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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.



## 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

*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 motorcyclists 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 drivers' stability, handling and adherence, in peculiar in emergency situations. This is for these reasons that, in many countries, the first part (or even the whole examination) for motorcycling license is focused on closed environment test (on parking), testing motor skills which are required to control a PTW (speed control, alarm use, motorcycle position) [25–27].

The goal of this review is to provide an improved understanding of how sleepiness may impact on various physiological and behavioral factors specifically involved in a rider's safety. Different models have been developed to evaluate these risks [12,28] and three major categories have been considered: i) the PTW by itself, ii) the riding environment, and iii) the PTW rider [29,30]. The goal of the current review is to give knowledge around this third aspect.

In the first part the specific physiology and behavior of PTW riders will be explained in order to better understand how sleepiness may impact the cognitive, psychomotor and behavioral components of riding.

In the second part the epidemiological data on sleepiness and PTW accidents will be reviewed.

Then a third part will discuss more precisely the influence of circadian and homeostatic factors on motor coordination, postural control, muscle flexibility and strength, which may contribute to a road traffic accident while riding a PTW.

In conclusion, some suggestions, on how reducing the incidence of PTW accidents will be presented.

## Physiology and behavior of two-wheeler riders

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:

- First, cognition, which allows the riders to predict the intentions and behavior of other drivers in order to make the correct decisions at the right time.
- Second, perceptive skills are needed in order to interpret visual, auditory, proprioceptive and/or kinesthetic information [33,34]. For example, these perceptual abilities are necessary to determine the minimal safe inter-vehicular distance between the PTW and the vehicle ahead or to estimate the maximal speed at which a turn can be negotiated safely (depending on the radius of curvature …) [35].
- Third, good motor skills and physical coordination are useful to achieve complex and fast maneuvers. Some examples include coordination when using the throttle and the clutch with different hands in order to feel the PTW moving forward, and the need for simultaneous pressure on the front and rear brakes (mechanically separated) while turning the handlebar to change the PTW's direction [36].

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].

### *Reaction time*

Reaction time is generally regarded as the time interval between the onset of a stimulus and the initiation of the motor response induced by this stimulus [44]. Simple reaction time is considered as

**Table 1**
Effects of decreased vigilance on various components involved in PTW riding (adapted from Horberry et al., 2008 [39]).

| Effects | Examples of riding situations affected |
|---|---|
| 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 |
| | Forget wallet after refueling |
| 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 |
| | Forget to put both feet on the ground at the crossroad |
| | Stop in high gear |
| | Do not move when the light turns green |
| General decline in performance | Unable to determine a route |
| | Poor communication with road partners |
| | Remain attached to a task or a part of the visual field |

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 ($\approx$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].

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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 a 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 awaking 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

**Table 2**
Studies conducted to quantify the impact of some sleep-related or circadian factors on riding with possible implications on PTW rider resources or performance.

| Studied resource | Study | Disturbance factor | Measures | Impact observed |
|---|---|---|---|---|
| *Laboratory tests* | | | | |
| Sleepiness | Kraemer et al., 2000 [148] | Time of day | Sleep latency on MSLT | Sleep latencies showed clear time-of-day variations, being maximal in the morning and decreasing with time awake. |
| | Durmer and Dinges, 2005 [143] | Sleep deprivation | Sleep latency on MSLT | After a night without sleep the daytime sleep latency decreases, by an order of magnitude, to less than a min or two on average. |
| Attention | VandenBerg and Neely, 2006 [140] | Sleep deprivation | Reaction time | Participants had slower reaction times when sleep deprived. |
| | Bougard et al., 2008 [113] | Time-of-day | Reaction time | The improvement in reaction time between 06:00 h and 18:00 h follows the rise of body temperature. |
| Hazard perception | Porcu et al., 1998 [160] | Time-of-day | Smooth pursuit and saccadic eye movements | Both the smooth pursuit variables considered (velocity gain and phase) were significantly impaired only in the last nocturnal trial, when levels of sleepiness were maximal. Saccadic accuracy showed the same trend. |
| | deGennaro et al., 2000 [156] | Sleep deprivation | Smooth pursuit and saccadic eye movements | Results showed that sleep deprivation deteriorated smooth pursuit and saccadic movements (speed and accuracy). |
| Motor coordination | Foo et al., 1995 [183] | Sleep deprivation | Manual dexterity | Acute sleep deprivation (up to 30 h) had a deleterious effect on fine motor coordination evaluated in the perdue pegboard. |
| | Bougard et al., 2008 [113] | Time-of-day | Manual dexterity | Time necessary to complete the pegboard test was significantly shorter at 18:00 h than at 06:00 h (−9%). |
| Muscular strength | Bulbulian et al., 1996 [191] | Sleep deprivation | Maximal torque | Sleep deprivation affected peak torque but had no effect on fatigue index. |
| | Gauthier et al., 2001 [185] | Time-of-day | Constant angular torque | 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. |
| Flexibility | Tazawa and Okada, 2001 [192] | Sleep deprivation | Muscle stiffness | Excessive television-game playing associated with sleep deprivation is linked to the occurrence of muscle stiffness in the shoulder. |
| | Reilly et al., 2007 [124] | Time-of-day | Lumbar flexibility | Diurnal variation was found for performance tests, including sit-and-reach flexibility. Peaks occurred between 16:00 h and 20:00 h. |
| Balance | Nakano et al., 2001 [205] | Time-of-day | COP surface area | The greatest sway was observed during the 3-h period when rectal temperature was at its minimum. |
| | Bougard et al., 2011 [202] | Sleep deprivation | COP surface area | Sleep deprivation increased COP surface area. |
| PTW riding | | | | |
| Vigilance | Nakahara et al., 2005 [95] | Time-of-day | Accidents | There were more fatal accidents during the night than during the day. |
| | Bougard et al., 2006 [112] | Sleep deprivation | PTW riding licence tests | After 36 h of wakefulness, PTW riders could not obtain their PTW riding license. |
| Attention | Bougard et al., 2008 [113] | Sleep deprivation | Start reaction time | Sleep deprivation significantly increased reaction times and the diurnal fluctuation observed between 06:00 h and 18:00 h was no longer observed. |
| | Bougard et al., 2012 [122] | Time-of-day | Crash avoidance reaction time | 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. |
| Motor coordination | Bougard et al., 2006 [112] | Time-of-day | Braking precision | Subjects stopped more precisely at 18:00 h than at 06:00 h (−48%). |
| | Bougard et al., 2008 [113] | Sleep deprivation | Slalom time | 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. |
| Muscular strength | Bougard and Davenne, 2012 [114] | Time-of-day | Maximal anaerobic alactic power | PTW riders made longer jumps at 18:00 h than at 06:00 h. |
| | Bougard and Davenne, 2012 [114] | Sleep deprivation | Maximal anaerobic alactic power | Sleep deprivation had no effect on the recorded values. |
| Flexibility | Bougard and Davenne, 2012 [114] | Time-of-day | Lumbar flexibility | PTW riders passed under lower rods at 18:00 h than at 06:00 h. |
| | Bougard and Davenne, 2012 [114] | Sleep deprivation | Lumbar flexibility | After the night of sleep deprivation, PTW riders passed under the same level rods at 18:00 h as at 06:00 h. |
| Balance | Bougard et al., 2012 [122] | Sleep deprivation | Lateral deviations | Sleep deprivation had no influence on lateral deviations. |
| | Bougard and Davenne, 2012 [114] | Time-of-day | Narrow board riding | The time subjects spent riding on the narrow board significantly improved from 06:00 h to 18:00 h. |
| *Simulated PTW riding* | | | | |
| Attention | Bougard et al., 2013 [147] | Sleep deprivation | Braking reaction time | Sleep deprivation severely affected the total distance necessary to stop the motorcycle at 40 kph (+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%). |

COP: center of pressure; MSLT: multi sleep latency Test; PTW: powered two wheelers.

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 answers [132].

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° $s^{-1}$ et 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 [174,187,188]. 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 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 footrests, 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

*[1] Philip P, Sagaspe P, Lagarde E, Leger D, Ohayon MM, Bioulac B, et al. Sleep disorders and accidental risk in a large group of regular registered highway drivers. Sleep Med 2010;11:973–9.

[2] Verster JC, Taillard J, Sagaspe P, Olivier B, Philip P. Prolonged nocturnal driving can be as dangerous as severe alcohol-impaired driving. J Sleep Res 2011;20:585–8.

[3] Akerstedt T, Hallvig D, Anund A, Fors C, Schwarz J, Kecklund G. Having to stop driving at night because of dangerous sleepiness—awareness, physiology and behaviour. J Sleep Res 2013;22:380–8.

[4] Phillips RO, Sagberg F. Road accidents caused by sleepy drivers: update of a Norwegian survey. Accid Anal Prev 2013;50:138–46.

[5] Léger D, Bayon V, Ohayon MM, Philip P, Ement P, Metlaine A, et al. Insomnia and accidents: cross-sectional study (EQUINOX) on sleep-related home, work and car accidents in 5293 subjects with insomnia from 10 countries. J Sleep Res 2014;23:143–52.

[6] Ohayon MM. Determining the level of sleepiness in the American population and its correlates. J Psychiatr Res 2012;46:422–7.

*[7] Philip P, Sagaspe P, Taillard J, Chaumet G, Bayon V, Coste O, et al. Maintenance of wakefulness Test, obstructive sleep apnea syndrome, and driving risk. Neurol 2008;64:410–6.

[8] Philip P, Chaufton C, Taillard J, Capelli A, Coste O, Léger D, et al. Modafinil improves real driving performance in patients with hypersomnia: a randomized double-blind placebo-controlled crossover clinical trial. Sleep 2014;37:483–7.

[9] Kivistö M, Härmä M, Sallinen M, Kalimo R. Work-related factors, sleep debt and insomnia in IT professionals. Occup Med (Lond) 2008;58:138–40.

[10] Léger D, Roscoat Ed, Bayon V, Guignard R, Pâquereau J, Beck F. Short sleep in young adults: Insomnia or sleep debt? prevalence and clinical description of short sleep in a representative sample of 1004 young adults from France. Sleep Med 2011;12:454–62.

[11] Leger D, Beck F, Richard JB, Godeau E. Total sleep time severely drops during adolescence. PLoS One 2012;7(10):e45204.

[12] Haworth N, Rowden P. Investigation of fatigue related motorcycle crashes-literature review. Report to VicRoads. Brisbane: Queensland University of Technology; 2006 (Report N°RSD0261), http://eprints.qut.edu.au/6250/1/6250.pdf.

[13] Sexton B, Fletcher J, Hamilton K. Motorcycle accidents and casualties in Scotland 1992–2002. Transport Planning Group, Scottish Executive Social Research; 2004. http://www.scotland.gov.uk/Resource/Doc/26350/0029551.pdf.

[14] Association des Constructeurs Européens de Motocycles (ACEM). The yearbook. Facts and figures on PTWs in Europe. Brussels, Belgium: Association des Constructeurs Européens de Motocycles; 2008. http://www.acem.eu/images/stories/doc/marketfigures/d_ACEM_yb_08_75492.pdf.

[15] Gururaj G. Road traffic deaths, injuries and disabilities in India: current scenario. Natl Med J India 2008;21:14–20.

*[16] Bednar F, Billheimer JW, McRea K, Sabol SA, Syner J, Thom DR. Motorcycle safety. TRB transportation in the new Millennium paper series. A3B14. 2000., http://gulliver.trb.org/publications/millennium/00075.pdf.

[17] Dandona R, Mishra A. Deaths due to road traffic crashed in Hyderabad city in India: need for strengthening surveillance. Natl Med J India 2004;17(2):74–9.

[18] Elvik R. The trade-off between efficiency and equity in road safety policy. Saf Sci 2009;47:817–25.

[19] Horswill MS, Helman S. A comparative approach to differential accident liability: motorcyclists versus car drivers. In: Grayson GB, editor. Behavioural research in road safety: eleventh seminar. London: Department of Environment, Transport, and the Regions; 2001.

[20] Clarke DD, Ward P, Bartle C, Truman W. The role of motorcyclist and other driver behaviour in two types of serious accident in the UK. Accid Anal Prev 2007;39(5):974–81.

[21] Guyot R. Gisement de sécurité routière: les deux roues motorisés. Paris, France: Documentation Française; 2008. http://developpementdurable.documentation.developpement-durable.gouv.fr/documents/Urbamet/0286/Urbamet-0286194/PREDIT0109.pdf.

[22] European Transport Safety Council (ETSC). Road accident data in the enlarged European Union: learning from each other. Brussels, Belgium: European Transport Safety Council; 2006. http://etsc.eu/wp-content/uploads/Road_accident_data_in_the_Enlarged_European_Union.pdf.

[23] Observatoire National Interministériel de la Sécurité Routière (ONISR). La sécurité routière en France: bilan de l'année 2013. Documentation Française; 2014. http://www.securite-routiere.gouv.fr/la-securite-routiere/l-observatoire-national-interministeriel-de-la-securite-routiere/bilans-annuels/les-bilans-annuels-de-la-securite-routiere-en-france.

[24] Chen D, McMahan S. Development and testing of self-assessment tests for increasing motorcycle safety for aging motorcyclists. 2006.. In: http://www.msf-usa.org/imsc/proceedings/c-Chen-SelfAssessmentMeasuresforAgingMotorcyclists.pdf.

[25] Amans B, Moutreuil M. Projet RIDER (Recherche sur les accidents impliquant un Deux Roues motorisé). Rapport final, nRIDER200503–10. <www.fondation-maif.fr>. 2005.

[26] Koornstra M, Broughton J, Esberger R, Glansdorp C, Koppel W, Taylor F, et al. Transport safety performance in the EU: a statistical overview. Brussels, Belgium: European Transport Safety Council; 2003. http://etsc.eu/wp-content/uploads/2003_transport_safety_stats_eu_overview.pdf.

[27] Haworth N, Mulvihill C. Review of motorcycle licensing and training. Monash University Accident Research Centre; 2005 (Report N°240), http://www.monash.edu.au/miri/research/reports/muarc240.pdf.

[28] vanElslande P. Analyse approfondie d'accidents de deux-roues à moteur, défaillances fonctionnelles et scénarios d'erreurs. Rapport de convention DSCR-INRETS. 2002.

* The most important references are denoted by an asterisk.

[29] Almeida RL, Bezerra Filho JG, Braga JU, Magalhães FB, Macedo MC, Silva KA. Man, road and vehicle: risk factors associated with the severity of traffic accidents. Rev Saude Publica 2013;47:718–31.
*[30] Association des Constructeurs Européens de Motocycles (ACEM). MAIDS: the first results of a European motorcycle in-depth accident study. In: Proceedings of the 11th IFZ; 2004.
[31] Klarica AJ. Performance in motor sports. Br J Sports Med 2001;35(5):290–1.
[32] Parkes AM. Data capture techniques for RTI usability evaluation. In: Proceedings of DRIVE conference. Commission of the European communities, advanced telematics in road transport; 1991. p. 1440–56.
[33] McKnight AJ, Fitzgerald RM. Photographic analysis of control responses of motorcycle operators. National Public Services Research Institute; 1976.
[34] Welford AT. The fundamentals of skill. London, England: Methuen and Co., Ltd; 1968.
[35] McKnight AJ, McPherson K, Knipper AC. Motorcycle rider advancement courseplan. Washington, DC: National Highway Traffic Safety Administration; 1980.
[36] Mannering FL, Grodsky LL. Statistical analysis of motorcyclists' perceived accident risk. Accid Anal Prev 1995;27(1):21–31.
[37] Roads and Traffic Authority (RTA). Motorcycle Safety: issues and countermeasures. 2004. www.rta.nsw.gov.au.
[38] Arthur D. Fatigue and motorcycle touring. 2005. www.ride4ever.org/news/fatigue.php.
*[39] Horberry T, Hutchins R, Tong R. Motorcycle rider fatigue: a review. Department of TransportRoad Safety Research; 2008 (Report N°78, 4–63), http://aka.dft.gov.uk/ukgwacnf.html?url=http://aka.dft.gov.uk/pgr/roadsafety/research/rsrr/theme2/report95.pdf.
[40] Sturm W. Rééducation des troubles de l'attention. In: Azouvi P, Perrier D, vanderLinden M, editors. La rééducation en neuropsychologie: études de cas. Marseille: Solal; 1999. p. 125–37.
[41] Sturm W. Neuro-anatomie fonctionnelle de l'attention. In: Couillet J, Leclercq M, Moroni C, Azouvi P, editors. La neuropsychologie de l'attention. Marseille: Solal; 2002. p. 55–72.
[42] vanZomeren AH, Brouwer WH. Clinical neuropsychology of attention. New York: Oxford Univeristy Press; 1994.
[43] Haworth N, Mulvihill C, Wallace P, Symmons M, Regan M. Hazard perception and responding by motorcyclists: summary of background, literature review and training methods (Report N°234; ISBN 0732623049). 2005., http://www.monash.edu.au/miri/research/reports/muarc234.pdf.
[44] Triggs TJ, Harris WG. Reaction time of drivers to road stimuli. In: Triggs TJ, Harris WG, editors. Victoria: Monash University; 1982. http://www.monash.edu.au/miri/research/reports/other/hfr12.pdf.
[45] Prem H, Good MC. Motorcycle rider skills assessment. Canberra, Australia: Federal Office of Road Safety, Dept. of Transport; 1984.
[46] Watanabe Y, Yoshida K. Motorcycle handling performance for obstacle avoidance. In: Proceedings of second international congress on automotive safety, San Francisco, CA; 1973 (Paper 73033).
[47] Ecker H, Wassermann J, Ruspekhofer R, Hauer G, Winkelbauer M. Brake reaction times of motorcycle riders. In: Proceedings of international motorcycle safety conference, March 1–4. Orlando, Florida; 2001.
[48] Thom DR, Arao HG, Hancock PA. Hand position and motorcycle front brake response time. In: Proceedings of human factor society, 29th annual meeting; 1985.
[49] Étude FMQ-TRF 0.154 Fondation Promocycle. Évaluation du temps de réaction au freinage sur une motocyclette. 2003., http://www.promocycle.com/documentations/etudes-fr/evalfrein_f.pdf.
[50] Tofield MI, Wann JP. Do motorcyclists make better car drivers?. In: Proceedings of psychological Post-graduate affairs group conference. Glasgow, Scotland; 2001.
[51] Nagayama Y, Morita T, Miura T, Watanabem J, Murakami N. Motorcyclists' visual scanning pattern in comparison with automobile drivers'. Society of Automotive Engineers; 1980 (Paper N°790262).
[52] Association des Constructeurs Européens de Motocycles (ACEM). Guidelines for PTW-safer road design in Europe. Brussels, Belgium: Association des Constructeurs Européens de Motocycles; 2006. http://www.acem.eu/images/stories/doc/publications/d_ACEMinfrastructurehandbookv2_74670.pdf.
[53] Hosking SG, Liu CC, Bayly M. The visual search patterns and hazard responses of experienced and inexperienced motorcycle riders. Accid Anal Prev 2010;42:196–202.
[54] Chapman PR, Underwood G. Visual search of driving situations: danger and experience. Perception 1998;27(8):951–64.
[55] Katayama T, Motoki M. Comparison of riding behaviour between inexperienced riders and experienced riders. In: Proceedings of 1991 international motorcycle conference; 1991. p. 382–403.
[56] Liu CC, Hosking SG, Lenne MG. Hazard perception abilities of experienced and novice motorcyclists: an interactive simulator experiment. Transp Res Part F 2009;12:325–34.
[57] Crundall D, van Loon E, Stedmon AW, Crundall E. Motorcycling experience and hazard perception. Accid Anal Prev 2013;50:456–64.
[58] Hayward JM, Marsh RJ. Visual field restriction caused by motor cycle helmets. In: Freeman MH, Haslegrave CM, Smith P, Taylor SP, Gale AG, editors. Vision in vehicles 2. Amsterdam: Elsevier Science Publishers; 1988. p. 119–29.
[59] Mcknight AJ, Mcknight AS. The effects of motorcycle helmets upon seeing and hearing. Accid Anal Prev 1995;27(4):493–501.
[60] Fleishman EA, Hempel WE. A factor analysis of dexterity tests. Pers Psychol 1954;7:15–32.
[61] Rothe JP, Cooper PJ. Motorcyclists: who are they and why they do what they do. Transp Res Rec 1988;1168:78–85.
[62] Whitaker J. Survey of motorcycle accidents. Crowthorne, Berkshire, UK: Transport and Road Research Laboratory (TRRL); 1980 (Report N°LR913).
[63] Chinn BP. Motorcycle safety. Transport and Road Research Laboratory; 1990 (Safety Report N°91).
[64] Parry M. Skin temperature and motorcyclists' braking performance. Percept Mot Ski 1982;54(3):1291–6.
[65] Motorcycle Council of New South Wales. Fatigue. 2006. www.roadsafety.mccofnsw.org.au/cgi-bin/printable.pl?id=50.
[66] Gobbi AW, Francisco RA, Tuy B, Kvitne RS. Physiological characteristics of top level off-road motorcyclists. Br J Sports Med 2005;39(12):927–31.
[67] Gyi DE, Porter JM. Musculoskeletal problems and driving in police officers. Occup Med 1998;48(3):153–60.
[68] Mirbod SM, Yoshida H, Jamali M, Masamura K, Inaba R, Iwata H. Assessment of hand-arm vibration exposure among traffic police motorcyclists. Int Arch Occup Environ Health 1997;70(1):22–8.
[69] Gillen L. Motorcycle rider fatigue: survey results. 1998. www.gillengineering.com/fatigue%20paper.htm.
[70] Ma T, Wiliamson A, Friswell R. . A pilot study of fatigue on motorcycle day trips. Sydney, Australia: NSW Injury Risk Management Research Centre; 2003.
[71] Robertson S, Porter JM. Motorcycle ergonomics: an exploratory study. Contemp Ergon 1987:173–8.
[72] Sugizaki M. Example of a motorcycle manufacturer's approaches to usability. In: Proceedings of tenth international conference on human-computer interaction; 2003. p. 574–8.
[73] Fitts RH. Muscle fatigue: the cellular aspects. Am J Sports Med 1996;24(6):9–13.
[74] Ascensão A, Ferreira R, Marques F, Oliveira E, Azevedo V, Soares J, et al. Effect of off-road competitive motocross race on plasma oxidative stress and damage markers. Br J Sports Med 2007;41(2):101–5.
[75] Konttinen T, Hakkinen K, Kyrolainen H. Cardiopulmonary loading in motocross riding. J Sports Sci 2007;25(9):995–9.
[76] Konttinen T, Kyrolainen H, Hakkinen K. Cardiorespiratory and neuromuscular responses to motocross riding. J Strength Cond Res 2008;22(1):202–9.
*[77] Sharp RS. The stability and control of motorcycles. J Mech Engng Sci 1971;13(5):316–29.
[78] Weir DH. Motorcycle handling dynamics and rider control and the effect of design configuration on response and performance. Thèse de doctorat. Los Angeles: de l'Université de Californie; 1972.
[79] Katayama T, Aoki A, Nishimi T. Control behaviour of motorcycle riders. Veh Syst Dyn 1988;17:211–29.
[80] Yokomori M, Oya T, Katayama A. Rider control behavior to maintain stable upright position at low speed. JSAE Rev 2000;21:61–5.
[81] Yokomori M, Yamaguchi S, Oya T, Katayama A. The rider's motion for control of stability of motorcycle and rider system on low speed. SAE Trans 1999;108(3):1913–8.
[82] deRome L, Stanford G. Motorcycle protective clothing: fashion or function?. In: Proceedings of international motorcycle safety conference, California; 2006.
[83] Siple PA, Passel CF. Measurements of dry atmospheric cooling in subfreezing temperatures. Proc Amer Phil Soc 1945;89:177–99.
[84] Rubin LS. Manual dexterity of gloved and bare hand as a function of the ambient temperature and duration of exposure. J Appl Psychol 1957;41:377–83.
[85] Clark RE. The limiting hand skin temperature for unaffected manual performance. J Appl Psychol 1961;45:193–4.
[86] Lockhart JM, Kiess HO. Auxiliary heating of the hands during cold exposure and manual performance. Hum Factors 1971;13(5):457–65.
[87] Clarke DH, Royce J. Rate of muscle tension development and release under extreme temperatures. Int Z Angew Physiol 1962;19:330–6.
[88] Pease DG, Ludwig DA, Green EB. Immediate and follow-up effects of cold on performance time and its components, reaction time and movement time. Percept Mot Ski 1980;50:667–75.
[89] Moore-Ede MC. Physiology of the circadian timing system: predictive versus reactive homeostasis. Am J physiology 1986;250:R737–52.
[90] Borbely AA. A two process model of sleep regulation. Hum Neurobiol 1982;1(3):195–204.
[91] Kasantikul V, Ouellet JV, Smith T, Sirathranont J, Panichabhongse V. The role of alcohol in Thailand motorcycle crashes. Accid Anal Prev 2005;37(2):357–66.
[92] Bastos YG, Andrade SM, Soares DA. Characteristics of traffic accidents and victims treated through a pre-hospital service in a city in southern Brazil, 1997/2000. Cad Saude Publica 2005;21(3):815–22.

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[93] Conrad P, Bradshaw YS, Lamsudin R, Kasniyah N, Costello C. Helmets, injuries and cultural definitions: motorcycle injury in urban Indonesia. Accid Anal Prev 1996;28(2):193–200.
[94] Harrison WA. An exploratory investigation of the crash involvement of disqualified drivers and motorcyclists. J Saf Res 1997;28(2):105–11.
[95] Nakahara S, Chadbunchachai W, Ichikawa M, Tipsuntornsak N, Wakai S. Temporal distribution of motorcyclist injuries and risk of fatalities in relation to age, helmet use, and riding while intoxicated in Khon Kaen, Thailand. Accid Anal Prev 2005;37(5):833–42.
[96] Simoncic M. Road accidents in Slovenia involving a pedestrian, cyclist or motorcyclist and a car. Accid Anal Prev 2001;33(2):147–56.
[97] Wong TW, Phoon WO, Lee J, Yiu IP, Fung KP, Smith G. Motorcyclist traffic accidents and risk factors: a Singapore study. Asia Pac J Public Health 1990;4(1):34–8.
[98] Cirera E, Plasencia A, Ferrando J, Segui-Gomez M. Factors associated with severity and hospital admission of motor-vehicle injury cases in a southern European urban area. Eur J Epidemiol 2001;17(3):201–8.
[99] Italian National Institute of Statistics (ISTAT). Statistica incidenti stradali anno 2001. In: Traffic accidents statistics: year 2001. Annuario Statistico Italiano, Roma; 2003.
[100] Jain A, Menezes RG, Kanchan T, Gagan S, Jain R. Two wheeler accidents on Indian roads-a study from Mangalore, India. J Forensic Leg Med 2009;16(3):130–3.
[101] Lin MR, Chang SH, Huang W, Hwang HF, Pai L. Factors associated with severity of motorcycle injuries among young adult riders. Ann Emerg Med 2003;41(6):783–91.
[102] Quddus MA, Noland RB, Chin HC. An analysis of motorcycle injury and vehicle damage severity using ordered probit models. J Saf Res 2002;33(4):445–62.
[103] Valent F, Schiava F, Savonitto C, Gallo T, Brusaferro S, Barbone F. Risk factors for fatal road traffic accidents in Udine, Italy. Accid Anal Prev 2002;34(1):71–84.
[104] Observatoire National Interministériel de la Sécurité Routière (ONISR). La sécurité routière en France : bilan de l'année 2006. Documentation Française; 2007. http://www.ladocumentationfrancaise.fr/var/storage/rapports-publics/074000686/0000.pdf.
[105] deLapparent M. Empirical Bayesian analysis of accident severity for motorcyclists in large French urban areas. Accid Anal Prev 2006;38:260–8.
[106] Schneider 4th WH, Savolainen PT, Van Boxel D, Beverley R. Examination of factors determining fault in two-vehicle motorcycle crashes. Accid Anal Prev 2012;45:669–76.
[107] Sagberg F. Road accidents caused by drivers falling asleep. Accid Anal Prev 1999;31(6):639–49.
[108] Carré JR, Filou C. Accidents risks for two-wheelers in France: safety of two-wheelers is largely subject to the skill and vigilance of cars drivers. In: Proceedings of ESV conference; 1994.
*[109] Hurt HH, Ouellet JV, Thom DR. Technical Report. Motorcycle accident cause factors and identification of countermeasures, vol. 1. Los Angeles, California: Traffic Safety Center, University of Southern California; 1981. 90007, (Contract N°DOT HS-5–01160).
[110] Glaser R, Klaus DJ. Proficiency measurement: assessing human performance. In: Gagne RM, editor. Psychological principles in system development. New York: Holt, Rinehart and Wiston Inc; 1962. p. 419–74.
[111] Häkkinen A. Traffic accidents and psychomotor performance. Mod Problems Psychopharmacol 1976;11:51–87.
[112] Bougard C, Moussay S, Davenne D. Effets combinés de l'heure de la journée et de la privation de sommeil sur les performances de pilotage d'un deux roues. Recherche Transp Sécurité 2006;91:137–51.
[113] Bougard C, Moussay S, Davenne D. An assessment of the relevance of laboratory and motorcycling tests for investigating time-of-day and sleep deprivation influences on motorcycling performance. Accid AnalPrev 2008;40:635–43.
[114] Bougard C, Davenne D. Effects of sleep deprivation and time-of-day on selected physical abilities in off-road motorcycle riders. Eur J Appl Physiol 2012;112(1):59–67.
[115] Ervin RD, MacAdam CC, Watanabe Y. Summary technical report. Motorcycle braking performance, vol. I. Highway Safety Research Institute; 1977.
[116] Juniper RG, Good MC. Braking, stability and handling of motorcycles. Canberra: Federal Office of Road Safety, Dept. of Transport, Australia; 1983.
[117] Varat MS, Husher SE, Shuman KF, Kerkhoff JF. Rider inputs and powered two Wheeler response for pre-crash maneuvers. In: Proceedings of 11th IFZ; 2004.
[118] Creaser JI, Ward NJ, Rakauskas ME, Shankwitz C, Boer ER. Effects of alcohol impairment on motorcycle riding skills. Accid Anal Prev 2009;41(5):906–13.
[119] Stedmon AW, Hasseldine B, Rice D, Young M, Markham S, Hancox M, et al. 'MotorcycleSim': an evaluation of rider interaction with an innovative motorcycle simulator. Comput J 2011;54(7):1010–25.
[120] Folkard S, Wever RA, Wildgruber CM. Multi-oscillatory control of circadian rhythms in human performance. Nature 1983;305(5931):223–6.
[121] Monk TH, Weitzman ED, Fookson JE, Moline ML, Kronauer RE, Gander PH. Task variables determine which biological clock controls circadian rhythms in human performance. Nature 1983;304(5926):543–5.
*[122] Bougard C, Espié S, Larnaudie B, Moussay S, Davenne D. Effects of time of day and sleep deprivation on motorcycle-driving performance. PLoS One 2012;7(6):e39735.
[123] Lafrance C, Paquet J, Dumont M. Diurnal time courses in psychomotor performance and waking EEG frequencies. Brain Cogn 2002;48(2–3):625–31.
[124] Reilly T, Atkinson G, Edwards B, Waterhouse J, Farrelly K, Fairhurst E. Diurnal variation in temperature, mental and physical performance, and tasks specifically related to football (soccer). Chronobiol Int 2007;24(3):507–19.
*[125] Hockey GR, Colquhoun WP. Diurnal variation in human performance: a review. In: Colquhoun WP, editor. Aspects of human efficiency: diurnal rhythm and loss of sleep. London: English Universities Press; 1972. p. 1–23.
[126] Kleitman N. Sleep and wakefulness. Londres: University of Chicago Press; 1963.
[127] Monk TH, Weitzman ED, Fookson JE, Moline ML. Circadian rhythms in human performance efficiency under free-running conditions. Chronobiologia 1984;11(4):343–54.
[128] Wright Jr KP, Hull JT, Czeisler CA. Relationship between alertness, performance, and body temperature in humans. Am J Physiol Regul Integr Comp Physiol 2002;283(6):1370–7.
[129] Winget CM, deRoshia CW, Holley DC. Circadian rhythms and athletic performance. Med Sci Sports Exerc 1985;17(5):498–516.
[130] Graw P, Kräuchi K, Knoblauch V, Wirz-Justice A, Cajochen C. Circadian and wake-dependent modulation of fastest and slowest reaction times during the psychomotor vigilance task. Physiol Behav 2004;80(5):695–701.
[131] Reilly T, Hales A. Effects of partial sleep deprivation on performance measures in females. In: McGraw ED, editor. Contemporary ergonomics. London: Taylor and Francis; 1988. p. 509–13.
[132] Pallesen S, Johnsen BH, Hansen A, Eid J, Thayer JF, Olsen T, et al. Sleep deprivation and hemispheric asymmetry for facial recognition reaction time and accuracy. Percept Mot Ski 2004;98(3 Pt 2):1305–14.
[133] Corsi-Cabrera M, Arce C, Ramos J, Lorenzo I, Guevara MA. Time course of reaction time and EEG while performing a vigilance task during total sleep deprivation. Sleep 1996;19(7):563–9.
[134] Doran SM, vanDongen HP, Dinges DF. Sustained attention performance during sleep deprivation: evidence of state instability. Arch Ital Biol 2001;139(3):253–67.
[135] Fu ZJ, Ma RS. Effects of sleep deprivation on human performance. Space Med Med Eng 2000;13(4):240–3.
[136] LeDuc Jr PA, Caldwell Jr JA, Ruyak PS. The effects of exercise as a countermeasure for fatigue in sleep-deprived aviators. Mil Psychol 2000;12(4):249–66.
[137] Linde L, Bergstrom M. The effect of one night without sleep on problem-solving and immediate recall. Psychol Res 1992;54(2):127–36.
[138] Lorenzo I, Ramos J, Arce C, Guevara MA, Corsi-Cabrera M. Effect of total sleep deprivation on reaction time and waking EEG activity in man. Sleep 1995;18(5):346–54.
[139] McCarthy ME, Waters WF. Decreased attentional responsivity during sleep deprivation: orienting response latency, amplitude, and habituation. Sleep 1997;20(2):115–23.
[140] vandenBerg J, Neely G. Performance on a simple reaction time task while sleep deprived. Percept Mot Ski 2006;102(2):589–99.
[141] Gillberg M, Kecklund G, Akerstedt T. Relations between performance and subjective ratings of sleepiness during a night awake. Sleep 1994;17(3):236–41.
[142] Drummond SP, Brown GG. The effects of total sleep deprivation on cerebral responses to cognitive performance. Neuropsychopharmacology 2001;25(5):68–73.
[143] Durmer JS, Dinges DF. Neurocognitive consequences of sleep deprivation. Semin Neurol 2005;25(1):117–29.
[144] Jennings JR, Monk TH, vanderMolen MW. Sleep deprivation influences some but not all processes of supervisory attention. Psychol Sci 2003;14(5):473–9.
[145] Bougard C, Chennaoui M, Espié S, Moussay S, Davenne D. Influences of sleep deprivation and time-of-day on different components of executive functioning. Sleep downUnder 2013-river of dreams, 17–19 October. 2013. Brisbane, Australia. Sleep and Biological Rhythms Journal, Abstract Supplement.
[146] Krull KR, Smith LT, Sinha R, Parsons OA. Simple reaction time event-related potentials: effects of alcohol and sleep deprivation. Alcohol Clin Exp Res 1993;17(4):771–7.
[147] Bougard C, Moussay S, Espié S, Chennaoui M, Léger D, Davenne D. Total sleep deprivation and time-of-day influences on simulated pre-crash manoeuvres of motorcyclists. Sleep DownUnder 2013-river of dreams. Brisbane, Australia; 17–19 October 2013. Sleep and Biological Rhythms Journal, Abstract Supplement.
[148] Kraemer S, Danker-Hopfe H, Dorn H, Schmidt A, Ehlert I, Herrmann WM. Time-of-day variations of indicators of attention: performance, physiologic parameters, and self-assessment of sleepiness. Biol Psychiatry 2000;48(11):1069–80.
[149] Tassi P, Pellerin N, Moessinger M, Eschenlauer R, Muzet A. Variation of visual detection over the 24-hour period in humans. Chronobiol Int 2000a;17(6):795–805.

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[150] Tassi P, Pellerin N, Moessinger M, Hoeft A, Muzet A. Visual resolution in humans fluctuates over the 24h period. Chronobiol Int 2000b;17(2):187–95.
[151] deGennaro L, Ferrara M, Curcio G, Bertini M. Visual search performance across 40 h of continuous wakefulness: measures of speed and accuracy and relation with oculomotor performance. Physiol Behav 2001;74(1–2):197–204.
[152] Kleitman N, Schneider J. Sleepiness and diplopia. Am J Physiol 1940;129:398–404.
[153] Horne JA. Binocular convergence in man during total sleep deprivation. Biol Psychol 1975;3(4):309–19.
[154] Rowland LM, Thomas ML, Thorne DR, Sing HC, Krichmar JL, Davis HQ, et al. Oculomotor responses during partial and total sleep deprivation. Aviat Space Environ Med 2005;76(7):104–13.
[155] Ferrara M, deGennaro L, Casagrande M, Bertini M. Selective slow-wave sleep deprivation and time-of-night effects on cognitive performance upon awakening. Psychophysiology 2000;37(4):440–6.
[156] deGennaro L, Ferrara M, Urbani L, Bertini M. Oculomotor impairment after 1 night of total sleep deprivation: a dissociation between measures of speed and accuracy. Clin Neurophysiol 2000;111(10):1771–8.
[157] Russo MB, Kendall AP, Johnson DE, Sing HC, Thorne DR, Escolas SM, et al. Visual perception, psychomotor performance, and complex motor performance during an overnight air refueling simulated flight. Aviat Space Environ Med 2005;76(7):92–103.
[158] Russo M, Thomas M, Thorne D, Sing H, Redmond D, Rowland L, et al. Oculomotor impairment during chronic partial sleep deprivation. Clin Neurophysiol 2003;114(4):723–36.
[159] Thomas M, Sing H, Belenky G, Holcomb H, Mayberg H, Dannals R, et al. Neural basis of alertness and cognitive performance impairments during sleepiness II. Effects of 48 and 72 h of sleep deprivation on waking human regional brain activity. Thalamus Relat Syst 2003;2:199–229.
[160] Porcu S, Ferrara M, Urbani L, Bellatreccia A, Casagrande M. Smooth pursuit and saccadic eye movements as possible indicators of nighttime sleepiness. Physiol Behav 1998;65(3):437–43.
[161] Roge J, Gabaude C. Deterioration of the useful visual field with age and sleep deprivation: insight from signal detection theory. Percept Mot Ski 2009;109(1):270–84.
[162] Roge J, Muzet A. Analysis of the deformation of the useful visual field: a comment on Rantanen (2003). Percept Mot Ski 2003;97(2):635–8.
[163] Roge J, Kielbasa L, Muzet A. Deformation of the useful visual field with state of vigilance, task priority, and central task complexity. Percept Mot Ski 2002;95(1):118–30.
[164] Roge J, Pebayle T, El Hannachi S, Muzet A. Effect of sleep deprivation and driving duration on the useful visual field in younger and older subjects during simulator driving. Vis Res 2003;43(13):1465–72.
[165] Babkoff H, Sing HC, Thorne DR, Genser SG, Hegge FW. Perceptual distortions and hallucinations reported during the course of sleep deprivation. Percept Mot Ski 1989;68(3 Pt 1):787–98.
[166] Drummond SP, Brown GG, Stricker JL, Buxton RB, Wong EC, Gillin JC. Sleep deprivation-induced reduction in cortical functional response to serial subtraction. Neuroreport 1999;10(18):3745–8.
[167] Thomas M, Balkin T, Sing H, Wesensten N, Belenky G. PET imaging studies of sleep deprivation and sleep: implications for behavior and sleep function. J Sleep Res 1998;7(2):274.
[168] Thomas M, Sing H, Belenky G, Holcomb H, Mayberg H, Dannals R, et al. Neural basis of alertness and cognitive performance impairments during sleepiness. I. Effects of 24 h of sleep deprivation on waking human regional brain activity. J Sleep Res 2000;9(4):335–52.
[169] Blake MJF. Time of day effects on performance in a range of tasks. Psychon Sci 1967;9:349–50.
[170] Colquhoun WP. Biological rhythms and human performance. New York: Academic Press; 1971.
[171] Monk TH, Buysse DJ, Reynolds 3rd CF, Berga SL, Jarrett DB, Begley AE, et al. Circadian rhythms in human performance and mood under constant conditions. J Sleep Res 1997;6(1):9–18.
[172] Ferrario VF, Tredici G, Crespi V. Circadian rhythm in human nerve conduction velocity. Chronobiologia 1980;7(2):205–9.
[173] Strenge H, Niederberger U, Seelhorst U. Correlation between tests of attention and performance on grooved and Purdue pegboards in normal subjects. Percept Mot Ski 2002;95(2):507–14.
[174] Bellamy N, Sothern RB, Campbell J, Buchanan WW. Circadian rhythm in pain, stiffness, and manual dexterity in rheumatoid arthritis: relation between discomfort and disability. Ann Rheum Dis 1991;50(4):243–8.
[175] Bellamy N, Sothern RB, Campbell J, Buchanan WW. Rhythmic variations in pain, stiffness, and manual dexterity in hand osteoarthritis. Ann Rheum Dis 2002;61(12):1075–80.
[176] Deschodt VJ, Arsac LM. Morning vs. evening maximal cycle power and technical swimming ability. J Strength Cond Res 2004;18(1):149–54.
[177] Kline CE, Durstine JL, Davis JM, Moore TA, Devlin TM, Zielinski MR, et al. Circadian variation in swim performance. J Appl Physiol 2007;102(2):641–9.
[178] Moussay S, Bessot N, Gauthier A, Larue J, Sesboue B, Davenne D. Diurnal variations in cycling kinematics. Chronobiol Int 2003;20(5):879–92.
[179] Bessot N, Moussay S, Laborde S, Gauthier A, Sesboue B, Davenne D. The role of the slope of oxygen consumption and EMG activity on freely chosen pedal rate selection. Eur J Appl Physiol 2008;103:195–202.
[180] Eastridge BJ, Hamilton EC, O'Keefe GE, Rege RV, Valentine RJ, Jones DJ, et al. Effect of sleep deprivation on the performance of simulated laparoscopic surgical skill. Am J Surg 2003;186:169–74.
[181] Leung L, Becker CE. Sleep deprivation and house staff performance. Update 1984–1991. J Occup Med 1992;34:1153–60.
[182] Taffinder NJ, McManus IC, Gul Y, Russell RC, Darzi A. Effect of sleep deprivation on surgeons' dexterity on laparoscopy simulator. Lancet 1998;352:1191.
[183] Foo SC, How J, Siew MG, Wong TM, Vijayan A, Kanapathy R. Effects of sleep deprivation on naval seamen: II. Short recovery sleep on performance. Ann Acad Med Singap 1994;23:676–9.
[184] How JM, Foo SC, Low E, Wong TM, Vijayan A, Siew MG, et al. Effects of sleep deprivation on performance of Naval seamen: I. Total sleep deprivation on performance. Ann Acad Med Singap 1994;23:669–75.
[185] Gauthier A, Davenne D, Martin A, Van Hoecke J. Time of day effects on isometric and isokinetic torque developed during elbow flexion in humans. Eur J Appl Physiol 2001;84:249–52.
[186] Gifford LS. Circadian variation in human flexibility and grip strength. Aust J Physiother 1987;33:3–9.
[187] Atkinson G, Coldwells A, Reilly T, Waterhouse J. A comparison of circadian rhythms in work performance between physically active and inactive subjects. Ergonomics 1993;36:273–81.
[188] Atkinson G, Reilly T. Circadian variation in sports performance. Sports Med 1996;21:292–312.
[189] Adams MA, Dolan P, Hutton WC. Diurnal variations in the stresses on the lumbar spine. Spine 1987;12:130–7.
*[190] Reilly T. Human circadian rhythms and exercise. Crit Rev Biomed Eng 1990;18:165–80.
[191] Bulbulian R, Heaney JH, Leake CN, Sucec AA, Sjoholm NT. The effect of sleep deprivation and exercise load on isokinetic leg strength and endurance. Eur J Appl Physiol Occup Physiol 1996;73:273–7.
[192] Tazawa Y, Okada K. Physical signs associated with excessive television-game playing and sleep deprivation. Pediatr Int 2001;43:647–50.
[193] Liu Y, Higuchi S, Motohashi Y. Changes in postural sway during a period of sustained wakefulness in male adults. Occup Med 2001;51:490–5.
[194] Forsman P, Haeggstrom E, Wallin A, Toppila E, Pyykko I. Daytime changes in postural stability and repeatability of posturographic measurements. J Occup Environ Med 2007;49:591–6.
[195] Kohen-Raz R, Himmelfarb M, Tzur S, Kohen-Raz A, Shub Y. An initial evaluation of work fatigue and circadian changes as assessed by multiplate posturography. Percept Mot Ski 1996;82:547–57.
[196] Avni N, Avni I, Barenboim E, Azaria B, Zadok D, Kohen-Raz R, et al. Brief posturographic test as an indicator of fatigue. Psychiatry Clin Neurosci 2006;60:340–6.
[197] Gribble PA, Tucker WS, White PA. Time-of-day influences on static and dynamic postural control. J Athl Train 2007;42:35–41.
[198] Morad Y, Azaria B, Avni I, Barkana Y, Zadok D, Kohen-Raz R, et al. Posturography as an indicator of fatigue due to sleep deprivation. Aviat Space Environ Med 2007;78:859–63.
[199] Forsman P, Hæggström E. Circadian amplitude and homeostatic buildup rate in postural control. Gait Posture 2012;38:192–7.
[200] Jorgensen MG, Rathleff MS, Laessoe U, Caserotti P, Nielsen OB, Aagaard P. Time-of-day influences postural balance in older adults. Gait Posture 2012;35:653–7.
[201] Deschamps T, Magnard J, Cornu C. Postural control as a function of time-of-day: influence of a prior strenuous running exercise or demanding sustained-attention task. J NeuroEng Rehabil 2013;10:26.
[202] Bougard C, Lepelley MC, Davenne D. The influences of time-of-day and sleep deprivation on postural control. Exp Brain Res 2011;209:109–15.
[203] Gomez S, Patel M, Berg S, Magnusson M, Johansson R, Fransson PA. Effects of proprioceptive vibratory stimulation on body movement at 24 and 36h of sleep deprivation. Clin Neurophysiol 2008;119:617–25.
[204] Fabbri M, Martoni M, Esposito MJ, Brighetti G, Natale V. Postural control after a night without sleep. Neuropsychologia 2006;44:2520–5.
[205] Nakano T, Araki K, Michimori A, Inbe H, Hagiwara H, Koyama E. Nineteen-hour variation of postural sway, alertness and rectal temperature during sleep deprivation. Psychiatry Clin Neurosci 2001;55:277–8.
[206] Patel M, Gomez S, Berg S, Almbladh P, Lindblad J, Petersen H, et al. Effects of 24-h and 36-h sleep deprivation on human postural control and adaptation. Exp Brain Res 2008;185:165–73.
[207] Uimonen S, Laitakari K, Bloigu R, Sorri M. The repeatability of posturographic measurements and the effects of sleep deprivation. J Vestib Res 1994;4:29–36.
[208] Seliga R, Bhattacharya A, Succop P, Wickstrom R, Smith D, Willeke K. Effect of work load and respirator wear on postural stability, heart rate, and perceived exertion. Am Ind Hyg Assoc J 1991;52:417–22.
[209] Schlesinger A, Redfern MS, Dahl RE, Jennings JR. Postural control, attention and sleep deprivation. Neuroreport 1998;9:49–52.
[210] Forsman P, Wallin A, Tietäväinen A, Haeggström E. Quantifying time awake posturographically. In: Conf Proc IEEE Eng Med Biol Soc; 2008.

[211] Gribble PA, Hertel J. Changes in postural control during a 48-hr. sleep deprivation period. Percept Mot Ski 2004;99:1035–45.
[212] Brenac T, Fleury D. Le concept de scenario type d'accident de la circulation et ses applications. Rech Transp Sécurité 1999;63:63–76.
[213] Brenac T. L'analyse séquentielle de l'accident de la route (Méthode INRETS), comment la mettre en pratique dans les diagnostics de sécurité routière. Rapport INRETS, Outils et Méthodes n° 3. Arcueil: INRETS. 1997.
[214] Kahneman D. Attention and effort. New Jersey, U.S.A.: Prentice Hall; 1973.
[215] Tagliabue M, Da Pos O, Spoto A, Vidotto G. The contribution of attention in virtual moped riding training of teenagers. Accid Anal Prev 2013;57:10–6.
[216] deWaard D. The measurement of drivers' mental workload. Thèse de doctorat de l'Université de Groningen. Haren, The Netherlands: University of Groningen, Traffic Research Centre; 1996., http://apps.usd.edu/coglab/schieber/pdf/deWaard-Thesis.pdf.
[217] O'Donnell RD, Eggemeier FT. Workload assessment methodology. In: Boff KR, Kaufman L, Thomas JP, editors. Handbook of perception and human performance. cognitive processes and performance, vol. II. New York: Wiley; 1986. p. 1–49.
[218] Norman DA, Bobrow DG. On data-limited and resource limited processes. Cogn Psychol 1975;7:44–64.
[219] Wickens CD. Multiple resources and performance prediction. Theor Issues Ergonomics Sci 2002;3:159–77.
[220] Van Elslande P, Fournier JY, Jaffard M. In-depth analysis of road crashes involving powered two-wheelers vehicles: typical human functional failures and conditions of their production. Work 2012;41:5871–3.
[221] Woratanarat P, Ingsathit A, Suriyawongpaisal P, Rattanasiri S, Chatchaipun P, Wattayakorn K, et al. Alcohol, illicit and non-illicit psychoactive drug use and road traffic injury in Thailand: a case-control study. Accid Anal Prev 2009;41:651–7.
[222] Atkinson G, Speirs L. Diurnal variation in tennis service. Percept Mot Ski 1998;86:1335–8.
[223] Baxter C, Reilly T. Influence of time of day on all-out swimming. Br J Sports Med 1983;17:122–7.
[224] Lucas SJ, Anson JG, Palmer CD, Hellemans IJ, Cotter JD. The impact of 100 hours of exercise and sleep deprivation on cognitive function and physical capacities. J Sports Sci 2009;27:719–28.
[225] Bennet G. Medical and psychological problems in the 1972 singlehanded transatlantic yacht race. Lancet 1973;2:747–54.
[226] Smith RS, Walsh J, Dement WC. Sleep deprivation and the race across America. Sleep 1998;22:303.
[227] Minors DS, Waterhouse JM. Circadian rhythms and the human. Bristol: Wright PSG; 1981.
[228] Reilly T, Atkinson G, Waterhouse J. Travel fatigue and jet-lag. J Sports Sci 1997;15:365–9.
[229] Reilly T, Edwards B. Altered sleep-wake cycles and physical performance in athletes. Physiol Behav 2007;90:274–84.
[230] Ankarath S, Giannoudis PV, Barlow I, Bellamy MC, Matthews SJ, Smith RM. Injury patterns associated with mortality following motorcycle crashes. Injury Int J Care Inj 2002;33:473–7.
[231] Ichikawa M, Chadbunchachai W, Marui E. Effect of the helmet act for motorcyclists in Thailand. Accid Anal Prev 2003;35:183–9.
[232] Liu BC, Ivers R, Norton R, Boufous S, Blows S, Lo SK. Helmets for preventing injury in motorcycle riders. Cochrane Database Syst Rev 2008;1: CD004333.
[233] Dandona R, Kumar GA, Dandona L. Risky behavior of drivers of motorized two wheeled vehicles in India. J Saf Res 2006;37:149–58.
[234] Elliott MA, Baughan CJ, Sexton BF. Errors and violations in relation to motorcyclists' crash risk. Accid Anal Prev 2007;39:491–9.
[235] Pileggi C, Bianco A, Nobile CG, Angelillo IF. Risky behaviors among motorcycling adolescents in Italy. J Pediatr 2006;148:527–32.
[236] Symeonidis I, Kavadarli G, Erich S, Graw M, Peldschus S. Analysis of the stability of PTW riders in autonomous braking scenarios. Accid Anal Prev 2012;49:212–22.
[237] Savino G, Pierini M, Rizzi M, Frampton R. Evaluation of an autonomous braking system in real-world PTW crashes. Traffic Inj Prev 2013;14: 532–43.

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