TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 67, Issue III, September, 2024

SOME INVESTIGATION ON THE MODELLING OF THE BIOMECHANICAL RIDER AND STABILITY OF MOTORCYCLE

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Abstract: *The goal of this paper is to improve the safety and stability of motorcycle by analyzing the impact of the rider on control of motorcycle and predicting potential unstable scenarios. We are used the multibody approach to design a rider using biomechanical properties. The aim is to create a control strategy that utilizes the electromyogram (EMG) signals from the rider's muscles and that can efficiently handle multi-joint muscles during reaching movements. These signals will be used to give commands for controlling the motorcycle. To achieve our goal, we have introduced a PID feedback control scheme that takes neural commands as input and used a heuristic strategy to determine the required steer and roll angles based on the motion of the rider. The results indicate that the developed controller effectively stabilizes the motorcycle model when operating at high range of speeds mainly in the wobble and capsize mode.*
Key words: *motorcycle; biomechanics; neural command; dynamics; control design; heuristic search.*

1. INTRODUCTION

Two-wheeled vehicles are the most common form of mechanized transportation on the planet. For example, we recall that the bicycle is one of the first two-wheeled vehicles known to humanity. The dynamics of two-wheeled vehicles have been the subject of numerous studies and form the basis of most vehicle dynamic analyses. These dynamics are not only fundamental to the transportation sector, but they are rather elegant, linking various aspects of kinematics, dynamics and physics. The dynamics of two-wheeled vehicles are complex and require an understanding of various physical aspects such as translational and rotational mechanics. Additionally, it involves devising control strategies, considering environmental conditions, integrating sensor data and incorporating control inputs into mathematical models or simulations to predict the movement and behavior of these vehicles. Since the early sixties, research in the area of two wheeled vehicle dynamics and control theory has gradually become more systematic and intensive. It involves the safety and discusses the crucial aspects and criteria that affect the stability and maneuverability. The primary obstacle to developing more comprehensive models lies in the mathematical complexity of constructing models with sufficient degrees of freedom to accurately represent the dynamics of two-wheeled vehicles. Despite this challenge, ongoing research endeavors aim to refine modeling approaches and incorporate a more realistic representation of the rider's influence on vehicle dynamics.

In literature, the rider and their effects on motorcycle dynamics are considered unrealistically, in the first, they are modeled as a simple rigid body models with a lean upper body [1, 2], and in the second case as a passive system [3 - 5] attached to the chassis of motorcycle, or in the third case by limited biomechanical properties of a rider [6 -8]. There have been several research studies on the advancements in biomechanical models of bike riders. One such study conducted by A. Doria and Tognazzo [9] looked into how biomechanical factors, including arm and waist movements, affect the stability of a bicycle. So, F. Cheli et al. [10] examined the impact of a rider's motions on the

Received: 30.07.24; **Similarities**: 19.08.24: **Reviewed**: 20.08./31.07.24: **Accepted**:20.08.24.

performance of a motorcycle in lateral dynamics. While, H. Lai [11] discussed the riding comfort of electric motorcycles, which are divided into two segments: a motorcycle, and the rider who follows a circular path in order to maintain the stabilization of the model for specific ranges of speed, considering the rider model, which consists of 12 rigid bodies, and the biomechanical characteristics, the rider model is linked by three types of joints: spherical, planar, and revolution connections, also, P. Talaia et al. [12] applied multibody approaches by including muscle skeleton models to more accurately analyze rider control actions,

Furthermore, this paper first aims to clarify how the rider affects the motorcycle's stability. Also, the second section a survey of literature in order to show the different approach of modeling used in literature, third section highlights the development of the motorcycle-rider model modeling. The fourth part the mathematical modelling of rider and the stability analysis of Capsize, weave, and wobble mode and describe the suggested proportional integral derivative controller and the control architecture. The simulation results are also shown in the five parts. Last but not least, the fifth section offers a conclusion that briefly goes over the outcomes and discoveries of our research.

2. INFORMATION

Research into the dynamics of two-wheeled vehicles has been conducted for over a century. Early research into two-wheeled vehicle dynamics progressed slowly and conflicting results were obtained at first. Many authors has been presented an overview of development of control action of rider. M. Garziad and A. Saka [13] introduced an overview of the previous work conducted on the dynamic of the two-wheeled vehicle on and the strategies of control developed to stabilize the bicycle. A. Popov [14] reviewed the modeling of the rider models and rider control for motorcycle steering. A. Schwab and J. Meijaard [15] and presented a review of the control strategies and schemes to stabilize the motorcycle - rider.

The Modelling and development of rider model of two wheeled vehicle have progressed along three main lines. These models may be conveniently categorized as: Passive rider, Upper Body of rider, and Biomechanical Model of rider

- **Passive rider**

A passive rider on two-wheeled vehicle is someone who is not actively controlling the vehicle's movement, So, many researchers used the passive rider in order to develop the mathematical model and control scheme in order to stabilize and integrate an advanced control strategy. The main body of literature on two-wheeled vehicle dynamics was developed and expanded in the 1970s. A significant step in the theoretical analysis of the motorcycle was presented by R. Sharp [16]. In this research, a Lagrangian analysis of a motorcycle system was carried out. The motorcycle model consisted of two rigid frames articulated by an inclined steering axis where the driver was considered to be a rigid body attached to the rear chassis.

Finally, we can consider that the works Meijaard [17], Meijaard and Schwab 2006 [19], Schwab et al 2005 [18], Schwab et al. 2006 [20] and Kooijman et al. 2007 [21] have produced a set of dynamic equations in the lateral configuration and represent the definitive references for stability analysis. They established the necessary formulas for the linearized equation and theoretical analysis of two-wheeled vehicles. They identified the main modes of instability such as Rollover, Swaying and Guiding by calculating the eigenvalues. These modes of instabilities have been widely interpreted and illustrated.

A. Schwab et al. [22] addressed the impact of passive driving on the lateral dynamics of the Basic Bicycle Model using simultaneous steering torque control and driver tilting movements.

Schwab A. et al (Schwab et al. 2008) used an LQR controller to study the effects of the driver on the stability of the bicycle through two situations. In the first, he studied a rigid conductor attached to the bicycle frame. He showed that the system could be stabilized easily thanks to the steering torque control, but only at low speeds when the roll feedback gains became unrealistic.

- **Upper Body**

Many researchers used upper body to maintain the stability of two wheeled vehicle and to elaborate the dynamics model and control strategy. Whereas, R. Sharp et al. [23] included the lean motion of the rider's upper body in an advanced motorcycle model. On the other hand, T. Liu and J. Chent [24] displayed a linear and nonlinear analysis of motorcycle-rider motion. They examined the stability of the motorcycle-rider system. Mears [25] discussed the effect of the moment of inertia of the wheels on stability. They added the lean of the upper body rider model to the motorcycle model. R. Sharp and D. Limebeer [26] presented a thorough breakdown of the fundamental traits of a motorcycle and its rider. In an experimental study, The capacity of a rider to maintain the stability of a motorbike at low speed without grasping the handlebars and instead controlling the motorcycle's stability exclusively through body lean and forces on the pedals was demonstrated by Yokomori et al. [27] while M. Garziad and A. Saka [28] introduced a comparative analysis of LQR and PID controllers to choose the best and most efficient strategies and parameters contributing to stability based to motion of lean motion of rider upper body. M. Calì et al. [29] investigated the effect of the motion of the rider's body on the motorcycle's performance. S, Zhu, et al. [30] analyzed the rider's impact on motorcycle motion taking into account the tilting motion of the rider's upper body and arms during stationary turns. Klinger et al. [31] focused on the influence of the rider's body in the wobble mode of instability of a bicycle. Schwab et al. [32] modelled the driver as an inverted pendulum. He noticed that adding a rotating body does not affect the eigenvalues of the uncontrolled system much. However, at low speeds the upper part of the pendulum requires large roll angle feedback gains, as in the case of the rigid driver large roll feedback gains are required for steering torque.

- **Biomechanical Model of rider**

The field of biomechanical modeling of motorcycle riders has made significant advancements in recent times. The latest approaches incorporate various anatomical, physiological, and mechanical factors to create sophisticated models. The primary aim of these models is to simulate the interactions between the rider, motorcycle, and the surrounding environment. They consider a range of variables such as the rider's body position, muscle activation patterns, joint angles, and forces exerted during riding maneuvers. Advanced technologies like motion capture systems, force plates, and computational modeling techniques are used to refine these models. They provide insights into rider behavior, ergonomic design improvements, and injury prevention strategies. H. Imaizumi and T. Fujioka [33] Concentrating on examining the dynamics of the motorcycle-rider system model, specifically analyzing elements such as frame stiffness, suspension system, and rider control. Huyge K. et al. (34) integrated an eight-degree-of-freedom driver biomechanical model into the motorcycle model. The controller applies a steering torque to the handlebars in order to generate the required roll angle and to correct if the targeted roll angle was not respected and to follow a desired trajectory. V. Keppler [35] identified the critical parameters of the biomechanical rider and the influence of these parameters on the stability of the motorcycle. Also, G. Sequenzia et al. [36] revealed the most important aspects of the advanced multibody modeling of a motorcycle and virtual rider, the rider, modeled on real anthropomorphic characteristics. Then, A. Doria et al. [3] identified the biomechanical properties of a rider and their effects on the roll motion of the bike. Furthermore, F. Cheli et al. [10] examined the impact of a rider's motions on the performance of a motorcycle in lateral dynamics.

Despite, P. Talaia et al. [12] applied multibody approaches by including muscle skeleton models to more accurately analyze rider control actions. Alternatively, A. Doria and M. Tognazzo [9] integrated a biomechanical body of a rider with a bike in order to interpret and analyze the stability in an open loop. They also construct equipment to measure the dynamic response of the rider's body and its impact on the stability of a bicycle. Additionally, M. Garziad and A. Saka [36] introduced an investigation on motorcycle and rider interaction modeling. They introduced a biomechanical model of a rider in order to stabilize the motorcycle, mainly in the wobble mode. V. Bulsink et al. [5] analyzed the parameters that influence stability: the weave and capsize Modes of the bicycle-rider system.

3. PHYSICAL AND GEOMETRICAL DESIGN OF MOTORCYCLE RIDER

3.1. System description

Our studies utilize a multibody motorcycle and rider model, which is depicted in Figure 1. The motorcycle rider system under consideration comprises 11 degrees of freedom, as shown on figure 2.a. This system model includes the front fork with its handlebar and wheel and the rear frame with the rider body and suspension, motorcycle body, and rear wheel. The motorcycle characteristics include the radii of its wheels, the position of the centers of gravity, and the height of the ground. The proposed model also considers several factors that affect stability, such as head-angle, trail, the center of gravity's position, and the front tire's weight. However, the rider plays a crucial role in controlling the motorcycles, and their behavior can influence the motorcycle movement, affecting the rider's perception.

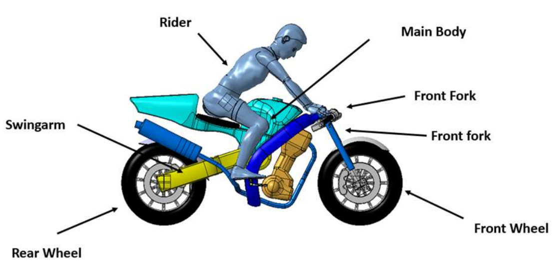


Fig. 1. Multibody model of Motorcycle Rider.

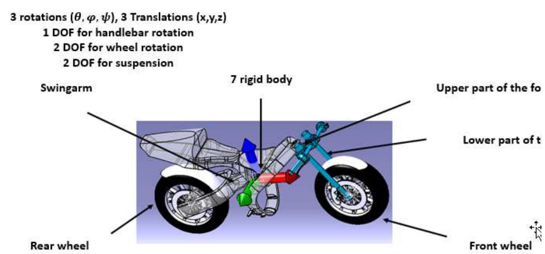
The elastic properties of the rider are modeled by a spring that resists the lean motion of the upper body.

The arms are modelled by spring systems (K_a), The leaning motion of rider is also modelled by a spring to (K_φ) opposed to the rotation.

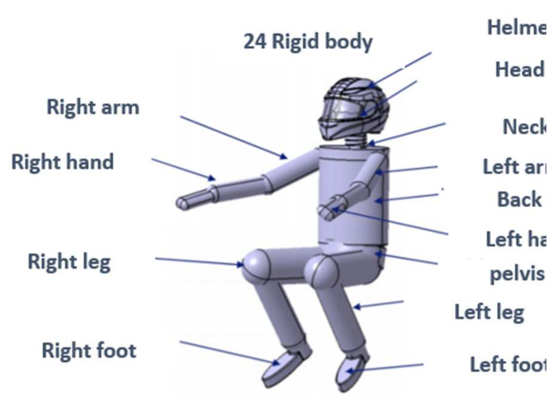
Therefore, the movements of the upper body parts can be used to characterize and assess rider motion. Pelvic mobility is essential to a rider's success since the pelvis makes direct contact with the saddle.

Figure 2.b displays the configuration of the rider model, comprising the rigid bodies mainly the arm, forearm, upper-body, lower body, leg, head, neck, torso, and pelvis, and connections between them as illustrated in Table 1. The main movements of the rider model encompass steering, body leaning, and pitching, such as:

- The act of steering is illustrated through torques applied at the revolute joint.
- The handlebars are connected to the elbows via rotating joints.
- The leaning and pitching movements of the body are represented by torques acting at the revolute joint of the waist.



a.



b.

Fig. 2. a. 3D model of motorcycle; **b.** Biomechanical Rider

Table 1 provides a comprehensive overview of the interconnections among the rigid bodies involved in the system. It delineates the intricate network of relationships and dependencies that govern the behavior and interactions of these bodies within the framework of the study. Each entry in the table offers valuable insights into the structural and functional links between the various components, serving as a roadmap for understanding the complex dynamics at play.

Table 1.

Mechanical Joint and links

Connected bodies	**Joint type**
Arm-L - forearm-L	Revolute joint
Arm-R, forearm-R	Revolute joint
Forearm-L, front-frame,	Revolute joint
Forearm-R, front-frame,	Revolute joint
Arm-L, upper-body	Spherical joint
Arm-R, upper-body	Spherical joint
Upper-body, lower-body	Revolute joint
lower-body, Upper Leg –L	Revolute joint
lower-body, Upper Leg –R	Revolute joint
Upper Leg-L, Lower Leg –L	Spherical joint
Upper Leg -R, Lower Leg –R	Spherical joint
Pelvis, main-frame	Planar joint
lower-body, main-frame	Spherical joint
Head – Neck	Spherical joint
Neck Upper-body	Revolute joint
Head- Torso	Fixed joint

Expanding on the notation provided, the designation "L" signifies the left side of the system, while "R" corresponds to the right side. These labels serve as crucial markers for differentiating between the two sides and play a pivotal role in defining the spatial orientation and directional aspects of the system's components.

3.2. Physical Modelling

It is crucial to understand that creating a precise and all-encompassing physical model of a motorcycle rider is a complicated process that demands interdisciplinary expertise in areas like mechanical engineering, biomechanics, control systems, and human factors. As computational methods and simulation technologies advance, the accuracy of these models and their practical use also improves. When it comes to physically modeling a motorcycle rider, there are several important factors to consider. These include modeling the rider's body movements and posture, as well as the geometry and mechanical properties of the motorcycle, such as its mass distribution, suspension properties, and tire characteristics. Additionally, the model should take into account environmental factors such as road surface and wind, as well as sensor data to capture real-time information about the rider's movements and the motorcycle's behavior. Finally, control algorithms must be developed to accurately simulate the rider's motion as shown in the figure 3.

3.3. Mathematical modeling

To create a mathematical model for the physical interaction between a motorcycle and its rider, there are several steps to follow. Here is a general outline of the process:

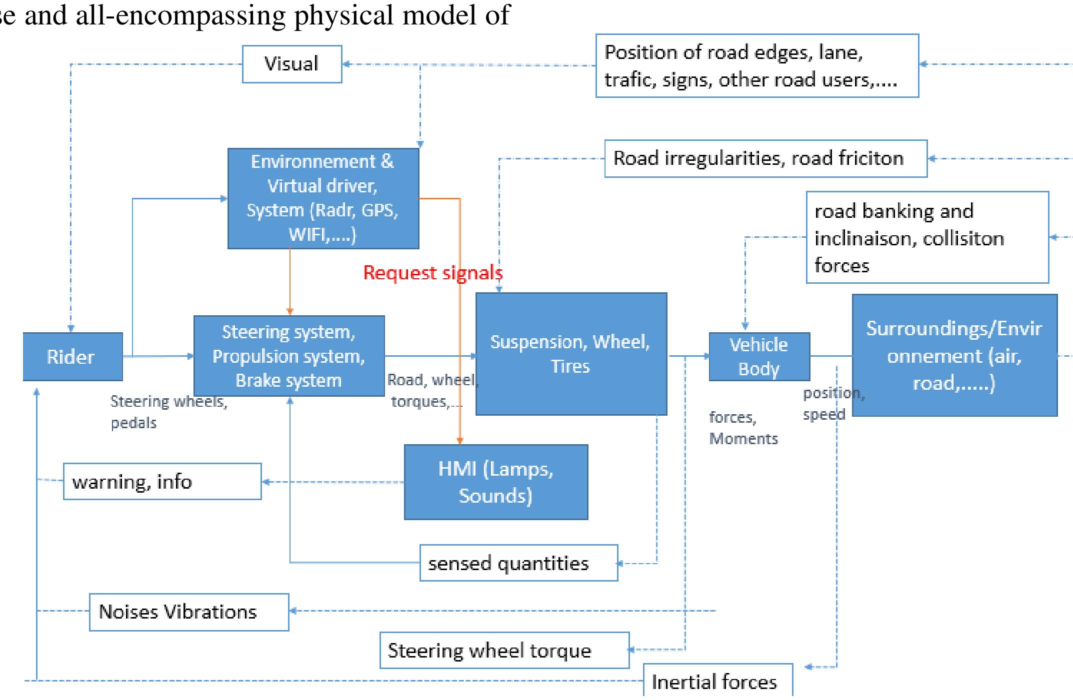


Fig. 3. Physical modelling of Rider - motorcycle.

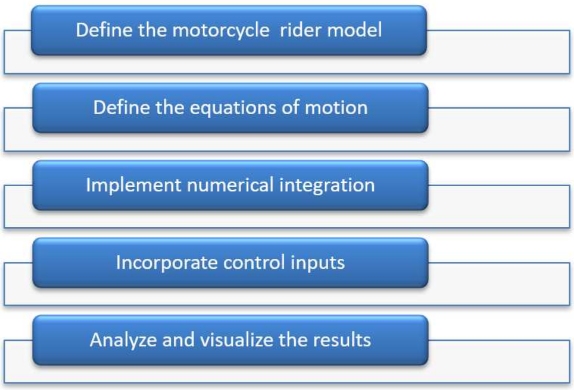


Fig. 4 . Flowchart of modelling process

The mathematical model was formulated using the holonomic Euler-Lagrange equations, the initial step involved generating kinetic and potential energy. The lateral model of the rider's motorcycle can be expressed in the following manner:

An effective method to represent the rider is by breaking down the body into various connected segments such as the torso, upper arms, lower arms, thighs, lower legs, etc. Each segment would have its own mass, inertia, and range of motion. The Lagrangian would then incorporate both the kinetic and potential energy associated with the motion of these segments. With these eleven degrees of freedom, we would need to define generalized coordinates q_i for each degree of freedom and their corresponding velocities $\dot{q}_i$.

The generalized coordinates representing the configuration of the system. These coordinates would include the position and orientation of the motorcycle and various aspects of the rider's body posture and movement, as the corresponding generalized velocities.

$$L = T(q_1, q_2, \dots, q_n, \dot{q}_1, \dot{q}_2, \dot{q}_i \dots, \dot{q}_n) - U(q_1, q_2, \dots, q_n) \quad (1)$$

$$L = T_{motocycle} + T_{rider} - U_{motocycle} - U_{rider} \quad (2)$$

The equations of motion for the system can be derived using the Euler-Lagrange equations:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \left(\frac{\partial L}{\partial q_i}\right) = 0 \quad (3)$$

The kinetic energy of the motorcycle is:

$$T_{motocycle} = \frac{1}{2} M_{mi} v_{motorcycle}^2 \quad (4)$$

The kinetic energy of the rider is :

$$T_{motocycle} = \frac{1}{2} \sum_{i=1}^{n} m_{ri} v_{ri}^2 \quad (5)$$

The potential energy of motorcycle is:

$$U_{motorcycle} = M_{motorcycle} gh \quad (6)$$

The potential energy of rider is:

$$U_{motorcycle} = \sum_{i=1}^{n} m_{ri} g\, h_{ri} \quad (7)$$

While h_{ri} represent the height of the rider body segment.

To represent the equations of motion for the rider-motorcycle system in matrix form, we can derive them from the Euler-Lagrange equations. Let's denote:

$$M\ddot{q} = F_{ex} - C\dot{q} - G \quad (8)$$

While $\ddot{q}$ represent the vector generalized acceleration, M is the matrix mass, C, is the Coriolis and centrifugal forces matrix, G is the vector of gravitational forcesm and finally the F_{ex} is the external forces.

4. BIOMECHANICAL RIDER

4.1. Mathematical modeling of rider

To study human movement in a dynamic way, the system takes in the neural command as input as shown in Figure 5.

To measure muscle activation, we use a single value for each muscle, denoted as a_i. This value ranges from zero to one and is represented mathematically. However, converting EMG into muscle activation requires additional steps.

Musculotendonic dynamics control the transformation of muscle activation into muscle force Fi. Once the muscle develops a force, the tendon also begins to bear a load. Depending on the kinetics of the joint,

The force exerted by each muscle unit contributes to the total moment around a joint, with the muscle's moment arm being determined by musculoskeletal geometry. Joint dynamics and muscle strength are interconnected through a feedback loop. A muscle length affects strength, as shown by the "length-tension curve" of muscles. The angles of the joints play a crucial role in determining changes, and it is important to consider each joint's multiple degrees of freedom since a muscle can have various actions depending on its geometry. Lastly, it should be noted that the common moment T_i is significant.

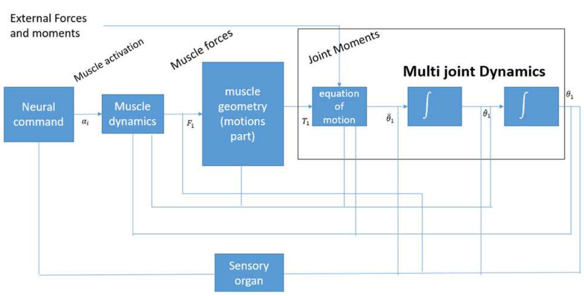


Fig. 5. Block diagram design of Controller.

In order to maintain proper posture and facilitate movement, actuators must be installed at every joint in the human body model. To calculate the torques that act between the coupling points of the segments, equation 9, 10, 11 and 12 is used.

The actuator has three different modes of operation:

- Passive torque for maintaining posture.
- Active movement defined by the controller.
- Steering is represented by torques acting on the steering to rotate the handlebars. The handlebar control is based on a PID control determining the steering torque.
- The inclination of the body is represented by torques (Semi-active movement acting as an actuator of the upper part of the driver's body).
- The lateral movement of the driver is represented by torques acting on the hip joints to transform the connection of the legs.
- Driver's legs used to control transverse movements of two-wheeled vehicle.

  The leg forces is:

$$F = K_{P2}[C_2(\varphi_d - y_d)] + K_{I2}\left[\int_0^t (\varphi_d - y_d)dt\right] + K_{D2}\cdot\left(\frac{dy_d}{dt}\right) \quad (9)$$

The torque responsible for the lateral displacement of the rider concerning the two-wheeled vehicle is:

$$T_y = K_{p3}[C_3(\varphi_d - \varphi_{rider})] + K_{I3}\int_0^t (\varphi_d - \varphi_{rider})dt + K_{D3}\left(\frac{d(\varphi_d - \varphi_{rider})}{dt}\right) \quad (10)$$

The torque applied to the handlebar is:

$$T_\delta = -K_{str_P}(\varphi_{ref} - \varphi) - K_{str\_I}\int(\varphi_{ref} - \varphi) + K_{str\_D}\dot{\varphi} \quad (11)$$

The roll torque of the controller is:

$$T_\varphi = -K_{Ltr_P}(\varphi_{ref} - \varphi) - K_{Ltr_I}\int(\varphi_{ref} - \varphi) + K_{Ltr_D}\dot{\varphi} \quad (12)$$

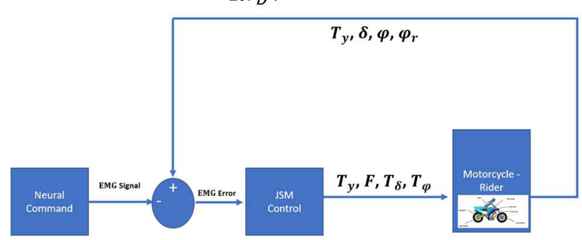


Fig. 6. Block diagram design of JSM.

The neural command systems are used to interpret the EMG signals and create control commands for the motorcycle's actuators, allowing for actions such as rolling and steering. Our innovation involves utilizing a PID feedback control system that uses a heuristic approach to determine the required steering and rolling angles, guided by the rider's movements.

4.2. Stability Analysis

Through the analysis of the eigenvalues of the linearized system, we can gain insights into the system's behavior. To demonstrate this concept, we will investigate the eigenvalue and create a graph to identify distinct modes of instability and the self-stabilizing region of an uncontrolled two-wheeled vehicle.

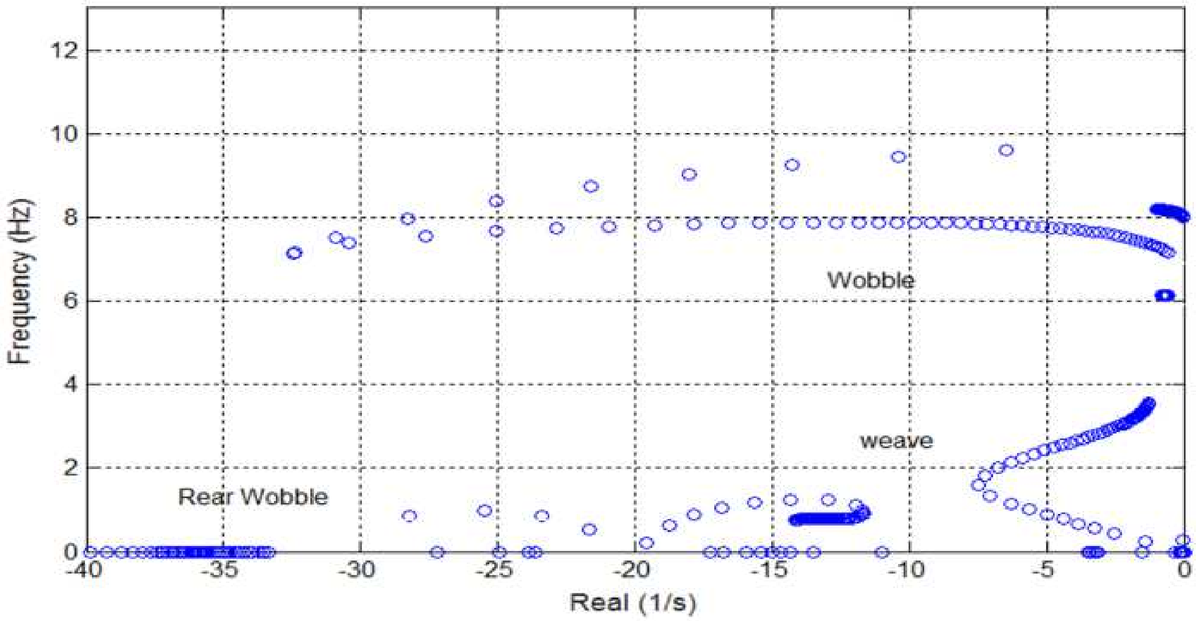


Fig. 7. Eigenvalues Analysis

In Figure 6 and 7, the vibrational modes highlighted are the Weave and Wobble. Weave refers to the unstable 2-3 Hz vibration in yaw and lateral motion of the entire chassis. It has a positive real part in the root locus at very low and high speeds. While, The wobble mode at a frequency of 10-13 Hz remains stable throughout the entire speed range.

As speed increases, all modes tend to become unstable. This is because higher speed produces more energy for movement. When analyzing the eigenvalues for average to high velocities (10-80 m/s), the real part of the eigenvalues for these modes typically only include small positive values, which makes them unstable. However, in this case, the wobble and weave modes remain well-damped throughout the speed range. The two-wheeled vehicle does not experience high-speed stability issues under constant speed conditions. As the steady-state roll angle increases, there is an improvement in damping in the high-speed ride mode, accompanied by increases in frequency in the same mode.

First, a note should be made regarding driver safety. The attenuation of the two-wheeled vehicle steering mode at a given speed depends on the overall physical properties of the two-wheeled vehicle and the rider. This model is characterized by an oscillatory movement of the front fork, which produces a risk of ending in a crash or collision. The impulse given by the driver must be carefully prepared during preparations. In this case, the driver can become familiar with the temporary instability of a two-wheeled vehicle.

This mode operates at a frequency between 8 and 10Hz and is not affected by the vehicle's speed. It is well-damped at low and medium speeds but moderately damped at high speeds. This mode is activated when the handlebar moves from side to side, ultimately resulting in the vehicle tipping over.

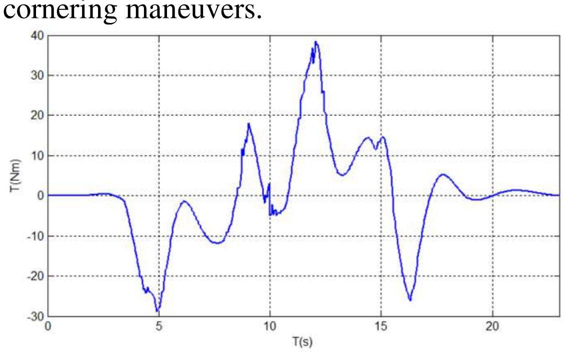
When a driver rides a two-wheeled vehicle, their movements can impact the driving pattern, causing it to sway. We studied the dynamics of this coupled system and analyzed its behavior during the darting mode, where we applied a sudden disturbance at 60 m/s by moving the driver's pelvis. This caused the vehicle to experience a negative damped oscillation, resulting in a sharp drop in yaw angle and an exponentially increasing amplitude. Our findings suggest that biomechanical factors have a significant influence on driving dynamics.

5. DISCUSSION

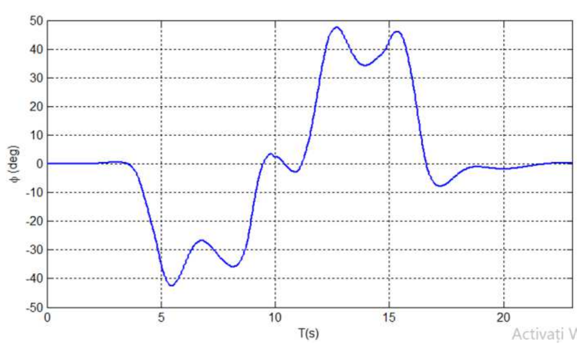
The motorcycle and the rider are a combined system that operates based on the interaction of both entities. Based on the results, it appears that biomechanical factors have a significant impact on ride dynamics. We ran a series of simulations using the rider-motorcycle model, we obtained the controller's parameters through a heuristic search.

When it comes to tuning the PID controller for the system we're proposing, there is only a limited range of stability. As a result, there is a significant overshoot even though the system stabilizes quickly. However, simulations show that we can achieve a reasonably good response by adjusting the PID controller and carefully observing the errors.

As shown in Figure 8, when a rider takes a lean on a motorcycle, the torque T comes into play. This torque is a crucial aspect of the rider-motorcycle interaction, especially in terms of controlling the dynamics of the system during cornering maneuvers.



a.



b.

Fig. 8. a. Steer torque; **b.** Steer angle

The torque T is generated primarily by the rider's body movements, particularly through the application of muscular forces to the handlebars, foot pegs, and seat. By leaning the body relative to the motorcycle, the rider effectively shifts the center of mass of the combined rider-motorcycle system, inducing a torque about the motorcycle's vertical axis.

These graphs display the correlation between the steering torque, lean rate, and steer angle. The positive steering torque appears to reach a high peak, with a maximum exerted torque of 39 N.m for less than a second. This peak torque likely corresponds to a critical moment during a dynamic maneuver, such as initiating a sharp turn or making a rapid adjustment in response to changing road conditions or traffic.

The transient nature of this peak torque suggests that it is a short-lived burst of effort, likely occurring during a rapid change in direction or when the rider is actively controlling the motorcycle to navigate a challenging curve.

The correlation between the steering torque, lean rate, and steer angle provides valuable insights into the dynamic interaction between the rider's input and the motorcycle's response.

The subjectively reasonable effort required to achieve this indicates a highly dynamic situation. This torque gradually decreases as the rider leans the motorcycle. However, it doesn't completely disappear until the required position is reached due to the constant increase in forward speed. After the curve, a greater torque is necessary to recover the vertical position.

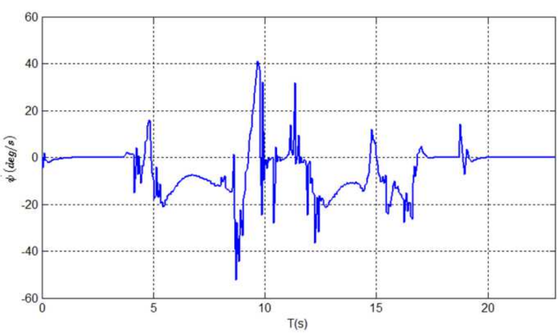
After 3 seconds of simulation, an oscillation is observed in the steering angle. The system's steering angles are notably large. It is worth noting that the rider executes a counter-steering maneuver to create the required angle and a favorable inclination. This counter-steering technique is a fundamental aspect of motorcycle riding, especially during dynamic maneuvers such as cornering.

Counter-steering involves briefly steering in the opposite direction to the intended turn to initiate the lean angle.

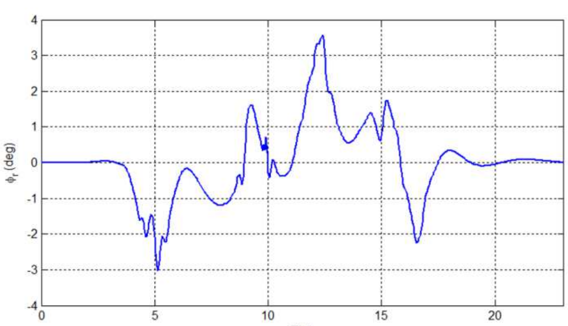
The observed oscillation in the steering angle after 3 seconds of simulation may be a result of the dynamic interaction between the rider's input and the motorcycle's response. This oscillation could occur due to factors such as rider input variability, road surface conditions, or inherent instability in the system dynamics. However, the rider's skillful use of counter-steering helps to manage these oscillations and maintain control over the motorcycle's trajectory.

Figure 9 shows how this aspect behaves during the simulation. As can be seen, the system remains stable throughout the simulation. The maximum angle is reached with a maximum value of 41° due to the large curvature of the trajectory. When a rider leans their body in the direction of a turn, it impacts the motorcycle's roll angle. The closer the rider leans towards the road, the greater the angle of lean for the motorcycle. This can impact the motorcycle's stability and cornering abilities.

The stability of the system throughout the simulation is a testament to the effectiveness of the rider's control inputs and the motorcycle's design in maintaining dynamic equilibrium. Despite the large steering angles and lean angles reached during the maneuver, the system demonstrates resilience against instability, ensuring a smooth and controlled trajectory through the turn.



a.



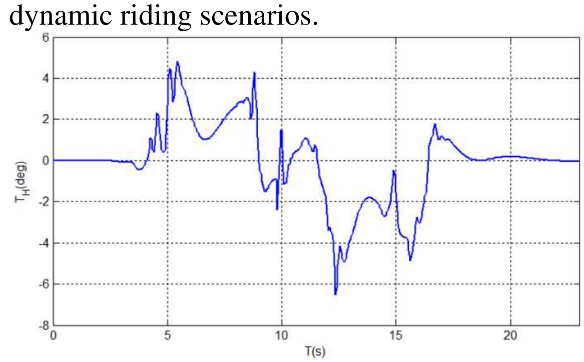
b.

Fig. 9. a. Roll angle rate; **b.** Roll angle of rider

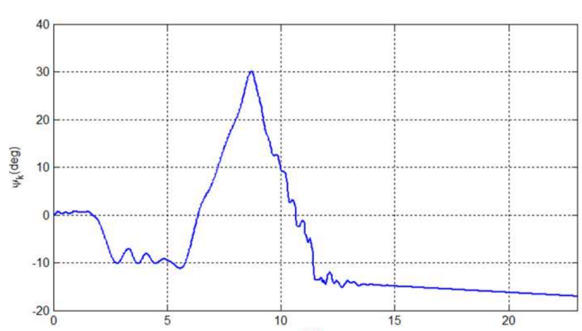
The maximum angle of 41° reflects the significant demands placed on the motorcycle's suspension and chassis during aggressive cornering. Such extreme lean angles require precise control and coordination between the rider and the motorcycle to maintain stability and prevent loss of traction.

The relationship between the rider's body position and the motorcycle's roll angle underscores the importance of rider technique in optimizing cornering performance. By leaning their body towards the road, the rider effectively shifts the center of mass of the combined rider-motorcycle system, facilitating the generation of lateral forces necessary for cornering. However, excessive body lean can also affect the motorcycle's stability, potentially leading to instability or loss of control if not managed correctly.

Overall, Figures 9 and 10 provides valuable insights into the dynamic behavior of the rider-motorcycle system during cornering maneuvers, highlighting the interplay between rider inputs, motorcycle dynamics, and stability considerations. Understanding and optimizing this interaction are essential for riders and engineers seeking to enhance motorcycle performance, safety, and rider comfort during dynamic riding scenarios.



a.



b.

Fig. 10. A. Lateral motion of Rider; **b.** Knee motion of rider

The positioning of the knees on the motorcycle's tank can have an impact on the rider's body posture, affecting weight distribution, stability, and control. Depending on the type of riding, riders may adjust their knee placement for cruising, cornering, or accelerating.

By placing their knees against the fuel tank or the sides of the motorcycle, riders can have more contact points and receive better feedback. This helps riders sense the motorcycle's movements more accurately and make appropriate adjustments, increasing control and responsiveness. The rider's knees serve as a crucial point of contact with the motorcycle, enabling them to sense the motorcycle movements and react promptly to changes in stability.

The results demonstrate a significant correlation between our virtual tests and the results obtained by [38-39], particularly regarding lean and steering torque and angle.
During our investigation, we discovered that the motorcycle leaned at an angle of 41 degrees. It is interesting to note that study G. Moreno [38] recorded a lean angle of 49 degrees, which is greater than ours, while study R. Barbagallo [39] reported a lean angle of 37 degrees, which is lesser than ours. Our study also documented a steer angle of 3 degrees, which is slightly higher than the 1.3 degrees reported in study G. Moreno [38]. We measured the steer torque at 39 units, which closely aligns with the 40 units reported in study G. Moreno [38].

6. CONCLUSION

The stability and control of motorcycles are critical factors for rider safety and performance. This study focuses on understanding the biomechanical aspects of how riders control and stabilize the motorcycle through coordinated movements of various joints.

The primary objective of this research was to develop a control system that utilizes EMG signals from the rider's muscles and translates them into commands for motorcycle control. So, the neural command systems are then employed to interpret the EMG signals and generate appropriate control commands for the motorcycle's actuators, such as rolling, and steering. We have introduced a PID feedback control scheme that takes neural commands as input and uses a heuristic strategy to determine the required steer and roll angles based on the motion of the rider. Based on simulations results, the maximum lean angle of 41° is reached due to the trajectory's large curvature and a torque of 39 N.m, also the weave mode became unstable vibration in yaw and lateral motion at 2-3 Hz, while wobble mode is stable at 10-13 Hz across all speeds.

According to the findings, the created controller is successful in keeping the motorcycle model steady, especially when traveling at high speeds in the wobble and capsize modes.

7. REFERENCES

1. Oliveri SM, Calı` M and Catalano L. Dynamics of motorcycle using flexible elements. In: Proceedings of the international design conference, Dubrovnik, 14–17 May 2002, pp.1227–1236
2. Imaizumi, H., & Fujioka, T. (1997). Motorcycle-Rider System Dynamics by Multibody Dynamics Analysis-Effects of the Rear Load on Wobble Motions and the Control Assembly. JSAE Review, 2(18), 201.
3. Doria A, Tognazzo M and Cossalter V. The response of the rider's body to roll oscillations of two wheeled vehicles; experimental tests and biomechanical models. Proc IMechE, Part D: J Automobile Engineering 2013; 227(4): 561–576.
4. Schwab, A. L., Meijaard, J. P., & Kooijman, J. D. G. (2012). Lateral dynamics of a bicycle with a passive rider model: stability and controllability. Vehicle system dynamics, 50(8), 1209-1224.
5. Bulsink, V. E., Doria, A., van de Belt, D., & Koopman, B. (2015). The effect of tyre and rider properties on the stability of a bicycle. Advances in mechanical engineering, 7(12), 1687814015622596.
6. Saccon A, Hauser J and Beghi A. A virtual rider for motorcycles: an approach based on optimal control and maneuver regulation. In: 3rd International symposium on communications, control and signal

processing, ISCCSP 2008, Malta, 12–14 March 2008, pp.243–248. 25.

7. M. Yokomori, T. Oya, and A. Katayama, Rider control behavior to maintain stable upright position at low speed, JSAE Rev. 21 (2000), pp. 61–65.
8. DORIA, Alberto, TOGNAZZO, Mauro, et COSSALTER, Vittore. 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, 2013, vol. 227, no 4, p. 561-576.
9. Doria A, Tognazzo M. The influence of the dynamic response of the rider's body on the open-loop stability of a bicycle. Proc Inst Mech Eng, Part K: J Multi-Body Dyn. 2014;228(17):3116–3132.
10. Cheli F, Pezzola M, Taroni N, et al. Driver's movements influence on the lateral dynamic of a sport motorbike. In: 19th Mediterranean conference on control and automation, Corfu, Greece, 20–23 June 2011
11. Lai, H. C., Liu, J. S., Lee, D. T., & Wang, L. S. (2003). Design parameters study on the stability and perception of riding comfort of the electrical motorcycles under rider leaning. Mechatronics, 13(1), 49-76.
12. Talaia P, Moreno D, Hajzman M, and Hyncik L. A 3D model of a human for powered two-wheeler vehicles. Proceedings of the international conference on noise & vibration engineering; 2008 Sept; Leuven. p. 2229– 2238.
13. Garziad, M., & Saka, A. (2019). Review on Dynamics, Control and Stability of Two Wheeled Vehicle. International Journal of Mechanical Engineering, 6(7), 1-7.
14. A.A. Popov, S. Rowell, and J.P. Meijaard, A review on motorcycle and rider modelling for steering control, Veh. Syst. Dyn. 48 (2010), pp. 775–792
15. Kooijman JDG and Schwab AL. A review on bicycle and motorcycle rider control with a perspective on handling qualities. Veh Syst Dyn 2013; 51(11): 1722–1764.
16. R.S. Sharp, S. Evangelou, and D.J.N. Limebeer, Advances in the modelling of motorcycle dynamics, Multibody Syst. Dyn. 12 (2004), pp. 251–283
17. Meijaard, J. P. Derivation of the linearized equations for an uncontrolled bicycle. Internal report, University of Nottingham, UK, 2004.
18. Schwab, A. L., Meijaard, J. P., & Papadopoulos, J. M. (2005). Benchmark results on the linearized equations of motion of an uncontrolled bicycle. Journal of mechanical science and technology, 19, 292-304.
19. Meijaard, J. P., & Schwab, A. L. (2006). Linearized equations for an extended bicycle model. In III European Conference on Computational Mechanics: Solids, Structures and Coupled Problems in Engineering: Book of Abstracts (pp. 772-772). Springer Netherlands.
20. Schwab, A. L., Meijaard, J. P., & Kooijman, J. D. G. (2006, June). Experimental validation of a model of an uncontrolled bicycle. In Proceedings of the Third European Conference on Computational Mechanics: Solids, Structures and Coupled Problems in Engineering (p. 16citation_URL_Access_Date). Lisbon, Portugal.
21. Schwab, A. L., Meijaard, J. P., & Kooijman, J. D. G. (2007, June). Some recent developments in bicycle dynamics. In Proceedings of the 12th World Congress in Mechanism and Machine Science (pp. 1-6). Moscow, Russia: Russian Academy of Sciences.
22. Schwab, A. L., Meijaard, J. P., & Kooijman, J. D. (2012). Lateral dynamics of a bicycle with a passive rider model: stability and controllability. Vehicle system dynamics, 50(8), 1209-1224.
23. Sharp, R. S. (2012). Rider control of a motorcycle near to its cornering limits. Vehicle system dynamics, 50(8), 1193-1208.
24. Liu, T. S., & Chen, J. S. (1992). Nonlinear analysis of stability for motorcycle–rider systems. International journal of vehicle design, 13(3), 276-294.
25. Mears, B. C. (1989). Open loop aspects of two-wheeled vehicle stability characteristics. University of Illinois at Urbana-Champaign.
26. Sharp, R. S., & Limebeer, D. J. (2001). A motorcycle model for stability and control analysis. Multibody system dynamics, 6, 123-142.
27. Yokomori, M., Nakagawa, T., & Matsumoto, T. (1986). Handlebar vibration of a motorcycle during operation on different road surfaces. Scandinavian journal of work, environment & health, 332-337.
28. Garziad, M., & Saka, A. (2019). A comparative assessment between LQR and

PID strategies in control of two wheeled vehicle. In International Journal of Engineering Research in Africa (Vol. 43, pp. 59-70). Trans Tech Publications Ltd.
29. Sequenzia, G., Oliveri, S. M., Fatuzzo, G., & Calì, M. (2015). An advanced multibody model for evaluating rider's influence on motorcycle dynamics. Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics, 229(2), 193-207.
30. Zhu, S., Murakami, S., & Nishimura, H. (2012). Motion analysis of a motorcycle taking into account the rider's effects. Vehicle system dynamics, 50(8), 1225-1245.
31. Klinger F, Nusime J, Edelmann J, et al. Wobble of a racing bicycle with a rider hands on and hands off the handlebar. Veh Syst Dyn. 2014;52(Suppl 1):51–68.
32. Schwab, A. L., & Kooijman, J. D. G. (2010, May). Lateral dynamics of a bicycle with passive rider model. In The 1st Joint International Conference on Multibody System Dynamics.
33. Imaizumi H, FujiokaT, Omae M. Rider model by use of multibody dynamics analysis. Jpn SAE. 1996;17:75–77.
34. Huyge, K., Ambrósio, J.; Pereira, M., A control strategy for the dynamics of a motorcycle, including rider, Proceedings of the ENOC-2005, 2005.
35. Keppler, V., & Solutions, B. (2010, October). Analysis of the biomechanical interaction between rider and motorcycle by means of an active rider model. In Proceedings, Bicycle and Motorcycle Dynamics 2010 Symposium on the Dynamics and Control of Single Track Vehicles (pp. 20-22).
36. Sequenzia, G., Oliveri, S. M., Fatuzzo, G., & Calì, M. (2015). An advanced multibody model for evaluating rider's influence on motorcycle dynamics. Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics, 229(2), 193-207.
37. Garziad, M., & Saka, A. (2019). Influence of rider on the stability and control of two wheeled vehicles. Journal Européen des Systèmes Automatisés, 52(5), 515-520.
38. Moreno Giner, D., Brenna, C., Symeonidis, I., & Kavadarlic, G. (2008, January). MYMOSA: Towards the Simulation of Realistic Motorcycle Manoeuvres by Coupling Multibody and Control Techniques. In ASME International Mechanical Engineering Congress and Exposition (Vol. 48784, pp. 263-275).
39. Barbagallo, R., Sequenzia, G., Oliveri, S. M., & Cammarata, A. (2016). Dynamics of a high-performance motorcycle by an advanced multibody/control co-simulation. Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics, 230(2), 207-221.

8. APPENDIX

Table 2.

Parameters and Values

R_{wf}	radius of front wheel	0.35 m
R_{wr}	radius of rear wheel	0.3 m
W	Wheelbase	1.02 m
c	Trail	0.08m
l_r	horizontal distance from A	0.3m
h_{lr}	height of the Lower body	0.9m
M_r	Mass of rear frame	35Kg
M_f	Mass of front frame	4Kg
M_{rw}	Mass of rear wheel	3Kg
M_{fw}	Mass of front wheel	3Kg
M_{ur}	Mass of upper body	23.52
I_{rw}	mass moment of inertia rear wheel	$\begin{pmatrix} 0.0603 & 0 & 0 \\ 0 & 0.12 & 0 \\ 0 & 0 & 0.0603 \end{pmatrix}$ (kgm^2)
I_{Fw}	mass moment of inertia front wheel	$\begin{pmatrix} 0.1405 & 0 & 0 \\ 0 & 0.28 & 0 \\ 0 & 0 & 0{,}1405 \end{pmatrix}$ (kgm^2)
I_F	Front fork	$\begin{pmatrix} 0.05892 & 0 & -0.00756 \\ 0 & 0.06 & 0 \\ -0.00756 & 0 & 0.00708 \end{pmatrix}$
I_{ur}	mass moments of inertia of the upper body	$\begin{pmatrix} 4.299 & 0 & 1.444 \\ 0 & 5.186 & 0 \\ 1.444 & 0 & 1.413 \end{pmatrix}$
I_B	moments of inertia of the chassis	$\begin{pmatrix} 3.8690 & 0 & 1.3 \\ 0 & 4.667 & 0 \\ 1.3 & 0 & 1.272 \end{pmatrix}$
l_F	horizontal distance from B	0.06976 m
l_r	horizontal distance from A	0.06976 m
h_{lr}	vertical distance from B	0.1302 m
M_{wr}	Mass of rear wheel	2kg

M_{wp}	Mass of front wheel	3kg
ε	Caster angle	18°
K_{φ}	lean stiffness	1289
C_{φ}	lean damping	60.9
K_a	arms stiffness	257Nm/rad
C_a	arms damping	12.8 Nm/rad
h_{ur}	height of the upper body	0.16
h_{lr}	height of the lower body	0.9m
θ_r	Pitch angle of rider	15°

INVESTIGAȚII PRIVIND MODELAREA CĂLĂREȚULUI BIOMECANIC ȘI STABILITATEA MOTOCICLETEI

Rezumat: *Scopul acestei lucrări este de a îmbunătăți siguranța și stabilitatea motocicletei prin analiza impactului conducătorului asupra controlului motocicletei și predicția unor potențiale scenarii instabile. Abordarea ideii de sistem multicorp pentru a proiecta un călăreț folosind proprietăți biomecanice a dus la crearea unei strategii de control care să utilizeze semnalele electromiogramei (EMG) de la mușchii călărețului și care să poată gestiona eficient mușchii cu mai multe articulații în timpul mișcărilor de atingere. Aceste semnale vor fi folosite pentru a da comenzi pentru controlul motocicletei. Pentru a ne atinge obiectivul, am introdus o schemă de control al feedback-ului PID care ia ca intrare comenzile neuronale și a folosit o strategie euristică pentru a determina unghiurile de virare și rulare necesare în funcție de mișcarea călărețului. Rezultatele indică faptul că controlerul dezvoltat stabilizează în mod eficient modelul de motocicletă atunci când funcționează la o gamă mare de viteze, în principal în modul de balansare și răsturnare.*

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