speed across seasons.

applied on the brake lever for this track, which requires 8 braking actions per lap, was 8.3 ± 3.3 kgf.

During dry competitions, 3.2 ± 2 riders crashed per race, with a maximum of 7 riders crashing in three events (6.5 % of the total sample analysed). Trivial to small correlations were found (r < ± 0.3) between the count of crashes per race and the speeds of racing (i.e. MS (r = 0.03; CI: −0.26 to 0.32) and the mean speed of the winning rider (r = 0.05; CI: −0.24 to 0.34)) or the track characteristics (i.e. straight length (r = 0.08; CI: −0.21 to 0.36), number of curves on track (r = −0.13; CI: −0.41 to 0.16), number of curves per race (r = −0.28; CI: −0.52 to 0.01)) or braking variables (i.e. number of brakes per race (r = −0.16; CI: −0.43 to 0.14), time spent braking (r = −0.05; CI: −0.33 to 0.25), mean braking duration (r = 0.17; CI: −0.12 to 0.44), mean peak force on lever (r = 0.09; CI: −0.21 to 0.37)). Correlation coefficients were also small (r between 0.1 and 0.3) when relating the count of crashes with the environmental conditions of racing (i.e. air temperature (r = 0.26; CI: −0.04 to 0.51), air humidity (r = −0.11; CI: −0.39 to 0.19) and ground temperature (r = 0.25; CI: −0.05 to 0.5)). The strongest association (moderate magnitude, r = 0.31; CI: 0.02 to 0.55) was found between crashing events and curve ratio (i.e. MLT divided the sum of left and right corners in that circuit).

Discussion

A few scientific publications (D'Artibale et al., 2008; D'Artibale, Tessitore, Lupo, & Capranica, 2013; D'Artibale et al., 2007; Filaire et al., 2007) have described the metabolic load of circuit race motorcycling, however no studies have profiled the forces acting on the rider with direct measurements (i.e. instrumenting the bike or the rider). This paucity of research could be attributed to the difficulty of using experimental apparatus in such unique competitive settings and the tendency for racing teams/factories to operate in strict secrecy so as to maintain a competitive advantage. In addition, being a high-risk and high-cost sport, riders along with teams are reluctant to allow the collection of experimental data, as it is perceived that data collection may influence performance and safety. Nonetheless this study has profiled the stresses experienced by riders by analysing race results and kinematic data from top-class circuit racing motorcycle competitions. Furthermore, this analysis incorporated information in regards to the crashing events, which are a determinant variable of the final outcome in this sport. With this in mind, the aim of this study was to quantify the physical stresses experienced by riders competing at the top-level in circuit race motorcycling (i.e. FIM Road Racing Grand Prix World Championship) and explore potential relationships between performance related variables such as speed of racing and crashes.

The main findings of this study were: (1) professional top-level riders are relatively light male athletes with a mean stature above 170 cm and a mean age of 27 years; (2) the mean speed of racing has increased over the three years of competitions – riders are going faster; (3) during racing, riders are exposed to a considerable volume of high intensity actions required to both counteract inertial stresses generated by positive and negative accelerations in the horizontal plane while increasing and decreasing speed, as well as counteracting lateral centrifugal forces while cornering; (4) there are no clear relationships between the amount of crashes and competition-related factors (i.e. racing speed, track characteristics, brakes, environmental conditions).

The rider's body mass and stature can be considered influential on riding performance. The final mass of the rider-motorcycle affects the engine power-to-weight ratio and consequently the ability to obtain high accelerations, therefore, since motorcycles are weight-regulated, a lighter and smaller rider intuitively advantages the final performance (D'Artibale et al., 2008; Sánchez-Muñoz et al., 2011). Despite anthropometrics not being a focus of this study, the data analysed offer a unique view of the general body size of the top level riders, which may represent valuable information for aspiring riders and future research directions centered on inertial mechanisms and preparation methods in this sport. Anthropometrically, it can be concluded from the current analysis that professional top-level riders are males who are relatively light (from 63.2 ± 5.3 kg to 65 ± 6.7 kg) in the lower percentile range of stature (from 171.1 ± 6.2 cm to 172.8 ± 6.9 cm) (Fryar, Gu, Ogden, & Flegal, 2016). A small and light rider might be particularly advantageous for lower categories of racing (Sánchez-Muñoz et al., 2011) where the power-to-weight ratio is more affected by the human portion of the total mass due to a limited engine capacity. However, further data and analysis is required as it may be assumed that professional riders with longer limbs may be biomechanically advantaged in combatting the inertial forces associated with leaning and braking, and as a result successful in riding bigger, heavier and more powerful motorcycles.

The mean speed of racing increased across the three years from 161.7 ± 6 km.h^{-1} during the 2013 season to 164.5 ± 6 km.h^{-1} during the 2015 championship. Whether this can be attributed to mechanical and/or human factor was beyond the scope of this article, however, the constant improvements of the technological components of the motorcycle such as braking systems, electronic engine power control and tyres compounds no doubt has increased the physical stresses experienced by racers to counteract the forces of faster racing (D'Artibale et al., 2013; Lippi, Salvagno, Franchini, & Guidi, 2007). In particular, since the front brake is used to decelerate the bike in circuit racing motorcycles (operated by a lever with the fingers of the right hand), riders are exposed to frequent and substantial muscular activity in the upper limbs, generating exceptional tension in the forearm region to properly operate the handlebars while counteracting inertial forces acting on the whole body (Barrera-Ochoa et al., 2016; Marina et al., 2011). Findings from this study reported mean peak force applied on the brake lever increasing from 5.1 ± 1.2 kgf in 2013 to 5.4 ± 1.6 kgf in 2014 and 2015. In synergy with these results, the incidence of chronic exertional compartment syndrome of the upper limb seems to be increasing between motorcycle racers in recent years (Barrera-Ochoa et al., 2016; Goubier & Saillant, 2003). Interestingly, even though the use of surgical interventions such as a fasciotomy has proven successful in the treatment of this syndrome, the efficacy of non-operative treatments or preventative methods (i.e. specific muscular strengthening, stretching or technical adaptations) seems unexplored.

Professional riders are required to perform at their best for more than 40 minutes, where they continuously coordinate their technical skills (i.e. synchronised multi-limb actions such as up/downshifting, throttle and brakes control, clutch for some classes) and their postural adaptations in a high-density rhythmical sequence of actions. When averaging the duration of a lap with the track layout, a rider experiences a 4.2 second braking action (i.e. postero-anterior inertial acceleration) every 11.6 seconds of racing and turns the motorcycle into a corner every 7.1 seconds of riding. Leaning a high-speed motorcycle to turn requires application of force on the handlebars (i.e. counter-steering, steering) and to laterally shift rider's body weight (Cossalter, 2006; Evertse, 2010); these actions can be performed up to 400 times per race at the top level of racing (see Figure 1). In addition, to minimise their lap-time, riders experience intense accelerations when exiting corners and abrupt decelerations (25% > 1g) when braking. Considering the quantity (175 ± 42 brakes per race), the duration (27% of lap-time), and the intensity of the braking actions (13% begin at speed > 300 km.h^{-1} and 40% at above 260 km.h^{-1}) it can be assumed that racing at professional level requires considerable muscular demands.

Despite finding the high and increasing speed of competitions over three seasons of racing, all but one correlation between the amount of crashes recorded during the races and the factors surrounding these events, were trivial or small. With a mean of 3.2 ± 2 riders crashing each dry race the only predictor of moderate magnitude (r = 0.31; CI: 0.02 to 0.55) was the frequency of turns faced by racers when riding in different track layouts, which might mean connecting corners (i.e. curves where the ideal racing line involves multiple consecutive corners) could represent an extra challenging task when performed at high speed. Other track characteristics such as the amount of corners or the length of the main straight (i.e. higher top speeds), braking features, the speed of racing, or the environmental conditions were not significantly correlated with the amount of accidents happening during official top-level races. Perhaps a much larger sample and a more detailed analysis (i.e. site and typology of crash) might clarify information about these unwanted events.

Conclusion

Manoeuvring a motorcycle at high-speed in an official competition setting has been shown to expose the riders to a substantial and complex mechanical load. The main findings and practical applications of this study suggest that: (1) Circuit race motorcycling riders aiming at achieving the top level of the sport might consider monitoring anthropometric measurements and following nutritional plans with the intent of optimizing their body composition i.e. balancing low body weight with the necessary muscular mass to control the forces required to control the motorcycle while racing. (2) The muscular demands of professional riders during top-level competitions are considerable in volume and intensity, especially when considering that official events last three or four consecutive days. Therefore, riders performing at high level should possess pre-requisite levels of cardiovascular and muscular endurance as well as muscular strength. (3) To counteract the repetitive positive and negative inertial stresses of racing, riders should implement training that focuses on site-specific eccentric, isometric and concentric strength in the lower and especially the upper limbs. (4) Due to the exceptional stress accumulated in the upper limbs, in particular in the forearm region (Marina et al., 2011), and due to the potential risks of overload (i.e. surgery to solve forearm compartmental syndrome) (Barrera-Ochoa et al., 2016; Goubier & Saillant, 2003), riders may have particular interest in programming exercises aiming at decreasing the muscular tension and future research may investigate the effects of specific exercises aiming at increasing the elastic properties of the affected tissues (i.e. muscular stretching, high range of motion antagonists exercises, etc.). (5) Due to the quota of racers crashing at each event, in order to minimise injuries, increase confidence and extend a riders career, competitors might consider including crash-skills training in their preparation plan (i.e. tumbling techniques).

Finally, this study provides original and novel information quantifying indirectly the mechanical stresses and subsequent muscular demands of top-level circuit race motorcycling. Furthermore, no other scientific publications studied crashes and performance-related variables. It is acknowledged that there a number of limitations of the current analysis, however, until riders can be directly instrumented and in-field measurements collected across a number of racers and teams, then the methodological approach undertaken in this study would seem very useful to provide fundamental information for the design of rider preparation programs.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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