The Link Between Roll and Steering Torque in Motorcycles

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Abstract—**Steering torque is the most important control input for motorcycle turning; however, some riders believe they can steer using upper body roll alone. As other investigations have shown rider roll to be an ineffective for path control, there is likely a link between rider roll and steering torque in motorcycles. This paper examines new results, looking at the relationship between roll and steering. The specific results look at the connection in two directions. First, results examine how steering torque is generated due to motorcycle roll. Secondly, the rider's roll and yaw response to steering motion is presented. The results show strong links between motorcycle roll rate and steering, as well as steering and rider motion. The link between steering and rider roll implies the rider can generate steering torque by leaning their upper body. As the generated forces and motions are non-negligible they need to be investigated further. This information, is being used to develop a new model of the rider's passive impedance. In turn this model can be used to ensure the stability of motorcycles, regardless of the rider.**

Index Terms—**motorcycle, rider, roll, steering-torque, control**

I. Introduction

ONE of the most important controls for a motorcyclist is steering torque. Steering torque can be intentionally provided by the rider or caused by other motions, such as rider roll. Understanding how steering torque is generated is of key importance, as it is the primary method of directional control for a motorcycle.

A common concept in motorcycle riding is that a rider can corner by leaning their body into the turn, rather than using steering torque. This idea is refuted by [1] that shows steering torque is more than ten times as effective, at turning a motorcycle, than rider roll alone. This idea is shown directly by [2], meaning rider roll must have a secondary effect. This paper intends to examine the possibility of a link between steering torque and roll, of both motorcycle and rider.

This paper is part of a larger investigation on how the rider affects motorcycle stability. The rider can respond to motorcycle motions in two ways, actively or passively. The active response occurs at frequencies below 2 Hz, where the rider has control of their body. This active response includes functions such as keeping the trunk vertical, and controlling steering inputs. Above 2 Hz [3] the rider can no longer control their body to respond to motions in time, this is the passive region. In the passive region the rider has no cognitive effect on body movement, so can be modelled as a multibody system of masses, springs, and dampers.

When exploring the link between roll and steering, it is useful to include this passive region, as the rider can be measured without knowingly changing the result. In the active region, if the rider knew the purpose of the test, they may change how they use their arms or trunk, affecting the steering torque result. By using a frequency that the rider can't actively respond to, the result is likely to be closer to the real world case, where they are focused on path following and navigation.

The order of the paper is as follows: first there is an introduction to the equipment used for this investigation, followed by an explanation of the tests undertaken. Results are presented to show the effect of motorcycle roll on steering torque, as well as steering movement on rider roll and yaw. These results are analysed to understand the possible link between rider roll and steering torque, along with suggestions for further research.

II. Specialist Equipment

This investigation used a rig specially designed to measure motorcycle rider impedance, pictured in Figure 1, to ensure the results represented the real world. This rig is capable of replicating motorcycle roll, yaw and steering motions, with the rider's posture matched closely to currently available motorcycles. This rig also allows the posture to be altered, representing either sports or touring motorcycles for the first time, depending on the test requirements. An important difference between this rig and used in previous investigations, is the location of the roll axis. Whilst [4] & [5] use a roll axis along the ground, this rig places the roll axis about $\sim$100 mm below the seat. This location is thought to give a better representation of motorcycle weave and wobble.

This rig uses a bespoke measurement system that collects 34 channels of data. This system consists of 4 six axis inertial measurement units (IMUs) and an assortment of load cells. Two IMUs record rig motion, one being placed to measure roll and yaw rotation, whilst the other measures steering rotation. The other two IMUs are attached to the rider's upper and lower back, aligned with the spine, to record rider motion.

Bespoke load cells are used with this system, measuring how the rider interacts with the motorcycle. Two types of cell are used. The first measures lateral force and moment applied to the seat, tank, and foot pegs. The second type is used for the handlebars only, measuring roll torque, vertical force, lateral force and steering torque. A key benefit of this system, over those from previous investigations, is that every measurement is taken on every test. This technique is allowing new connections to be explored, such as the link
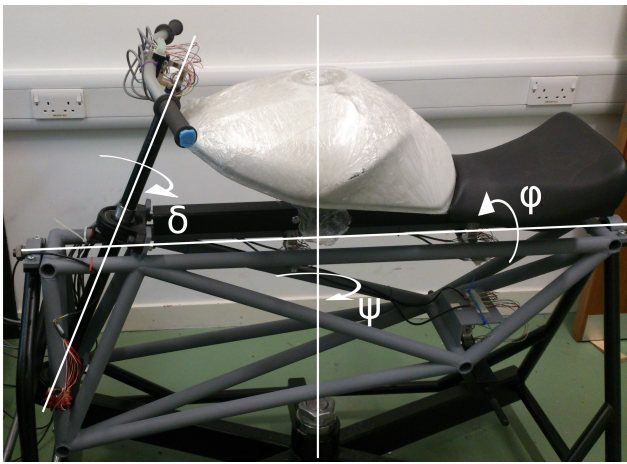
Fig. 1. Image of the motorcycle rig used for testing. Roll frame in grey, Yaw frame in black, and handlebar in silver. Rotation axes are highlighted in white

Fig. 3. Overlay plot showing the results of steering torque for 8 riders during a motorcycle roll test. The average result is shown in black

between rider roll and steering torque. The full capabilities of this rig, as well as more details about the design and operation, are available in [6].

III. TEST PROTOCOL

Rider forces and motions can be classified as either active or passive. Active inputs are those which the rider intends to make, whereas passive inputs are those made by the rider involuntarily. These passive inputs can either be generated as a response to an intended motion, or as a reaction to an external input. In the active case the rider may change their behaviour dependent on where their attention is placed. For instance, if a rider knows that the steering torque is being measured, being conscious of this fact may change the way they use their arms if asked to lean their torso. As such, using an input they can only respond to passively, and focusing their attention elsewhere, is most likely to give results that represent the real world. To ensure the rider has a full passive response, a vibration input can be used. This works as humans can only actively respond to vibrations below 2 Hz [3]. Using this knowledge, a frequency sweep of 0.5 - 12 Hz was used for these experiments, allowing for a comparison between active and passive response. This frequency range was selected based on those used in previous investigations (such as [4] [5] [7]), which cover the range of the most dangerous motorcycle stability modes.

The other consideration was how to excite the rider. The most straightforward approach would have been to move the rider's upper body directly; this was not feasible as it does not represent a normal input for the rider, which could skew the results, as well as presenting an ethical issue. Another approach would have been to excite the steering column with a given steering torque and measure the rider's upper body response. This was discounted, as the current set-up is not capable of this type of control. Therefore, to elicit the most natural response from the rider, an input that mimics normal riding is used; in this case steering and motorcycle roll inputs. The steering input uses a constant 1.75° rotation amplitude throughout the frequency range. A constant amplitude was chosen as it overcomes limitations in shaker control whilst being acceptably comfortable for the rider at high frequencies. The limitation of this approach is that low frequencies
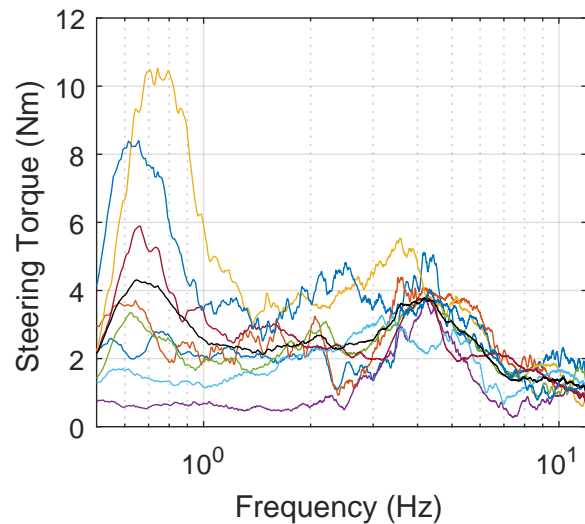
have a relatively low input energy. To help spread the input energy an exponential swept sine is used, which changes frequency faster at higher frequencies. Whilst the frequency changes in the same manner, the amplitude is different for the roll tests. A constant velocity amplitude, with a maximum rotation of 6° at 0.5 Hz was chosen. Using a constant velocity amplitude provides a good level of input energy throughout the frequency range. This input also gives accessible roll angles at the start of the test, and tolerable acceleration levels at the end.

In the context of this paper the key measurements are steering and roll rate for the rig. The key rider measurements are steering torque and rider upper body roll rate. These measurements were selected from those available, as they allow the relationship between the rider and steering to be investigated in two directions. Motorcycle roll and steering torque allow for a direct excitation of the rider, but it is not certain if rider roll is directly causing the output. This result can be sided by exciting the steering rotation to see the effect on rider body roll. From these quantities it is possible to infer, if not calculate, the relationship between rider roll and steering torque.

IV. RESULTS

A. Steering torque due to motorcycle roll

The first result to be examined, is the relationship between motorcycle roll and steering torque. This is a good starting point, as it is the best alternative to exciting the rider's upper body directly.

The first consideration is the magnitude of steering torque; no further investigation would be necessary if the levels were low. Figure 2 shows a magnitude of approximately 10 Nms/radian, throughout the frequency range. This equates to an average steering torque of 2 - 4 Nm below 6 Hz, as shown by Figure 3. This torque level is significant, as the rider can use 8 Nm to generate 20° roll angles during a slalom manoeuvre [8].

Secondly, to ensure this torque is being generated in response to roll, rather than at random, the coherence must be
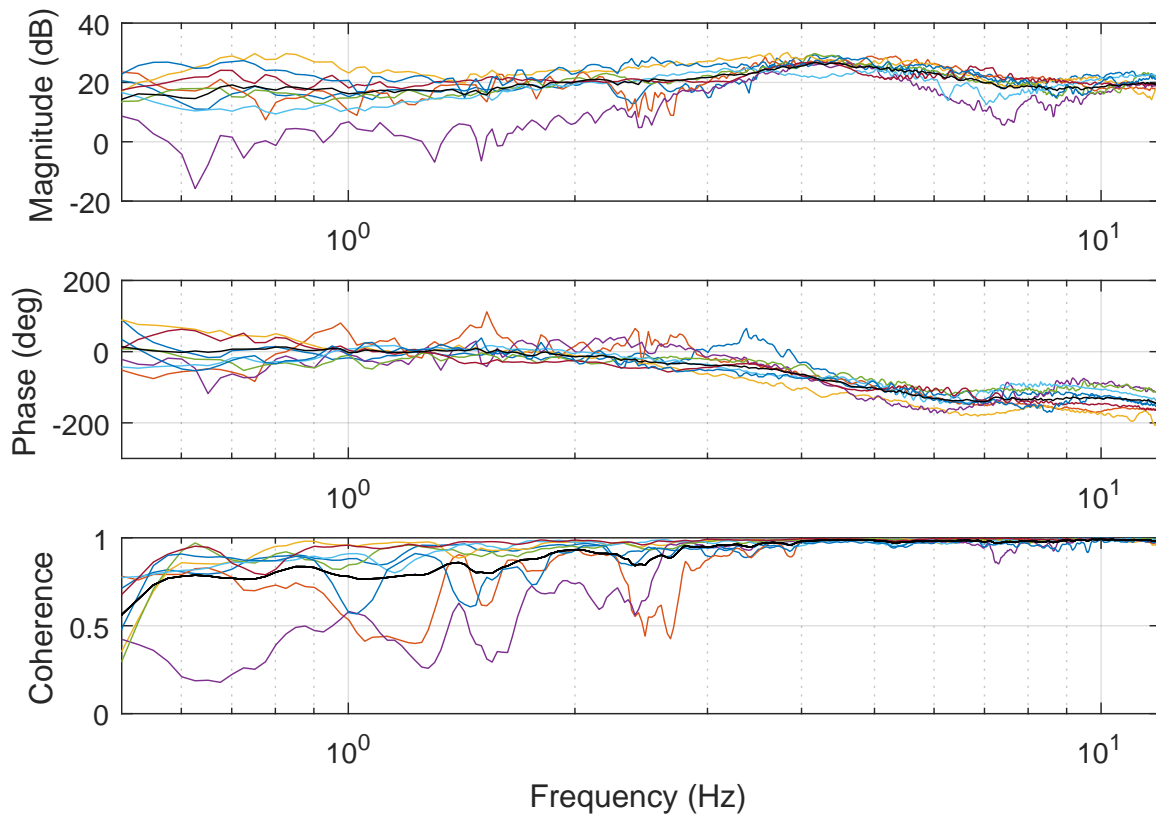
Fig. 2.   Overlay plot showing the results of steering torque / Rig roll rate for 8 riders. The average result is shown in black

checked. Figure 2 shows high coherence across the frequency range for most riders, increasing as the rider's response becomes more passive. This is the first investigation to show that steering torque is generated due to motion in another plane. The magnitude of the steering torque, indicates this connection should not be omitted from motorcycle stability investigations, or the errors could be significant. Therefore, how this steering torque develops must be investigated.

Finally, we must establish if the rider causes this steering torque, or if it is due to some other factor. As the steering column is inclined, it could be created due to the roll motion exciting the steering directly, with the handlebar inertia generating the torque. However, there are two issues with this hypothesis. In this experiment the force would increase linearly throughout the frequency range, as acceleration does; The results are much more constant throughout the frequency range and drop off at higher frequencies. Secondly, the form of steering torque generated, and the magnitude, differs significantly from that obtained in preliminary tests without a rider. The rider is the only other connection to the steering column, and the only one flexible enough to generate the observed response. As such it must be concluded that the rider generates this steering torque.

Now that the rider is shown to cause of this steering torque, the link between rider and steering must be examined more closely. Specifically, the rider must be excited by the steering, and their upper body response measured.

B. Rider roll and yaw due to steering input

The most direct way of testing the link between rider's torso and steering, using the current equipment, is to measure the rider's motion as a result of steering movement. Rider roll is presented first as a strong connection would show good evidence for our hypothesis. Rider yaw is also shown for comparison, as it is the most directly excited by steering

Figure 4 shows how the rider rolls in response to the steering input. A strong link between steering and rider roll is seen above 3 Hz, where the coherence is around 0.96. The coherence could be caused by the rider moving of their own accord, or due to the low input energy at lower frequencies. The reason is likely to be a combination of these two factors.

The motion ratio varies between 0.1 & 0.4, showing the link between rider roll and steering rate. This result would indicate a motion ratio of 10 to 1 between rider roll and steering, if it could be inverted. This is not directly possible as in the real world the rider leans far to much to assume linearity; the coupled dynamics on a motorcycle also mean that high steering rates would be hard to achieve. However, this result does show steering torque could be generated due to rider roll.

The result for upper body yaw to steering, also shows a strong connection (Figure 5). Firstly, the coherence is better than for roll in the low frequency range, showing yaw is more reliant on the steering input than roll in this range. In part, this could be due to the rider not needing to rotate their spine for balance. The yaw response to steering is also larger than roll, with a peak of 0.8. This is expected as the torso is more closely aligned with the steering column. This
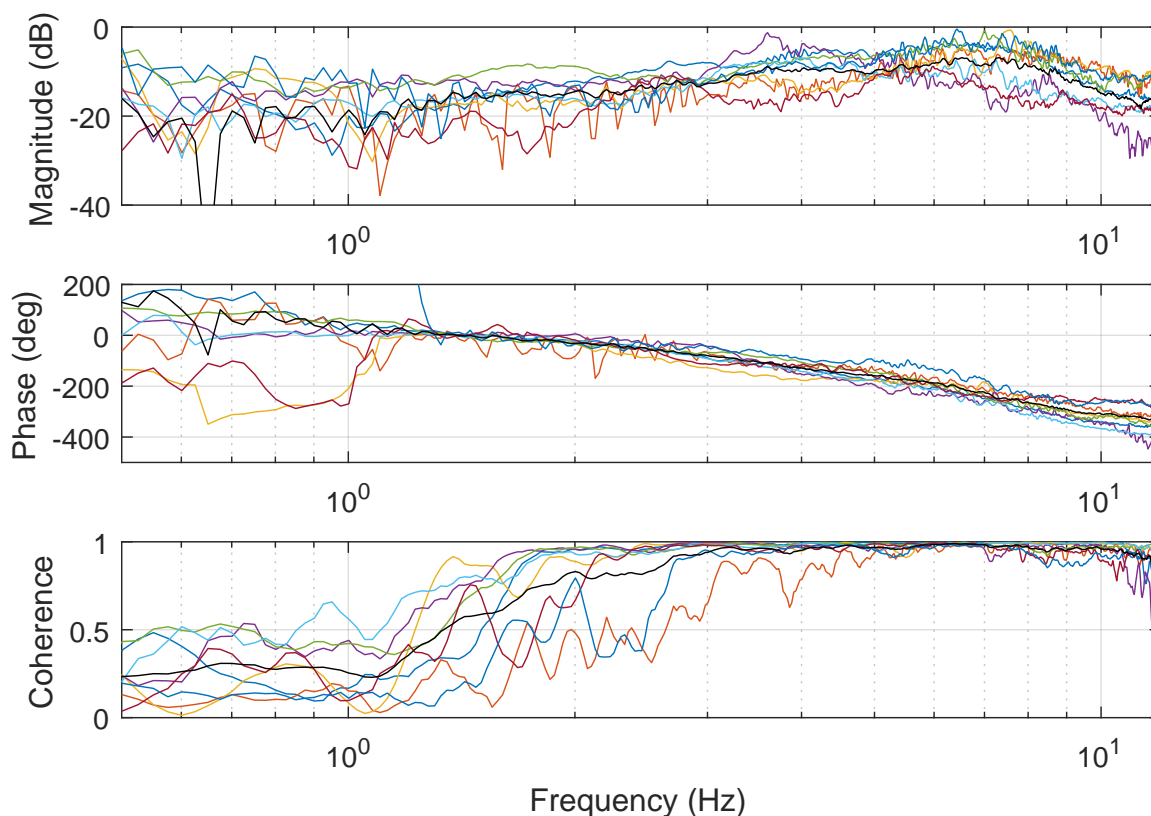
Fig. 4.   Overlay plot showing the results of rider upper body roll rate / steering rotation for 8 riders. The average result is shown in black
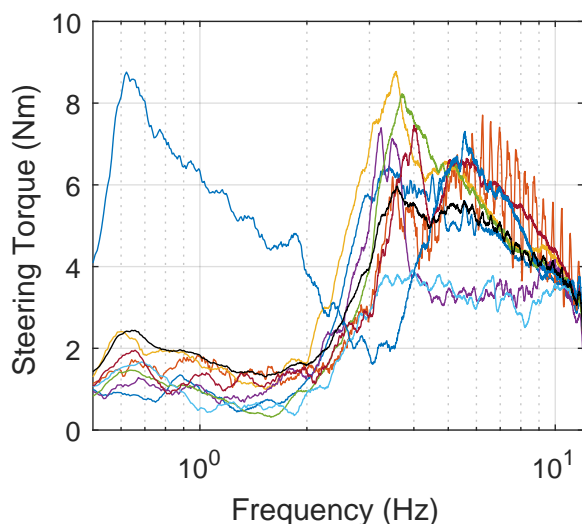

Fig. 6.   Overlay plot showing the results of steering torque for 8 riders during a motorcycle steering test The average result is shown in black

erates steering torque. Figure 6 shows a similar trend in steering torque to the coherence of rider roll and yaw. For every participant except one, there is very little steering torque below 2 Hz, this indicates that the rider is relaxed and trying not to impede steering motion. The torque generated here is due to acceleration the handlebar and portions of the rider's arm. As frequency increases into the passive region, the steering torque increases, as the rider can no longer control their arms well enough to isolate their upper body; The increased effective mass increases the steering torque.

V. HOW STEERING TORQUE IS GENERATED FROM RIDER ROLL

The following is a hypothesis as to how steering torque is generated from rider roll. As the rider leans on the motorcycle their shoulders move laterally relative to the steering column. This movement causes their arms to elongate and rotate across their body. To retain a more neutral position the rider turns their shoulders towards the steering column, this movement makes their arms an uneven length. To match the length of each arm, so it does not feel like they are steering, the rider attempts to turn the steering parallel to their shoulders. Trying to straighten their arms has thus generated the steering torque.

This hypothesis should also be valid in the vibration case, as the rider's body is acting as a series of springs and dampers, leading to a similar effect when the vibration is small. Further work on modelling the rider, specifically their arms, will give further insight into how the steering torque is generated.

is represented in the result, as the peak rider response is the cosine of angle between rider's torso and steering column, which is around 40° in this test.

A key difference between roll and yaw results is the frequency of maximum response. Yaw is greatest at 4 Hz, whilst roll is greatest around 7 Hz. This result shows that whilst the steering input generates mainly yaw at low frequencies, as expected, roll is dominant above 6 Hz.

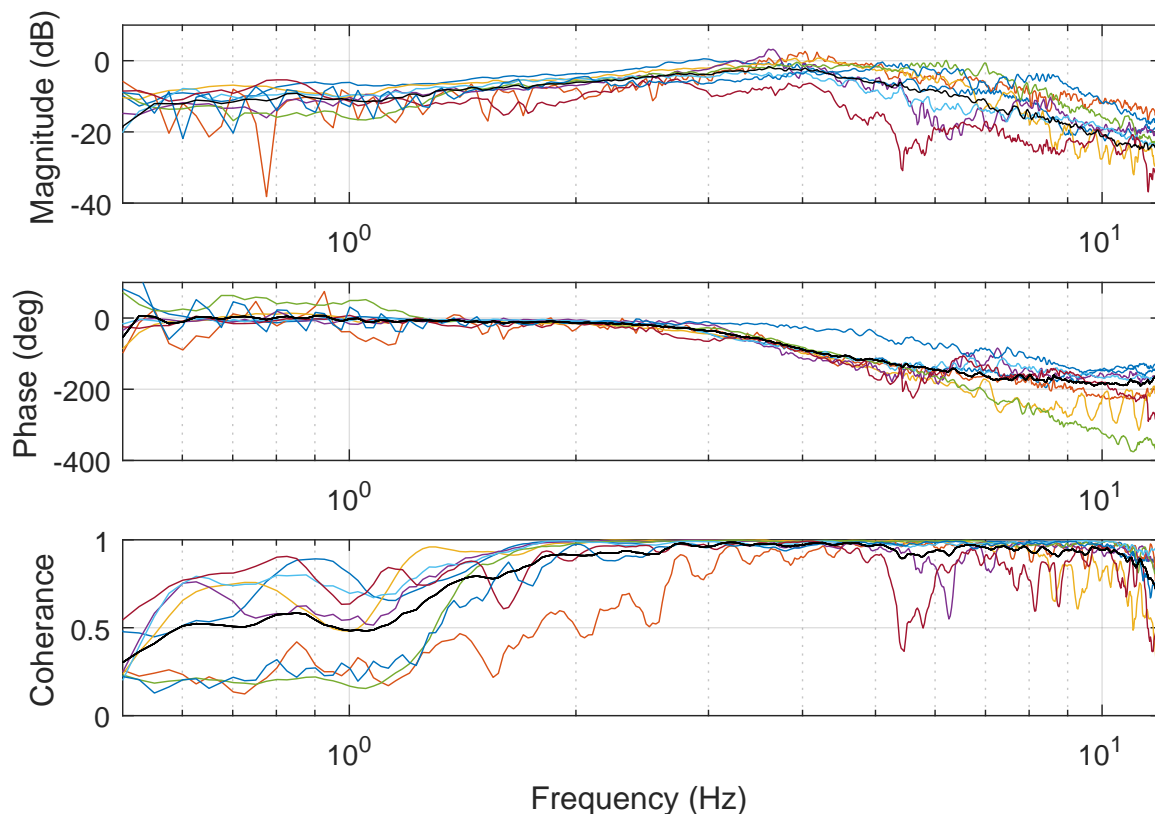Another point of interest is how the steering input gen-

Fig. 5.   Overlay plot showing the results of rider upper body yaw rate / steering rotation for 8 riders. The average result is shown in black

VI. CONCLUSION

This paper has shown several important links between the motorcycle, rider, and steering system. A direct link between motorcycle roll and steering torque has been shown. This link creates steering torque of a non-negligible magnitude, with good coherence throughout the frequency range. This output must be a product of the rider, as the output is significantly larger with a participant on the rig. Strong links are also seen between steering input, roll, and yaw of the rider's upper body. Coherence is good for both FRFs above 2 Hz, where the rider's response becomes passive. There is a greater magnitude of yaw below 6 Hz, whilst rider roll is more prominent above. The FRFs indicate that it would be possible for the rider to create steering torque purely by rolling, though further investigation is needed.

To prove this hypothesis, further tests should be conducted. It would be possible to use static tests, where rider is asked to lean and steering torque is measured. The directness of this approach is an advantage, but results may be skewed as the rider is aware of the purpose of this test. This knowledge may cause the rider to react differently than normal, thus skewing the results.

This paper is part of a larger work on motorcycle stability being undertaken at the University of Southampton. This project aims to create a comprehensive model of the rider's passive response, based on new data. The more comprehensive data set, including links between motions and forces in different planes, will allow the rider's response to be represented more faithfully. The final model will provide greater insight into the rider's effect on motorcycle stability, including how steering torque is generated due to roll.

REFERENCES

[1] R. S. Sharp, "Stability, control and steering responses of motorcycles," *Vehicle system dynamics*, vol. 35, no. 4-5, pp. 291–318, 2001.
[2] K. Code, "A twist of the wrist ii [dvd]," 2009.
[3] M. Massaro and D. Cole, "Neuromuscular-steering dynamics: motorcycle riders vs. car drivers," in *ASME 2012 5th Annual Dynamic Systems and Control Conference joint with the JSME 2012 11th Motion and Vibration Conference*.   American Society of Mechanical Engineers, 2012, pp. 217–224.
[4] T. Nishimi, A. Aoki, and T. Katayama, "Analysis of straight running stability of motorcycles," SAE Technical Paper, Tech. Rep., 1985.
[5] A. Doria, M. Tognazzo, and V. Cossalter, "The response of the rider's body to roll oscillations of two wheeled vehicles; experimental tests and biomechanical models," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 227, no. 4, pp. 561–576, 2013.
[6] R. Lot and T. Lane, "A new test rig for motorcycle rider impedance measurement," October 2017. [Online]. Available: https://eprints.soton.ac.uk/416217/
[7] V. Cossalter, A. Doria, R. Lot, and M. Massaro, "The effect of rider's passive steering impedance on motorcycle stability: identification and analysis," *Meccanica*, vol. 46, no. 2, pp. 279–292, 2011.
[8] F. Cheli, P. Mazzoleni, M. Pezzola, E. Ruspini, and E. Zappa, "Vision-based measuring system for rider's pose estimation during motorcycle riding," *Mechanical Systems and Signal Processing*, vol. 38, no. 2, pp. 399–410, 2013.