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Abstract: This study aimed at identifying the roll motion parameters of a motorcycle simulator prototype. Experienced motorcyclists tuned the angular physical movement of the mock-up and that of the visual scene to achieve an optimal riding experience during curves. The participants exceeded the rolling angles that would be required in real-world riding, while avoiding leaning the mock-up beyond 10°. In addition, they were more influenced by the speed of the virtual motorcycle than by road curvature, especially in a wide field of view. Heterogeneity was found in the roll applied to the visual scene. The overall patterns suggest that at least when washout is not applied to remove the side forces that in real-world riding are compensated by a centrifugal force, greater roll of the visual at the expense of the mock-up is mandatory to avoid performance biases that might be enhanced due to fear of falling off the simulator. Future roll motion models must take into consideration factors such as riding postures, which might not only influence the forces operating on the rider-motorcycle system, but also how motorcyclists perceive the visual world.

Highlights

► An experiment aimed to identify the roll motion parameters of a motorbike simulator. ► Motorcyclists tuned the angular rolls of the mock-up and of the visual scene. ► They exceeded the theoretical lean angles, but avoided leaning the mock-up beyond 10° . ► Heterogeneity was found in the direction of roll applied to the visual scene. ► Implications of the results for future motorcycle simulations are discussed.

Towards identifying the roll motion parameters of a motorcycle simulator

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Towards identifying the roll motion parameters of a motorcycle simulator

Abstract

This study aimed at identifying the roll motion parameters of a motorcycle simulator prototype. Experienced motorcyclists tuned the angular physical movement of the mock-up and that of the visual scene to achieve an optimal riding experience during curves. The participants exceeded the rolling angles that would be required in real-world riding, while avoiding leaning the mock-up beyond 10°. In addition, they were more influenced by the speed of the virtual motorcycle than by road curvature, especially in a wide field of view. Heterogeneity was found in the roll applied to the visual scene. The overall patterns suggest that at least when washout is not applied to remove the side forces that in real-world riding are compensated by a centrifugal force, greater roll of the visual at the expense of the mock-up is mandatory to avoid performance biases that might be enhanced due to fear of falling off the simulator. Future roll motion models must take into consideration factors such as riding postures, which might not only influence the forces operating on the rider-motorcycle system, but also how motorcyclists perceive the visual world.

Keywords: Driving simulation; Simulator fidelity; Field of view

1. Introduction

The application in recent years of motorcycle simulators to study motorcycle riding skills (e.g., Di Stasi, Álvarez-Valbuena, Cañas, Maldonado, Catena, Antolí et al., 2009; Di Stasi, Contreras, Cándido, Cañas and Catena, 2011; Hosking, Liu & Bayly, 2010; Liu, Hosking and Lenné, 2009; Shahar, Poulter, Clarke and Crundall, 2010) has the potential to contribute to the development of rider skill and safety.

Although low fidelity driving simulators can be effective tools for assessing various issues, simulators that do not incorporate motion capabilities are more limited and their use to study certain matters may well be inappropriate. Vestibular and somatosensory motion cues have a beneficial effect on driver behaviour in sensorimotor tasks such as braking (e.g., Malaterre and Fréchaux, 2001; Siegler et al., 2001) and lateral trajectory control (McLane and Wierwille, 1975; Siegler et al.). When riding a motorcycle however, roll is actually being used to control trajectory. Indeed, researchers in the area of motorcycle safety are motivated to develop motion-based motorcycle simulators and to apply them toward studying motorcycling performance, especially in tasks such as curve negotiation, where the use of static simulators seems to be less appropriate (e.g., Crundall et al., 2010).

However, the benefits of motion cues might be outweighed by adverse effects if false forces and cues are generated, or when poor coupling between inertial and visual cues is achieved (Pinto et al., 2008). Studies looking into the coupling between visual and inertial cues typically aim to characterize the proportions between the movements of the base of the simulator and of the visual scene. Such investigation has been undertaken in the context of flight simulation for angular movements (e.g., Reid and Nahon, 1985; Van Der Steen, 1998) and in driving simulation with longitudinal movements (e.g., Filliard, 2009; Neimer and Mohellebi, 2009) as well as in a tilt-coordination task (e.g., Groen and Bles, 2004).

This study was concerned with the coupling between visual and inertial cues in a motorcycle simulator. To date, there have been only very few studies working toward these ends (Cossalter et al., 2010; Kageyama and Tagani 2002; Stedmon et al. 2009).

All motion-base simulators including driving, riding and flight simulators have a limited range of movement due to restricted actuators. Flight roll has the same basic dynamics as motorcycle roll. Absolute roll angles of motorcycles are never rendered not only due to these physical limits, but because doing so introduces lateral and a gravity forces that in real riding are balanced by centrifugal and centripetal forces, which allow the motorcyclist to maintain balance. In more detail, in order to pass through curves, real motorcycles must reach lean angles (hereafter, theoretical lean angles) that correspond to both their linear speed and their trajectory's curvature (which is typically nearly identical to the road curvature). For a given curvature, greater speeds require more extreme lean angles. Similarly, for a given speed, larger curvatures, hence, tighter curves require more extreme lean angles. When leaning a real motorcycle, the continuous forces, mainly gravity "pulling" the rider toward the ground, are compensated during the steady state part of the curve by a centrifugal force. Consequently, there are virtually no lateral forces operating on the rider.

One manner to cope with the false side forces generated when tilting a motorcycle mock-up is delivering most of the tilt sensation by rolling the visual scene (e.g., Cossalter et al. 2010). In flight simulators high-pass filters are used so that the roll cue is generated without a continuous lateral force false cue. However, the pilot seats in a sealed cab, whereas on motorcycle simulators the rider can see the floor. Importantly, the proximity to the ground when leaning a motorcycle might actually be an important component in the motorcycling experience, one that is lost when the roll is delivered through the visual. Moreover, there are a few other substantial differences between steering and angular movements of an aircraft and a motorcycle, such as the manner by which the posture adapted by a motorcyclist when

negotiating curves can affect the coordinated motion of the motorcycle/rider system, suggesting that knowledge from aircraft simulation needs be implemented in motorcycle simulators with some caution.

Kageyama and Tagani (2002) have examined the relationship between the physical movement of the simulator on the roll axis and the roll motion of the visual scene (hereafter, physical roll and visual roll) associated with a credible illusion of roll among motorcyclists. They successfully reproduced the most realistic illusion when the scale factor for the motorcycle mock-up was twice as large as compared to the visual scene. These findings however are based on a sample of only four participants. In Cossalter et al. (2010), the opposite pattern was found, that is, the most realistic riding feeling was reported when the roll of the visual scene was proportionally larger than that of the mock-up of the motorcycle.

Stedmon et al. (2009) compared conditions where the visual scene has been rolled in the opposite direction from that of the motorcycle roll movement on the same axis and conditions where it remained horizontal. While both of these conditions resulted in similar riding performance, 10 of 16 riders preferred the configuration where the visual scene was rolled, 2 preferred the configuration where it was not rolled, whereas 4 participants had no preference. Although rolling the visual scene in the opposite direction from that of the motorcycle roll movement on the same axis seems to comply with geometric principles if the motorcyclist's head is perfectly aligned with his or her body and with the motorcycle when leaning into the bend, motorcyclists often keep their head upright, thereby keeping their eyes parallel to the road. In the context of an aircraft simulator, it has been found that visually induced roll sensation is influenced by head orientation (Young et al., 1975). On a motorcycle, the proximity to the road surface and the exact point of fixation might both operate as moderating factors, which further influence the illusion of a rolled visual scene. In

this regard, it is quite likely that both the direction of the roll and its amplitude (roll angle) are dependent on the riding posture and on the visual strategies.

In the current study, experienced riders were required to tune the visual and physical roll to achieve a realistic sensation of leaning for a variety of theoretical lean angles and road curvatures. They thus received a greater level of freedom than in previous studies, where participants had to judge pre-determined gains. As such, this study would a), provide useful insight on motorcyclists' own preferential coupling between the physical and the visual rolls and b), allow examining whether indeed motorcyclists have a clear preference for a visual scene that is rolled in the opposite direction of the bend. Selecting some theoretical lean angles that exceed the limits of our simulator's actuators, would allow further insight into the extent to which experienced motorcyclists might be willing to accept visual angular roll to compensate for the limited physical angular roll.

Finally, the current study aimed to further explore the effects of the size of the visual display and of the visual angle on the rendering model. Based on evidence demonstrating that speed is perceived to be faster when visual information is presented on a wide- than on a narrow-display (e.g., Alfano and Michel, 1990; Jamson, 2000; Pretto et al., 2009; Toet et al., 2007) and given that higher speeds (for a given curvature) require more radical lean angles, one might expect that the participants would reach greater overall rolls for the same riding conditions (i.e., linear speeds and curve characteristics), when these are presented on a wide- as compared to a narrow-display.

2. Method

2.1. Design

A 3 x 2 x 2 within subjects design was employed with three theoretical lean angles (10°, 20° or 30°), two road curvatures (150 or 300 m) and two conditions of field of view

(narrow and wide). Specifically, the visual representation of the riding conditions with respect to the radii of curvatures and approaching speeds was such that if occurred on a real road the rider would have had to lean the motorcycle by 10°, 20°, or 30° in order to pass safely through the bend. Thus, given the theoretical lean angles and the radii of curvatures chosen, six passing speeds were obtained (see Table 1), of which each two corresponds to the three theoretical angles per each of the curvatures. The participants underwent the same type of task twice, once with a narrow field of view (FoV) and once with a wide FoV.

For each of the FoV conditions, the test consisted of one block per each of the six sub-conditions created by the theoretical lean angles x radii of curvatures design. Each block had two trials that ended with a left bend and two trials that ended with a right bend and that were randomly distributed within that block. The six blocks within each of the FoV conditions were presented in a random fashion, with a five minutes break between each three blocks. There was a 10 minutes break between the two FoV conditions. Half of the participants completed the narrow FoV blocks before the wide FoV blocks and half of them completed the narrow FoV blocks after the wide FoV blocks. Half of each of these sub-groups completed the training in the narrow FoV and half of them completed the training in the wide FoV.

<Table 1>

2.2. Participants

Twenty nine motorcyclists (27 males and 2 females, mean age = 36 years, SD = 8.1, mean license seniority = 11.3 years, SD = 8.9) volunteered to participate in this study. They were recruited through advertisements that were posted via mailing lists of the French Institute of Sciences and Technology for Transport, Development and Networks (IFSTTAR) and in motorcyclist forums. All of them had normal or corrected-to-normal vision. The study was approved by the local ethics committee (IFSTTAR Ethics Committee).

2.3. Experimental setup and task

The experiment was conducted on a powered motion-base motorcycle simulator (Nehaoua et al., 2007; see Fig. 1), a project initiated by INRETS - MSIS and carried out in collaboration with IBISC (Université Evry Val d'Essonne) and IEF (University Paris-Sud) laboratories. The simulator consists of a standard motorcycle (125 cm³) equipped with all basic parts including steering column with handlebars, gas tank, seat, footrests, throttle, front and rear brakes, and a gearbox. The steering column is equipped with a force feedback motor. Beyond several actuators and sensors used to generate motion in the three axes, roll motion was obtained via two lateral electric activators that replaced the front fork. The highest roll motion that was used was $\pm 12.5^\circ$ due to actuator limitations. In accordance with real-world riding, higher speeds and larger lean angles resulted in faster rolls. The rolling center was located approximately 30 cm below the simulator's seat. In the narrow FoV condition, the simulated scene was played through a Projection-design F-22 projector (1024 x 1280 pixel resolution) onto a white screen (1.88 m width x 2.40 m height). When seated on the simulator the participants faced the screen at a distance of approximately 1.65 m, with images subtending a visual angle approximating $60^\circ \times 70^\circ$. In the wide FoV condition, two additional identical projectors were used for playing the side views onto two further identical screens positioned to the left and right of the central screen at a set angle of 120° . The side screens extended the 60° horizontal visual angle of the central screen to 180° .

<Figure 1>

The visual scene represented a single carriageway winding road with standard white lane-markings in a traffic-free rural environment and was refreshed at a rate of 30 Hz. The scene displayed within each trial consisted of a 100 m long straight road followed by four successive bends, which included two left and two right bends that were separated by a 100 m long straight road. All of the bends within a trial had the same radius of curvature. Each trial

terminated 50 m after the last bend. Participants were informed on-screen that the trial has ended.

The virtual motorcycle rode at the center of the right lane of the road; its trajectory and speed were both computerized and automated. The task was to tune the visual and the physical roll motions when riding through curves aiming to reach a similar leaning sensation to real-world riding. The participants were allowed to tune during both the transition from straights to turns and during the steady state section of the bend. Two pairs of push buttons allowed the participants to perform this task. The horn and the starter, which were located on the left and right handlebars and were pressed with the thumbs, leaned the simulator in the direction of the press. The lean angle of the simulator continued to increase for as long as the button was being pressed (until the maximum degree was obtained). Once the button was released, the simulator remained at the angular position that has been reached. Participants could also decrease the lean angle by pressing the button located at the side counter to the side to which they were leaning. At the end of each bend the motorcycle automatically returned to the upright position. Two additional buttons that were fixed above the horn and the starter and that were pressed with the index fingers rolled the visual scene in the direction of the press. Operation of the buttons was such that both hands could be kept on the handlebar at all times.

2.4. Procedure

At the beginning of the experimental session, the experimenter explained the task to the participants and demonstrated them how to perform it. Participants were explained that they were free to roll the physical and visual dimensions at any time and magnitude as they saw fit, and that at the end of each bend the motorcycle and the visual scene would automatically return to the upright position. They were further explained that following the initial calibration obtained during the first bend, their input would be registered and automatically delivered in the next bend, and so forth in each of the consecutive bends. Consequently, from

the second bend onwards, they would be given the opportunity to readjust their initial tuning by increasing or reducing the roll angle until they achieve the optimal sensation of riding.

The participants then wore a motorcycle helmet and sat on the simulator facing the screen. They completed a training session, after which they completed the test phase. The complete session lasted approximately 50 minutes.

2.5 Data analysis

In each trial, the magnitude of the physical and of the visual roll angle obtained at the end of the fourth and final bend was used for the analyses. The overall roll (i.e., the sum of the visual and the physical roll) was also calculated. Each of these three dependent measures were subjected to a 3 x 2 x 2 (Theoretical lean angle x Road curvature x FoV) repeated measures analysis of variance (ANOVA). The data of one participant who did not complete the session due to motion sickness were excluded from all of the analyses.

3. Results

Qualitative analysis has revealed that although all of the 28 participants have leaned the motorcycle in the direction of the bend, only 18 of them have consistently leaned the visual scene in the opposite direction to the bend. The data of the remaining 10 participants are discussed separately (section 3.5). ANOVAs were initially performed with bend direction in the model. As this factor did not yield any significant effect, it was removed from the model. Figure 2 displays the magnitudes of physical and visual rolls for the 12 sub-conditions created by the theoretical roll x road curvature design x FoV design.

<Figure 2>

3.1. Visual roll

The 3 x 2 x 2 ANOVA revealed a significant main effect for road curvature ($F(1,17) = 13.96, p < .01$), indicating that the magnitude of the visual roll in the 300 m curvature was larger than in the 150 m curvature. A post-hoc test (Newman-Keuls hereafter) on the significant effect of theoretical lean angle ($F(2,34) = 54.56, p < .001$) showed that the magnitude of the visual roll was larger in the 20° than in the 10° angle and larger yet in the 30° theoretical lean angle ($ps < .001$). Although the main effect of FoV was not significant [$p > .10$], the 3-way interaction approached significance ($p = 0.06$). The patterns of the interaction were identical to those indicated by a significant 3-way interaction yielded by the ANOVA performed on overall roll (see 3.3).

3.2. Physical roll

The 3 x 2 x 2 ANOVA revealed a significant main effect for road curvature ($F(1,17) = 15.73, p < .001$), indicating that the magnitude of the physical roll in the 300 m curvature was larger than in the 150 m curvature. A post-hoc test on the significant main effect of theoretical lean angle ($F(2, 34) = 43.55, p < .001$) showed that the magnitude of the physical roll was larger in the 20° than in the 10° angle and larger yet in the 30° theoretical lean angle ($ps < .01$). The main effect of FoV was not significant [$p > .10$]. The interaction between FoV and theoretical lean angle ($p=0.08$) suggested slightly more roll in the wide-, than in the narrow-FoV, only in the 20° condition.

3.3. Overall roll (sum of visual and physical roll)

The 3 x 2 x 2 ANOVA revealed a significant main effect for road curvature ($F(1, 17) = 17.28, p < .001$), indicating that the magnitude of the overall roll in the 300 m curvature was larger than in the 150 m curvature. A post-hoc test on the significant effect of theoretical lean angle ($F(2, 34) = 77.79, p < .001$) showed that the magnitude of the overall roll was

larger in the 20° than in the 10° angle and larger yet in the 30° theoretical lean angle ($ps < .001$). Although the main effect of FoV was not significant [$p > .10$], the 3-way interaction was significant ($F(2,34) = 3.29, p < .05$). Post hoc tests for the interaction (see Fig. 3) indicated that while the magnitude of the overall roll was larger in the 300 m than in the 150 m curvature in both FoV conditions in the 20° as well as in the 30° theoretical rolls, in the 10° condition this difference between the curvatures appeared only in the wide FoV ($p < .01$) but not in the narrow FoV [$p > .10$]. Additionally, in the 10° condition the overall roll was larger in the narrow FoV than in the wide FoV, only in the 150 m curvature, but not in the 300 m curvature [$p = .05$]. A similar trend was found in the 30° condition [$p = .09$].

<Figure 3>

3.4. Speed and curvature

In the current experiment, the theoretical lean angles and road curvatures have both co-varied with speed, with faster average speeds in larger theoretical lean angles than in smaller angles and in wider bends than in tighter bends. Given our need to generate and control for specific theoretical rolls that correspond to particular road curvatures and due to the relations between speed, theoretical lean angle and road curvature, this confound was unavoidable. To further our insight in this regard, regression analyses were conducted separately for the narrow and wide FoV conditions, with speed and road curvature as independent variables and magnitude of the roll of the various measures as dependent variables. Significant models emerged for all dependent variables, for both FoV conditions ($F_s(2, 429) > 52.8, ps < 0.001$). For the narrow FoV the models accounted for 20%, 21% and 23% whereas for the wide FoV they accounted for 25%, 28% and 30% of the variances in the visual, physical and the overall rolls, respectively. For the narrow FoV, linear relationships were found between both factors and magnitude of the visual roll ($\beta_s = .53$ and $-.16, ps < .01$, for speed and curvature,

respectively), between only speed and the physical roll ($\beta = .51$, $p < .001$ for speed and $\beta = -.08$, $p > .10$ for curvature) and between both speed and curvature and the overall roll ($\beta_s = .56$ and $-.16$, $ps < .01$, respectively). For the wide FoV, linear relationships were revealed between both the speed and curvature factors and the visual roll ($\beta_s = .61$ and $-.20$, $ps < .001$, for speed and curvature, respectively), between speed and road curvature and the physical roll ($\beta_s = .61$ and $-.14$, $ps < .01$, respectively) and between both speed and road curvature and magnitude of the overall roll ($\beta_s = .66$ and $-.21$, $ps < .001$, respectively).

3.5. Other preferences of visual roll

Only 18 of the 28 participants have consistently leaned the visual scene in the opposite direction to the bend. Two motorcyclists did not lean the visual scene at all times. All of the remaining eight motorcyclists have leaned the visual scene in the same direction that they have leaned the motorcycle, hence, in the direction of the bend, on at least some of the trials. Four of them have consistently leaned the visual scene in the same direction that they have leaned the motorcycle. The remaining four participants were not as consistent, rolling the visual scene in the direction of the bend on some trials and not rolling it on other trials, or rolling it in the direction of the bend on some trials and in the opposite direction on others.

4. Discussion

The participants increased the roll angles with the increase in the theoretical lean angles (i.e., the angles that a motorcycle must reach to pass through bends), indicating that these motorcyclists were aware of the changes in the riding conditions and responded in a sensible manner to these changes. Although the participants overestimated the theoretical lean angles, these overestimations decreased with the increase in the theoretical lean angle. Such overestimations are consistent with studies comparing other real and virtual environment such

as ball catching (e.g., Baurès et al., 2009) or distance perception (e.g., Plumert et al., 2005), presumably suggesting that motorcycle simulations may require amplifying the subjective experience of the curves.

The increments in the roll angles were due to a rise in both visual and physical rolls. In the 10° condition the overall roll was distributed more or less equally between the visual and physical dimensions. Although also for the 20°, the tuning resulted in a gain (visual roll/physical roll ratio) of approximately 1, in the 30° condition, most of the roll was delivered through the visual. While one might argue that the extent that the motorcyclists rolled the visual scene was determined by their need to compensate for the limited motion base, perhaps a more plausible explanation is that they wanted to avoid sensation of falling off the simulator, possibly due to the lack of centrifugal forces that participate in the control of equilibrium in a dynamic natural situation. Indeed, in none of the conditions did the participants make use of the full 12.5° range of the roll motion. Moreover, only in one sub-condition (the 30° 300 m), the participants exceeded 12° and still they stayed below the actuators limits. This pattern was consistent across the two FoV conditions used in the experiment. Nonetheless, the explanation that the participants chose to roll the visual scene rather than to lean the simulator only because they feared falling off the simulator cannot account for a) the result showing that the physical roll, averaging on 10° in the 20° condition, was still significantly larger in that condition than in the 10° condition, even though in the 10° too all necessary roll was achievable through the physical, and b) the result showing that the physical roll was significantly larger in the 30° than in the 20° condition, even though both conditions exceed the 12.5 limits of the simulator. These results suggest that simulating the experience of leaning on a motorcycle is best achieved through a combination of visual roll and physical roll and that any changes in the theoretical lean angles require adjustments to both of these dimensions.

The significant main effects of road curvatures on both the visual and physical rolls indicated that the magnitude of the roll was greater in the wider 300 m curvature than in tighter 150 m bends. As explained above (3.4), the theoretical lean angles and road curvatures in this experiment have both co-varied with speed. In spite of this, since each of the curvature conditions consisted of an equal amount of theoretical roll trials, one might not expect to find an effect of road curvature on the magnitudes of any of the rolls. More than that, we found greater magnitudes in wider bends, while had the participants relied solely, or especially, on the curvature and ignored speed while performing the tuning task, the opposite pattern would be expected. This pattern therefore must indicate that when tuning the motorcyclists were more influenced by the speed of the motorcycle than by curvature or by the combination of speed and curvature. Indeed, the regression analyses revealed much stronger relations between speed and rolls ($\beta_s \geq 0.51$) than between road curvatures and rolls ($\beta_s \leq |0.21|$). These relations were generally stronger in the wide FoV, most probably reflecting the critical role that peripheral flow of information plays in the perception of speed (Shinar, 1978). Nevertheless, also in the narrow FoV, the visual, physical and overall rolls in the 150 m 20° condition ($M_s = 15.2^\circ, 9.7^\circ, 24.9^\circ$) were higher than the pertinent rolls in the 300 m 10° condition ($M_s = 11.6^\circ, 8.5^\circ, 20.1^\circ$), in spite of having effectually the same speeds (83 and 82 km/h, respectively for the two conditions). These patterns have repeated themselves in the wide FoV: higher rolls were obtained in the 150 m 20° condition (visual: $M = 17.2^\circ$; physical: $M = 10.4^\circ$) than in the 300 m 10° condition (visual: $M = 14^\circ$; physical: $M = 8.5^\circ$), providing direct evidence that the participants were also sensitive to changes in road curvature per se, accurately increasing the roll in tighter bends.

The prediction that due to faster perceived speeds in the wide-, than in the narrow-FoV, the participants would reach greater overall rolls in the former condition was not supported. It is quite possible that in addition to faster perceived speeds, the additional lateral information

at the same time also led to greater sensitivity to the changes in visual roll, resulting in conflicting influences and thus in the absence of a FoV effect on roll.

Finally, although most of the participants in this experiment have consistently rolled the visual scene in the opposite direction to which they have leaned the motorcycle, one third of them have either rolled the visual scene in the same direction of the bend, or have not rolled it in any direction. These different patterns might reflect differences between the body and head postures that motorcyclists tend to adapt when negotiating curves, the extent that they are used to reaching radical lean angles and that they lean off their bike into the turn, as well as their visual strategies. Extreme angles are more rarely reached by the average motorcyclist and are only common among sport bikers. Indeed, in the current experiment the majority of the motorcyclists have rolled the visual scene in the opposite direction from the bend. In this regard, our results are in agreement with Stedmon et al. (2009) who found that most of the riders prefer a configuration where the visual scene is rolled in the opposite direction to the motorcycle movement.

In sum, we have shown that experienced motorcyclists indeed have the capability of taking into consideration in a sensible manner, variables such as the linear speed of the simulated motorcycle and the road curvatures, while reproducing the lean angles that a real motorcycle must reach in order to navigate safely through a bend. They were capable of doing so even though some of the inertial cues such as acceleration, jerk and centrifugal force were absent. This suggests that experienced motorcyclists have some internal representation of the lean angle they would achieve in the real world. While keeping in mind the large differences between any simulation and that which is simulated and that simulators are incapable of delivering all of the physical stimulations a driver typically receives in real driving situations (Stoffregen et al., 2003), this study suggests that a realistic experience of negotiating curves can be created through amplifying the subjective experience of the curves by over-rolling the

visual scene. These patterns are in agreement with Cossalter et al. (2010), whose participants reported the most realistic riding feeling when the roll of the visual scene was proportionally larger than that of the mock-up of the motorcycle. However, this study also suggests that there is a certain minimum of angular roll motion of the simulator mock-up that experienced motorcyclists require and that the proximity to the ground when leaning a motorcycle might be an important component in the motorcycling experience, one that is lost when the roll is delivered through the visual. Nonetheless, this study shows that not only can over-rolling the visual scene be used to compensate for a limited motion base, it might be mandatory in order to reduce performance biases that can be enhanced due to fear of falling off the simulator, especially when the angle exceeds 10° and no form of washout is applied to remove the side forces (e.g., Cossalter, 2010; Reid and Nahon, 1985).

Finally, this study presents data suggesting that future research and roll rendering models for motorcycle simulators will need to take into consideration a variety of factors such as the characteristics of the visual display setup and the different types of riding styles and postures that can influence both the inertial forces operating on the motorcyclists and how these motorcyclists perceive the visual world.

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Table and Figure Captions

Table 1. Speeds of the virtual motorcycle (km/h) are given as a function of the theoretical lean angles and radii of curvatures. Speeds were determined on the basis of the following formula: $v = \sqrt{RC \cdot g \cdot \tan(\varphi)}$, where v is the passing speed, RC the radius of curvature, g the gravity and φ the roll angle of the theoretical lean angle.

Figure 1. Motion base motorcycle simulator.

Figure 2. A stacked bar graph displaying the magnitudes of physical and visual rolls for the 12 sub-conditions created by the theoretical lean angles (10°, 20° and 30°) x road curvatures (150 and 300 m) x field of view (1 and 3 screens) design. The lower part of each bar is the magnitude of the physical roll (motion base); the upper part is the magnitude of the visual roll (horizon). The visual/physical ratio represents the gain while the sum (the whole bar) represents the overall roll.

Figure 3. Roll magnitude (overall roll) as a function of the interaction between field of view, theoretical lean angle and road curvature. Error bars represent standard errors of means.

Table 1. Riding conditions.

Radius of curvature	Theoretical lean angle		
	10 deg	20 deg	30 deg
150 m	58	83	105
300 m	82	118	148

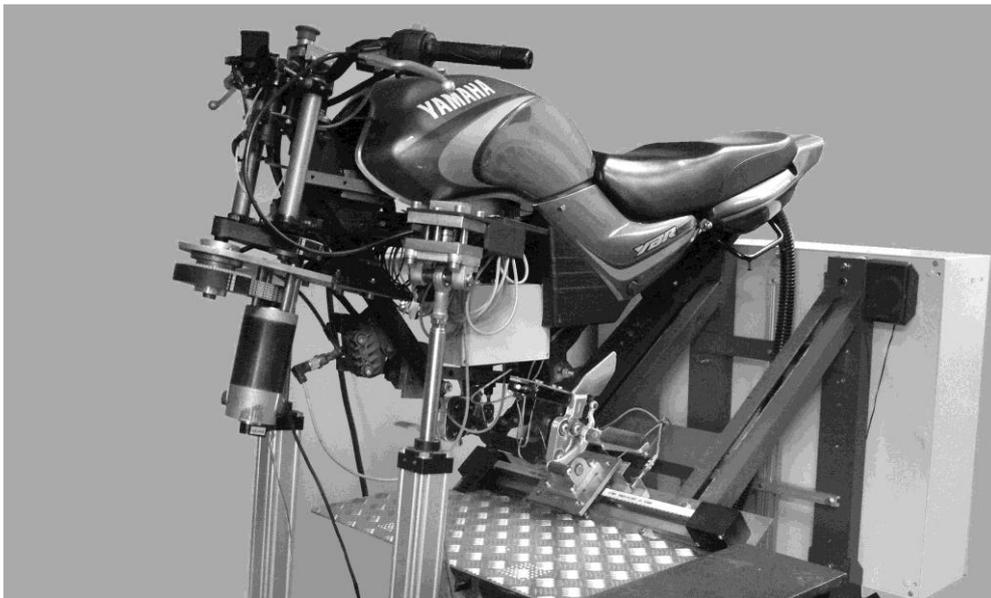
Figure 1.

Figure 2.

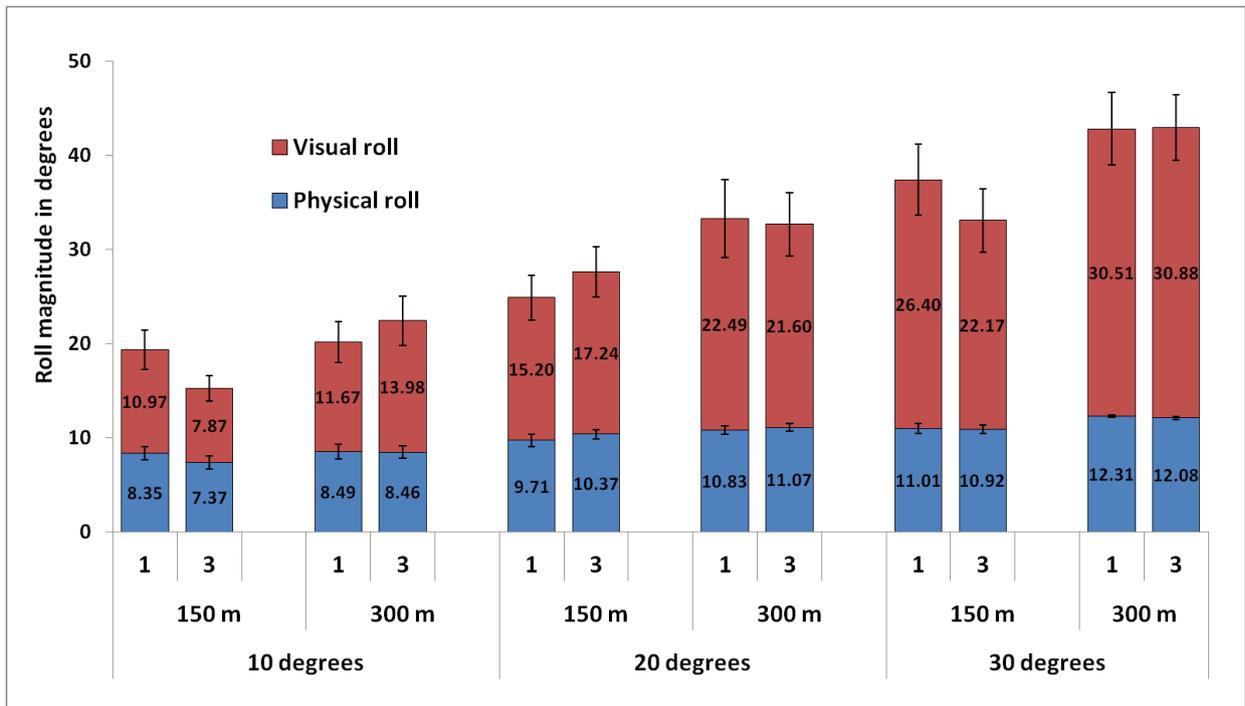


Figure 3.

