Neuromuscular Analysis as a Guideline in designing Shared Control

Abbink D.A. and Mulder M.
Delft University of Technology
The Netherlands

1. Introduction

The challenges in designing human-machine interaction have been around for decades: how to combine the intelligence and creativity of humans with the precision and strength of machines? It is well known that manual control tasks are prone to human errors. The conventional engineering solution is to either fully automate a (sub)task or to support the human with alerting systems. Both approaches have inherent limitations, widely described in literature (e.g., Pritchett, 2001; Sheridan, 2002).

Recently, an alternative solution is receiving increased attention: that of shared control. In the shared control paradigm, an intelligent system continually shares the control authority with the human controller. The idea behind shared control is to keep the human operator in the direct manual control loop, while providing continuous support. Shared control has been investigated for a wide range of applications, for example during the direct control of automobiles (e.g., Griffiths & Gillespie, 2005; Mulder et al., 2008a&b) and aircraft (e.g., Goodrich et al., 2008), or during tele-operated control to support gripping (Griffin et al., 2005), surgery (e.g, Kragic et al., 2005), micro-assembly (e.g, Basdogan et al., 2007) or the steering of unmanned aerial vehicles (e.g., Mung et al., 2009).

There is no strict definition of shared control, but the systems described in literature can be classified in two categories (see Figure 1 for an illustration):

1. "input-mixing shared control", which influences the input to the controlled system
2. "haptic shared control", which influences the forces on the control interface

Shared control of the first category shapes the input to the controlled system to be a mix of the output of the control interface (as a result of human input) and the output of an automation system. An example is the lane-keeping assistance system based on a potential-field approach (Switkes et al., 2006), in which a desired tyre angle is controlled by a steer-by-wire system, which combines the driver's desired steering angle with the steering angle from the assistance system. In other words, when the driver's actions agree with the goal of the assistance system, the system generates no additional steering input. But when the driver disagrees with the assistance system (i.e., steers out of the lane), an additional steering input is generated by the steer-by-wire system so that the command to the tyres will ensure good lane-keeping performance. Note that in this case, there can not be a direct

mechanical coupling between steering wheel angle and tyres. It is also important to realize that the driver cannot overrule the system, and may not even be aware of the system's activity, especially when there is no force information.
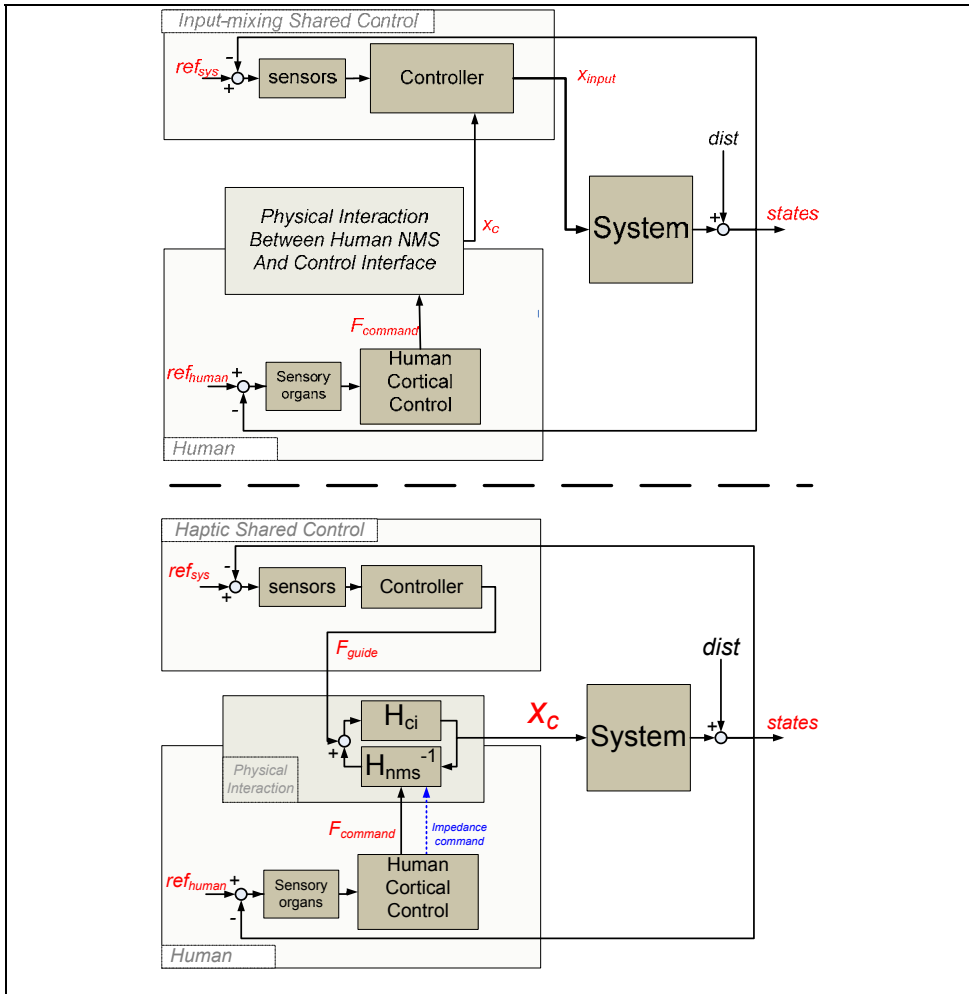

Fig. 1. A schematic, symmetric representation of both categories of shared control: input-mixing (top) and haptic shared control. In both cases, the human and system have sensors to perceive changes in system states (possibly perturbed by *dist*), each having a goal (ref$_{human}$ and ref$_{sys}$, respectively). During input-mixing shared control, the steering output X$_c$ is weighed by the controller that determines the input to the system. During haptic shared control, both human and system can act with forces on the control interface (with F$_{command}$ and F$_{guide}$ respectively). Through physical interaction, the control interface (H$_{ci}$) exchanges force and position with the human limb (H$_{nms}$), of which the neuromuscular impedance can be adapted.

Shared control of the second category allows both the human and the support system to exert forces on a control interface, of which its output (its position) remains the direct input to the controlled system. These systems are sometimes called haptic guidance systems, or force feedback systems and are essentially dynamic extensions from the static 'virtual fixtures' approach (Rosenberg, 1993). A good example is a lane-keeping assistance system in which a motor acts on the steering wheel by adding torques (Griffiths & Gillespie, 2005; Forsyth & MacLean, 2006; Brandt et al, 2008; Mulder et al., 2008b). Note that the relationship between steering angle and tyre angle remains constant, which has been found to be important for vehicular steering (Toffin et al., 2007). Moreover, the driver is not only aware of the system's actions, but can also choose to overrule the system's activity. Part of the driver's neuromuscular response to the feedback forces is passive (due to limb inertia), but it is well known that humans can greatly influence their effective stiffness and damping through muscle (co-)contraction and reflexive feedback.

The influence of neuromuscular adaptability in shared control is acknowledged in most literature, but not well understood. As a result, the tuning of the feedback forces is a trial-and-error process. This process is further complicated by the fact that there is a (probably subject-dependent) trade-off between good performance with a dominant system authority and mediocre performance with less system authority. Although in general the reported shared control systems provided beneficial results such as improved performance and reduced mental load, negative effects were reported as well that seem to indicate that forces were tuned too high. Many subjects did not feel completely in control (e.g., Forsyth & MacLean, 2006), and it was somewhat difficult for subjects to avoid collisions not foreseen by the system (e.g., Griffith & Gillespie, 2005). Lacking quantitative knowledge of neuromuscular response to forces, it is quite difficult to optimally design the feedback forces.

The underlying hypothesis in the current study is that measurements and models of the neuromuscular system will improve the understanding of human response to forces, and thereby, the design of haptic shared control (which will be the focus of this chapter).
Although much relevant knowledge is available in the field of neuroscience, the haptic community has left this knowledge largely unused for shared control design. Therefore, this chapter has the following goals:
1. to provide a brief introduction on human motion control for shared control researchers
2. to provide a novel architecture for shared control systems, based on human motion control models
3. to provide quantitative measurements for the neuromuscular properties for steering
4. to show how much neuromuscular feedback properties influence the steering behaviour during shared control.
In section 2, the brief introduction to human motion control is presented along with the novel shared control architecture. In section 3, the experimental methods will be shown for two experiments that address the third and fourth goal, respectively. Section 4 contains the experimental results. Section 5 will discuss the results, and finally in Section 6 the conclusions will be presented.

2. Neuromuscular control and shared control

2.1 Overview of neuromuscular control

Humans have the ability to adapt their neuromuscular system to the physical environment they interact with, through both feed-forward control and feedback control. For example, humans can learn fast and efficient goal-directed movements, and can realize these same movements with different levels of muscle co-contractions, in order to provide additional stability.

Feedback control of neuromuscular mechanisms, is often called impedance control (Hogan, 1984). Adaptations in impedance control do not only arise from changes in muscle-contraction, but also from changes in afferent feedback. Afferent feedback provides the nervous system with information about muscle stretch and stretch velocity (through muscle spindles) and muscle force (through Golgi Tendon Organs), and has been shown to substantially contribute to impedance control (e.g., Doemges and Rack 1992b, Mugge et al., 2009). Note that afferent feedback is much more energy-efficient than muscle co-contraction.

Impedance control is experimentally investigated by perturbing a limb, and measuring the mechanical and electromyographical responses. Literature shows that these responses are very adaptable, and depend on task instruction (e.g., Hammond 1956; Doemges and Rack 1992b; Abbink 2007), the level of muscle (co-)contraction (Jaeger et al. 1982), the displacement amplitude (Stein and Kearney 1995), the frequency content in the perturbation signal (Van der Helm et al. 2002, Mugge et al. 2007) and the mechanical load which the subject interacts with (De Vlugt et al. 2002).

Goal-directed control is hotly debated in literature, specifically whether it can better be explained by internal model control theories (e.g., Wolpert et al., 1998) or equilibrium-point control theories (e.g., Feldman et al, 1990). Recent studies have provided evidence that internal model control and impedance control can operate as separate mechanisms for motor control (Osu et al., 2002), and are both active during learning of new movements (Franklin et al., 2003). Results show substantial muscle co-contraction when faced with motion tasks in novel environments, which decreases when the task has been learned (after several repetitions), suggesting that impedance control assists in the formation of the inverse model, and provides stability during the learning process. Note that, theoretically, from an energy point of view, it would be optimal to have no co-contraction during well-learned goal directed movements when no perturbations are present. However, it has been suggested that some level of co-contraction is needed to overcome internal perturbations, from sensor and motor control noise (Osu et al., 2004).

This body of knowledge has unfortunately been largely ignored in haptic shared control design. It is common in human manual control literature to disregard impedance control. The neuromuscular system is often described either as a gain, or at best as a second-order low-pass filter, focusing on its role in limiting the position bandwidth of the control interface (e.g., McRuer & Jex, 1967; Keen & Cole, 2006). However, through impedance control of the neuromuscular system, human operators can respond much faster to forces on their control interface than visual or vestibular cues would allow. For example, through muscle co-contraction and reflexive feedback drivers can respond to steering wheel forces that arise from road irregularities, faster (i.e., at a higher bandwidth) than through slower visual feedback.

There are only a few studies that have evaluated neuromuscular feedback in the design of a haptic shared control system: only for car-following (Abbink, 2006) and for unmanned aerial vehicle control (Lam et al, 2009). Unsupported manual control has received slightly more interest: for example, neuromuscular models and measurements have been developed for side-stick control for aircraft (Van Paassen, 1995), gas pedal control (Abbink, 2007) and steering (Pick & Cole, 2007; Pick & Cole, 2008) for automobiles. Typically, the research approach consists of performing a separate experiment in which the response to perturbations is measured, usually during tasks where the subject is instructed to "relax / do nothing", or to "resist the perturbations" during postural tasks. The response is then characterized by a mass-spring-damper model, and subsequently used in model predictions. Recent work has shown that subjects can not only resist forces or relax, they can also decide to actively give way to forces (Abbink, 2006; Abbink, 2007), thereby decreasing their mechanical impedance even below relaxed impedance. Accurate (mechanical and electromyographical) measurements, closed-loop identification and advanced model parameterization techniques have shown that giving way to forces can be accomplished by Golgi Tendon Organ reflex activity (Abbink, 2006; Mugge et al, 2009).

In short, there is ample evidence that:
- manual control tasks require both feed-forward control and impedance control
- impedance control is not only achieved through muscle co-contraction but through afferent feedback as well.

How can we use this knowledge when analysing and designing shared control systems?

2.1 Shared Control based on knowledge of Neuromuscular Control

The main goal of haptic shared control is to keep the human in the loop and provide forces that will continuously assist the human, improving task performance at reduced levels of physical or mental load. Consequently, forces should not be experienced as a perturbation that has to be opposed through impedance control. From an energy perspective it would be optimal if the human is completely relaxed (no muscle co-contractions) in face of forces from the shared control system. However, the forces could also be designed so that subjects can actively give way to them, using their reflexive system for fast responses and little co-contraction. This idea was explored in our group during a research project sponsored by Nissan Motor Co., in which a continuous haptic support system for car following was developed (Abbink, 2006; Mulder et al., 2007). It was designed so that drivers could keep the distance to a lead vehicle constant if they kept the force on the gas pedal constant, thereby reducing control activity and muscle activity while maintaining the same car-following performance. Neuromuscular analyses provided evidence that subjects were indeed giving way (reduced mechanical impedance) when interacting with the haptic support system, and did so using Golgi Tendon Organ activity.

Can we use this kind of analysis already in the design phase of shared control systems? A biologically inspired shared control system would need a good internal representation of the environmental dynamics it is interacting with, more specifically: the impedance of the human operator's limb that is mechanically coupled to the control interface. Then, if the goals of the system and the human coincide, there will be a low-impedance interaction that will be beneficial to the human in terms of performance and control effort.

Moreover, a shared control system that is modelled after human motion control could not only generate forces, but could also adapt its impedance. In this way a smooth shifting of control authority can be realized, the benefits of which have been shown experimentally (Abbink & Mulder, 2009).

The generalized architecture for the proposed haptic shared control is presented in Figure 2.
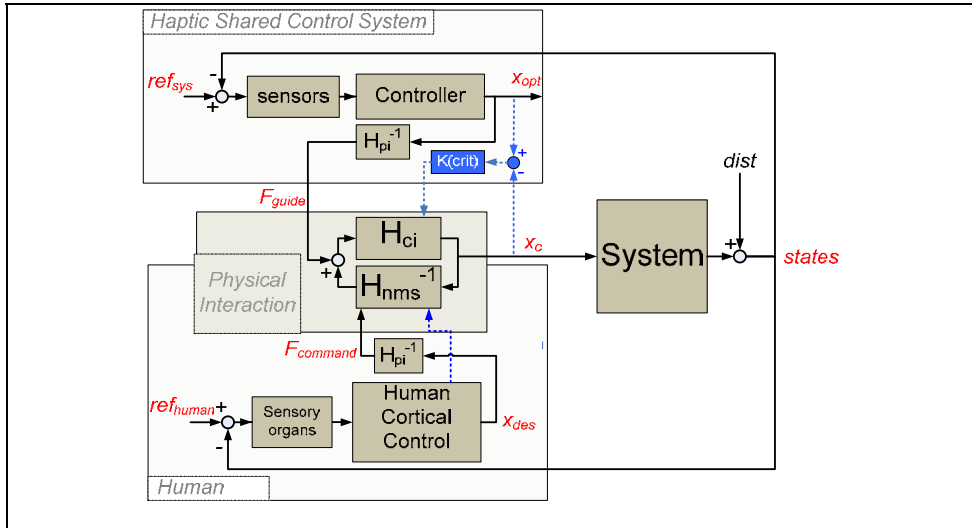

Fig. 2. A schematic, symmetric representation of the proposed haptic shared control architecture based on neuromuscular knowledge. The human operator can generate force ($F_{command}$) and adapt the impedance of her/his neuromuscular system H_{nms} (dotted line). Likewise, the system can not only generate force (F_{guide}) but also adapt the impedance of the control interface H_{ci} (shown by dotted line), for example changes in stiffness based on some criticality function K(crit). Moreover, the system needs to have a good internal representation of the total physical interaction dynamics (H_{pi}) just like the human.

Consider an application for lane-keeping. The support system needs sensor information from the road and car states relative to the road as an input for a control model that continuously calculates the optimal steering angle x_{opt}. Such a control model could be based on potential fields or optimal control, but perhaps an actual representation of a skilled, attentive driver would yield the best driver acceptance.
Note that this optimal control input x_{opt} could be used directly to control the vehicle, which would result in automation. But since the purpose is to share control, x_{opt} will, instead, be translated to a guiding force F_{guide}, which, by itself, would cause the steering wheel to move to that optimal angle x_{opt}. If there would be no driver to hold the steering wheel, the system would need to know only the steering wheel dynamics H_{ci} (in a linear case: stiffness, damping and inertia) to calculate the required guidance force F_{guide}. However, when the driver grips the steering wheel, the driver's neuromuscular dynamics H_{nms} will influence the response to feedback forces and the system should take into account the total physical interaction dynamics H_{pi} (the combined stiffness, damping and inertia of both the driver's

limbs and the steering wheel). The total physical interaction could be measured offline, during other experiments.

Tuning of shared control forces based on neuromuscular measurements
Then, if the system is tuned for the combined physical interaction during a 'relax' situation, drivers can simply hold the steering wheel and if they are indeed relaxed (i.e., do not generate forces or change their impedance) the systems desired steering wheel angel x_{opt} will result from the guidance forces F_{guide}, with an accompanying different vehicle trajectory. The system could also be tuned to only yield the correct x_{opt} during a 'give way' task, in which the driver would need to actively yield to the feedback forces (essentially amplifying them) in order to let the optimal position be reached. Then, smaller feedback forces could be used, and drivers would be more involved in the control loop then when they would only do a 'relax task'.
In either case, if drivers have a different reference trajectory ref_{human} - and therefore a different desired steering wheel angle x_{des} - they can use feed-forward or feedback control to resist the shared control forces.

Adaptive impedance of the shared control
The proposed architecture allows the steering wheel system to respond likewise: when a driver does not respond adequately to a critical situation, the impedance of the steering wheel around x_{opt} can be smoothly and temporarily increased, guiding the driver to more acceptable steering wheel angles, clearly communicating the severity of the situation. Essentially the wheel will act as a predictive display for steering actions that are incorrect from the system's point of view. Clearly, if the impedance is increased to the extent that the driver can not influence the steering wheel angle anymore, this will (temporarily) result in an automation system. For safety reasons, the maximal steering wheel impedance should be limited based on neuromuscular measurements of maximal human impedance (measured during a 'resist forces' task) and maximal steering wheel forces.

The effects of neuromuscular adaptability and adaptive impedance for shared control
In the remainder of this chapter, experimental evidence is provided to illustrate the extent to which drivers can vary their neuromuscular dynamics when interacting with a steering wheel. Also, it will be shown how several tunings for shared control system ('dominant', 'slack') are influenced by different neuromuscular settings ('give way', 'relax', 'resist'), in case feedback forces are given to support the driver during an evasive manoeuvre.

3. Experimental Methods

3.1 Apparatus
The experimental setup used for both experiments consists of a fixed-base driving simulator with an actuated steering wheel (Moog FCS ECoL-8000, "S"-actuator). The base-line steering wheel dynamics consisted of a slight centring stiffness $K_{sw}=4.2$ Nm/rad, a damping B_{sw} of 2 Nms/rad and an inertia I_{sw} of 0.3 Nms^2/rad, yielding a system with Eigen-frequency 0.6 Hz and relative damping of 0.89. Adaptations to the steering wheel dynamics and feedback forces could be communicated to the control loading computer of the steering wheel at 100 Hz. The steering wheel actuator was force controlled by the control loading computer at an

update rate of 2500 Hz. Subjects were asked to be seated in an adjustable car seat and were requested to hold the steering wheel (diameter: 38 cm) with both hands in a "ten-to-two" position (see Figure 3).

Fig. 3. A close-up of a subject holding the steering wheel, which could be perturbed or which could provide haptic guidance. The human reaction torque T_c and the resulting angular rotations X_c were measured.

During experiment 1, task-related information was shown by means of a Sanyo PLC-XU33 multimedia projector, projected on a screen in front of the subject at a distance of approximately 2.9 m from the eye-reference-point of the experiment subjects. The projector was positioned such that the centre of projection was aligned with the eye-reference-point. Refresh rate of the displayed image was 50 Hz. Graphical resolution of the projected image was 1280x1024 pixels at a screen width and height of 3.3x2.1 m².

3.2 Experiment 1: Neuromuscular Adaptability

The goal of the first experiment was to quantify the adaptability of the neuromuscular dynamics as a function of task and hand placement. Ten subjects (5 male, 5 female) participated in the first experiment. The subject's age was 26.4 (+/- 3.3) years. All subjects were recruited from the university student population. Participation was voluntary, no financial compensation was given.

Task instruction

Subjects were told they would experience torque perturbations on the steering wheel and were given three tasks to perform: resist the forces (or position task: PT), give way to the forces (or maintain force task: FT), and relax (RT). When resisting or giving way to forces, subjects received visual information of their task. During the 'resist force' - task a white, vertical line indicated the target position. A red, vertical line, starting in the middle of the screen indicated the current steering wheel position. The red, vertical line expanded upwards as a time-history of the measured wheel positions, so that subjects could monitor their performance. Performance is defined here as how well subjects could maintain the steering wheel position on the target position as indicated by the white line. For the 'give way' task, the goal was essentially to maintain zero force on the steering wheel, therefore the white, vertical line indicated zero force. The red, vertical line, showed a time-history of

the measured wheel forces. For the relax task, no visual information was shown. Before the experiments, participants were told that for the force and position task, "…you will see a white line and a red column. In either task, the purpose is to maintain the red column on the while line to the best of your ability, while your steering wheel is disturbed." For the relax task they were told to "…do nothing, just leave your hands on the steering wheel, while it is being disturbed."

Hand positioning
The experiment was conducted for three hand positions on the steering wheel: both hands (BH), left hand only (LH) and right hand only (RH). When only one hand was used during the relax task, the steering wheel would have a bias angle to that side due to the weight of the arm turning the steering wheel somewhat. To prevent this, a bias torque of approximately ±0.2 Nm was added to the torque perturbation signal in these cases. This bias torque effectively put the steering wheel in the centre position with a passive arm holding it on either the left or right side.

Perturbation design
The torque perturbation was an unpredictable multi-sine signal, scaled such that for each task approximately similar steering wheel rotations were obtained in order to prevent effects of amplitude non-linearity (e.g., Stein & Kearney, 1995). The frequency content of the perturbation was designed according to the Reduced Power Method (Mugge et al., 2007). This method yields perturbations with full power at low frequencies (in this case 0.02 - 0.5 Hz) and only a small percentage of that power at higher frequencies (in this case up to 20 Hz). This is done to avoid the suppression of reflexive activity that occurs when exciting reflexes at frequencies beyond their bandwidth (van der Helm et al., 2002). The method effectively evokes low-frequent behaviour, while allowing the estimation of neuromuscular dynamics over a large bandwidth.

Experiment protocol
The nine different conditions (3 tasks, 3 hand positions) were each repeated four times. The positioning of the hands was randomized within the subjects. Between subjects the order of the task was also randomized. To prevent fatigue, the tasks were then alternated in this random order for each hand position and each repetition within each subject. Participants were trained for each task until satisfactory performance was. The total duration of the experiment was approximately 30 minutes.

Data Analysis
The following signals were logged at 100 Hz: steering wheel torque (T_c), steering wheel position (X_c), and torque disturbance (D). All repetitions were averaged in the time-domain. Subsequently, closed-loop system identification based on spectral densities (e.g., van der Helm et al., 2002) was done to calculate the dynamics of the human, of the steering wheel and of the combined physical interaction. They are all represented not as impedance, but as its mathematical inverse: the admittance, the causal relationship between input force and output position: admittance.

3.3 Experiment 2: Neuromuscular Adaptability for different Shared Control Impedance

The goal of the second experiment was to show how different neuromuscular settings (give way to forces, resist forces, relax) would influence shared control. A small group of three male subjects (mean age 30) participated in the experiment, for which no financial compensation was given.

Task instruction

Subjects were told they would experience torque feedback on the steering wheel from several shared control systems, some of them strong, some of them weak. This torque feedback would guide them to perform steering activity to make a fast lane change. Subjects were asked to hold the steering wheel with both hands (as shown in Figure 3) and to resist the torques, give way to them, or be relaxed in face of the forces.

Shared Control Design

The actuated steering wheel provided the subject with shared control, which was identical to the look-ahead based haptic guidance controller for curve negotiation used in previously published research (Mulder et al., 2008b). Essentially, the system guides drivers along an optimal path. The properties of the shared control could be tuned to yield desirable response, by means of two parameters: the force feedback gain and the stiffness feedback gain (Abbink et al., 2009). Through the force feedback gain, the strength of the feedback forces in response to look-ahead errors could be influenced (essentially determining the force F_{guide} from Figure 2). Stiffness feedback was an implementation of the idea to dynamically change impedance discussed in section 2.2. The additional stiffness acted around the optimal angle calculated by the look-ahead controller, and was designed to dynamically depend on the current lateral error with respect to the system's reference trajectory (the function *K(crit)* in Figure 2). Through the stiffness feedback gain, the gain on this lateral error could be increased. Note that because of the baseline steering wheel stiffness K_{sw}, there would always be some steering wheel impedance even if the stiffness feedback gain would be zero.

For this experiment, several settings were investigated, of which three will be presented here:

- the weakest shared controller (baseline force gain, no stiffness gains). The human has most authority in this situation – the driver easily overrides the haptic guidance controller in case there is disagreement on x_{opt};
- the medium shared controller (baseline force gain, double stiffness gain). The human and the haptic guidance controller have similar authority – the driver and controller present forces of similar magnitude to the interface;
- the strong shared controller (double force gain, double stiffness gain). The haptic guidance controller has most authority in this situation – the driver will have to use considerable force to override the haptic guidance controller in case there is disagreement on x_{opt}.

Note that although the shared control architecture is as proposed in this chapter, the gains were not based on neuromuscular measurements, but determined by trial-and-error. The purpose here was to show how different neuromuscular settings influence the functioning of different shared control systems.

Experiment protocol

Subjects were presented with a two-lane driving track on which the shared controller's reference trajectory would shift to the other lane and back, three times. The change in reference trajectory for the shared controller caused it to generate force feedback to follow that trajectory. The tracks were driven for the three shared control settings, and three different task instructions. The distance between changes in the reference trajectory was random, to prevent learning effects. The total duration of the experiment was approximately 10 minutes.

Data Analysis

The following signals were logged at 100 Hz: steering wheel torque (T_c), steering wheel position (X_c), and the lateral and longitudinal position of the car's centre of mass.

4. Experimental Results

4.1 Results for Experiment 1

Figure 4 shows the estimated admittances for a typical subject. These results were similar for all subjects. The squared coherence was generally high, indicating linear behaviour for the experimental conditions studied.

In the left column the solid lines denote the admittances estimated with both hands. There is a large difference in admittance at low frequencies. For example, subjects substantially reduced their admittance when resisting forces (position task, PT) compared to the relax task (RT). This indicates that, as expected, the steering wheel angles as a result of a external forces are much smaller when subjects try to resist those forces. It also shows that subjects can substantially increase their admittance when trying to give way. The wide range of admittances (FT more compliant than RT; PT behaviour much more stiff than RT) is consistent with previous experiments on the arms (Damveld et al., 2009) and the ankle joint (Abbink, 2006; Abbink 2007; Mugge et al., 2009).

Another result is that with both hands on the steering wheel, subjects could perform their task better (larger admittance during 'give way' tasks, and a smaller admittance during 'resist' tasks) than with only one hand. During the relax task, not much effect was found as a result of different hand placement.

In the middle column the estimated steering wheel dynamics are shown, which correspond to how the dynamics were set: that of a well-damped second-order system with eigen-frequency of 0.6 Hz. Naturally, the steering wheel dynamics are not affected by hand position or task instruction.

In the right column the total physical interaction dynamics was estimated, arising from both the human limbs and the steering wheel. It can be seen that the smallest admittance (i.e., the highest impedance) dominates the total physical response: during PT the total physical admittance is bounded by the driver, during FT the total physical admittance is bounded by the steering wheel stiffness.
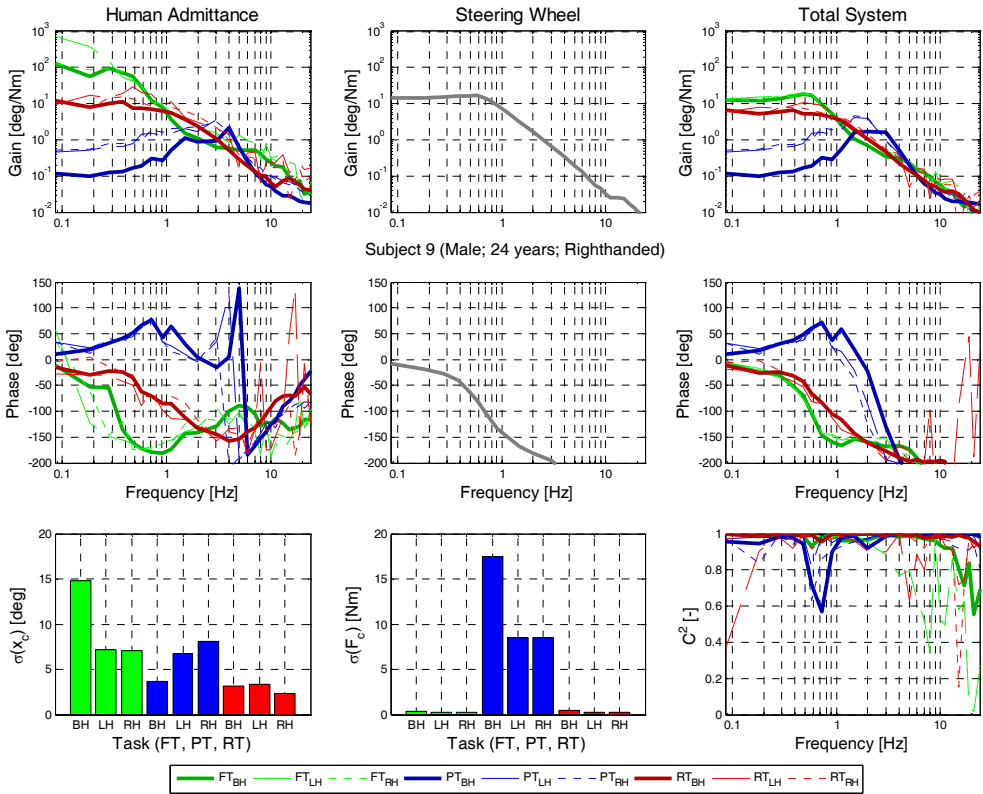
Fig. 4. Results of experiment 1: the estimated admittance for a typical subject, for three tasks (resist forces 'PT'; relax 'RT'; and give way to forces 'FT') and three hand positions: left hand only (LH - thin line), right hand only (RH – thin dashed line) and both hands (BH solid line). The top panels show the magnitude of the admittance, the middle panels the phase, and the bottom right panel the squared coherence. The lower left panel shows the standard deviations of the steering wheel angle, X_c. The lower middle panel shows the standard deviations of the steering wheel torques F_c. The left column shows the admittance of the human, the middle column that of the steering wheel, and the right column the combined physical interaction dynamics.

4.2 Results for Experiment 2

Figure 5 shows the results for a single lane change manoeuvre of a typical subject, guided by three different shared control systems: the lightest system (left column), the medium system (middle column) and the strong system (right column). The stronger the shared control, the stronger it guides the driver during relax and force tasks (give way) towards the optimal trajectory, but also, the more difficult it is to overrule the feedback forces and drive straight on (as can be seen from the forces f_c and position x_c).

Another interesting result is that by giving way (FT), the driver is always closer to the system's desired trajectory: the human is then cooperating with the system. The required forces to do so are small (in the same order of magnitude as during the relax task).
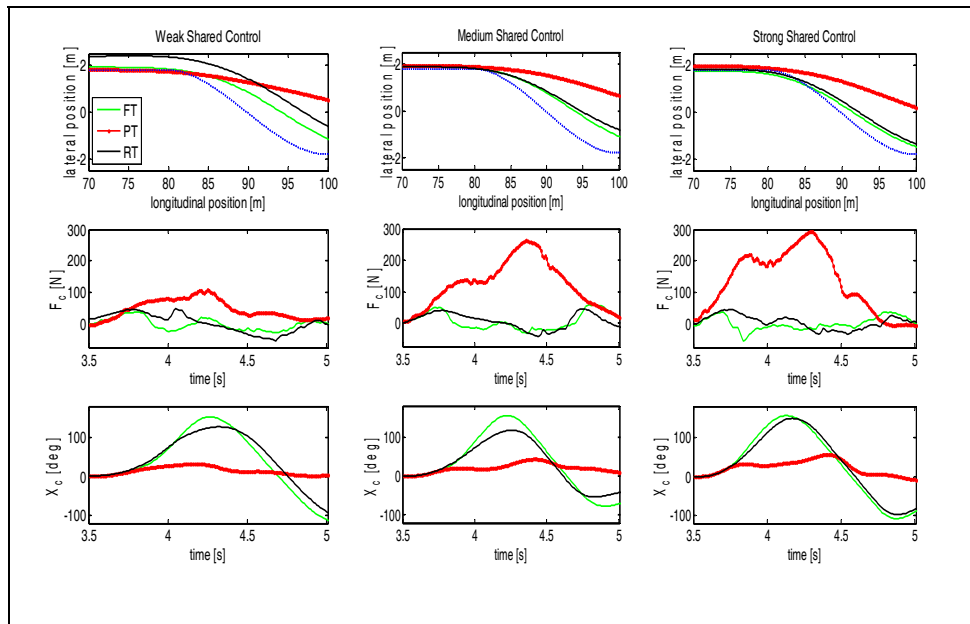

Fig. 5. Results of experiment 2: a single lane-change manoeuvre for a typical subject, to illustrate the influence of the strength of shared control and the neuromuscular dynamics on lane position (top), driver's force (middle) and steering wheel angle (bottom). The dashed line in the top row denotes the system's reference trajectory, to steer from the centre of one lane (1.8 m), to the centre of an adjacent lane (-1.8 m).

5. Discussion

The experiments showed that the possible adaptation range in human impedance control is extremely large when controlling a steering wheel: at low frequencies a factor of a 1000 could be distinguished between giving way to forces and resisting them. This adaptability confirms the underlying hypothesis of this chapter that it is difficult to design shared control forces if the neuromuscular impedance is not known. Even if the system's goals and controller completely match the human goals and control strategy, when trial-and-error tuning has tuned the forces to be optimal for a slightly 'resist forces' task (somewhere in between relaxed state and maximally resisting state) the feedback forces will be too large, and the human will have to resist them sometimes, or be satisfied with a different trajectory.

Moreover, the experimental results strengthen the evidence found in other studies (Abbink, 2006; Abbink, 2007), which suggest that minimizing force errors (i.e., giving way to external forces) is not only *possible*, but also *useful* when interacting with guidance forces from shared

control systems. The second experiment – shared control for a lane-change – showed that also in that situation subjects could effectively give way to feedback forces. Consequently, appropriate steering actions could be made faster and with less effort, resulting in a trajectory that more closely matched the system's reference trajectory, without the need to increase feedback forces or control interface impedance.

The admittance results during relax tasks closely resembles those found in other studies (e.g., Pick & Cole, 2007), but that during 'resist force' tasks an even larger decrease in admittance was encountered for the subjects in the present study. This is probably caused by the different perturbation signals used. When using perturbations with full power up to 10 Hz, all reflexive activity will be suppressed, as has been shown in previous research (van der Helm et al., 2002; Mugge et al., 2007). The additional low-frequent stiffness found in the present study is likely the result of reflexive activity, although visual contributions may not be ruled out at low frequencies (below approximately 1 Hz).

The idea of scaling the impedance of the steering wheel (Abbink et al., 2009) has been shown in this study to be compatible with adaptations in neuromuscular impedance. The studied shared control system provides continuous support that can cause drivers to steer faster (when giving way to forces), and still be always overruled (when resisting forces). It was observed that at high authority levels of shared control the difference between giving way and relaxing became smaller. This corresponds to the results in experiment 1, which demonstrates that –according to the laws of mechanics – the strongest spring (highest impedance) dominates the dynamic behaviour of the combined physical interaction. In other words, at high authority levels of shared control the steering wheel became more stiff than the relaxed human impedance, reducing the influence of a more compliant human (during give way tasks) on the combined physical impedance.

Future Work

This chapter has provided arguments that it is beneficial to base shared control properties on neuromuscular analyses, as well as some experimental evidence. The designed shared control system with variable impedance should be tested more thoroughly then was done in experiment 2, with a larger subject group and with more in-depth analyses.

Even then, it is evident that more evidence is needed, in the form of a full design cycle for a novel shared control system based on the architecture presented in Figure 2. The design cycle should consist of in-depth modelling, shared control design, human-in-the-loop experiments, evaluation and model parameter estimation and validation. This will be the subject of further publications from the authors.

An important issue to address in future work is the extent to which the stationary measured neuromuscular response to perturbations during postural tasks corresponds to the actual impedance control during goal-directed movements of the steering wheel. To answer this question, two problems must be solved. First of all, unobtrusive estimations of admittance are needed while the human is engaged in a manual control task. Initial attempts during car-following (Abbink et al., 2006) and pitch control of an airplane (Damveld et al., 2009) are promising but require further investigation. Second, the time-variant nature of admittance needs to be quantified, for example through wavelets (e.g., Thompson et al., 2001).

Another interesting research spin-off would be to apply human motor-learning skills (Osu et al., 2002 ; Franklin et al. 2003) to the shared control system. If the system continuously feels resistance from the driver in certain curves, the system could learn that the driver cuts

corners differently than the system and could, with time, update the reference trajectory or the internal model for the physical interaction (Goodrich & Quigley, 2004).

All such future research could shed more light on how humans control their movements and control forces when interacting with feedback forces and changing impedance of the control interface. This is expected to substantially assist in the design of shared control systems.

6. Conclusions

From a literature survey and the proposed novel shared control architecture, the following conclusions are drawn:
- two kinds of shared control systems can be recognized in literature
  - input-mixing shared control which changes the control input to the system
  - haptic shared control in which the support system and the human operator exchange forces on the control interface
- Haptic shared control offers the human the possibility of fast and intuitive communication about system's actions, as well as the possibility to respond through changes in neuromuscular impedance.
- Although haptic shared control systems have shown interesting benefits in a number of applications, several issues remain. Subjects have reported the feeling that one is not in complete control; large forces are needed to overrule the system
- Quantitative measurements of neuromuscular impedance can be used to understand the human response to forces, and can serve as a basis to design shared control forces. This step is expected to aid the design process of shared control systems and avoid the current trial-and-error tuning.
- Dynamically changing the impedance of the control interface is an interesting way to smoothly shift control authority, and provide more guidance only when needed. A larger impedance of the control interface communicates the criticality of a situation to the driver, and helps to attenuate control actions that the system deems undesirable.

From the experiments, the following conclusions can be drawn:
- Subjects could substantially adapt their neuromuscular impedance during a steering task. Compared to the relaxed state, they could increase their neuromuscular impedance (during 'resist force' tasks) or decrease it (during 'give way' tasks).
- In agreement with the rules of mechanics, the impedance of the combined physical interaction was shown to be dominated by the largest impedance
- A shared control support system to assist with lane changes was investigated for three different levels of control system authority. The larger the control interface impedance, the more closely the drivers matched the necessary steering angle to follow the desired trajectory.

Acknowledgements

7. References

Abbink D.A. (2006). *Neuromuscular Analysis of Haptic Gas Pedal Feedback during Car Following*. Delft University Press, ISBN:978-90-8559-253-2

http://repository.tudelft.nl /file/447893/371671

Abbink DA (2007) Task instruction: the largest influence on Human Operator Control Dynamics. *Proceedings of World Haptics 2007*, pp. 206-211, Tsukuba, Japan, 22-24 March 2007.

Abbink, D.A & Mulder M. (2009). Exploring the dimensionalities of Haptic Feedback Support in Manual Control. *ASME Special Haptics Issue of JCSIE,* Vol. 9, No. 1, March 2009, pp 011006_1-9

Basdogan, C.; Kiraz, A.; Bukusoglu, I.; Varol, A. & Doğanay, S. (2007). Haptic Guidance for Improved Task Performance in Steering Microparticles with Optical Tweezers. *Optics Express*, Volume 15, No. 18, pp. 11616-11621.

Brandt, T.; Sattel, T. & Böhm, M. (2007). Combining Haptic Human-Machine Interaction with Predictive Path Planning for Lane-Keeping and Collision Avoidance Systems. *Proceedings of the IEEE Intelligent Vehicles Symposium*, Istanbul, Turkey, pp. 582-587.

Damveld, H.J.; Abbink, D.A.; Mulder, M.; Mulder, M.; van Paassen, M.M.; Van Der Helm, F.C.T. & Hosman, R.J.A.W. (2009). Measuring and Modeling the contribution of Neuromuscular Dynamics to Pitch Control Tasks. *In: Proceedings of the AIAA Conference*, August 2009, Chicago, USA

Doemges F. & Rack P.M.H. (1992b) Task-dependent changes in the response of human wrist joints to mechanical disturbance. *Journal of Physiology*, 447:575–585

Feldman, A.G.; Adamovich S.V.; Ostry, D.J. & Flanagan J.R. (1990) *In: Multiple Muscle Systems*, edited by Winters JM, Woo SL-Y. New York: Springer, 1990, ch. 43, p. 195–213.

Forsyth, B.A.C. & MacLean, K.E. (2006). Predictive Haptic Guidance: Intelligent User Assistance for the Control of Dynamic Tasks. *IEEE Transactions on Visualization and Computer Graphics*, Volume 12, No. 1, pp. 103-113.

Franklin, D.W.; Osu, R.; Burdet, E.; Kawato, M & Milner, T.E. (2003). Adaptation to stable and unstable dynamics achieved by combined impedance control and inverse dynamics model. *Journal of Neurophysiology* 90: 3270–3282

Goodrich, K.H.; Schutte, P. & Williams, R. (2008). Piloted Evaluation of the H-Mode, a Variable Autonomy Control System, in Motion-Based Simulation. *AIAA Conference*, August 2008, Hawaii pp.574-590

Goodrich, M.A. & Quigley, M. (2004) Learning Haptic Feedback for Guiding Driver Behavior. *Proceedings of the 2004 IEEE Conference on Systems, Man, and Cybernetics.* October 10-13, 2004, The Hague, The Netherlands.

Griffin, W.B.; Provancher, W.R. & Cutkosky M.R. (2005). Feedback Strategies for Telemanipulation with Shared Control of Object Handling Forces. *Presence*, 14(6): 720-731

Griffiths, P. & Gillespie R.B. (2005). Sharing Control Between Humans and Automation Using Haptic Interface: Primary and Secondary Task Performance Benefits. *Human Factors,* Vol.47, No. 3, Fall 2005, pp.574-590

Hammond P.H. (1956) The influence of prior instruction to the subject on an apparently involuntary neuro-muscular response. *Journal of Physiology* 132(1):17–18

Hogan, N. (1984). Adaptive Control of Mechanical Impedance by Coactivation of Antagonist Muscles. *IEEE Transactions on Automatic Control*, 29(8) (1984), pp. 681-690.

Jaeger R.; Gottlieb G. & Agarwal G. (1982) Myoelectric responses at flexors and extensors of the human wrist to step torque perturbations. *Journal of Neurophysiology*, 48:388–402

Keen S.D., Cole D.J., (2006). Steering control using model predictive control and multiple internal models. *Proceedings of AVEC '06. The 8th International Symposium on Advanced Vehicle Control*, August 20-24, 2006, Taipei, Taiwan

Kragic, D.; Marayong, P.; Li, M.; Okamura, A.M. & Hager, G.D. (2005). Human-Machine Collaborative Systems for Microsurgical Applications. *International Journal of Robotics Research*, Volume 24, No. 9, pp. 731-741.

Lam, T.M.; Mulder M.; Van Paassen M.M.; Mulder J.A. & Van Der Helm, F.C.T. (2009). Force-Stiffness Feedback in Uninhabited Aerial Vehicle Teleoperation with Time Delay. *Journal of Guidance, Control and Dynamics,* Vol.32, No. 3, May-June 2009, pp.821-835

McRuer, D.T. & Jex, H.R. (1967) A review of quasi-linear pilot models. *IEEE Trans Human Factors Electron* 8(3):231–249

Mugge W.; Abbink D.A. & Van der Helm F.C.T. (2007). Reduced Power Method: how to evoke low-frequent behaviour while estimating high-bandwidth admittance. *Proceedings of the IEEE International Conference on Robotics and Rehabilitation*, Noordwijk, the Netherlands, June 2007

Mugge, W.; Abbink, D.A; Schouten, A.C.; Dewald, J.P.A. & Van der Helm, F.C.T. (2009). A rigorous model of reflex function indicates that position and force feedback are flexibly tuned to position and force tasks. *Experimental Brain Research,* Published online, August 2009

Mulder, M. (2007). *Haptic Gas Pedal Feedback for Active Car-Following Support*. Delft University Press, ISBN: 978-90-8559-266-2, http://repository.tudelft.nl/assets /uuid:008d10dc-3aa1-4b29-b445-579278543057/ae_mulder_20070130.pdf

Mulder, M.; Mulder, M.; van Paassen, M.M. & Abbink, D.A. (2008a). Haptic Gas Pedal Feedback. *Ergonomics*, Vol. 51, No. 11, pp.1710-1720.

Mulder, M.; Abbink, D.A. & Boer R. (2008b). The effect of Haptic Guidance on Curve Negotiation Behaviour of Young, Experienced Drivers, *Proceedings of IEEE SMC Conference*, pp. 804-809, Singapore, 12-15 Oct 2008

Osu, R.; Franklin, D. W.; Kato, H.; Gomi, H.; Domen, K.; Yoshioka, T. & Kawato, M. (2002). Short- and Long-Term Changes in Joint Co-Contraction Associated With Motor Learning as Revealed From Surface EMG. *Journal of Neurophysiology.*, 88, pp. 991–1004.

Osu, R., Kamimura, N., Iwasaki, H., Nakano, E., Harris, and C. M., Wada, Y. (2004). Optimal Impedance Control for Task Achievement in the Presence of Signal-Dependent Noise. *Journal of Neurophysiology* 92, pp. 1199–1215

Pick, A.J. & Cole, D.J. (2007). Dynamic properties of a driver's arms holding a steering wheel. *Proc. IMechE.* Vol. 221 Part D: J. Automobile Engineering, pp 1475-1486

Pick, A.J. & Cole, D.J. (2008). A Mathematical Model of Driver Steering Control Including Neuromuscular Dynamics. *Journal of Dynamic Systems, Measurement, and Control* MAY 2008, Vol. 130, pp. 031004 1-9

Pritchett, A.R. (2001). Reviewing the Roles of Cockpit Alerting Systems. *Human Factors in Aerospace Safety*, Vol. 1, No. 1, pp. 5-38

Rosenberg, L.B. (1993). Virtual Fixtures: Perceptual Tools for Telerobotic Manipulation. *Proceedings of the IEEE International Conference on Robotics and Automation*, pp. 76-82.

Sheridan, T.B. (2002). *Humans and Automation: System Design and Research Issues.* HFES Issues in Human Factors and Ergonomics Series, Volume 3, John Wiley, New York 2002, ISBN 0-471-23428-1

Stein R.B. & Kearney R.E. (1995) Nonlinear behavior of muscle reflexes at the human ankle joint. *Journal of Neurophysiology* 73(1):65–72

Switkes, J.P.; Rossetter E.J.; Coe I.A. & Gerdes J.C. (2006). Handwheel Force Feedback for Lanekeeping Assistance: Combined Dynamics and Stability. *Journal of Dynamic Systems, Measurement, and Control*, Volume 128, Issue 3, pp. 532-542.

Thompson, P.M.; Klyde, D.H. & Brenner M.J. (2001). Wavelet-based time-varying human operator models. *Proceedings of the AIAA Conference* August 6-9, Montreal, Canada

Toffin, D.; Reymond, G.; Kemeny, A. & Droulez, J. (2007). Role of steering wheel feedback on driver performance: driving simulator and modeling analysis. *Vehicle System Dynamics*, 45:4, 375 – 388

Van der Helm F.C.T.; Schouten, A.C.; De Vlugt, E. & Brouwn, G.G. (2002). Identification of intrinsic and reflexive components of human arm dynamics during postural control. *J Neurosci* 119: 1-14

Van Paassen, M.M. (1995). A Model of the Arm's Neuromuscular System for Manual Control. Proc. IFAC Analysis, Design and Evaluation of Man-Machine Systems, Cambridge, USA 1995.

Wolpert, D.M.; Miall, C. & Kawato, M. (1998). Internal models in the cerebellum. *Trends Cogn Sci* 2: 338–347