

# Study of Human Steering Tasks using a Neuromuscular Driver Model

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The aim of this work is the creation of a realistic driver model to help develop new technologies to aid drivers in the execution of their driving tasks. A realistic driver model can reduce the time-consuming trial and error process of designing products, and thereby reduce the vehicle's development time and cost. The overall goal of this research is to develop an interface between driver and vehicle for designing Electric Power Steering (EPS) controllers that can account for the driver's characteristics and preferences. To develop such an interface, a predictive driver model is utilized to estimate the steering wheel angle required to follow a desired path. To provide a physiologically realistic steering manoeuvre, a musculoskeletal arm model considering the neuromuscular system is included in the driver model. This driver model can provide insights into task performance and energy consumption of the driver, including fatigue and co-contraction dynamics of a steering task. In addition, this driver model in conjunction with a high-fidelity steering model can be used to develop new steering technologies such as EPS and lane keeping.

Neuromuscular driver model, Human musculoskeletal system, Electric power steering system, Vehicle dynamics, Control, Multi-body dynamics modeling, Hill muscle model

## 1. INTRODUCTION

Steering systems are one of the most important components in automobiles because they directly interact with drivers, and their performance considerably affects the steering feel. New steering technologies are developing to aid drivers in the execution of their driving tasks, and to improve their steering feel. One way to improve the traditional design of steering systems is to consider the driver's characteristics and preferences in the design process. However, developing driver-based technologies requires proper understanding of the driver itself. With such understanding, one possible solution might be augmenting the actuator controller with driver feedbacks and preferences to provide improved steering response and better steering feel. However, how steering response and steering feel can be measured or even defined is the subject of ongoing research and debate. One important tool for designing new steering products is to develop a realistic driver model to reduce the time-consuming trial and error process of designing products, and eventually reduce the vehicle's development time and cost.

The majority of research papers on car steering

present a path-following driver model in which the driver chooses the proper steering wheel angle based on the vehicle's states and the desired path. The physical characteristics and limitations of the driver are not included in these controllers. A minority of research papers have followed a different approach and focused on the human musculoskeletal system (HMS), which gives insight into task performance, disturbance rejection and energy consumption. For example, Pick and Cole in a series of papers [1-4] introduced a comprehensive neuromuscular system (NMS) model structure, and studied the effect of steering torque feedback and driver learning behavior. Later in [5], the authors identified the torque generating muscles in a steering maneuver task by measuring the muscle activation voltage (electromyography).

Hoult [6] developed a neuromuscular driver model based on the Zahalak Modified Distribution-Moment approximation (MDM) method, which demonstrates contribution to motor behavior and states that metabolic energy consumption considerations may influence motor control.

However, these models cannot predict the neural excitation and activation dynamics signals, cannot easily consider the effects of age and gender in the force

producing muscles. Activation dynamics are the processes that describe the delay between neural excitation arriving at the muscle and the input to the contractile element of muscle. Activation dynamics and neural excitation provide a representation of muscle fatigue and energy consumption.

The ultimate goal of this ongoing research is to study and eventually design an Electric Power Steering (EPS) controller that accounts for the driver's characteristics and preferences. The first necessary step to study and design an EPS controller is to develop an interface between the driver and vehicle. To develop such an interface, a predictive driver model in conjunction with a HMS model of a driver arm is developed. A multi-point predictive controller is utilized to estimate the steering wheel angle required to follow a desired path. The HMS model of driver arm is added to the model to provide physiologically realistic steering maneuvers as shown in Fig. 1. This driver model can provide insights into task performance and energy consumption of the driver, including fatigue and co-contraction dynamics of a steering task. In addition, this driver model with a high-fidelity vehicle model can be used to develop new steering technologies such as EPS and lane keeping.

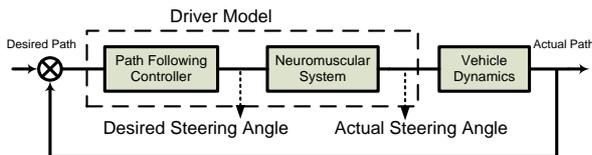


Fig. 1: Schematic block diagram of a driver model

## 2. DYNAMICAL MODELING

The development of more reliable and precise dynamical models is a key step for developing objectives and repeatability in the design process. Based on different demands and applications, different models of vehicle and human drivers have been developed to better understand, analyze and improve the combination of driver and automobile.

In this research, to study the driver-steering interaction, a simulation setup including a driver model with multi-body vehicle dynamics is developed as shown in Fig. 1.

### 2.1 Vehicle Dynamics

The dynamical equations of motion of a full vehicle including a double-wishbone front suspension, semi-trailing arm rear suspension, and a column-type EPS system were developed using the MapleSim multi-body dynamic package. The graphical representation of the developed steering system is shown in Fig. 2. The major mechanical components of EPS systems are the steering wheel, rack, EPS motor and gearbox. The dynamic equations of the DC motor and nonlinear friction of the steering column, motor

shaft and rack are added to the model to provide higher fidelity. The nonlinear frictions are represented by a continuous piecewise linear friction profile. Three external loads, the driver torque, assist torque and road-tire friction force, are applied to the steering system at the steering wheel, steering column and rack, respectively. In this research, the road-tire friction force is modeled using a Fiala tire model within MapleSim environment, the assist torque is produced by an EPS controller based on the EPS characteristic curves, and the neuromuscular driver model produces the driver torque.



Fig. 2: The developed vehicle model in MapleSim

In this paper, a Proportional-Integral-Derivative (PID) controller is utilized to assure a suitable assist torque extracted from a pre-established EPS characteristic curve.

### 2.2 HMS Driver Model

In this research, a neuromuscular driver model including a path-following controller in conjunction with a human musculoskeletal system model of driver arm is developed. For the path-following controller, a multi-point predictive controller is utilized [7]. This controller considers both the dynamics of the vehicle and path-previewing techniques, and is developed based on the steady-state response of the vehicle in a circular path. The multi-point predictive controller uses the weighted sum of lateral displacements of several preview points from the desired path to compensate for the predicted displacement error. On the other hand, an HMS gives insight to task performance [8], disturbance rejection [9] and energy consumption [6]. The HMS is a complex system including chemical, electrical and mechanical components. Skeletal muscle as a component of HMS involves all the mentioned perspectives. For example, muscle activation dynamics is a chemical-electrical process and contraction dynamics is a highly nonlinear procedure. This section covers the development of a simple HMS model of the driver arm for use in driver simulation.

As shown in Fig. 3, the driver model consists of a one degree of freedom segment, representing a human arm pivoting at the shoulder, and including two muscles, one flexor and one extensor. Muscle models are inspired

from the popular Hill muscle model [10]. The three-element Hill-type model is shown in Fig. 4. This model includes a Contractile Element (CE), a Parallel Elastic element (PE), and a Series Elastic element (SE). The CE is the muscle's actuator and is representative of the active part of the muscle. The PE models the tissue parallel to the CE element, and the SE represents the tendon [11].

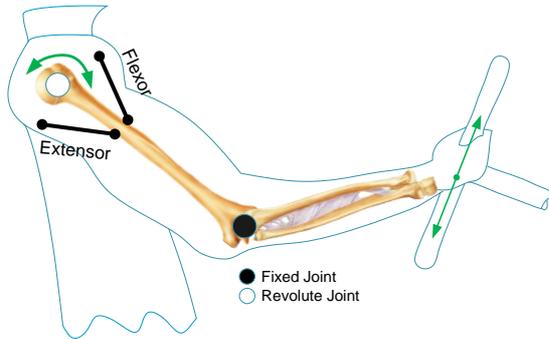


Fig. 3: The simplified driver model

Fig. 5 shows the schematic view of the HMS driver model. The neuromuscular model is an indeterminate dynamic system because the number of muscles is more than the degrees of freedom (DOF), which requires an extra criterion to reach a unique solution. Usually this muscle redundancy is solved by assuming that a human minimizes a specified cost to perform the desired motion. This cost could be metabolic energy [12], muscle fatigue [13], [14], etc. Here, the driver's muscle fatigue is considered as the objective function of the optimization.

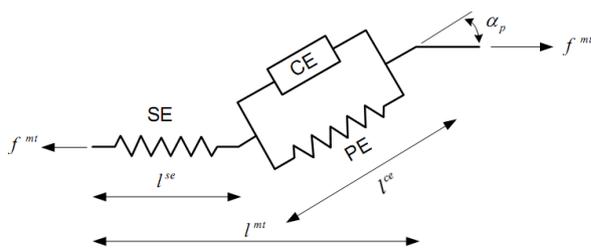


Fig. 4: An example of a Hill-type muscle model [10]

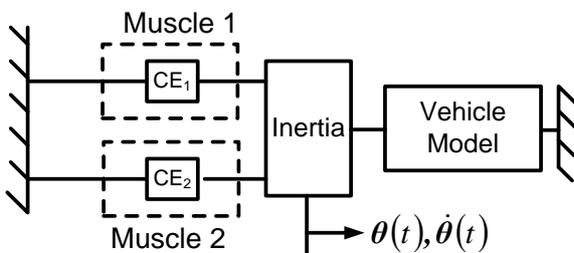


Fig. 5: Schematic of the HMS driver model

This proposed neuromuscular driver model is human-centered, meaning that the capabilities, limitations and preferences of the driver can be taken into account in the design process. The proposed driver

model with activation dynamics can consider many factors such as age and posture and also can be utilized to quantify driver characteristics such as fatigue and total mechanical energy consumption which then can be applied in the control design process. Therefore, this simulation setup can provide a good interface between driver and vehicle to study and design new steering technologies.

The force generated by a muscle can be separated into force-length and force-velocity dependent functions. A schematic diagram of these two relations is shown in Fig. 6. There are some studies in the literature regarding how to calculate the force from the length, velocity and activation. In this research, a similar formulation from Buchanan [15] is used. Considering the CE only and a constant moment arm for muscles, the muscle torque as a function of joint angle, joint angular velocity, and activation can be written as follows:

$$T_m = T_0^m \bar{T}_\theta^{CE}(q) \bar{T}_\omega^{CE}(\dot{q}) a(t) \quad (1)$$

The torque-angle dependent function is approximated with the following formula:

$$\bar{T}_\theta^{CE}(\theta) = A + B\theta - K\theta^2 \quad (2)$$

The  $\bar{T}_\theta^{CE}(\theta)$  relation was considered such that the produced torque greater than  $\theta = 90^\circ$  and less that  $\theta = -180^\circ$  would be zero;  $\theta = 0^\circ$  is where the upper arm is perpendicular to the driver's trunk. Furthermore, the peak value, which is the maximum normalized torque, must be equal to one and occurs at  $\theta = -45^\circ$  which seems reasonable for a driver. This posture is the most convenient where the driver's hand can exert force on the steering wheel. Considering the above, the shape parameters of the  $\bar{T}_\theta^{CE}(\theta)$  curve can be calculated symbolically.

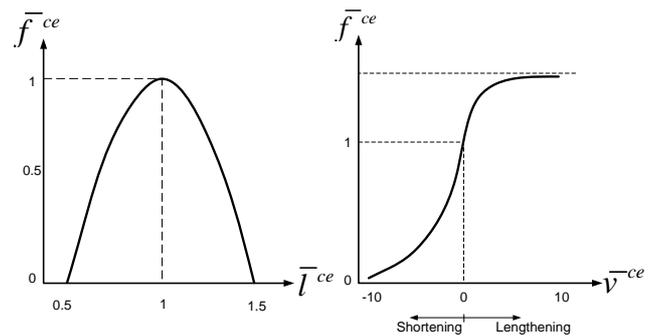


Fig. 6: Force-length and Force-velocity relationships [16]

The torque-angular velocity dependent function is approximated with the following formula:

$$\bar{T}_\omega^{ce} = \begin{cases} (1.8 + 0.8C_{ecc}) \dot{\theta} / (\dot{\theta} + C_{ecc}) & \dot{\theta} \geq 0 \\ (\dot{\theta} + 1) / (-C_{conc}\dot{\theta} + 1) & \dot{\theta} < 0 \end{cases} \quad (3)$$

where in equations 2 and 3,  $A$ ,  $B$ ,  $K$ ,  $C_{ecc}$ ,  $C_{conc}$  are the constant shape parameters of the muscle dynamic equations and the piecewise  $\bar{T}_\omega^{CE}(\dot{\theta})$  is defined such that continuity of the function at  $\dot{\theta} = 0$  is guaranteed.

### 3. EPS CONTROLLER

In this paper, an EPS system is used to show the effectiveness of the proposed simulation setup to study assistant steering technologies.

In this section, a Proportional-Integral-Derivative (PID) strategy is implemented on the described column-type EPS system and performance of this method is investigated. The job of the EPS controller is to provide assistance and comfort for drivers and to reduce the driver's physical effort to improve the steering feel. However, performance criteria in EPS systems such as comfort and feel are subjective matters and are not directly quantifiable by physical measurements. To alleviate this problem, automobile manufacturers developed EPS characteristic curves. These curves usually are developed based on a series of experiments on a group of drivers with different levels of experience, sex, and age. These curves suggest the suitable amount of additional assistance torque to achieve an appropriate steering feel for an average person. Typical EPS characteristic curves are shown in Fig. 7, which shows the assist current (torque) plotted against measured driver torque. For safety reason, the assist torque decreases as the vehicle speed increases.

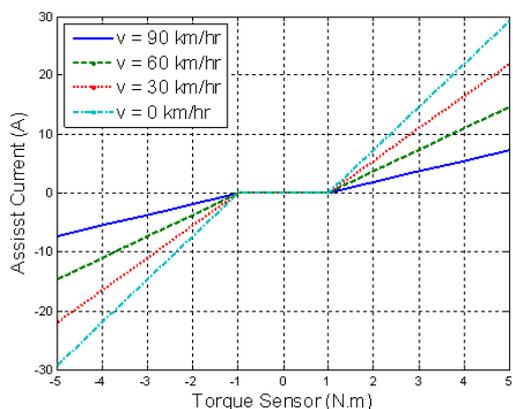


Fig. 7: Typical characteristic curves of an EPS system

In this section, a classic PID control strategy is applied to the EPS system to track the desired torque. Based on the steering torque and vehicle speed and pre-established characteristic curves, the target current of the electric motor is defined. The difference between the target current and the feedback current measurements feeds into a PID control algorithm to reduce the error. The dynamic equations of the EPS and vehicle generated by the MapleSim program were exported to Matlab/Simulink environment, where the control logic of the EPS was implemented. Fig. 8 shows the schematic diagram of the simulation setup.

### 4. SIMULATION

To study performance of this model and EPS controller, two examples are simulated for the system

shown in Fig. 8. The first example is simulating a sinusoidal steering maneuver to identify shape parameters of the torque-angular velocity function, which are unknown due to the unavailability of experimental measurements at this time. The second example is performing a closed-loop simulation including the neuromuscular driver model and full multi-body vehicle model, as well as the EPS system to study the effectiveness of the simulation setup as a suitable simulation environment to study steering technologies.

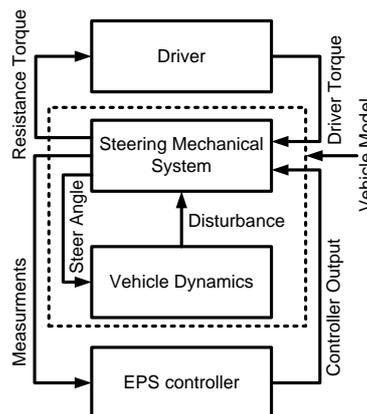


Fig. 8: Schematic flowchart of the simulation setup

In this model, activation signals of flexor and extensor muscles are assumed unknown. Fig. 9 shows the schematic workflow for estimating activation signals. Based on the specified steering wheel motion, the motion of shoulder can be calculated using inverse kinematics (IK) as shown in Fig. 3. Then, to determine the activation of each muscle, the total required shoulder torque is calculated using inverse dynamics. Next, the portion of participation of each muscle and the related activation can be computed by minimizing a physiological cost function (CF).

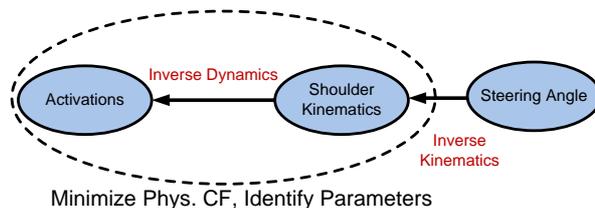


Fig. 9: Schematic work flow for identifying the muscle's parameters

In the first example, to identify the shape parameters of torque-angular velocity function, an optimization is done for the system shown in Fig. 5 with a simple sinusoidal steering wheel maneuver with amplitude of 60 degrees and frequency of 0.5 Hz. In this model, for simplicity the steering system is replaced with a rotational spring and damper. In this optimization, activation signals and shape parameters of muscle relations were assumed unknown, and they were identified by using the specified steering wheel angle

and minimizing muscle fatigue:

$$CF = \sum_{i=1}^2 a_i^2 \quad (4)$$

Fig. 10 and Fig. 11 show the optimal activation, and torque-angular velocity dependent responses with optimal parameters for the aforementioned maneuver. Trends of the torque-angular velocity plot seems to be physiological and in good agreement with popular models in the literature. The transition slope between centric ( $\dot{\theta} > 0$ ) and concentric ( $\dot{\theta} < 0$ ) contractions is also in a reasonable range [17].

Fig. 10 shows that there is no co-contraction between muscles, which is consistent with the assumed cost function, i.e. to minimize fatigue, the muscles never work against each other.

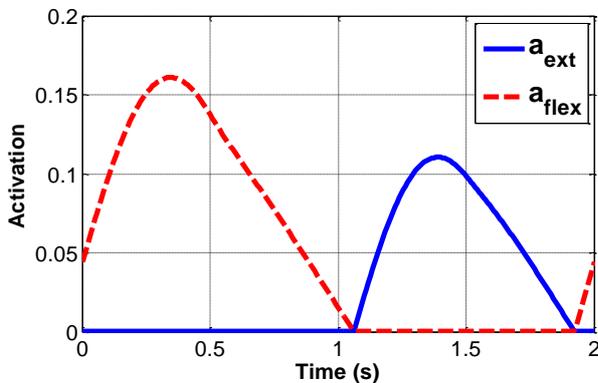


Fig. 10: Optimized activation signals for flexor and extensor muscles

After identifying the muscle shape parameters, they are used in the neuromuscular driver model to perform a closed-loop simulation including the EPS controller. A closed-loop simulation is necessary to study the controller in a steering maneuver. For the second example, the standard ISO double lane-change maneuver is performed with and without the EPS system. This maneuver is typically utilized to simulate the behavior of the system in an obstacle avoidance maneuver, when a quick driver response is required. In this simulation, the velocity of the vehicle is assumed to be constant and equal to 20 m/s.

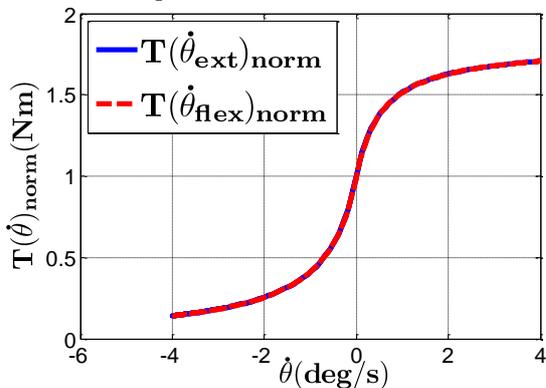


Fig. 11: Identified torque-angular velocity dependent function

In this simulation, activation signals were estimated using an optimization algorithm that minimized muscle fatigue and the error in tracking the specified steering wheel angle:

$$CF = \int_{t_0}^{t_f} w_1 \sum_{i=1}^2 a_i^2 + w_2 \left( \frac{\theta - \theta_{des}}{\theta_{max}} \right)^2 dt \quad (1)$$

where  $w_1$  and  $w_2$  are the weighting factors tuning the contributions of each sub-cost function. The purpose of  $\theta_{max}$ , the maximum of desired steering wheel angle, is to non-dimensionalize the tracking error term.

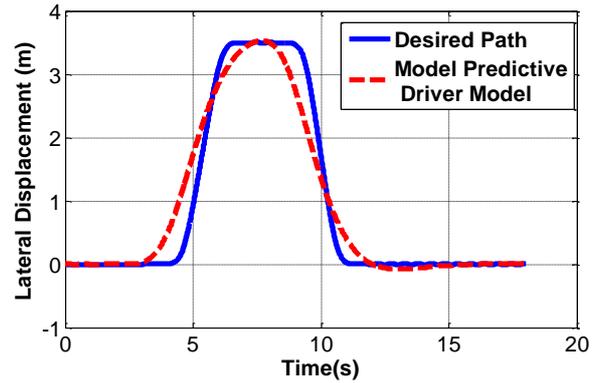


Fig. 12: Model predictive driver model for ISO lane change path

Fig. 12 shows the desired path and the actual path of the vehicle using the neuromuscular driver model. The slight difference between the actual and desired paths is due to the slow vehicle's dynamic response. Therefore, the driver steers before the corners to be able to follow the trend of the desired path. The actual path of the vehicle with and without EPS is the same; therefore, the steering wheel angle is also the same for both conditions.

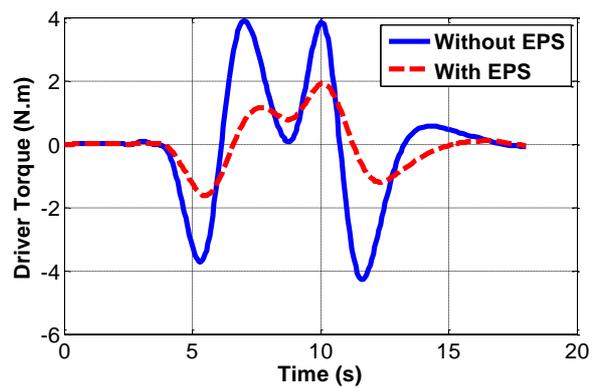


Fig. 13: Driver torque with and without EPS

In Fig. 13, the solid and dashed lines show the required driver torque to follow the desired path with and without the EPS system. This figure shows that the vehicle equipped with an EPS system can effectively reduce the driver's physical effort to steer the vehicle. The results reflect the effects of the steering system on the driver, and vice-versa, which can be used in the

steering design process.

### 5. CONCLUSION

Driver models of various degrees of complexity have been developed over the last half-century, but a significant portion of the research has focused on the brain's use of the internal vehicle model for tracking a desired path. Consequently, few research studies concentrated on the human neuromuscular system, which contributes to task performance, disturbance rejection and energy consumption.

In this paper, a simple neuromuscular driver model including a multi-point predictive controller and a pair of agonist and antagonist Hill-type muscles is developed. This model can predict muscle activation signals, which can be used to quantify objective criteria such as fatigue, which can be represented by the summation of the squared activation signals. This model can be easily manipulated to take preferences and limitations of a specific driver such as satisfactory co-contraction and maximum driver torque into account. Then, this information can be utilized in the designing process of steering technologies, for example in the designing process of EPS characteristics curves. So far, no major study has focused on the effect of considering a neuromuscular driver model in the designing of a steering system.

Based on the aforementioned discussions and simulations, the usage of such systems in the design process can significantly reduce the vehicle's development time and cost, and improve the quality of the final products. However, developing such models is still the subject of ongoing research.

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### APPENDIX

#### Nomenclature

Notation	Description	Value
$T_0^m$	Maximum muscle torque	150
$A$	Constant shape parameter	8/9
$B$	Linear shape parameter	-8/(9 $\pi$ )
$K$	Quadratic shape parameter	16/(9 $\pi^2$ )
$C_{ecc}$	Eccentric shape parameter	0.1
$C_{conc}$	Concentric shape parameter	7.8