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Analysis of the Biomechanical Interaction between Rider and Motorcycle by Means of an Active Rider Model

Valentin Keppler*

* Biomotion Solutions
Appenbergstr. 4, 72072 Tübingen, Germany
e-mail: keppler@biomotion-solutions.de

ABSTRACT

Compared with other vehicles like cars, the mechanical interaction between rider and his motorcycle is much closer. Dynamics of motorcycles is well understood [1] and even complex multibody models of real bikes have been realized [2]. But models which consider the influence of the rider on the dynamics of the man-machine system are restricted to upper body lean and artificial steering torques. To enable the analysis of issues like motorcycle ride comfort, safety and instable ride modes Biomotion Solutions has developed a biomechanical rider model for motor-cycle simulations which is capable of steering the motorcycle by moving the handlebars. This model is used to identify parameters of rider vibration characteristics and the influence of the rider's biomechanical parameters on the dynamic ride stability. The developed rider model is capable of stable track following by preview sensor and can be used in ride comfort analysis.

Keywords: motorcycle rider, biomechanics, simulation, active movements.

1 INTRODUCTION

Biomechanical models of the human operator can be used in a broad variety of application fields. Prominently known are whole body simulation models for car crash simulation in which the exposure and influence of external forces on the human driver can be analyzed. As the human body mass and the forces applied from the human to the car are small in comparison to the car the man-machine interaction is neglected in most cases. On the other hand it has been shown that, surprisingly, the coupling of a pilot and his F-16 fighter on the other hand is too strong to be neglected. The so-called roll ratcheting is caused by the high amplification of the fighter pilot's steering commands to the aircraft as it is fly-by-wire controlled. Pilot induced oscillations have been described in [4]. Clearly it has to be expected that the rider's motions can not be neglected in the case of rider-motorcycle interaction, the development of a biomechanical full body model was the goal of our development. The rider model should be able to be used in a broad range of applications and it should be able to perform standard riding tasks like cross over maneuvers or cycle passing.

2 THE MODEL

Motorcycle dynamics is well understood by analytical models [1] which due to the chosen analysis method require stringent model reduction. Nowadays it is even possible to simulate complex motorcycle models based on real existing designs [2]. By using one of the available industry standard multi body simulation packages even complex three dimensional simulations can be handled comfortable. The underlying multi body package used in our simulation is SIMPACK (SIMPACK AG, Gilching Germany) which often is used in automotive or wheel rail simulation. The simulation is based on three models: The human body, the motorcycle, and the motion control model.

2.1 The Human Body Model:

Based on anthropometrical data [3] we have implemented a 17-segment full body model. The model consists of 2 legs (foot, shank and thigh), a 3-parted trunk, neck head and two arms (hand, fore-arm, upper arm) as depicted in figure 1. Furthermore, each of these rigid bodies is coupled with a so-called wobbling mass which takes into account that human body tissue is not a rigid material (see figure 3). The consideration of wobbling masses [7, 8] is crucial - especially for ride comfort simulations.

Figure 1. Human body model consisting of 17 segments.

Based on regression equations a human body model can be built up from scratch piece by piece using the SIMPACK preprocessor. But due to the large number of model parameters building a human body model is an elaborate and error-prone task. Taking into account that it might be interesting to generate a range of different rider anthropometrics we decided to use an automatic model wizard (Varibody, Biomotion Solutions figure 2) to generate the human body model based on user input of gender, stature and body weight.

2.1.1 Wobbling Masses

Considering impacts and vibration in multi body systems needs to take into account the fact that human beings are built from an endoskeleton which is surrounded by soft tissues. Otherwise simulation may result in erroneous data. To solve this problem the so-called "wobbling mass model" has been introduced in [5]. Wobbling mass model has shown to be important in simulation of impact dynamics ([7] ,[6]) and in ride comfort analysis [8].

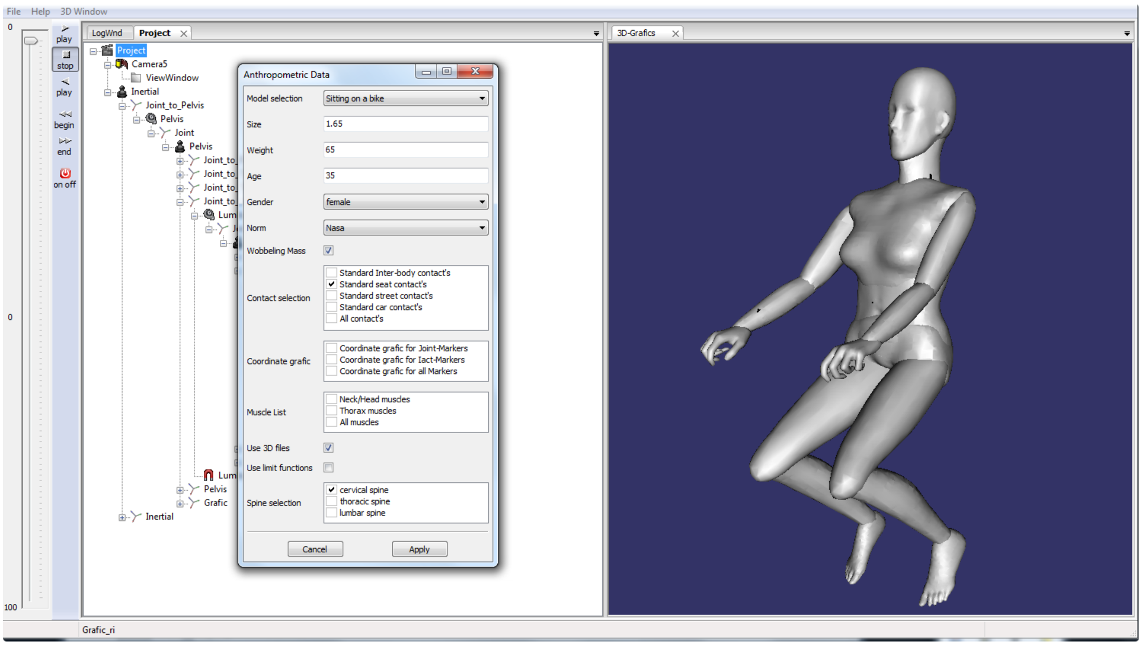

Figure 2. Automatic model generation allows for variation of anthropometrical parameters like stature, body weight and gender.

$$
\begin{aligned}
Fel\left(r_{i,\ i\in\{x,y,z\}}\right) &= A_c * \left(Cnl_i * \Delta r_i^{Se_{ct}} + C_i * \Delta r_i\right) \\
Fdiss\left(r_{i,\ i\in\{x,y,z\}}\right) &= A_c * \left(Dnl_i * \frac{d}{dt}\left(r_i\right)^{Se_{dt}} + D_i * \frac{d}{dt}\left(r_i\right)\right) \\
Tel\left(r_{i,\ i\in\{al,be,ga\}}\right) &= A_c * \left(Cnl_i * \Delta r_i^{Se_{cr}} + C_i * \Delta r_i\right) \\
Tdiss\left(r_{i,\ i\in\{al,be,ga\}}\right) &= A_c * \left(Dnl_i * \frac{d}{dt}\left(r_i\right)^{Se_{dr}} + D_i * \frac{d}{dt}\left(r_i\right)\right) \\
F\left(r_{i,\ i\in\{x,y,z\}}\right) &= Fel_i + Fdiss_i \\
T\left(r_{i,\ i\in\{al,be,ga\}}\right) &= Tel_i + Tdiss_i
\end{aligned}
\tag{1}
$$

Parameter symbols are explained in table 1.

2.1.2 Joint Actuators

To enable both, the passive posture maintenance and the active motion generation actuators have to be implemented at each joint of the human body model. The torques which are acting between the two coupling points at the segments are calculated following equation 2 and the actuator works at four different modes:

- passive torque for posture maintenance
- active motion defined by motorcycle rider controller
- torque/force by motorcycle rider controller

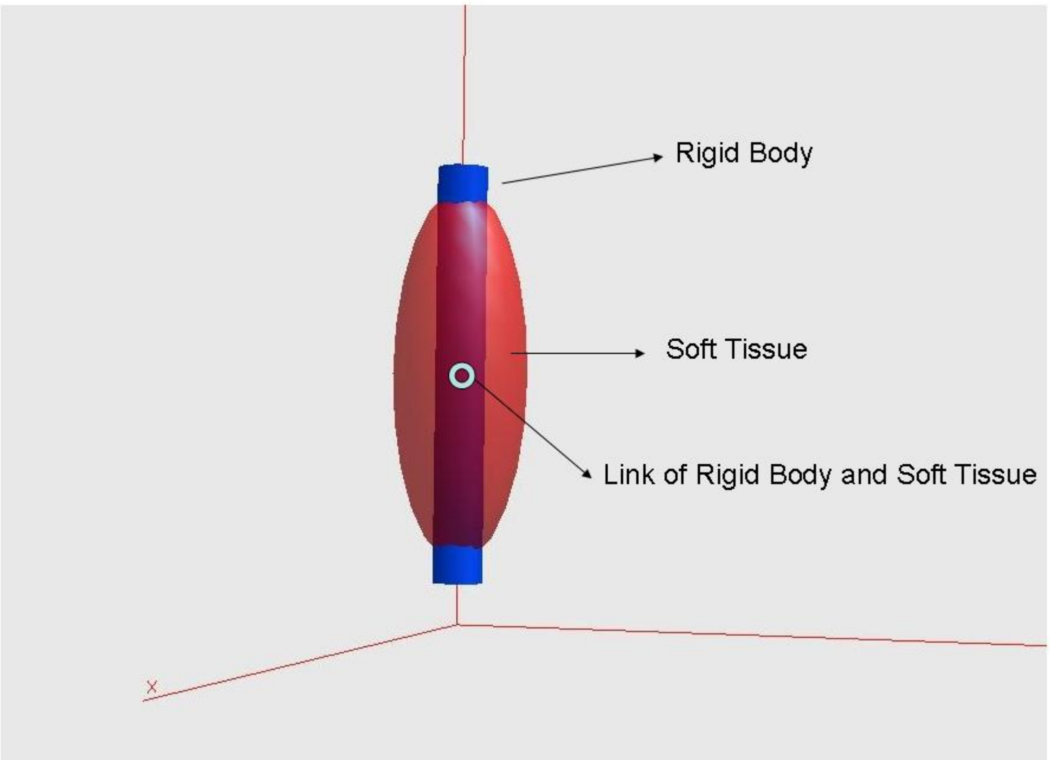

Figure 3. Wobbling Mass Model: second rigid body as "soft tissue" parallel to the bone which can rotate and translate with respect to coupling marker and is connected by a non linear force element.

In the "defined motion" case PID controllers are used to let the joint DOF follow set values. The formula for the PID-controllers are as follows: The set point (SP) is the value to be reached by the controller, the process variable (PV) is the measured value. The only variable used by the controller is $\Delta(t) = SP - PV$.

$$P_{out}(t) = K_P * \Delta(t) + K_D * \frac{d}{dt}(\Delta(t)) + K_I * \int_{-\inf}^{t} \Delta(t')dt' \tag{2}$$

The parameters are explained in table 2 and suitable parameter values have been identified by comparison with measurement data found in literature.

2.1.3 Grip Force

There are grip force models described in literature (e.g. [9]) which are mainly used to calculate vibration issues. We implemented a simplified grip force model as a three component force and torque model as described in equation (3) and parameter symbols are declared in table 3. Parameter values for the grip force model have been taken in agreement with literature data ([9]).

Table 1. Symbols for wobbling mass force law

	$Unit$	$Description$
F_i	N	Force acting in i
T_i	Nm	Torque acting about i
Fel_i	N	Force Elastic in i
$Fdis_i$	N	Force Dissipative in i
Tel_i	Nm	Torque Elastic in i
$Tdis_i$	Nm	Torque Dissipative in i
Δr_i	m	Delta Translation in r_i $i \in \{x, y, z\}$
$\frac{d}{dt}(r_i)$	m/s	Velocity Translation in r_i
Δr_i	rad	Delta Rotation r_i $i \in \{al, be, ga\}$
$\frac{d}{dt}(r_i)$	rad/s	Velocity Rotation in r_i $i \in \{al, be, ga\}$
A_c	m^2	Cross sectional area scaling
C_i	N/m	Stiffness linear in i
Cnl_i	N/m^{Se}	Stiffness non-linear in i
Se		Exponent nonlinear term
D_i	Ns/m	Damping linear in in i
Dnl_i	Ns/m^{Se}	Damping non-linear in i
C_a	Nm/rad	Stiffness linear rotational
Cnl_a	Nm/rad^{Sr}	Stiffness non-linear rotational

Table 2. Symbols for joint actuators

	$Description$
K_P	proportional gain
K_D	derivative gain
K_I	integral gain

$$
\begin{aligned}
F_i \left(r_i, \frac{d}{dt}(r_i) \right)_{i \in \{x,y,z\}} &= C_t * (r_i - r_i^{offset}) + D_t * \frac{d}{dt}(r_i) \\
T_i \left(r_i, \frac{d}{dt}(r_i) \right)_{i \in \{al,be,ga\}} &= C_r * (r_i - r_i^{offset}) + D_r * \frac{d}{dt}(r_i)
\end{aligned} \tag{3}
$$

2.1.4 Seating Force

The seat contact force has been modeled as a simplified sphere to plane contact as described in equation 4. To ensure for accurate results the force element uses the root switching functionality from the SODASRT solver from SIMPACK. Tangential forces are calculated with an velocity regularization friction model.

$$
F_z \left(z, \frac{d}{dt}(z) \right) = \begin{cases} z \geq 0 & : \quad 0 \\ z < 0 & : \quad C_z * z + Fd_z \end{cases} \tag{4}
$$

$$
v_{tan} = \sqrt{ (\sum \frac{d}{dt}(r_i)^2) } |_{i \in \{x,y\}}
$$

Table 3. Symbols for grip force law

	$Unit$	$Description$
F_i	N	Force acting in i
T_i	Nm	Torque acting about i
Δr_i	m	Delta Translation in r_i $i \in \{x, y, z\}$
$\frac{d}{dt}(r_i)$	m/s	Velocity Translation in r_i
Δr_i	rad	Delta Rotation r_i $i \in \{al, be, ga\}$
$\frac{d}{dt}(r_i)$	rad/s	Velocity Rotation in r_i $i \in \{al, be, ga\}$
C_i	N/m	Stiffness linear in i
D_i	Ns/m	Damping linear in in i
C_a	Nm/rad	Stiffness linear rotational
D_a	Nm/rad	Damping linear rotational

$$F_{tan}\left(r_i, \frac{d}{dt}(r_i)\right)_{i\in\{x,y\}} = \begin{cases} F_z \geq 0 & : \quad 0 \\ F_z < 0 \wedge v_{tan} > v_{reg} & : \quad \mu * F_z \\ F_z < 0 \wedge v_{tan} \leq v_{reg} & : \quad \mu * F_z * (v_{tan}/v_{reg}) * (2 - v_{tan}/v_{reg}) \end{cases}$$

$$F_i\left(r_i, \frac{d}{dt}(r_i)\right)_{i\in\{x,y\}} = F_{tan}\left(r_i, \frac{d}{dt}(r_i)\right) * (\frac{d}{dt}(r_i)/v_{tan})$$

$$Fd_z\left(z, \frac{d}{dt}(z)\right) = \begin{cases} \frac{d}{dt}(z) \geq 0 & : \quad 0 \\ \frac{d}{dt}(z) < 0 & : \quad D_z * \frac{d}{dt}(z) * \begin{cases} z \geq l_{dt} & : \quad 1 \\ z < l_{dt} & : \quad z/l_{dt} \end{cases} \end{cases}$$

2.2 The Motorcycle Model

The motorcycle model is built as a 3d multi body system using SIMPACK as simulation platform. The bike consists of a fork mounted front wheel connected to the steering axis by a 1 DOF (*degree of freedom*) prismatic joint. The steering is connected by a 1 DOF hinge joint to the frame. The swing arm mounted rear wheel has also 1 DOF of rotation (see fig. 4. Parameters for inertia and masses were chosen in agreement with commonly used literature. Suspension systems were modeled as linear spring damper force elements.

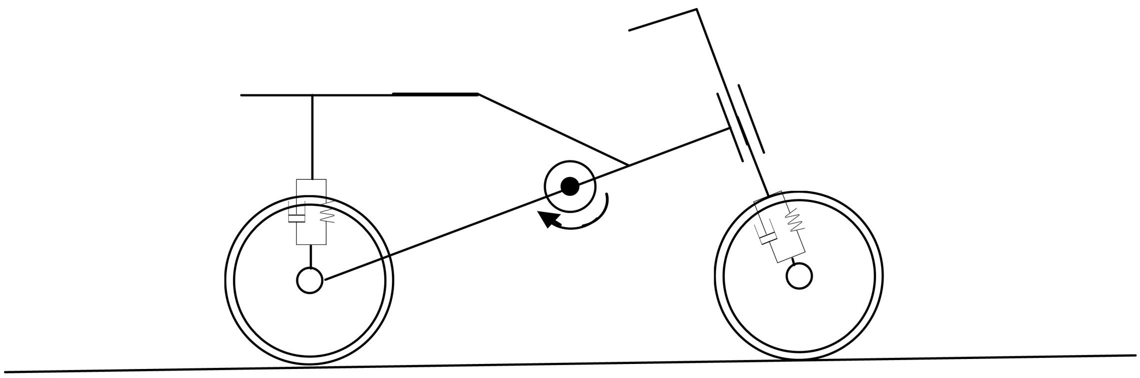

Figure 4. Motorcycle Model consisting of six rigid bodies.

2.3 Enabling Active Movement

We have implemented passive and active actuators into the model. The lower extremities, the trunk and head-neck are stabilized by passive impedances whose parameters are chosen according to literature values [10]. To enable the rider model to control the handlebars shoulders and elbows are actuated via muscle torque generators. Muscle torques are generated by PID-Controllers in the joints, which take the desired joint space configuration as set value. Their input is provided by the Biomotion motorcycle rider model controller. The controller layout follows the scheme in figure 5 and extends roll-angle control (as described in [11]) to a joint space model controller. For every desired steering angle a $R^1 \Rightarrow R^n$ transformation has to be provided by the controller (where n gives the number of controlled segment angles). The motorcycle rider controller is a standard SIMPACK control loop element which is available as an add-on.

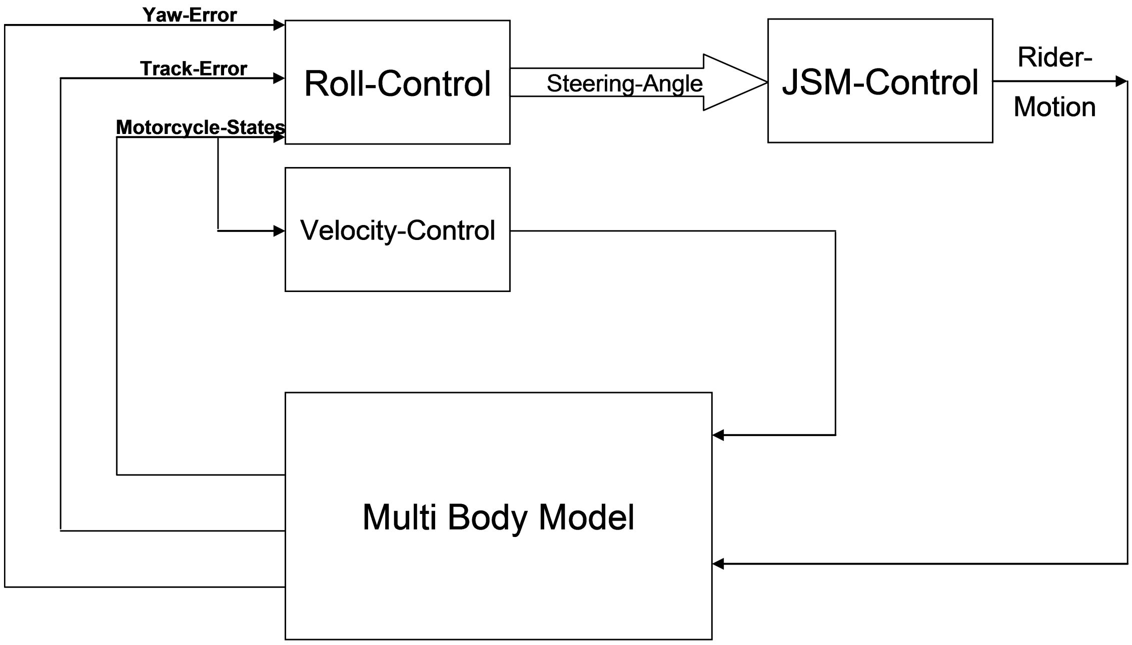

Figure 5. Human body model consisting of 17 segments.

Appropriate roll angles can be computed by PID-Controllers using as input the lateral track error of the bike's position and the yaw-angle, which describes the difference between the bike's direction and the curvature of the road trajectory. The model uses a speed dependent road preview with a proportional preview time $t_{preview}$ of one second. The calculation of the preview point follows equation 5 and is explained with figure 6. PID-parameters have to be chosen carefully to allow for stable operation. Due to the fact that in heavier motorcycles the influence of the (counter) steering is the dominant mode [12] we have not implemented a lean control.

$$s_{preview} = s_{motorcycle} + s0 + t_{preview} * \dot{s}_{vehicle} \tag{5}$$

Speed control is currently implemented as a PID control which allows the model to maintain the predefined set value by applying an appropriate torque at the rear wheel.

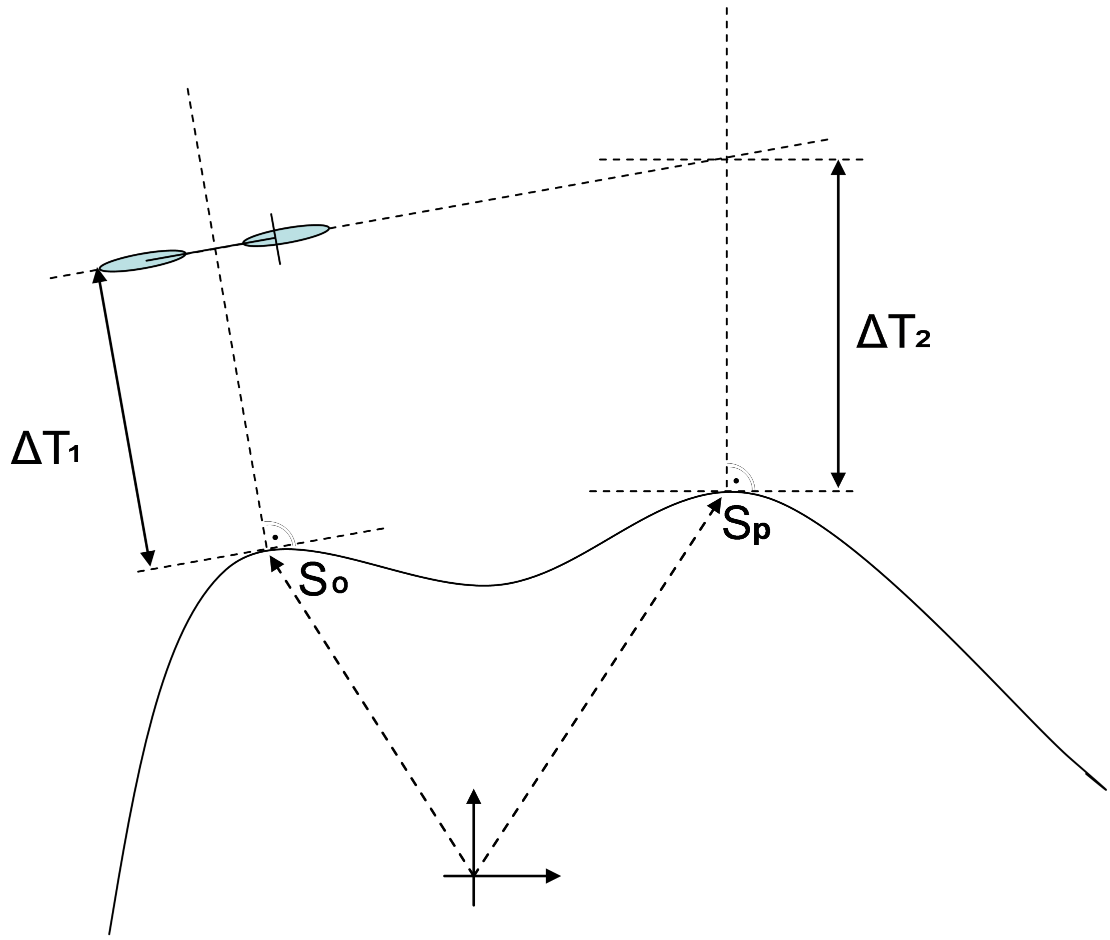

Figure 6. Velocity dependent track preview sensor

3 SIMULATIONS AND RESULTS

With the rider-motorcycle model we conducted a set of simulations. At first step we identified the joint impedances for a motorcycle rider by comparing the FRF of the rider with measured data from literature [10]. With this validated model we performed variation of biomechanical factors and analyzed their influence to the ride stability and ride comfort.

3.1 Parameter Identification

Values for joint stiffness and damping vary over a broad range in biomechanical literature. In [10] measurement data describing the rider's frequency response function (FRF, cross spectrum from steering axis acceleration and excitation torque)to steering axis excitation can be found. Cossalter matched the measured data using a reduced rider model and he optimized the parameters for inertia, stiffness and damping. For the whole body model we took this measurement of the FRF and compared it with the vibrational characteristics of the complex rider model. We performed some parameter variations to evaluate the influence of segment stiffness of trunk and hand arm system. The biomechanical rider model showed a good accordance to the measured data from Cossalter.

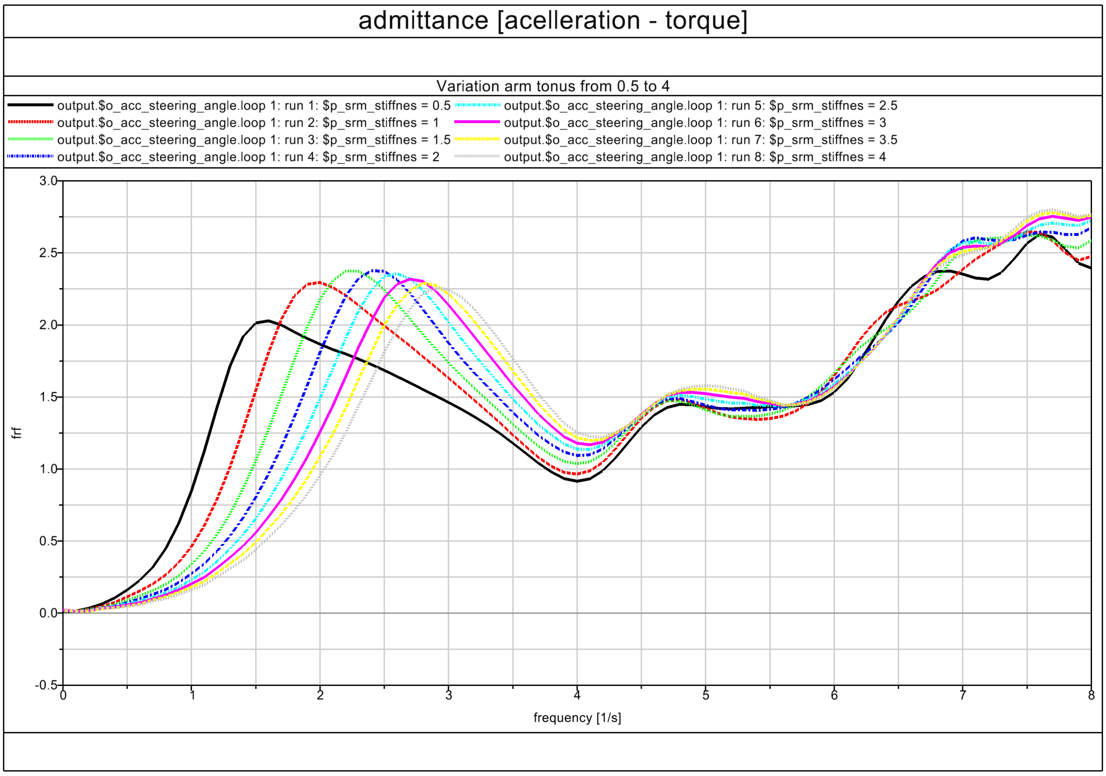

Figure 7. Parameter variation of the arm joint stiffness

Table 4. Parameter identification of riders joints

Joint	Stiffness [Nm/rad]	Damping [Nms/rad]
Wrist	25	1
Ellbow	25	1
Shoulder	45	1
Lumbus	550	35
Thorax	400	25

3.2 Influence of Physical Fitness

To get insight which factors are dominant to the ride stability we varied the muscular tension of the rider under a circuit ride as depicted in 10. When entering the circuit the rider-bike system has to adapt to the new roll angle which then has to be held constant. So we took the parameters identified in the latter section and multiplied them with a "strength" factor.

As can been seen in plots 11 and 12 the rider-bike system tends to oscillate the more the lesser the rider's physical strength is (which may indicate also a correlation with the rider's age). We performed the same parameter variation with a cross over maneuver as shown in plot 13 which shows the same tendency.

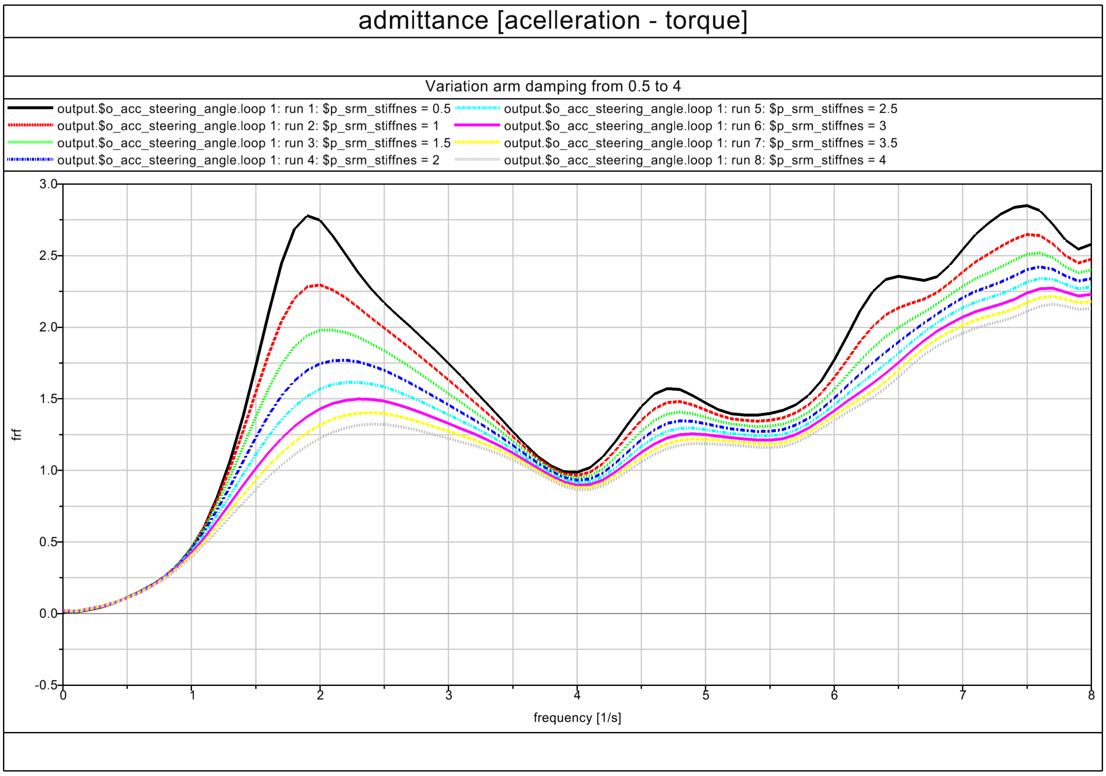

Figure 8. Parameter variation of the arm joint damping

3.3 Analyzing Safety Issues

Motorcycle and rider are a coupled system whose dynamics emerge from the interaction of both. Experienced riders are reporting possibilities to provoke or to damp down highly dangerous instable ride modes like weave or wobble. We used our rider model to analyze the rider-bike system near weave mode. Riding with 60 meters per second a transient disturbance moment has been applied by a sudden hip shake of the rider. The bike then showed a short latency time in which a negative damped oscillation showed up which finally led to exponential rising amplitude in yaw angle and to crashing. Furthermore we have analyzed the sensitivity of the weave phenomenon to the muscular tension of the rider's body as depicted in plot 14. The results predict strong influence of biomechanical factors on ride dynamics.

3.4 Road Excitation and Ride Comfort

According to ISO 2631-1:1997 (Mechanical vibration and shock – evaluation of human exposure to whole-body vibration) ride comfort can be expressed by weighted acceleration exposure. To perform a parameter variation of the saddle we simulated a parameter variation of saddle stiffness and damping and than calculated the acceleration of seat-pelvis under ”bad road” conditions. The results are depicted in plot 15. Having a whole body model allows also for the estimation of medical or psychophysical ride comfort measures at the head or the wearing comfort of helmets which may correlate with forces and torques at the cervical spine. In most cases a subjective ride comfort value is a superposition of different ride comfort measures and it's still an open question in vehicle dynamics simulation which values correlate with a common subjective ride comfort perception.

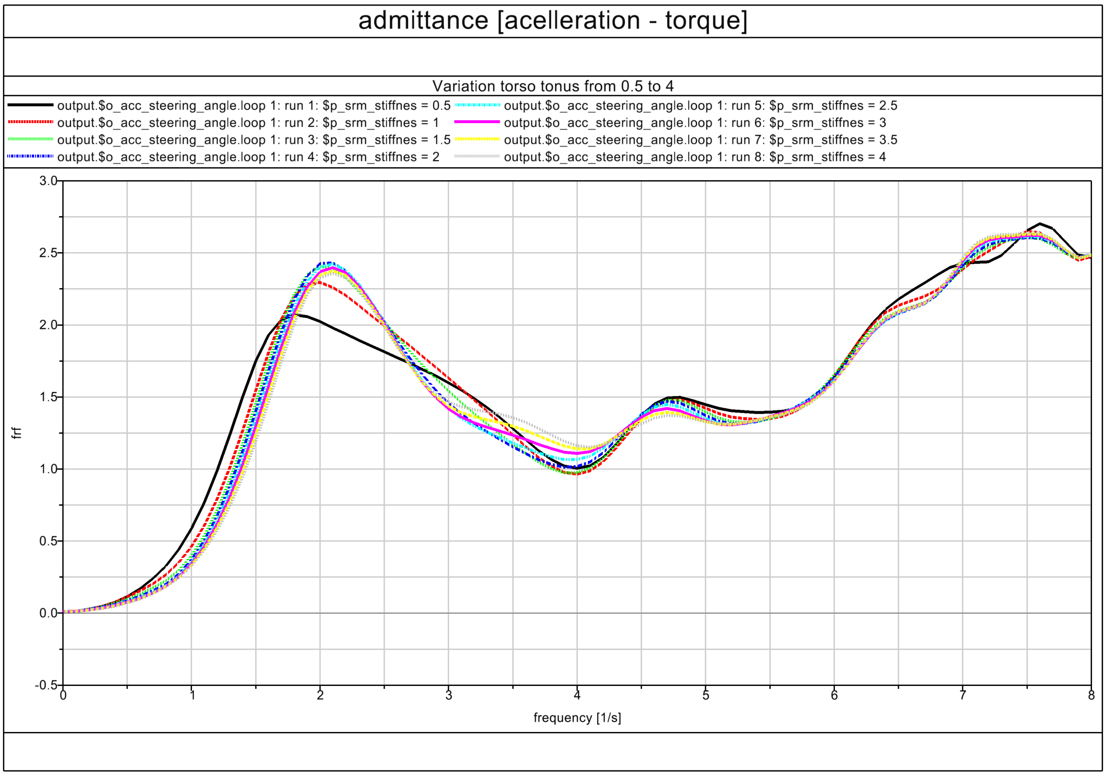

Figure 9. Parameter variation of the trunk joint stiffness

4 CONCLUSIONS

We have shown that it is possible to simulate stable track following by steering the motorcycle with the handlebars, which allows for taking the rider-bike interaction into account. Simulation results gained by this coupled system implicate a strong influence of the rider's biomechanics to the dynamics of rider-bike systems. Taking the human factor into account during the engineering design task may help to accelerate the development process and and to enhance efficiency in prototyping and testing. By the use of state of the art multi body simulation systems it is possible to run a broad variety of motorcycle rider simulations even on so-called "netbooks" in only a few seconds. As we could show it is helpful to use realistic biomechanical models to understand and interpret measured data. As a prospect for further research we see many open fields which can be worked with biomechanical rider models. Especially measurements during riding would be of interest, as we had the impression that the impedances gained by the parameter identification from the measurement data are perhaps too low. It might be possible that under "riding condition" the co-contraction of the rider's musculature would lead to higher values for joint stiffness and damping.

5 ACKNOWLEDGEMENT

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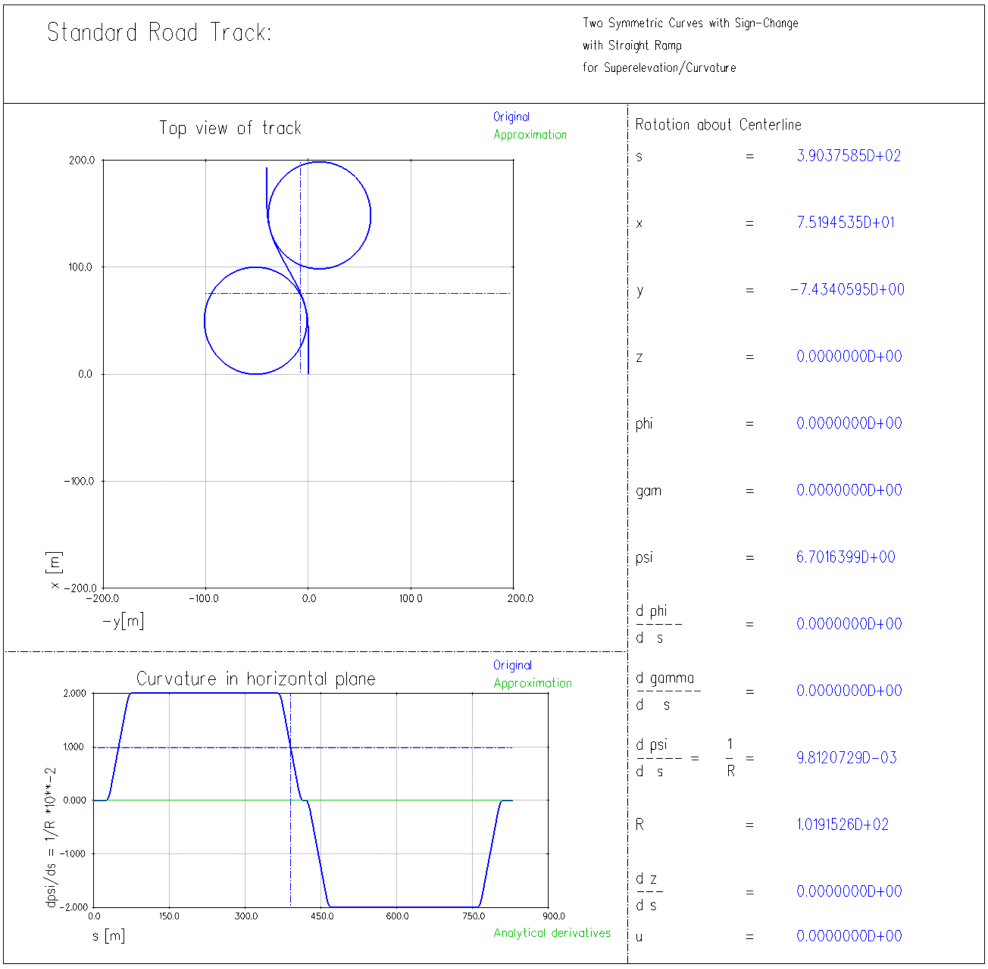


Figure 10. Track profile of circuit

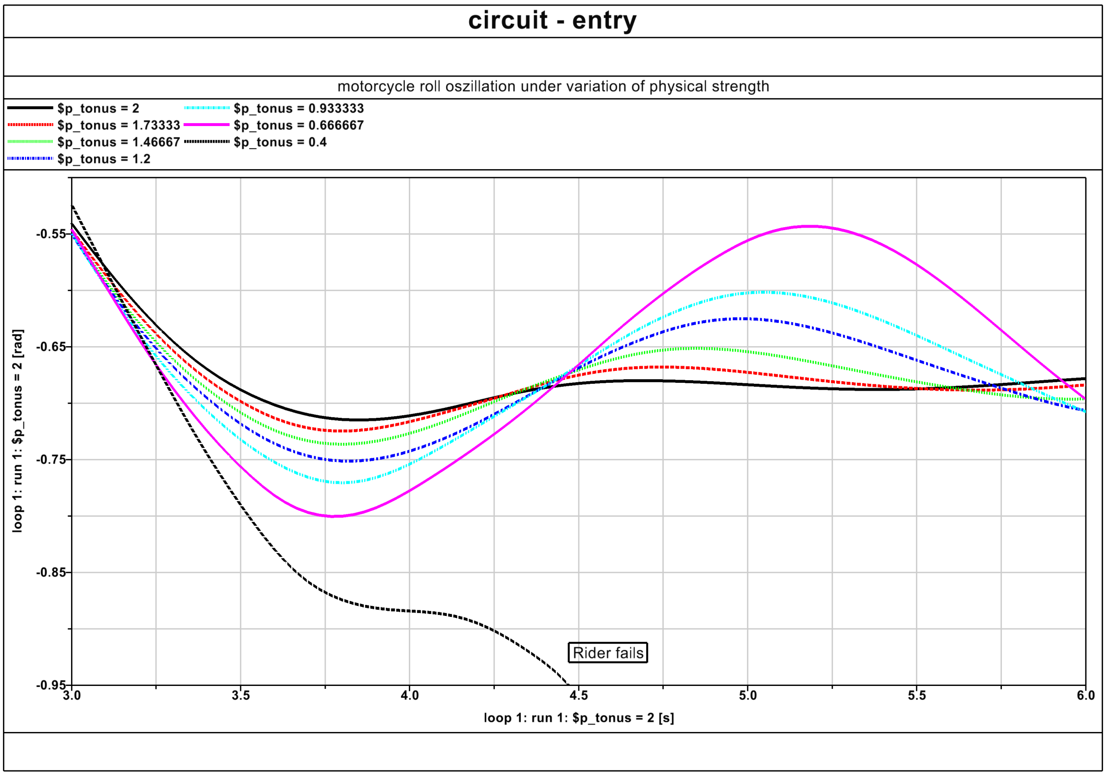


Figure 11. Circuit ride under variation of muscular tension

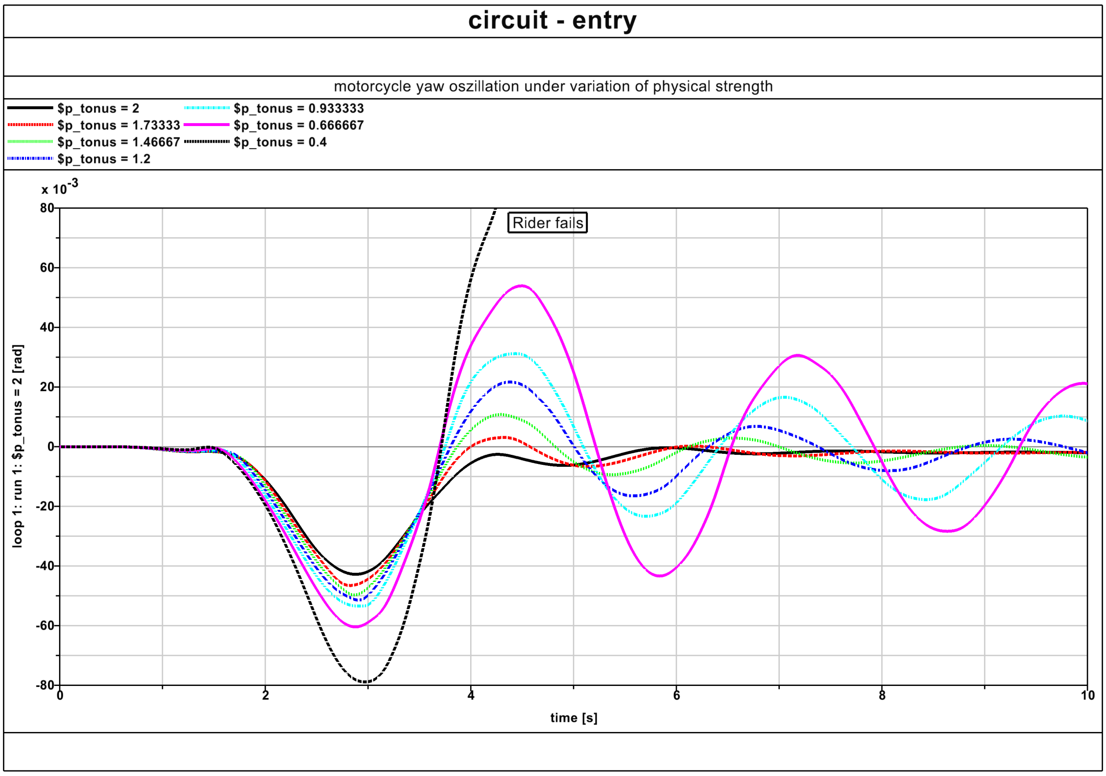


Figure 12. Circuit ride under variation of muscular tension

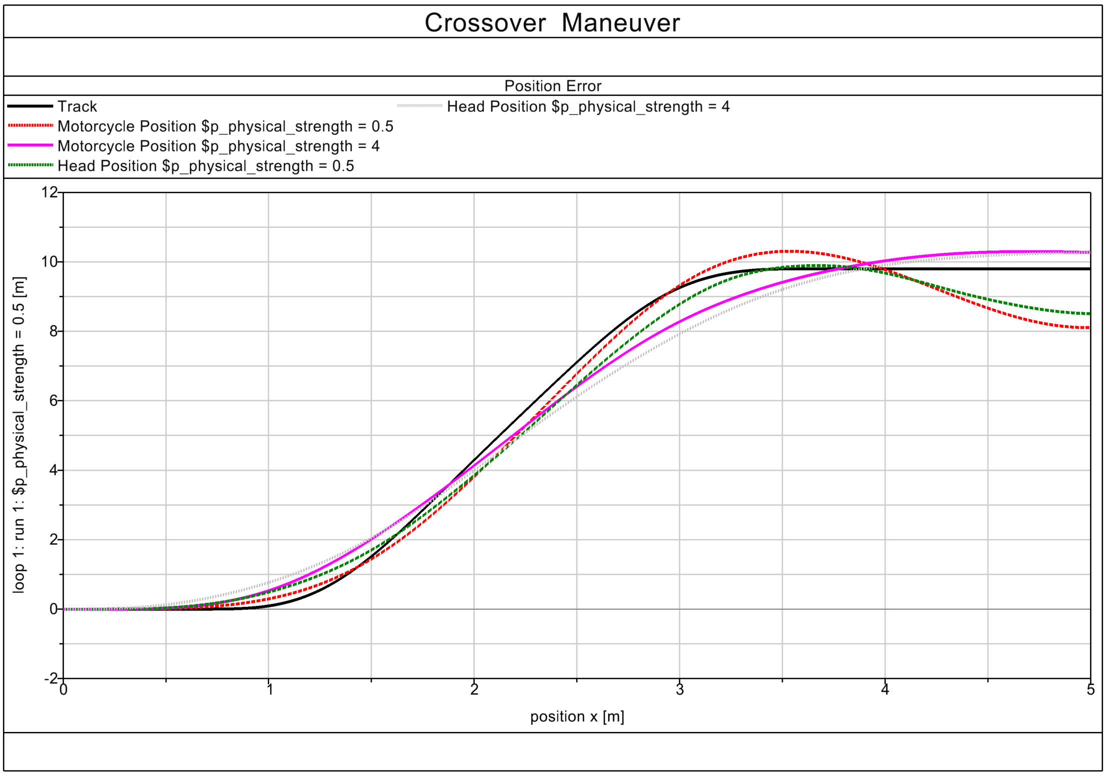


Figure 13. Crossover under variation of muscular tension

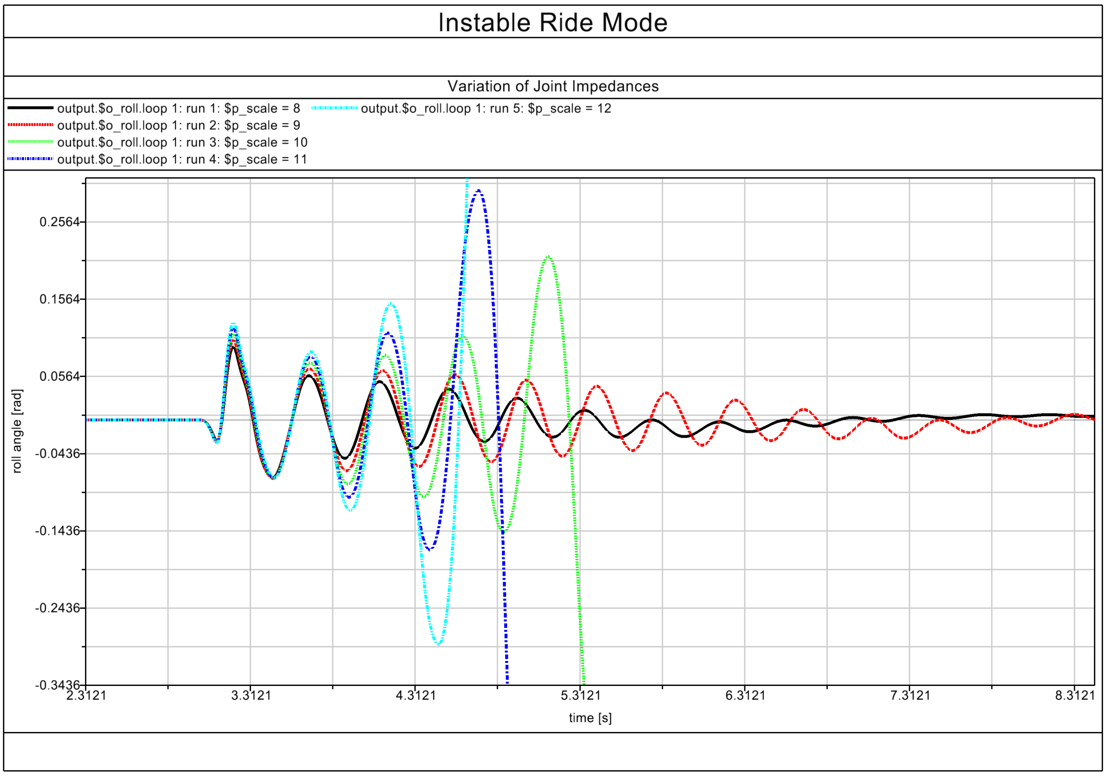


Figure 14. Influence of muscular tension on weave

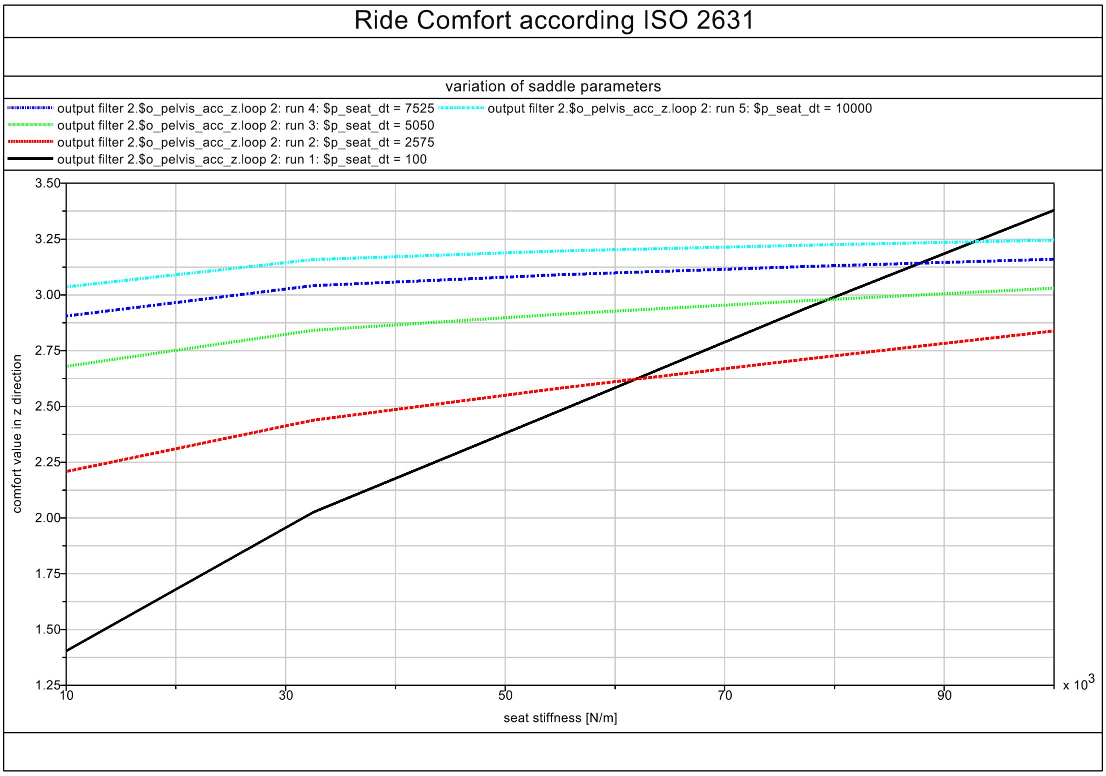
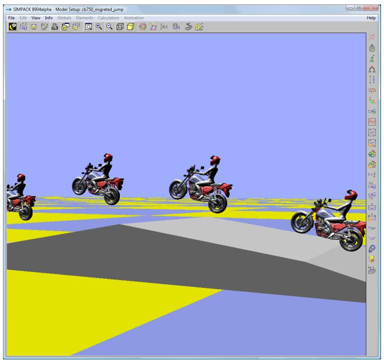


Figure 15. Ride comfort analysis (ISO 2631) under saddle parameters variation.



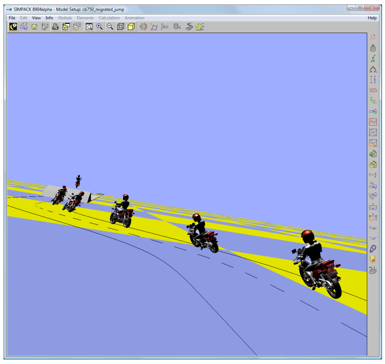


Figure 16. The biomechanical rider is capable of handling tasks like straight running, cornering and even jumping (some animations can be found under http://www.biomotion-solutions.de/motorcycleridersimulation.0.html).

6 REFERENCES

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