GEOMETRIC AND MULTIBODY MODELING OF RIDER-MOTORCYCLE SYSTEM

M. Calì[(a)], S. M. Oliveri[(a)], G.Sequenzia[(a)], F. Trovato [(b)]

[(a)]*Università di Catania, Dipartimento di Ingegneria Industriale e Meccanica, viale A Doria, 6 – 95125 Catania*
[(b)]*Moto Guzzi S.p.A., via E. V. Parodi, 57 Mandello del Lario (Lecco)*

[(a)]mcali@diim.unict.it

ABSTRACT
In this study, a methodology based on co-simulation was developed for the multibody parametric modelling of a motorcycle with an anthropomorphic model of the rider. This co-simulation uses two different software programs, integrated to ensure a complete exchange of information between them in real time.
The paper reports the effects induced by the movement of the rider's body on the dynamics and performance of a motorcycle. The legs of an anthropomorphic model were used as kinematics to control transverse movements of the motorcycle.
The control system inputs are the geometric characteristics of the road (length, width and radius of curvature) and the speed of the vehicle along the track. For the dynamic behaviour of the motorcycle, the only channels currently operated by the control system are steering angle and engine torque, which are determined in accordance with the input parameters.

Keywords: motorcycle, rider, control, multibody, dynamic

1. INTRODUCTION

On the saddle of a motorcycle, the rider enjoys considerable mobility offering appreciable movement of his body and, thereby, of the barycentre of the rider/motorcycle system. The movements he makes are directed at improving the performance achieved by the motorcycle in the course of certain manoeuvres, so that, in the dynamics of a motorcycle, the rider's contribution is often a decisive factor in improving performance. It is therefore of interest to analyse the relation between the movements of the rider's body and the dynamic characteristics of the motorcycle.
Theoretical instruments have allowed the study of motorcycle dynamics only under certain conditions of motion, in the main constant, and often imposing rather restrictive hypotheses. The problem is commonly analysed using multibody software programs, without attention ever being focussed on how movements of the rider's body can influence the dynamic behaviour of the motorcycle, and certainly without ever implementing a system of active control which optimises these movements.

In previous research (Oliveri, Calì and Catalano 2002) the authors studied the dynamics of the motorcycle, using multibody modelling in which the rider was considered as an immobile equivalent mass.
To calculate the exact value of the polar moments of inertia of the wheels complete with accessories, reported with the values of mass supplied by the manufacturer in Table 1, it was necessary to construct MCAD models.

Table 1: Inertial characteristics of wheels

Front wheel		***Rear wheel***	
Mass	12 kg	**Mass**	14 kg
Moment of inertia	0,5 kg m^2	**Moment of inertia**	0,7 kg m^2

The wheels were modelled with particular accuracy due to the fact that they have a predominant influence on the dynamics of the motorcycle. In fact, their moment of inertia effects both acceleration and braking, the gyroscopic effect determines the stability of the motorcycle and, as suspended masses, they contribute to the correct function of the suspension units.
The present study investigates the effect produced by the movement of the rider's body on the achievable performance of the motorcycle. With a view to developing an actively controlled motorcycle model, an anthropomorphic schematic of a mobile rider was introduced in order to analyse its interactions with the motorcycle and its influence on the overall dynamics when travelling along a rectilinear path and moving through a curve.

2. MODELLING OF RIDER-SYSTEM

NURBS Rhinoceros modelling software was used to construct a parametric model of the human body, which could then describe any subject by inserting his anthropometric measurements in an apposite form.
The model of the rider meets the following requirements:

1. opposes dynamic forces when the motorcycle performs particular manoeuvres;
2. moves in agreement with reality;
3. minimises the calculation time due to the increased number of degrees of freedom.

The model of the rider consists of 15 parts plus eight parts of negligible mass which were inserted in order to be able to correctly position and centre the constraints to which they refer.

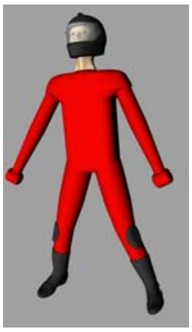

Figure 1: Model of rider constructed using Rhinoceros

Overall, the rider has 24 d.o.f., of which five are controlled in the more demanding manoeuvre (moving through a curve), while the remainder are activated indirectly. The choice of the types of constraints at the joints was principally based on the study of the kinematics activated by the rider during the execution of the manoeuvres.
The type of constraint between the joints making up the model are as follows (table 2):

Table 2: Kinematic constraints between the parts

PART	NECK	SHOULDER	ABDOMEN	ELBOW	HAND
HEAD	F		--	--	--
CHEST	F	S	R	--	--
ARM	--	F	--	F	--
FOREARM	--	--	--	R	R
PELVIS	--	--	R	--	--
THIGH	--	--	--	--	--
SHIN + FOOT	--	--	--	--	--
HANDLEBAR	--	--	--	--	R

PART	BUTTOCK	KNEE	PEDAL	SADDLE
HEAD	--	--	--	--
CHEST	--	--	--	--
ARM	--	--	--	--
FOREARM	--	--	--	--
PELVIS	F	--	--	P
THIGH	S	F	--	--
SHIN + FOOT	--	R	S	--
HANDLEBAR	--	--	--	--

Where: F= Fixed joint, R= Revolute joint, P= Planar joint S=Spherical joint

The postural angles were chosen after having measured, on the real motorcycle, the relative distances between the saddle, the handlebar and the footrest, and their respective spatial orientations.
Naturally, these "cyclistic" dimensions do not identify a unique possible posture. Figure 2 shows three views of the characteristic angles considered for the arrangement of the rider's limbs and body.
This represents the default configuration used as a starting point for considering the movement of different body parts during the simulations. The orientation of rider constraints with respect to the ground and the type are shown in the table 3, where φ_x φ_y φ_z are the angles measured in relation to the ground.

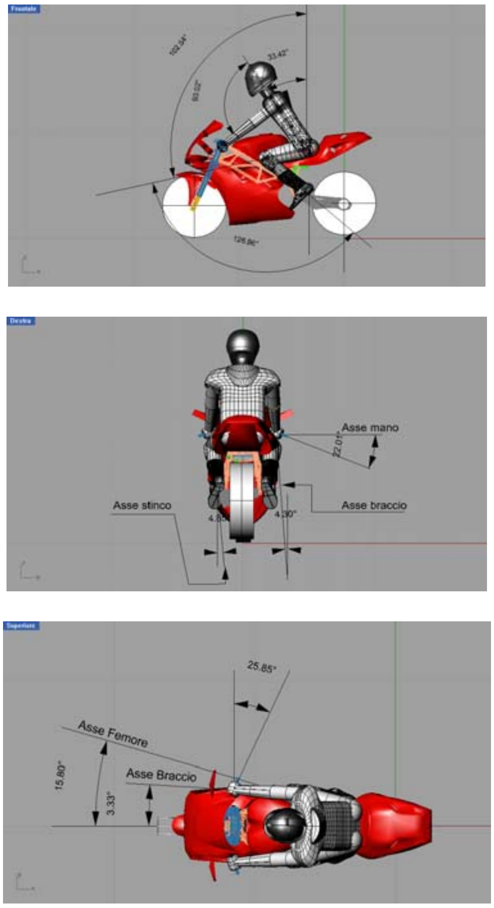

Figure 2: Arrangement of the axes of rider's body parts

Table 3: Orientation of rider constraints with respect to the ground

CONSTRAINT	TYPE	$\varphi_X, \varphi_Y, \varphi_Z$
HEAD-NECK	FIXED	
NECK-CHEST	SPHERICAL	5,-40,-4
SHOULDER-CHEST (SX)	SPHERICAL	0,0,0
SHOULDER-CHEST (DX)	SPHERICAL	0,0,0
ARM-FOREARM (SX)	REVOLUTE	-80,3,-43
ARM-FOREARM (DX)	REVOLUTE	80,3,43
CHEST-ABDOMEN	SPHERICAL	0,-35,6
ABDOMEN-PELVIS	REVOLUTE	0
PELVIS-THIGH (SX)	SPHERICAL	0,0,0
PELVIS-THIGH (DX)	SPHERICAL	0,0,0,
THIGH-SHIN (SX)	REVOLUTE	-70,-20,174
THIGH-SHIN (DX)	REVOLUTE	-70,20,-174

Exploiting the laws of the anthropomorphic model Hybrid III, the dynamic characteristics of the joint can be modified through a single parameter. This allowed the model to be managed more easily and, above all in the first phase, made it possible to understand which joints play an important role in the problem.
The constraints between the modelled rider and motorcycle are:

- the grip of the hands on the handlebar (bushing)
- the feet placed on the footrests (spherical joint)
- the contact between the chest and the saddle-fuel tank unit (contact force)

- the contact between the inside of the thigh and the sides of the fuel tank (contact force).

2.1. Lower limbs

Particular attention was paid to the lower limbs, given that these constitute a fundamental element for the lateral dynamics of the rider. It was observed that the axis of the pelvis and the line linking the knee joints tend to remain parallel during manoeuvres. The legs of the anthropomorphic model were, therefore, considered as a kinematic motion which can be used to guide the transverse movement of the body.

For this reason, the lower limbs were schematised as a deformable quadrilateral in the space constituted by 5 rigid bodies and 4 revolute-joints (Fig. 3):

- 2 parts represent the foot-calf (blue);
- 1 part represents the pelvis (yellow);
- 2 parts represent the thighs (red).

Figure 3: Schematisation of lower limbs

The analyses conducted on the motorcycle using ADAMS/View software showed that the lateral displacement of the rider can be reproduced effectively using this kinematic motion.

With the adoption of these constraints, it was possible to define an efficient schematic with 21 degrees of freedom.

2.2. Forearm-hand

When moving, the rider acts on the handlebar/steering column to correct the trajectory and maintain the desired angle of roll, and his hand and wrist are, therefore, particularly mobile. His wrist must, in fact, second his movements both when he has to “lean into the bend” on entering a curve and when his barycentre returns within the motorcycle’s plane of symmetry on exiting. To this end, two were used, positioned at the hand’s centre of mass. The first revolute joint, connecting the hand to the handlebar and the constraint along the axis coincident with this, allows the rotation of the forearm at the wrist due to the rider's pitching movements when he passes from a prone to supine position and *vice versa*. The second revolute joint, whose axis is orthogonal to the first, allows rotation between the wrist and forearm when the rider's body moves laterally.

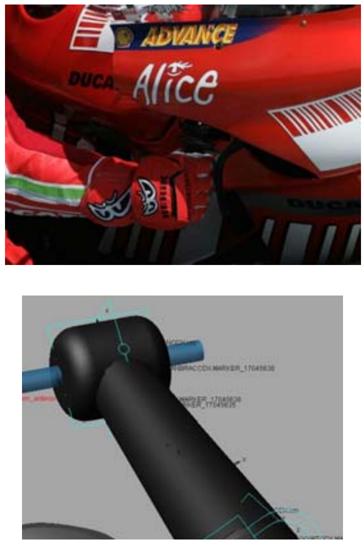

Figure 4: Forearm-hand constraint and hand-handlebar contact

2.3. Forearm-arm

For this constraint it was considered appropriate to use a revolute joint. In reality, the arrangement of the revolute joint axis is also influenced by the rotation of the wrist along the axis of the forearm. However, for simplicity, this aspect was ignored here since it is not relevant to the control of the motorcycle. The hinge axis was fixed with an inclination of 48° with respect to the handlebar axis.

2.4. Mass of individual parts

The inertia characteristics of the single parts making up the rider's body were deduced from the WORLD SID (World Side Impact Dummy) software program, which refers to the ISO/TC22/SC12/WG5 standard describing the anthropometric characteristics of an average-sized automobile driver on the basis of the data provided by AMVO (Anthropometric Specification For Mid-Sized Male Dummy). Table 4 shows the anthropometric characteristics of the various body parts and the position of their centres of mass, calculated with respect to the ground. Table 5 gives the principal moments of inertia of these body parts.

Table 4: Mass characteristics of the rider's body parts and their position with respect to the ground

PART	MASS [Kg]	DENSITY [kg/m^3]	VOLUME [m^3]	CM (x,y,z) [m]
HEAD + HELMET	5.639	1215.1581	0.004641	-0.772, 0.0007, 1.534
NECK	0.965	1347.0922	0.000716	-0.729, -0.0007, 1.399
CHEST	23.763	871.7488	0.027259	-0.606, -0.0007, 1.228
ABDOMEN	2.365	230.8081	0.010247	-0.449, -0.0008, 0.997
PELVIS	11.4	1320.8448	0.008631	-0.357, -0.0003, 0.865
SHOULDER	0.001	1.2434	0.000804	-0.641, 0.222, 1.272
ARM	1.769	757.3291	0.002336	-0.754, -0.228, 1.183
FOREARM	1.769	757.3291	0.002336	-0.754, 0.228, 1.183
ELBOW	0.001	1.8290	0.000547	-0.984, 0.241, 1.005
KNEE	0.001	0.8834	0.001132	-0.743, -0.218, 0.770
HAND	0.487	825.8475	0.000590	-1.153, -0.252, 0.876
THIGH	8.614	883.7219	0.009747	-0.514, -0.152, 0.821
BUTTOCK	0.001	0.3257	0.003070	-0.514, 0.152, 0.821
SHIN + BOOT + FOOT	5.57	807.2962	0.006900	-0.545, -0.203, 0.586
Total weight and global barycentre coordinates	80.558			-0.57,-2.68E-004,1

Table 5: Inertia characteristics of the body parts and global inertia of the rider with respect to his centre of mass

PART	Ixx, Iyy, Izz [kg m^2]
HEAD + HELMET	-0.772, 0.0007, 1.534
NECK	-0.729, -0.0007, 1.399
CHEST	-0.606, -0.0007, 1.228
ABDOMEN	-0.449, -0.0008, 0.997
PELVIS	-0.357, -0.0003, 0.865
SHOULDER	-0.641, 0.222, 1.272
ARM	-0.754, -0.228, 1.183
FOREARM	-0.754, 0.228, 1.183
ELBOW	----
KNEE	----
HAND	5.935E-004, 5.935E-004, 4.672E-004
THIGH	0.146, 0.416, 0.031
BUTTOCK	----
SHIN + BOOT + FOOT	0.1501, 0.1423, 0.01647
Overall inertia with respect to the CM	8.108, 8.735, 4.264

3. THE MOTORCYCLE CONTROL SYSTEM

The control of the motorcycle was effected adopting a system consisting of three modules: one proportional, one derivative and one a function of the second derivative, regulating the turning couple applied to the steering column and the torque applied to the rear wheel. In order to guarantee the correct kinematic behaviour of the motorcycle, the control system must be able to perform four fundamental functions:

- Impose the angle of roll as a function of the curvature of the trajectory and the velocity of the motorcycle
- Stabilise the falling motion of the motorcycle (CAPSIZE)
- Correct the trajectory
- Correct errors in the velocity

Figure 5 shows a schematic diagram of the input and output parameters of the motorcycle control system.

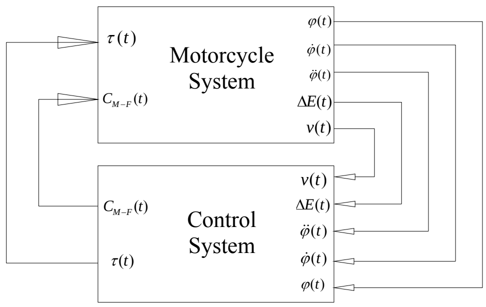

Figure 5: Block diagram of the control system

3.1. Control applied to the steering column

The equation regulating the directional behaviour of the system is:

$$\tau(t)=K_1(\varphi(t)-\varphi_{ideal}(t))+K_2(\dot{\varphi}(t)+K_3\ddot{\varphi}(t)+K_4\Delta E(t) \qquad (1)$$

where τ(t) is a couple applied to the steering column, φ(t) is a value of the motorcycle's roll angle at instant t, $\varphi_{ideal}(t)$ is the desired value at the same instant, expressed by:

$$\varphi_{ideale}=arctg\frac{R_g\cdot\Omega^2}{g}+arcsen\frac{t\cdot sen(arctg\frac{R_g\cdot\Omega^2}{g})}{h-t} \qquad (2)$$

and ΔE(t) is the distance from the reference trajectory. Expression (1) is that of a PD type controller with the addition of the term relative to the acceleration of roll. The function of the first and second derivatives of the roll angle is to allow the introduction of the concept of predicting the roll motion: i.e. it is supposed that the rider is able to perceive the magnitude of the variations in the roll angle and, therefore, the values of $\dot{\varphi}(t)$ and $\ddot{\varphi}(t)$. With this system, the controller applies a steering couple until the roll angle is equal to that desired, thereby zeroing the second element of the equation. Once the roll motion is stabilised, the couple at the steering column is still not zero due to the term relative to the deviation from the reference trajectory ΔE(t) and the controller therefore operates to compensate for this error by continuing to act on the steering column. It should also be noted that the difference between φ(t) and $\varphi_{ideal}(t)$ initially assumes a negative value and this

allows the simulation of the real behaviour. During the phase of entering a curve, in fact, every rider, whether consciously or not, tends to steer from the opposite side of the curve in order to generate a centrifugal force which provokes a "tipping over" towards the inside of the curve.
The variables determining the couple on the steering column are shown in Figure 6.

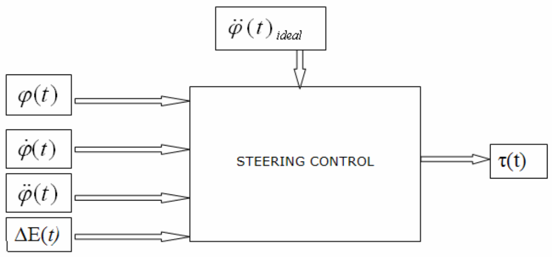

Figure 6: Schematic diagram of steering control

In the model developed in ADAMS/View, the couple at the steering column is introduced using an "SFORCE" (appendix A).
It can be seen that the controller for the calculation of the steering couple does not refer to the roll angle of the motorcycle, but to that of the global motorcycle-rider system. In this way is possible to take into consideration displacements in the rider's barycentre and to observe the effects of these on the dynamic parameters. The IF function multiplying the variables of the system allows the controller to intervene on the steering column only when the velocity of the motorcycle has reached a value which ensures its stabilisation (CAPSIZE) (Cossalter 1997).
In the equation (1) the four coefficients K_1, K_2, K_3 and K_4 together determine the trajectory prediction times and the "driving style" of the virtual rider. In particular, varying the coefficients one by one, produces the the following qualitative effects:
Increasing K_1: the system reacts more rapidly to perturbations in its state of equilibrium, advantageous in the case, for example, of a lateral disturbance caused by a gust of wind. There is, however, an increase in the oscillation of the roll motion around the equilibrium position which is disadvantageous when assuming the roll angle required for a given curve. In this case, too great an increase in K_1 results in exceeding the desired roll angle φ and this can lead to instability if the curve is particularly demanding.
Increasing K_2: there is greater damping of the roll motion oscillation around the equilibrium configuration, making the system more stable. Also here an excessive increase must be avoided or the system will again tend towards instability.
Increasing K_3: the system reacts more quickly to variations in the curvature of the trajectory, attaining the required roll angle more rapidly. The frequency of the roll motion oscillation increases as does its amplitude around the equilibrium position. Further increase in K_3 produces a second, higher frequency of the roll motion oscillation, making the system instable.
Increasing K_4: the system is more sensitive to corrections to errors of position and trajectory.

4.2 Control of velocity

In order to control the velocity of the motorcycle, torque was applied to the rear wheel. At running speed, this torque is described by the function:

$$C(t) = C_0 + K_5(V_{motorcycle}(t) - V_{desired}(t)) \tag{3}$$

The term C_0 has the function of accelerating the motorcycle, thereby regulating the transient. The proportional module manages the transient and, therefore, regulates the velocity of the motorcycle.

4. LOCALISATION OF THE MODEL'S BARYCENTRES AND IMPLEMENTATION OF THE ALGORITHM CONTROLLING THEIR DISPLACEMENT

As noted above, the rider's movements influence the dynamic parameters of the motorcycle during the execution of some manoeuvres. For this reason, it is important to localise the position of the centres of mass of the motorcycle, of the rider and of the overall system, and to monitor their displacements.
Calculating the global barycentre of the motorcycle-rider system, using the classic equation of Rational Mechanics (Oliveri 1993), six general constraints (GCON), one for each direction of the centre of mass, were introduced into the ADAMS model:

Fictitious part, roll angle allowing the calculation of the roll angle referring to the position of the global barycentre through the expression:

$$\varphi = a\tan\frac{S_y}{S_z} \tag{4}$$

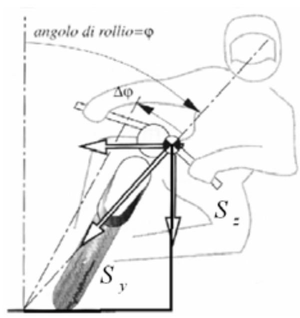

Figure 7: Calculation of overall roll angle

Fictitious part, pitch angle allowing the calculation of the pitch angle.

Sensor part, trajectory has the task of moving along the trajectory and continuously calculating the curvature (5) and, therefore, the ideal roll angle on the basis of equation (2). It also allows the calculation of the motorcycle's distance from the required trajectory.

$$C(t) = \left| \frac{a_n(t)}{V_x^2(t)} \right| \qquad (5)$$

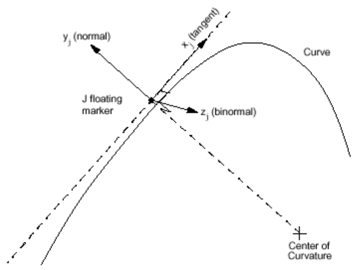

Figure 8: Alignment of marker tangent on curve

The syntax of the CURVATURE function is defined in ADAMS/View by expression in appendix B.
Analogously, two further fictitious parts were used in order to evaluate **roll velocity** and to apply **aerodynamic forces.**
A sixth power polynomial was used to describe the trajectory, providing the best compromise between oscillations of the curve and approximation of the points of control. This approach allowed an active control of the trajectory. The trajectory sensor reads the curve with a certain anticipation, chosen in function of the velocity, and the system (virtual rider) can choose the control parameters, operating on both motorcycle and body movement to obtain the optimal trajectory.

5. ANALYSIS OF RESULTS

The results of the simulations performed were analysed in order to determine the way in which the movements of the rider (Fig. 9) effect the dynamic parameters of the motorcycle.

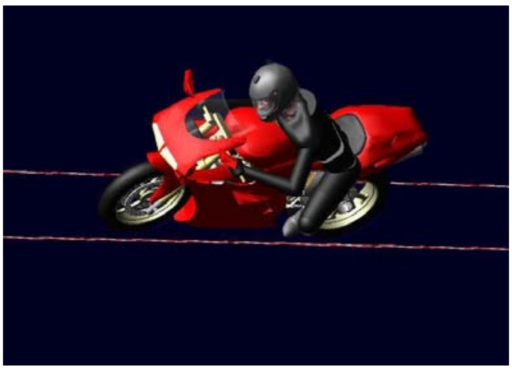

Figure 9: Model of motorcycle with rider moving through a curve

5.1. Motion through a curve

Over a simple track consisting of rectilinear entry path – constant radius curve – rectilinear exit path at constant velocity, it is possible to identify 5 phases: a condition of uniform rectilinear motion; the transient of entering the curve; a stationary condition reached within the curve; the transient of existing the curve; a final condition of uniform rectilinear motion.

Of these, the phases important for the lateral dynamics are those of the stationary state in the curve and the two transient states occurring between rectilinear motion and passing through the curve.
The characteristic phenomenon of the latter phase greatly depend on the driving style of the rider, i.e. on the characteristics of the control system. For this reason, three different rider positions are analysed below: fixed, displaced towards the inside of the curve and displaced towards the outside of the curve.

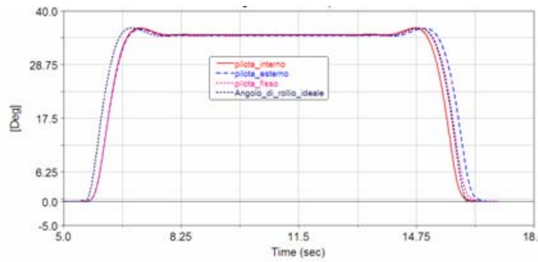

Figure 10: Roll angle relative to the global barycentre

The trend of the roll angle relative to the global barycentre makes it possible to assess the inclination of the motorcycle-rider system in the various sections of the track. In all three cases, this inclination coincides with the reference roll angle, except for a small error which becomes larger in the transients of entering and exiting the curve. No significant variations were observed during the phase of entering the curve, because of the rider anticipates this phase with his movements and the control system therefore has the time to compensate for the error. On exiting the curve, instead, the righting of the motorcycle is anticipated or delayed when the rider is, respectively, displaced towards the inside or outside of the curve.
The movement of the rider towards the plane of symmetry, in fact, favours the righting of the motorcycle in the first case and opposes it in the second.

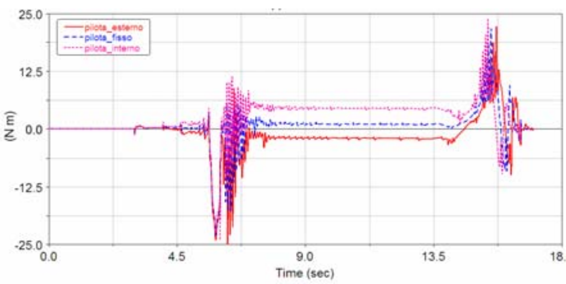

Figure 11: Torque applied to steering column

The turning couple at the steering column shows the continuous corrections made by the rider during the phases of entering and exiting the curve. It is clear that, to maintain the roll angle while passing through the curve, the rider exerts a greater action on the steering column when he moves towards the inside of the curve due to an increase in the moment of roll generated by the weight force. This requires him to act more strongly against "tipping over" by steering harder towards the inside of the curve.

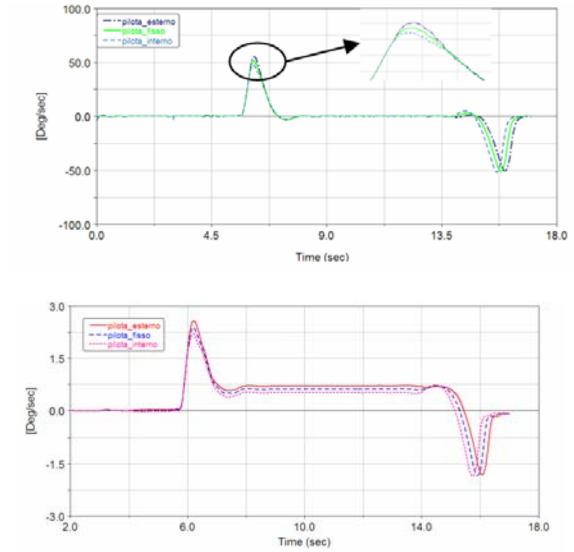

Figure 12: Velocity of roll and pitch

The trend of the motorcycle's roll velocity shows the presence of two peaks at entering and exiting the curve due to the greater action applied to the steering column during these phases. When running at speed, the motorcycle is stabilised and the roll velocity is zero. The offset of the peaks in the phase of entering the curve relative to the three cases should also be noted. This shows how, given parity of the time required to reach the reference roll angle, the movement of the rider towards the inside of the curve necessitates a slower roll velocity. Also the pitch velocity is reduced when the rider moves towards the inside of the curve in both the phase of entering the curve and to that of passing through it. However, since this is not a controlled parameter, it is possible to imagine that the system reacts somewhat slowly to pitching, probably due to the lesser inclination of the motorcycle and two lower value assumed by the lateral forces of adherence which, together with the centrifugal forces acting on the barycentre, are responsible for the moment of pitch.

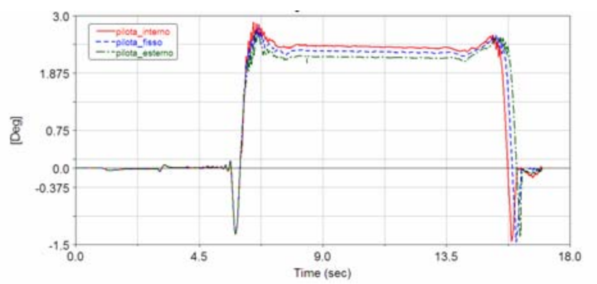

Figure 13: Angle of steering column

The trend of the steering angle allowed an assessment of the low values of the forces acting on the steering column. This made it possible to ignore the contribution due to the gyroscopic moments of the wheels with increasing roll angle. In the phase of entering the curve, there is a peak with a negative sign, representing the initial phase of "countersteering" which permits the insertion into the curve.

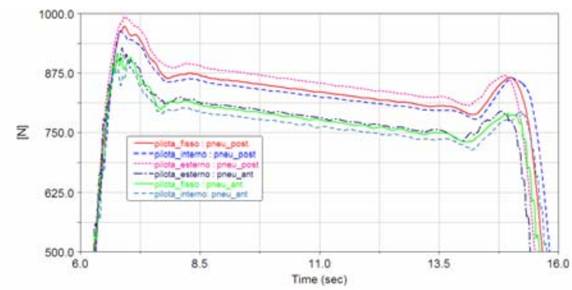

Figure 14: Comparison between the lateral forces acting on the tyres

Figure 14 shows a comparison between the three lateral reactive forces acting on the tyres. It can be seen that the rear wheel exerts greater adherence. Further, in the case of the rider displaced towards the inside of the curve, the lateral force is reduced. This allows the rider to delay the phenomena of slipping associated with the loss of adherence at the tyre-road surface which, given parity of trajectory curvature, will occur at higher velocities. The downward trend of the curve is due to the motorcycle deviating slightly from the intended trajectory.
Thus, the lateral displacement of the anthropomorphic model made it possible to take greater advantage of the characteristics of the tyres which was then translated into an increase in the maximum velocity possible along the track.

6. CONCLUSIONS

Based on co-simulation, the methodology used allows the parametric multibody modelling of a motorcycle with an anthropomorphic model of the rider. With this model, it is possible to evaluate the connection between the movement of the rider's body and that of the overall barycentre of the motorcycle. The approach to the problem of motorcycle dynamics described here is substantially innovative, in that it was complemented by and integrated with a biomechanical component. Numerous configurations were examined to determine the arrangement of the rider/motorcycle constraints and, above all, for the articulated model of the rider, arriving at the definition of an effective scheme with 21 degrees of freedom.
The simulations performed demonstrated the plausibility of the anthropomorphic model in terms of kinematic behaviour, interaction with the motorcycle, and biomechanics given that, even under the most demanding conditions, the physiological limits of joint mobility were always respected.
From the point of the achievable performance of the motorcycle, introducing the anthropomorphic model of the rider resulted in evident improvements, in particular when travelling through a curve.
The rider model developed here is simple and easily managed and can, therefore, be considered a valid

starting point for a future implementation of dedicated control systems.
The simulations revealed two degrees of freedom which, due to the kinematic characteristics of the model developed here, are particularly important: rotation in the sagittal plane of the elbow and the knee.
An active type of modelling would allow a more effective compensation for effects of the inertia forces during the phases of acceleration and braking. This would make it possible to define a more realistic distribution on the various constraints of the forces exchanged between the rider and the motorcycle.

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APPENDIX
A)
"IF(TIME3:0,0,1)*((850*(VARVAL(.model_deformabile_.ANGOLO_DI_ROLLIO_COMPLESSIVO)-VARVAL-(.model_deformabile.Phi_id_tot)))+VARVAL(.model_deformabile.VEL_ANGOLO_ROLLIO_COMPLESSIVO)+VARVAL(.model_deformabile_.ACC_ANGOLO_DI_ROLLIO_COMPLESSIVO))+VARVAL(.model_deformabile.ERRORE_DI_POSIZIONE))".

B)
ABS((ACCY(.MARKER_MOBILE_SU_TRAIETTORIA,MARKER_MOBILE_SU_TRAIETTORIA)+0.0000001)/(VX(.MARKER_MOBILE_SU_TRAIETTORIA,.mar_rif,.MARKER_MOBILE_SU_TRAIETTORIA)**2+0.0000001)).

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AUTHORS BIOGRAPHY
Michele Calì was born in Brindisi, on 19 Aug 1969. In 1974 he went to Catania were he was educated, and in 1996 he was graduated in Mechanical Engineering. In 2001 he achieved the PhD of Mechanic of Structures in Mechanical Engineering Department of the Catania University. Actually he is in Postdoc position and worked, as researcher, with Professor Massimo Oliveri, at the Design Technical researched group. He works in some projects with Ferrari S.p.A., Ducati Motorcycles Holding S.p.A., CIRA S.p.A. (Italian Aerospace Researched Centre), Centro Ricerche FIAT (CRF), Piaggio V.E. S.p.A. and Erg petrol S.p.A. He works in research on dynamic simulation and deformation studies of engine, timing system and mechanical system in generally. He takes part in European research projects, particularly in the research on engine 3D modelling. His 12-years research on mechanical system and design has documented by numerous papers, lectures and articles.

Massimo Oliveri, professor of Design and Method of the Industrial Engineering in Engineering Faculty of Catania. Professor of Computer Assisted Drawing to the same University in the degree in Mechanical Engineering.
He has developed, in the course of his academic career, scientific activities in different sectors of the Machine Design that get from strain and stress analysis, to CAD in mechanical design, to fatigue in welds, to study of complex kinematics using multi-body software. He has manage and cooperate to the research activity with some Italian University, with C.R.F. in Orbassano and ELASIS in Pomigliano d'Arco and with some Italian industries (Ferrari S.p.A., Ducati Motors Holding S.p.A., Fiat Auto and Piaggio V.E. S.p.A.)

Gaetano Sequenzia was born in Catania (Italy) on 19 January 1980, graduated at the University of Catania in 24 July 2004 in Mechanical engineering with bachelor ballot 110/110 cum laude.
Actually Philosophy Doctor (Mathematic engineering) at University of Catania. Recent technical interests regard dynamic simulations of mechanical components, as crankshaft cranktrain, valvetrain and chains.

Francesco Trovato was born in Catania (Italy) on 5 February 1981, graduated at the University of Catania in 24 July 2007 in Mechanical engineering. Actually he work at Moto Guzzi S.p.A.