CLINICAL REVIEW

Sleepiness, attention and risk of accidents in powered two-wheelers

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SUMMARY

In recent years, the role of “sleepiness at the wheel” in the occurrence of accidents has been increasingly highlighted with several national and international public health campaigns based on consensual research publications. However, one aspect of this phenomenon is rarely taken into account, i.e., the risk of sleep-induced accidents while riding powered two-wheelers (PTWs). PTWs are indeed involved in a high percentage of fatal accidents mostly with young male riders. The effects of sleepiness may be different in drivers and riders, partly because riders may be stimulated more by the road environment. But riders (differently from drivers) have also to maintain continuously a balance between their own stability and the need of following the road, even when they are directly exposed to adverse climatic conditions. We, therefore, gathered the limited scientific literature on this topic and tried to analyze how riders may be affected differently by sleepiness. Finally we provide some suggestions as to how this question may be better approached in the future.

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Introduction

“Sleepiness at the wheel” has become a more widely understood and openly discussed question of public health over the past few decades [1,2]. Safety campaigns have been launched in many countries and consensus recommendations have been given to drivers: avoid sleep debt before driving, stop when you feel sleepy, take a nap, don’t drive at night, don’t drive long distances without having a break [3,4]. There have been considerable amounts of research on the topic, highlighting the implications of sleep debt on the risk of driving when sleepy [1,5–8]. Indeed, it is generally considered that sleepiness is involved in 10–20% of fatal accidents [1,6]. Prevention campaigns are, however, not sufficient to control this problem, as sleep debt is very common in the general population, and especially in young adults and shift workers [9–11].

Curiously, the risk of sleep-related accidents while riding powered two-wheelers (PTWs) is rarely discussed. Yet, PTWs are implicated in many fatal accidents involving mostly young male riders. It is usually thought that sleepiness has fewer direct effects on PTW riders than on drivers, because of the more stimulating environment and increased inherent vulnerability of the riders to accidents, which promotes increased attention.

The continuous increase in the numbers of PTWs riders highlights the precariousness of their use compared to other classical means of transport like automobiles or public transportation [12,13]. In Europe, the number of circulating PTWs has increased by 50% over the last 15 y [14]. In some Asian countries, there are more PTWs than cars, particularly in big cities [15]. However, PTWs are considered as the most dangerous mode of transportation due to the rate of their involvement in accidents and the severity of the related accidents [13,16–19]. PTWs still only represent a small

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Abbreviations: BRT, brake reaction time; C, circadian process; COP, center of pressure; S, homeostatic process; MSLT, multiple sleep latency test; PTW, powered two-wheeler; SCN, suprachiasmatic nucleus; TBT, total braking time; TSD, total sleep deprivation.

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percentage of circulating vehicles in most countries (3–15%) and only around 2% of the total road traffic in terms of distance traveled, notably in Great Britain [20] and in France [21]. However, PTWs are involved in nearly 20% of fatal accidents [22,23]. Moreover, the risk of being involved in a fatal accident (as a function of the average number of kilometers driven) is significantly higher for PTW riders than for car drivers. The related increased risk is 26-fold in the United States [24], 20-fold in Europe [22,23,25,26] and 29-fold in Australia [27]. As motorists represent near 80% of PTW fatalities [14,21–23], this review will more precisely focus on it and not on mopped or low powered motorcycles.

PTW riding indeed differs from car driving by many points [19]. First PTW riders have to maintain continuously a balance between their own stability and the need of following the road. Secondly, they are directly exposed to climatic conditions which may affect their visibility and stability. Third, due to the fact of having only two-wheels, and also to their dynamic properties, PTW are much more sensitive to the effects of pitch (while accelerating/braking), roll (while bending in curves) and yaw (while the rear wheel is sliding on a pedestrian crossing) [27]. These PTW specificities, which do not affect car drivers, may have direct influences on the PTW riders’ stability, handling and adherence, in peculiar in situations where the骑手 may have direct influences on the PTW riders’ stability, handling and adherence, in peculiar in situations where the

The PTW rider has to operate his/her vehicle in a continuously changing environment, paying attention to other vehicles while staying balanced and upright, which is the main difference with car driving, in traditional traffic conditions and also in competitions [31,32].

From a physiological and behavioral point of view, riding a PTW requires three main abilities:

1. **Reaction time**
   - **Increase in reaction time**
     - Brake strongly faced with an unexpected event
   - **Decrease in the level of vigilance**
     - Drive more slowly than usual
     - Are surprised to be passed
     - Tailgate the vehicle in front
     - Do not see the dangers of traffic
   - **Memory loss**
     - Forget to stop at a gas station when the reserve lamp is on
   - **Lack of decision making**
     - Do not stop even if tired
     - Take the wrong direction
   - **Lack of situational awareness**
     - Do not recognize traffic signs
     - Forget to put the kickstand down
     - Stop in high gear
   - **General decline in performance**
     - Do not move when the light turns green
     - Unable to determine a route
     - Poor communication with road partners
     - Remain attached to a task or a part of the visual field

We will try and assess how sleepiness may affect these three cognitive, psychomotor and behavioral abilities.

Sleepiness and alertness while riding a PTW

Riding a PTW requires greater concentration and alertness than driving [37] because of the need to maintain cognitive attention and physical adaptation to the changing environment, even in normal riding conditions. Based largely on personal experience, several authors have listed examples of possible interactions between the level of vigilance and resources needed by riders to ride safely (Table 1) [38,39]. Attention can be defined as the ability of an individual to focus on relevant elements of a situation or a task, while ignoring distracters [40–42]. For PTW riders, attention is especially necessary for awareness of the road or track surface and for predicting the intentions of other road users or competitors [43]. However, few studies have focused on the relationships between vigilance, attention and PTW riding ability. It has been shown that a decreased level of vigilance globally affects motorcycling capabilities [38,39] and also, the various attention processes implied in motorcycling (perception, diagnostic, prognostic, decision making and execution) [28]. These modifications have direct repercussions on adaptive capacities, even when riding situations are not particularly difficult (low workload, low time pressure...). In contrast, attention failures mainly affect perception and diagnostic stages, which are implied in situations such as road crossing, overtaking and splitting lanes [28].

**Table 1**

<table>
<thead>
<tr>
<th>Effects</th>
<th>Examples of riding situations affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase in reaction time</td>
<td>Brake strongly faced with an unexpected event</td>
</tr>
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<td>Decrease in the level of vigilance</td>
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</tr>
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a good indicator of the level of alertness. For example, during competitions, PTW riders have to react as quickly as possible to the start signal. In experimental studies, the reaction time of PTW riders is commonly evaluated by riding tests (swerving, braking) during which riders are instructed either to turn the handlebar or to press brakes [45,46]. The assessment of reaction time in common riding situations involves the use of specific equipment added to the vehicle. The different parameters recorded are either the time required for the subject to activate the brakes (brake reaction time: BRT) or the time required to stop the bike (total braking time: TBT) [47].

Several studies have shown that both the position of the fingers and of the feet influence the time required to completely stop the PTW. For example, the rider may have his/her fingers firmly wrapped around the throttle grip and his foot flat on the footrest before the maneuver (uncovered position) or he may leave several fingers on the front brake lever and the foot above the rear brake pedal (ready-to-brake position) [47,48]. Under real driving conditions, the average BRT with an uncovered position is 0.540 s (front BRT = 0.545 s; rear BRT = 0.536 s) whereas in a ready-to-brake position, the average BRT is 0.386 s (front BRT = 0.359 s; rear BRT = 0.413 s). The movement time required to apply brake lever and pedal can be estimated at 0.154 s [49]. As a result, riding with the fingers in a ready-to-brake position greatly reduces the distances required to stop.

Hazard perception

Riding a PTW requires the ability to detect and interpret visual information in order to make appropriate choices [35,45]. For this, different visual strategies are needed. The rider needs to look forward to anticipate his/her trajectory according to the position and movement of other vehicles, while being aware of the environment in his/her peripheral vision [50]. However, PTW riders, frequently involved in accidents caused by irregularities of the road (bumps or slippery surfaces), also have to watch the road surface just in front of the front wheel [51]. Moreover, as the speed of a PTW is often higher than that of surrounding cars, the field of view of PTW riders is decreased [19] and becomes restricted to central vision [52]. To cope with these requirements, PTW riders have a wider spread of visual search, with more flexible visual search patterns in the horizontal and vertical planes and shorter gaze fixation times in comparison with car drivers [53]. This allows PTW riders to react faster than car drivers [54] and to approach hazardous scenarios at slower speeds, factors that improve with riding experience [55,56] and advanced training [57].

Wearing a helmet also reduces the vertical field of view of PTW riders (~38%) [58]. This constraint is linked to 11% of PTW rider accidents [35]. However, this limitation is largely offset by rotation of the head [59].

Motor coordination

We define motor coordination as the ability to plan and execute motor actions in order to achieve fine and precise movements [60]. PTW riding is commonly considered as requiring high motor coordination skills [61], somewhat exceeding the level of demand required by car drivers [27]. PTW riders must be able to manage many levers, such as brakes, clutch, gears and throttle, in order to set the PTW in motion and change direction while staying upright, within very short periods of time [45,62]. This fine coordination is vital in critical situations, such as emergency braking or swerving and many other crash avoidance maneuvers [63]. For example, when emergency braking with a PTW, use of the front brake requires consecutively: i) reaction to a signal; ii) the decision to stop; iii) extension of the fingers to grasp the brake lever; and iv) bending of the fingers in a controlled manner to press the lever. Flexion of the fingers and the applied force must be such that the PTW stops smoothly and safely to maintain balance. Such very complex motor coordination commands are influenced by many factors, including nerve conduction, sensitivity of sensory receptors, muscle activity, and the characteristics of joints and synovial fluids [61,64].

Neuromuscular constraints

The position of the rider on the PTW, which is far different from car driving, can induce fatigue and decrease riding performance [12,65]. This phenomenon is partially dependent on bike design and the size of the PTW rider, involving a more or less ergonomic riding style.

Most PTWs have a sporty design, such that many of the rider’s joints are held flexed, inducing significant muscle tension [25]. Specifically, contractions of many muscle groups (scapular and pelvic belt, back, neck) to maintain a comfortable riding position and to fight against transversal (turns), longitudinal (acceleration and braking) and vertical (road surface, suspensions) acceleration forces induce a significant decrease in muscle strength with riding duration [66]. Police motorcycle officers who frequently ride a PTW are particularly exposed to muscle pain in the shoulders, leading to absences from work [67]. The hands and feet are also frequently active on the levers and pedals, which can induce muscular fatigue.

Moreover, sitting in the same position during a long trip, with movements of limited amplitude is particularly tiring, and can induce joint stiffness and numbness [68]. PTW riders commonly report suffering from lower back pain, or soreness of the thighs, shoulders, arms, and hands as a result of the vibrations of the engine felt through the handlebar, which is exacerbated with the length of the trip (≈6 h) [69,70]. Vibrations caused by the engine or even by changes in road surface greatly affect the comfort of riding [71]. To reduce vibrations, manufacturers perform simulations during which an acceptable level of vibration is determined through physical and sensory measures on PTW riders [72]. However, the structure of a PTW frame is quite simple and manufacturing constraints make it difficult to adjust absorbent structures.

Muscle contractions are intense during competition and/or acrobatic rides, particularly in order to push strongly on the handlebar to raise the rear wheel when braking, or to pull on the handlebar to pitch the bike and thus to raise the front wheel [12]. These successive muscle contractions and relaxations are known to reduce muscular capacity [73]. In sports competitions, it has been shown that during a motocross test ranging from 15 to 30 min, the hand grasping force, rated at maximum isometric contractions before and after the test, decreased by 16% [74,75]. In the lower limbs, average muscle activation varied between 24 and 38% of maximal voluntary activation in trained riders and between 40% and 45% for occasional riders over the 30 min of a motocross test [76].

Stability

The balance or stability of PTW riders (or of the couple PTW/PTW rider) is a dynamic effect, depending on the adaptation of the rider to the moving engine [77,78]. Because of its dynamic properties, the faster the PTW, the more stable it is [79]. Conversely, when speed decreases, the PTW has a tendency to fall over, necessitating a number of compensatory movements by the rider to maintain stability. Thus, when the PTW tilts to the right, the rider turns the handlebar and leans to the opposite (left) side to regain stability [80].
At medium and high speeds (>15 km h⁻¹), it is possible for PTW riders to maintain a straight line by maintaining their position on the saddle [81], regardless of whether their hands are resting on the handlebar [77]. However, when the speed is less than 15 km h⁻¹, the angle of inclination of the rider on the saddle is significantly greater when he/she lets go of the handlebar. Therefore, when riders do not hold the handlebar and the speed decreases, they maintain stability of the PTW by shifting the upper body. When the PTW is ridden without hands, the inclination of the upper body of the rider thus determines the steering angle of the handlebar. In addition, maintaining a straight trajectory becomes impossible at speeds less than 3 km h⁻¹, even when riders hold the handlebar. Finally, it has also been shown that the greater the speed, the more the steering angle of the handlebar, the roll angle of the PTW or the angle of the rider on the saddle are reduced [81]. Furthermore, the stability of the PTW is improved not only when the wheelbase (distance between the wheels) and the weight of the PTW increase, but also when the weight of the rider decreases and the center of gravity of the PTW/rider is low [79,80].

Temperature

Because of the low level of protection offered by fairings (depending on the type of PTW), PTW riders are highly exposed to weather conditions. Nevertheless, the appropriate equipment for riding a PTW helps to limit the effects of bad weather on the level of fatigue occurring while riding [82]. Riding at 80 km h⁻¹ in an ambient temperature of 12 °C with a PTW corresponds to prolonged exposure to a temperature less than 0 °C [83]. Therefore, despite the use of protective gloves, skin temperatures can reach 12−18 °C on the back of the hand and 4−7 °C at the tips of the fingers when riding in cold weather [64]. When the skin temperature of the hand reaches such values, the sensitivity of the fingers [84], manual dexterity [85,86] or hand grasping force [87] decrease significantly and the time needed to extend the fingers [88], to press the brake levers and to exert maximum pressure increases. As a result, the time and distance required to stop the PTW also increases significantly [64], which may be dangerous in emergency situations. For example, at 113 km h⁻¹, an increase of 328 ms to apply the brakes corresponds to a 10 m increase in the stopping distance.

The magnitude of sleepiness while riding and PTW accidents while sleepy

The human sleep-wake rhythm is among one of the most extensively studied circadian rhythms [89]. Schematically, the propensity to sleep is regulated by two mechanisms: a circadian process (C) and a homeostatic process (S). Process C helps to organize the timing of sleep at night and is tightly controlled by the body’s “master clock”, located in the suprachiasmatic nucleus (SCN) [89]. The fundamental adaptive advantage of a temporal organization is that it allows for predictive, rather than reactive, homeostatic regulation of sleep. For example, several hours before the end of sleep, sympathetic autonomic tone and plasma cortisol levels rise in anticipation of energetic demands for wakefulness. Process S is a cumulative process that originates at awakening and whose evolution depends on the duration and the quality of prior wakefulness. In other words, the homeostatic drive for sleep increases as wakefulness continues and decreases after sleep in proportion to sleep duration [90]. Few studies have specifically investigated the implication of the time-of-day (circadian effect) and of sleepiness in the accident risk of PTW riders [91]. More accidents and risky behavior in PTW riders (alcohol abuse, riding without a helmet ...) have been reported between 18:00 h and 06:00 h than during the day [91–97]. In Brazil, Thailand, India and Italy, the risk of being seriously injured or killed in a road traffic accident when riding a PTW has been reported to be higher during the night than during the day [92,95,98–103].

In France, 2005 road safety statistics reported that 35% of fatal accidents involving PTW riders and 26% of those with a serious injury happened at night [104]. Although the number of accidents involving PTW riders is larger during the day than at night (+21.7%) because of greater traffic density [105], the severity of the accidents (number of fatalities/100 victims) is 1.5-fold higher at night than during the day [104]. When an accident occurs at night, it may be attributed to decreased visibility, but also to sleepiness because of the influence of circadian and homeostatic processes [105]. Which percentage of these accidents is attributable to sleepiness is particularly difficult to estimate. An accident is frequently the result of multiple factors, such as increased speed, alcohol abuse and/or drug intoxication, risky behavior, and fatigue, which may all interact with the effects of drowsiness [106]. It can also be hypothesized that accidents induced by attention failure and/or by an excessive level of sleepiness (at night) may cause more serious damage because of the lack of reaction of the rider(s) involved [107]. These accidents are mainly described as resulting from a run off the road (loss of control) without involvement of another vehicle [108,109]. As a result of this observation, a national traffic accident prevention campaign in Brazil primarily focused on PTW accidents involving a single unskilled, male rider at night on the weekend and on roads where they travel at higher speeds [29].

The impact of sleepiness on various components of PTW riding

In the previous section, we described the cognitive, psychomotor and behavioral factors that are involved in PTW. Here, we try to understand how sleepiness may affect these factors from analytical and ecological points of view [110,111]. Some of the studies we report have been conducted under laboratory conditions [64,85,88], others from rider trials [112–114], sometimes using an instrumented PTW [45,47,49,115–118]. More recently, a new experimental approach has enabled PTW riding performance to be studied in various situations using simulated conditions, i.e., at an intermediate level closer to real-life behavior [53,56,119] (Table 2).

Sleepiness and PTW riding

The level of sleepiness mainly influences attention and behavioral capacities. As a result, when the degree of sleepiness is low, a PTW rider can more easily focus his/her attention on the road surface and other vehicles than when they are sleepier. It may be reflected in the number of road accidents [12,120,121]. Using off-road tests set up for motorcycle driving license examination, it has been demonstrated that the number of riding errors is lower at the end of the afternoon than in the early morning after a normal night of sleep [112]. At 18:00 h after a night of total sleep deprivation (i.e., 36 waking hours) most PTW riders were not able to obtain their motorcycle driving license. More recently, it has also been noticed that PTW riders, consciously or not, adapt their speed while fatigued (after 36 waking hours) [122] when asked to perform an emergency brake or crash avoidance maneuver at 40 km h⁻¹; to maintain a correct performance level, PTW riders instinctively approached the exercise zone at nearly 36 km h⁻¹ instead of 40 km h⁻¹. This behavior was observed in an experimental paradigm with motivation to perform as well as possible [122], and it may be interesting to focus prevention campaigns on
such concrete observations, in order to improve the attitudes of PTW riders in real conditions.

**Reaction time**

The circadian rhythm of simple and complex reaction times [123,124] shows a dip at around 06:00 h and a peak at the end of the afternoon close to 18:00 h. The improvement in reaction time is correlated to the circadian rhythm of the internal temperature [125–128]. A 1°C increase in body temperature has been found to be associated with a 2.4 m s⁻¹ increase in nervous conduction velocity [129]. Complex reaction times also show the same kind of circadian rhythm [130,131] with a decrease in the rate of correct saccadic eye movements (speed and accuracy). Results showed that sleep deprivation deteriorated smooth pursuit and saccadic movements. Saccadic accuracy showed the same trend. The torque developed by elbow flexors in concentric contractions at different angular velocities (60° s⁻¹, 120° s⁻¹, 180° s⁻¹, 240° s⁻¹ et 300° s⁻¹) follows a diurnal fluctuation (between 8% and 13%) with maximal values observed between 17:00 h and 19:00 h. Excessive television-game playing associated with sleep deprivation is linked to the occurrence of muscle stiffness in the shoulder. The torque developed by elbow flexors in concentric contractions at different angular velocities (60° s⁻¹, 120° s⁻¹, 180° s⁻¹, 240° s⁻¹ et 300° s⁻¹) follows a diurnal fluctuation (between 8% and 13%) with maximal values observed between 17:00 h and 19:00 h. Excessive television-game playing associated with sleep deprivation is linked to the occurrence of muscle stiffness in the shoulder.

Table 2

<table>
<thead>
<tr>
<th>Studied resource</th>
<th>Study</th>
<th>Disturbance factor</th>
<th>Measures</th>
<th>Impact observed</th>
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<tr>
<td><strong>Laboratory tests</strong></td>
<td></td>
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<tr>
<td>Sleepiness</td>
<td>Kraemer et al., 2000 [148]</td>
<td>Time of day</td>
<td>Sleep latency on MSLT</td>
<td>Sleep latencies showed clear time-of-day variations, being maximal in the morning and decreasing with time awake.</td>
</tr>
<tr>
<td>&amp; Durmer and Dinges, 2005 [143]</td>
<td>Sleep deprivation</td>
<td>Sleep latency on MSLT</td>
<td>After a night without sleep the daytime sleep latency decreases, by an order of magnitude, to less than a min or two on average.</td>
<td></td>
</tr>
<tr>
<td>Attention</td>
<td>VandenBerg and Neely, 2006 [140]</td>
<td>Sleep deprivation</td>
<td>Reaction time</td>
<td>Participants had slower reaction times when sleep deprived.</td>
</tr>
<tr>
<td>&amp; Bougard et al., 2008 [113]</td>
<td>Time-of-day</td>
<td>Reaction time</td>
<td>The improvement in reaction time between 06:00 h and 18:00 h follows the rise of body temperature.</td>
<td></td>
</tr>
<tr>
<td>Hazard perception</td>
<td>Porcu et al., 1998 [160]</td>
<td>Time-of-day</td>
<td>Smooth pursuit and saccadic eye movements</td>
<td>The torque developed by elbow flexors in concentric contractions at different angular velocities (60° s⁻¹, 120° s⁻¹, 180° s⁻¹, 240° s⁻¹ et 300° s⁻¹) follows a diurnal fluctuation (between 8% and 13%) with maximal values observed between 17:00 h and 19:00 h. Excessive television-game playing associated with sleep deprivation is linked to the occurrence of muscle stiffness in the shoulder.</td>
</tr>
<tr>
<td></td>
<td>deGennaro et al., 2000 [156]</td>
<td>Sleep deprivation</td>
<td>Smooth pursuit and saccadic eye movements</td>
<td>Acute sleep deprivation (up to 30 h) had a deleterious effect on fine motor coordination evaluated in the pendue pegboard.</td>
</tr>
<tr>
<td>Motor coordination</td>
<td>Foo et al., 1995 [183]</td>
<td>Sleep deprivation</td>
<td>Manual dexterity</td>
<td>Time necessary to complete the pegboard test was significantly shorter at 18:00 h than at 06:00 h (r = -0.9).</td>
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<td></td>
</tr>
<tr>
<td>Muscular strength</td>
<td>Bulbulian et al., 1996 [191]</td>
<td>Sleep deprivation</td>
<td>Maximal torque</td>
<td>Sleep deprivation affected peak torque but had no effect on fatigue index.</td>
</tr>
<tr>
<td></td>
<td>Gauthier et al., 2001 [185]</td>
<td>Time-of-day</td>
<td>Constant angular torque</td>
<td>The torque developed by elbow flexors in concentric contractions at different angular velocities (60° s⁻¹, 120° s⁻¹, 180° s⁻¹, 240° s⁻¹ et 300° s⁻¹) follows a diurnal fluctuation (between 8% and 13%) with maximal values observed between 17:00 h and 19:00 h. Excessive television-game playing associated with sleep deprivation is linked to the occurrence of muscle stiffness in the shoulder.</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Tazawa and Okada, 2001 [192]</td>
<td>Sleep deprivation</td>
<td>Muscle stiffness</td>
<td>Excessive television-game playing associated with sleep deprivation is linked to the occurrence of muscle stiffness in the shoulder.</td>
</tr>
<tr>
<td></td>
<td>Reilly et al., 2007 [124]</td>
<td>Time-of-day</td>
<td>Lumbar flexibility</td>
<td>Diurnal variation was found for performance tests, including sit-and-reach flexibility. Peaks occurred between 16:00 h and 20:00 h.</td>
</tr>
<tr>
<td>Balance</td>
<td>Nakano et al., 2001 [205]</td>
<td>Time-of-day</td>
<td>COP surface area</td>
<td>The greatest sway was observed during the 3-h period when rectal temperature was at its minimum.</td>
</tr>
<tr>
<td>&amp; Bougard et al., 2011 [202]</td>
<td>Sleep deprivation</td>
<td>COP surface area</td>
<td>Sleep deprivation increased COP surface area.</td>
<td></td>
</tr>
<tr>
<td>PTW riding Vigilance</td>
<td>Nakahara et al., 2005 [95]</td>
<td>Time-of-day</td>
<td>Accidents</td>
<td>There were more fatal accidents during the night than during the day.</td>
</tr>
<tr>
<td>&amp; Bougard et al., 2006 [112]</td>
<td>Sleep deprivation</td>
<td>PTW riding licence tests</td>
<td>PTW riders were slower to turn the handlebar at 06:00 h than at 10:00 h, 14:00 h and 18:00 h.</td>
<td></td>
</tr>
<tr>
<td>Attention</td>
<td>Bougard et al., 2008 [113]</td>
<td>Sleep deprivation</td>
<td>Start reaction time</td>
<td>Sleep deprivation significantly increased reaction times and the diurnal fluctuation observed between 06:00 h and 18:00 h was no longer observed.</td>
</tr>
<tr>
<td></td>
<td>Bougard et al., 2012 [122]</td>
<td>Time-of-day</td>
<td>Crash avoidance reaction time</td>
<td>After a normal night, PTW riders were slower to turn the handlebar at 06:00 h than at 10:00 h, 14:00 h and 18:00 h. Subjects stopped more precisely at 18:00 h than at 06:00 h (r = -48%).</td>
</tr>
<tr>
<td>Motor coordination</td>
<td>Bougard et al., 2006 [112]</td>
<td>Time-of-day</td>
<td>Braking precision</td>
<td>Sleep deprivation induced performance degradation at 06:00 h and 18:00 h and erased the diurnal fluctuation observed after a normal night of sleep.</td>
</tr>
<tr>
<td>&amp; Bougard et al., 2008 [113]</td>
<td>Sleep deprivation</td>
<td>Slalom time</td>
<td>PTW riders made longer jumps at 18:00 h than at 06:00 h.</td>
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<tr>
<td>Muscular strength</td>
<td>Bougard and Davenne, 2012 [114]</td>
<td>Time-of-day</td>
<td>Maximal anaerobic alactic power</td>
<td>Sleep deprivation had no effect on the recorded values.</td>
</tr>
<tr>
<td>&amp; Bougard and Davenne, 2012 [114]</td>
<td>Sleep deprivation</td>
<td>Maximal anaerobic alactic power</td>
<td>PTW riders passed under lower rods at 18:00 h than at 06:00 h.</td>
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<td>Flexibility</td>
<td>Bougard and Davenne, 2012 [114]</td>
<td>Time-of-day</td>
<td>Lumbar flexibility</td>
<td>PTW riders passed under lower rods at 18:00 h than at 06:00 h.</td>
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<td>Balance</td>
<td>Bougard et al., 2012 [122]</td>
<td>Sleep deprivation</td>
<td>Lateral deviations</td>
<td>Sleep deprivation had no influence on lateral deviations. The time subjects spent riding on the narrow board significantly improved from 06:00 h to 18:00 h.</td>
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<tr>
<td>&amp; Bougard and Davenne, 2012 [114]</td>
<td>Time-of-day</td>
<td>Narrow board riding</td>
<td>Sleep deprivation had no effect on the recorded values.</td>
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<tr>
<td>Simulated PTW riding</td>
<td>Bougard et al., 2013 [147]</td>
<td>Sleep deprivation</td>
<td>Braking reaction time</td>
<td>Sleep deprivation severely affected the total distance necessary to stop the motorcycle at 40 kmh ( +1.57 m, i.e., +20.7%). This increase in stopping distance was directly connected to the increased reaction time (+0.13 s, +21.4%).</td>
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COP: center of pressure; MSLT: multi sleep latency Test; PTW: powered two-wheelers.
Numerous studies have also shown that attention capacities evaluated by problem solving exercises or simple reaction times are affected by total sleep deprivation (TSD) ([133–140]). The longer the sleep deprivation, the more deleterious the effects on simple reaction time ([134,141]). It seems that TSD preferentially affects the initial stages of stimulus detection (reflected by simple reaction time), which depend on frontal cortex activation ([142,143]) but not necessarily the higher capacities for stimulus treatment, which are involved in the interpretation and inhibition of motor action in case of non-relevant stimuli ([144–146]).

Different studies with riders have indicated that reaction times assessed by starting position, emergency braking or crash avoidance maneuvers, improve throughout the day after a normal night of sleep ([113,122]). PTW riders react faster in the afternoon than in the morning, allowing shorter stopping distances (0.35 m and 1.60 m between 06:00 h and 18:00 h at 20 km h⁻¹ and 40 km h⁻¹, respectively) and faster crash avoidance maneuvers. Following a night of TSD, braking performances remained unaffected, probably due to fear of falling. These results were confirmed in simulated riding situations ([147]). In a similar experimental paradigm, TSD was shown to severely influence the total distance necessary to stop the motorcycle at 40 km h⁻¹ (+1.57 m, i.e., +20.7%). This increase in stopping distance was directly connected to the increased reaction time (+0.13 s, +21.4%). As previously observed in rider trials, performances observed in simulated more complex tasks, such as crash avoidance, were not influenced by sleep deprivation, suggesting that the initial stages of executive functioning only were specifically affected.

Vision and hazard perception

To our knowledge, no study has specifically focused on the visual effects of sleepiness in PTW riders. However, it is important to describe how vision may be affected as it has a specific role in preventing accidents in PTW.

Pupillary diameter is usually accepted as an indicator of SCN activation as it allows light to enter the eye. It has been shown that this diameter decreases throughout the day but increases at night ([148]). This suggests that PTW riders can focus their attention on pertinent elements in their field of view more easily during the day. In contrast, pupillary diameter increases and becomes more variable in the afternoon and at night, indicating difficulties to adapt the visual system to light intensity fluctuations. Light sensitivity is low in the morning, with the lowest values recorded at 04:00 h. It then improves during the day to reach maximal values at 22:00 h ([149,150]). Consequently, it is easier to distinguish poorly illuminated targets in the evening than in the morning. Moreover, it has also been reported that saccadic and smooth pursuit eye movements fluctuate during the day. During the night, the latencies of saccadic and smooth pursuit eye movements increase, whereas their speed decreases ([151]).

Sleep deprivation is known to affect several characteristics of eye movements. Primary studies have reported a tendency to diplopia ([152]) and convergent eye movements ([153]) associated with sleep loss. On the one hand, prolonged wakefulness is associated with an increase in pupil constriction latency, promoted by a transitory dazzle ([154]) and, similarly, an increase in saccadic eye movement latency ([155]). On the other hand, sleep loss promotes a decrease in saccadic speed and accuracy ([154,156–159]) and in smooth pursuit eye movements ([156,160]). These modifications are accompanied by a reduced field of vision, creating a feeling of seeing through a narrow tube, so-called “tunnel vision” ([158,161–164]) and are correlated to a decrease in driving performance. Furthermore, sleep deprivation effects seem to accumulate as waking time increases, possibly inducing visual distortions and hallucinations, while diurnal fluctuations persist with more effects at 04:00 h and fewer between 16:00 h and 20:00 h ([165]). Nervous deactivation of several cerebral areas implicated in eye movements, including parietal and pre-frontal lobes, basal ganglia, thalamus and cerebellum, may partly explain these observations ([166–168]).

Motor coordination

The circadian rhythm of perceptual and motor skills is highly correlated with that of body temperature ([121,169–171]). The diurnal fluctuation of body temperature is accompanied by an increase in nervous conduction speed during the day ([172]) and an improvement in the vigilance level ([173]) with maximum values obtained late in the afternoon. It has also been reported that the time required to complete a task of manual dexterity (pegboard) decreased between 07:00 h and 14:00–18:00 h ([174]). The estimated time for better efficiency was between 15:28 h and 15:44 h ([175]). In sports competitions, swimmers had better coordination of the hands under the water in the evening than in the morning, allowing greater efficiency ([176,177]). In cyclists, it has also been shown that the pedal rate and pedaling technique are modified during the day, allowing better motor efficiency in the afternoon ([178,179]).

Few studies have focused on the effects of TSD on manual dexterity. Most of these have been conducted in medical residents and/or in military personnel. During simulations of surgical operations, doctors manipulate tools less precisely ([180,181]) and take longer to carry out the intervention after a night of sleep deprivation ([182]). Moreover, in marine officers, authors showed that grooved pegboard performance was altered by up to 30 h of sleep deprivation ([183]). This decrease in manual dexterity performance is correlated to subjectively rated levels of sleepiness and seems to increase with the waking time increase ([184]).

In different motorcycle tests, studies have reported that the motor coordination involved in precision braking, slalom and line maintenance improves progressively throughout the day between 06:00 h and 18:00 h ([112,113,122]). After a sleepless night, although morning values remained unaffected, most of the evening values were severely affected, suggesting a breaking point in motor coordination when motorcycling after 30 h of wakefulness.

Neuromuscular constraints

The level of muscular strength and flexibility is strongly influenced by circadian rhythms. For example, it has been shown that the torque developed by elbow flexors in concentric contractions at different angular velocities (60° s⁻¹, 120° s⁻¹, 180° s⁻¹, 240° s⁻¹ and 300° s⁻¹) follows a diurnal fluctuation (between 8% and 13%) with maximal values observed between 17:00 h and 19:00 h ([185]). Moreover, a circadian variation in the amplitudes of flexion and lumbar extension has been observed with differences of up to 20% of the average value recorded during the day ([186]). The diurnal fluctuation in flexibility was marked by a peak between 16:00 h and 22:00 h, concomitant with the peak of body temperature rhythm ([174,178,188]). The lumbar flexion in the frontal plane was reduced by 5.0° ±1.9° in the morning (10 min after waking up) compared with evening values ([189]). It should be noted that measuring the level of flexibility of subjects just after awakening exposes measurements to the effects of sleep inertia. The influence of exogenous factors, including physical activity, seems to be predominant ([190]), and may decrease joint stiffness during the day while effectively performing muscle warm-up.

Considering sleep deprivation, muscular strength is affected at low angular velocities (60° s⁻¹, 90° s⁻¹) after 30 h spent awake mainly due to an increased level of sleepiness and/or a lack of

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motivation which affect the possibility to realize a maximal effort [191]. Only one study to our knowledge has dealt with the relationship between prolonged wakefulness and the level of joint stiffness [192]. This study reported that video game players, who remained awake for long periods in front of their television screen, felt joint stiffness at the top of the back and shoulders. However, in this case, sleep deprivation was associated with prolonged immobility, which may probably bias the interpretation of the results.

In a task involving the maximal anaerobic power to jump as far as possible using an impulsive force applied to the footstools, PTW riders performed longer jumps at 18:00 h than at 06:00 h regardless of sleep condition [114]. When PTW riders were asked to ride under a rod as low as possible to evaluate their lumbar flexion, they performed better in the afternoon than in the early morning after a normal night of sleep [114]. However, after a night of sleep deprivation, this improvement was no longer observed, because of improved morning values probably induced by the lack of relaxation of the lower back muscles while remaining awake. These results suggest that physical performance observed while motorcycling may be related to the increase in temperature rhythm throughout the day.

**Stability/balance**

Diurnal fluctuations of postural control are now well-established. Although studies have been conducted using different materials, experimental procedures and evaluation criteria [193,194], the results confirm the influence of time-of-day on postural control [195–201]. When external parameters are controlled, the greatest variations in balance capacities throughout a normal day are observed between 06:00 h and 18:00 h [202]. However, the underlying processes responsible for these diurnal fluctuations in postural control have not yet been clearly identified.

Other studies have investigated the effects of sustained wakefulness for up to 36 h on postural control and reported that sleep deprivation can be a major risk factor for domestic accidents [203]. Most of these studies indicated that postural sway is altered during the night between 00:00 h and 06:00 h in subjects remaining awake [193,204]. Nevertheless, recorded performances in the morning (08:00 h–09:00 h) after a sleepless night are more controversial. Some studies reported a deleterious effect of sleep deprivation on postural sway [196,205,206], whereas others did not observe any effect [207], or only under particularly demanding situations, such as disturbance of visual and proprioceptive inputs [203,208], dual-task paradigm (multiple choice reaction times), or on an unstable platform [209]. Measurements taken throughout the day following a sleepless night indicated that postural control was still influenced by circadian rhythms [210]. Postural control assessed after 36 waking hours was less affected at the end of the afternoon than in the morning [202,206,211]. It seems that deleterious effects of sleep deprivation mainly depend on disturbed visual information or of its integration, which secondarily impact on postural control [206]. Other authors have suggested that disturbances in the vestibular system may also be responsible for these noxious effects [193,195].

When PTW riders were asked to ride on a narrow board using the first gear and the clutch to go as slowly as possible, they were able to stay on the narrow board for longer at 18:00 h than at 06:00 h, regardless of sleep condition [114]. These results have been confirmed in a recent study with an instrumented motorcycle, in which subjects had to ride on a line painted on the ground in first gear [122]. The authors observed that PTW riders had reduced lateral deviations (indicating better performance) in the afternoon in comparison with the early morning. According to these observations, PTW riders should be aware that they control their motorcycle better in the afternoon than in the morning. Cautionary advice must be given regarding the lack of sleep effects because in these studies, the tests were always performed at very low speed and always in isolated riding conditions (with no other vehicles).

**Risk of accidents in two-wheeler riders**

An accident is usually investigated while taking into account three main factors: the PTW rider, the PTW and the environment. Based on human factor studies, an accident may be defined as the inability of the PTW rider to adopt a correct behavior in response to changes in situation constraints due to traffic conditions or unexpected events [212]. Considering a sequential approach [213], an accident can be defined as a breaking point in the relationship between the situation requirements and the ability of the PTW rider to mobilize sufficient resources to cope with it.

Two kinds of accidents are mostly encountered by PTW riders [30]: i) single PTW accidents [12] and ii) accidents with numerous vehicles implicated [20]. Single PTW accidents represent 33% of injury accidents but 50% of fatalities [30]. In these scenarios PTW riders ride off the road alone, or without any other recognized responsible vehicle identified, probably due to a lack of control and/or an impairment of cognitive and psychomotor abilities [214]. This kind of accidents mainly occurs in curves and may be attributed to different factors among which vision, motor coordination, stability and muscular failures can play a role. In accidents with multiple vehicles, PTW riders are more often victims of right of way violations due to their poor visual and/or cognitive conspicuity [30,215]. According to the light dimensions of the motorcycle and its speed, other drivers “look but fail to see” the approaching PTW [20]. Consequently, drivers engage on the road without taking care of the driving rules and the PTW rider is not able to react appropriately, and to avoid the crash.

As we have demonstrated, motorcycling is a complex task, involving numerous components. The combination of these components (attention, hazard perception, reaction time, motor coordination, muscular constraints) may determine the rider’s performance level. This latter concept depends on training, experience, age, and external conditions, such as temperature, lighting, and traffic. According to the attention resource theories [214], when a PTW rider is in a low-demand riding environment, he/she can easily ride safely without soliciting all his/her resources [215]. However, when mental workload or riding demand progressively increase [216], the ability of the PTW rider to compensate some weakness with other resources becomes harder with decreased reserve abilities [217]. Nevertheless, taking into account his/her own abilities, the rider can modulate the involvement of each component depending on its availability and thus compensate for the potential failure of some components by an increased mobilization of others [218,219]. A critical point is reached when the PTW rider is in a high-demand environment; for example, in low visibility conditions or under time pressure, or when a parked vehicle suddenly opens the door, riding rapidly becomes too difficult and an accident may occur. Sleepiness, sleep deficit or circadian rhythms may impact more easily on a PTW rider’s resources when he/she has to face a high-demand situation [220].

**Conclusion/perspectives**

For various reasons, PTW riders may ride at different times of the day. In many circumstances (late dinner, early awakening, scheduled work...), they may have to ride at night or after having very little and/or poor sleep. Fatigue and sleepiness may affect
riding capabilities, increasing the risks of being involved in an accident. Other disruptive factors, such as alcohol [118] or drugs [221], can also affect riding performance. In such cases, PTW riders should be aware that the effects on riding ability may cumulate if several noxious parameters are combined.

Regarding competitions, as in many disciplines, testing and racing sessions are also scheduled at different times of the day [124,176,222,223]. In long duration races, such as “les 24 heures du Mans”, raid-adventures, or ultra-marathons, PTW riders also need to ride night and day [224]. In very long duration races, e.g., the “Paris-Dakar rally”, competitors accumulate days of competition, like solitary navigators or cyclists, with very short recovery periods [225,226]. Finally, during a season, many test sessions are set up in different countries. Riders therefore have to travel the globe frequently; they are subject to significant jet-lag and must, nevertheless, remain as effective as possible [227,228]. Taking into account these factors, biological rhythms and sleep deprivation seem to have a significant impact on riding performance [229]. However we acknowledge that this kind of competition is quite far from the usual task of PTW riders and those observations made in competition do not apply to ordinary and daily PTW rides conditions.

There has been considerable progress in passive and active safety techniques for PTW riders over the last decade. Passive safety mainly involves the development of impact protectors, such as airbags, helmets, lower limb protectors, and various protective clothing [59,230–232]. Active safety is defined as a better understanding of motorcycling constraints and environments in order to: i) organize effective prevention and awareness campaigns [233–235] and ii) contribute to the improvement in PTW dynamic properties (braking systems, handling capabilities) [236,237]. PTW simulators have been developed and some have been validated for investigating the influence of time-of-day and sleep deprivation on PTW rider behavior [147]. Further research should be encouraged using long duration driving sessions to better imitate real-life conditions.

Finally, fatal PTW accidents are still too common and prevention has to include evaluation of sleep and sleepiness factors as potential life-savers. Road safety cannot be limited to as driving alert but has also to include systematically the riding alert issue.

Conflict of interest

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References


* The most important references are denoted by an asterisk.
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