CUSTOMER APPLICATION | Matthias Nusser, Veit Wank, Eberhard Karls University of Tübingen;
Valentin Keppler, Biomotion Solutions GbR

Musculoskeletal Model of Bicycle Pedaling

The objective of this project was to simulate the pedaling movement of cycling based on a modified musculoskeletal model, and to compare the results with the actual movement. The different activation patterns of the leg muscles necessary for the simulation were collected, prior to simulation, with an ergometer. The goal was to gain insights from the results about the functionality and capacities of our model so further modifications and developments could be put into action.

From a practical viewpoint, a model like this can help prevent injuries, for example, in easily-injured areas like the patella. Especially in the area of rehabilitation, bicycle ergometers are widely used and integrated into therapy. The creation of a high capacity simulation model, which will enable the diagnosis of muscle strength and strains, can improve therapy quality. Such a model can also improve competitive and recreational sports, for example, through optimal saddle positioning.

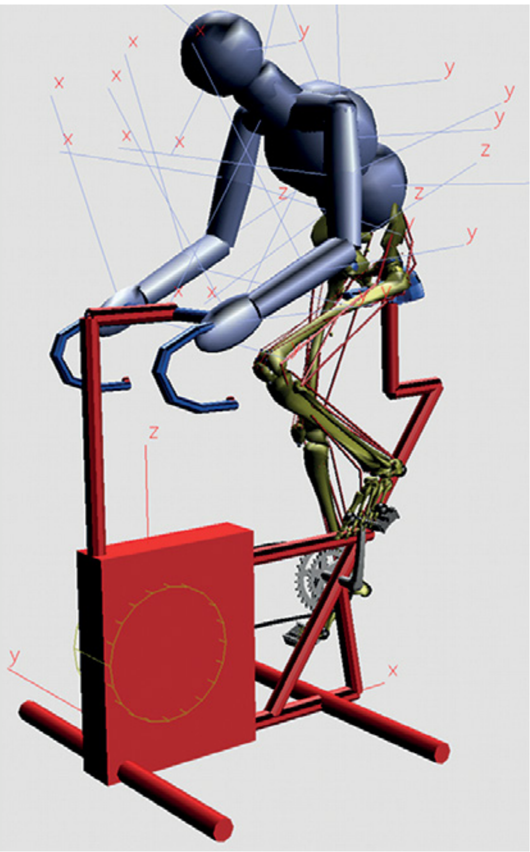


Fig. 1: Musculoskeletal model of the lower limb

The project for "modeling and simulating cycling based on a musculoskeletal model" was carried out as a thesis at the Institute of Sports Science, Sports Biomechanics and Exercise Science at the University of Tübingen, Department of Biomechanics, under the supervision of Professor Dr. Veit Wank and in cooperation with the company Biomotion Solutions GbR. The following text provides a short summary of the project and its results.

"The collected pedaling kinematics data was used to calculate an average motion pattern of a pedal cycle."

THE MECHANICAL MODEL

The foundation of our simulation was a musculoskeletal model of the lower extremities, which was formerly used at the University of Tübingen to calculate the pressure distribution within the hip joint [1]. The human body has been modeled by 23 rigid bodies. Data for mass and inertia of the body segments have been taken amongst other sources from NASA publications [2].

Most of the essential, anatomical data on the musculoskeletal model of the lower limbs was based on work by Scott L. Delp [3, 4]. The complex model for the lower extremities consisting of more than 40 muscles per leg was reduced to the simulation of these muscles that could be measured reliably. Therefore sixteen muscles (8 at each leg), generating moments for the cyclic movement of the legs during bicycling were adopted into the model.

The mechanical properties of each muscle were implemented in the model as contractile element (CE) parallel elastic element (PEE) and a serial elastic element (SEE). The mathematical formulas described by A.V. Hill [5] were used as a base for the force development of the muscle force element in the model.

As the muscles are acting along a complex path along the bones of the lower limbs, each muscle has been realized as a muscle force controller which calculated the muscle force and by one or more point to point force elements to actuate the bones with the muscle forces calculated by the controller. Some of the muscles are acting on a muscle path which calls for muscle wrapping. Therefore eight moved markers have been implemented at each femur. As some muscles in the leg can "lift off" at some of the contact points if the legs are in a stretched position, these moved markers allow the muscle to lift off the femur when knees are straight and to wrap around the femur and patella if the knees are bent.

The bicycle model consists of 6 bodies (crank, 2 pedals, fly wheel, chassis, and saddle). A torque element acting on the flywheel enabled the simulation of different brake torques to simulate, e.g., pedaling against constant power or velocity dependent brake torque. The feet of the human body model were connected to the pedals by force elements to simulate click-in pedals which were used during the measurements. The human body model was connected to the saddle by a bushing-like force element.

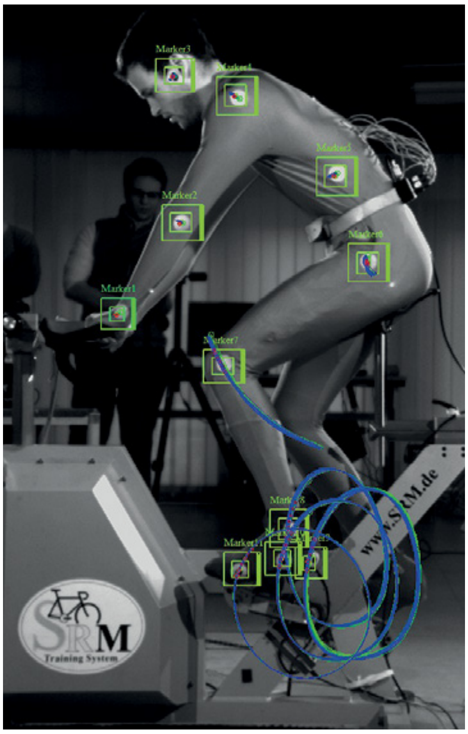


Fig. 2: Biomechanical motion analysis using high-speed video data

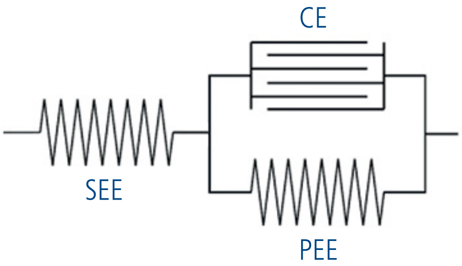
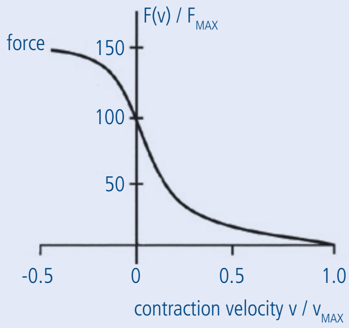


Fig. 3: Muscle model with contractile element (CE) and elastic structures (PEE, SEE)

Hill's Equation

The muscles' behavior in the model is described through Hill's 1938 empirical investigated equation.

In Hill's Equation, the hyperbolic connection between muscle force and contraction velocity is mathematically formulated.



$$\left(F_{CE}+a\right)\left(v_{CE}-b\right)=-\left(F_{CE}|_{v_{CE}=0}+a\right)b$$

EXPERIMENTAL SETUP

For further comparisons between simulated and real pedaling movement at the Karlsruhe Institute for Technology (KIT), data was collected in order to identify important physiological and biomechanical parameters of the performance of the bicycle rider. We used a scientific ergometer build by SRM (Schoberer Rad Messtechnik, www.srm.de) which was equipped with a 2D pedal force measurement device (Powertec®) which allowed for capturing the acting forces during pedaling in tangential and radial direction. The Powertec system measures the pedal forces by two sensors which determine the magnetic field variations (Hall-Effect) as a result of the displacement in respect to a magnet [6]. At different pedaling frequencies and power settings, together with the forces acting on the pedals, the total power and the activation pattern for each of the 16 muscles were recorded (Fig. 4).

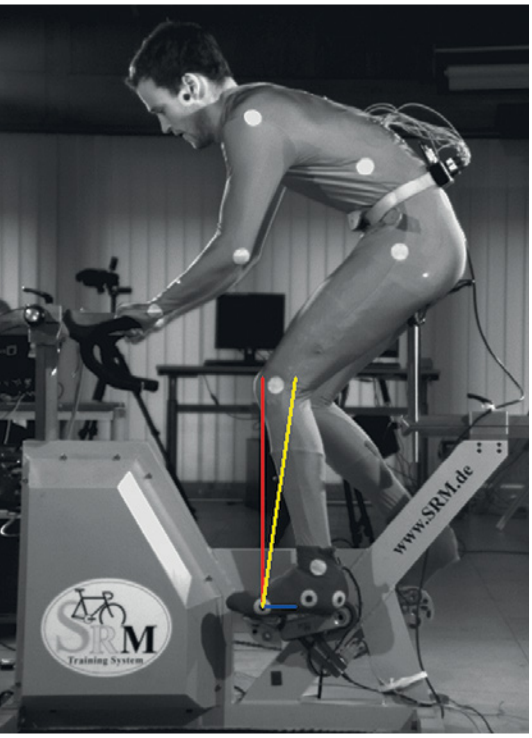


Fig. 4: Pedal forces measured by strain gauge system

A planar motion analysis was carried out with high speed videos and markers attached to the subjects joints (Fig. 2). Video analysis has been done with sub pixel accuracy by automatic pattern tracking using the software TraXXol. To enhance the accuracy of the measured motion data, large white markers have been placed on the subject who was additionally wearing a black elastic full body suit to maximize the contrast. The collected pedaling kinematic data was used to calculate an average motion pattern of a pedal cycle. To enhance the accuracy of pedal torque data, we captured the crank angle with a high speed camera and motion analysis, too. For reliable analysis, the data (pedal forces, crank-torque, both perspectives of the camera, as well as EMG-signals) was time synchronized.

"The simulation has been done by co-simulation between SIMPACK and SIMULINK."

MUSCLE ACTIVATION DURING SIMULATION

As a first simulation approach, the necessary activation patterns for the simulation were generated from the EMG data. The data was always synchronized with the current angle of the crank. The EMG-signal of each muscle was collected and averaged throughout up to 20 cycles. The identified strength of the signals, collected from the highest isometric contraction, was used for the standardization. The activation patterns gained through EMG-analysis were used to control the simulation. This has been done by co-simulation between SIMPACK and Simulink®.

The input for the controller given by the SIMPACK model was the crank angle. The Simulink model calculated the new stimulation vector for each leg (in total 16 activation signals) by use of a look-up table.

As the EMG-signals for both legs differed slightly, we decided to symmetrize the artificial EMG-Data so, we substituted the measured EMG-signals for the left leg by the 180 degree shifted signals from the right leg.

RESULTS

Three simulations were done in total, each with different adjustments. In the first simulation, the power was kept at a constant level; in the second simulation, the effective crank-torque was kept constant. The third simulation was performed using a speed-dependent damping for generating the crank-torque. A clear match was identified between measured and simulated crank speed. The minimum values of crank velocity occur in the upper and lower turning point; the maximum values occur on horizontal pedal position.

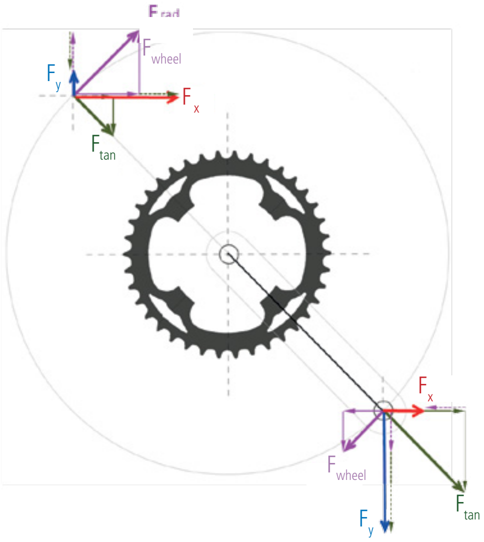


Fig. 5: Tangential and radial pedal forces acting at the crank

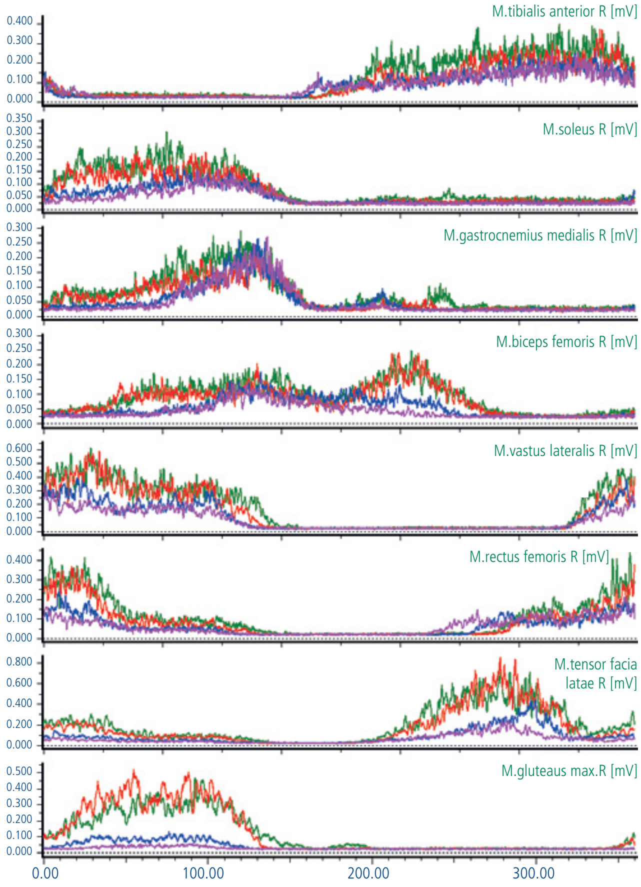


Fig. 6: Muscle activation patterns of pedaling measured with EMG

Looking at the animation or the joint angle velocities of the human body model revealed that the approach to activate the muscles by measured data is not sufficient to get a smooth and effective pedaling motion. This is based on the fact that our model contains only feed forward control so far. The lack of feedback partially leads to suboptimal stimulation timing. But the results of this study are very promising, and the model will be extended with a closed loop control for muscle stimulation.

SUMMARY AND VIEW

The simulation of the cyclic leg movement while cycling, based on EMG-measured muscle activation patterns, shows a correspondence with the collected data. In the first approximation, it can be proved that the model is valid. But it is obvious that modification and fine tuning of the muscle activation routines is necessary. To further fine tune the model, it may be necessary to pay attention to the smaller muscles of the leg. Specifically it can be assumed that implementation of a feedback loop for muscle stimulation control might enhance the quality of the results.

The generated model together with the SIMPACK model is a good basis for expansion and modification of the existing model, to possibly create more realistic results in future simulations.

Fig. 7: Muscle activation patterns were measured through electromyography (EMG)

BIBLIOGRAPHY

[1] Prochel, Anton; "Erstellung eines komplexen Muskel-Skelett-Modells zur Berechnung der Druckbelastung in Gelenken bei vorwärtsdynamisch simulierten Bewegungsformen" (2009)

[2] Chandler, R.F. Clauser, und C.E. MCConville; "Investigation of inertial properties of the human body"; AMRL Technical Report, NASA Wright-Patterson Air Force Base, 74, 1975

[3] Delp, Scott L., and J. Peter Loan, "A graphics-based software system to develop and analyze models of musculoskeletal structures", Computers in biology and medicine 25.1 (1995): 21–34

[4] Delp, Scott L., et al; "An interactive graphics-based model of the lower extremity to study orthopaedic surgical procedures"; Biomedical Engineering, IEEE Transactions on 37.8 (1990): 757–767.

[5] Hill, A. V.; "The heat of shortening and the dynamic constants of muscle"; Proceedings of the Royal Society of London. Series B, Biological Sciences 126.843 (1938): 136–195.

[6] Stapelfeldt, B., et al; "Development and evaluation of a new bicycle instrument for measurements of pedal forces and power output in cycling"; International journal of sports medicine 28.04 (2007): 326–332.

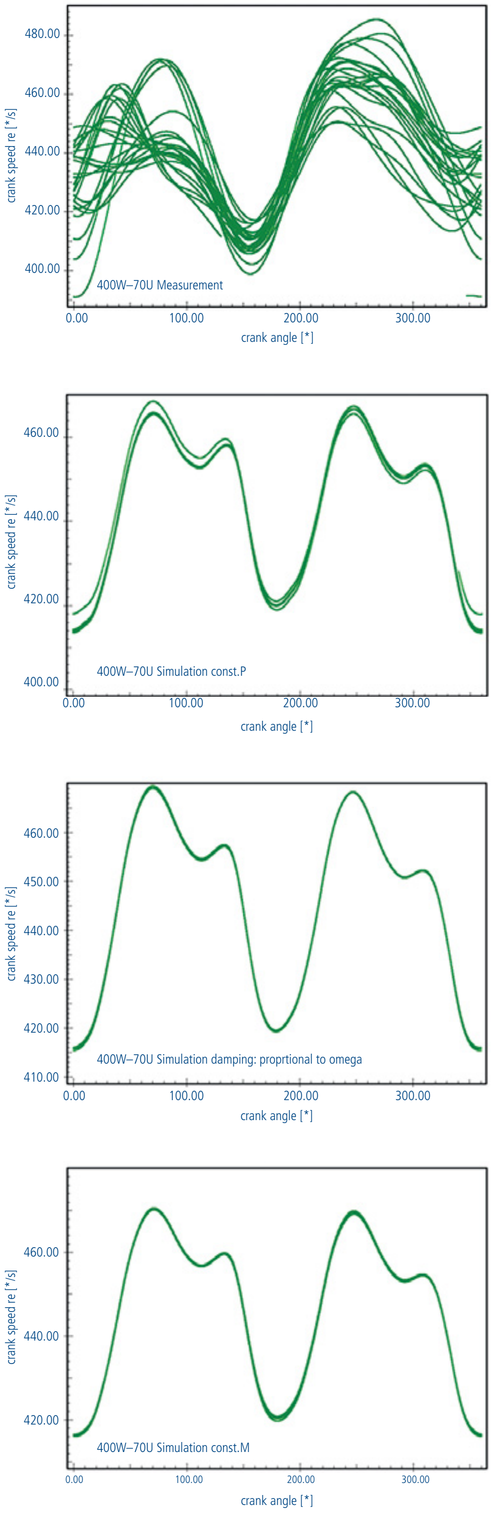


Fig. 8: Crank velocity of an average cycle in measurement (top) and results of simulations with different crank reaction torques