Design of Test Signals for Identification of Neuromuscular Admittance

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Abstract: The human neuromuscular system can be seen as a versatile and extremely adaptive actuator. Through co-contraction and reflex modulation, the properties of the neuromuscular system can be modified, leading to a change in movement response to externally applied forces. These properties are normally expressed in the form of the neuromuscular admittance. In a series of standard tasks, the force-, relax-, and position-task admittance of the neuromuscular system can be identified. However, the test signals used in these tasks can also limit the range of reflex adaptation possible and wrong choice can create a phenomenon analogous to cross-over regression in manual control tasks, and force the human to use only a limited range of the possible reflex adaptation. This paper presents a systematic investigation, through a model study, of the influence of test signals on the range of reflex adaptation. For this, criteria for test signal acceptability have been developed. The method is applied to the currently used test signals consisting of a high and a low shelf, and enables the selection of the high shelf bandwidth.

1. INTRODUCTION

Literature shows that the Neuromuscular System (NMS) settings of the human operator strongly depend on a variety of experimental conditions such as the level of muscle contraction Jaeger et al. (1982), displacement amplitude Stein and Kearney (1982); Cathers et al. (1999), interacted mechanical load Vlugt de et al. (2002), frequency content of the disturbance signal Van der Helm et al. (2002), and task instruction Abbink (2006); Doemges and Rack (1992a,b); Kurtzer et al. (2003). Neuromuscular admittance is the movement response of the neuromuscular system (i.e. the human’s limb) in response to an external force. Knowledge of the neuromuscular admittance is particularly important in situations where external disturbances act on the human’s limb Venrooij et al. (2014), and for situations where haptic support is given to the human operator through forces on a manipulator and/or modification of properties, such as stiffness, of the manipulator Abbink et al. (2012).

Identification of the neuromuscular system admittance is normally done with a random-appearing sum-of-sines signal. This measurement is regularly performed for standard task conditions, such as the Force-Task (FT), in which the human operator is instructed to keep the force on the manipulator constant, the position task (PT), in which the instruction is to keep the manipulator in a set position and relax task (RT), in which the operator should suppress responses to manipulator movement. Using the data from the test signal, measured force on the manipulator and measured manipulator displacement, and possibly aided by EMG measurement, the NMS admittance properties can be identified in several possible approaches Damveld et al. (2010) and Venrooij et al. (2014). An example of the results of such a measurement is given in Figure 1. The results from these measurements indicate the range over which admittance adjustment is possible. It has been found that the choice for the test signal can significantly influence the results from these standard tasks; specifically, high test signal energy at higher frequencies leads to suppression of reflexes, and if these test signals are used, identified neuromuscular system properties for the PT and FT move closer to those of the RT.

While the FT, RT and PT can be used to identify the possible range of adaptation of the NMS, the actual adaptation of the NMS during a specific task is still up to the human operator. To identify the admittance during such a task, for example UAV control with and without haptic feedback Sunil et al. (2014), the test signal needs to be both small enough to not disturb the main task, and at the same time sufficiently exciting to enable identification of the neuromuscular system admittance, also when the data for identification is influenced by the control inputs generated by the operator to perform the main task. While in a constrained manual control task this identification may be done for both the human control model and the neuromuscular model in parallel Van Paassen et al. (2004), in a more open task like car driving or UAV control, a simple model for the main control task may not be available, and any control actions for this task must be seen as a disturbance from the point of view of identification of the NMS admittance.

The choice of a test signal is often based on experience, and often a test signal found in literature or used before is re-used, without inspecting its influence on the subject’s
behavior. In this paper, design choices for the identification signal are evaluated by simulation of a PT and a FT experiment, and evaluation of the endpoint variance (manipulator position for the PT and manipulator moment for the FT) for consistent variation of the model parameters. It is argued that acceptable test signals are those that allow relevant NMS reflex parameters to vary over a wide range without significant changes in endpoint variance, since if that is possible, the human operator would not be led to adapting a specific neuromuscular system setting to increase comfort or reduce movement or moment of the manipulator. To evaluate this property, a criterion for the effect of NMS reflex parameter setting on the endpoint variance is defined, and using this criterion, the different design choices for test signals are evaluated. The paper first introduces the used neuromuscular system model and the set-up of the simulations. Then the criteria for acceptable test signals are discussed, and results from the simulations are presented.

2. SIMULATION SET-UP

2.1 Neuromuscular System Model

The NMS model is a control engineering model primarily based on the developments at Delft University of Technology, starting with (Vlugt de et al., 2006; Schouten et al., 2006). The model joins antagonist flexor and extensor muscles together as one muscle system. A total of six transfer functions characterizes this model, a seventh transfer function represents the properties of the manipulator. The transfer functions are listed in Table 1.

Table 1. Model transfer functions.

| Description                              | Transfer function |
|------------------------------------------|-------------------|
| Control stick dynamics                   | $H_0$             |
| Hand grip dynamics                       | $H_1 = B_g s + K_g$ |
| Arm dynamics                             | $H_2 = \frac{1}{\tau_{st} s + 1}$ |
| Intrinsic muscle feedback                | $H_3 = B_is + K_i$ |
| muscle spindle (MS) feedback             | $H_4 = (K_m s + K_p) e^{-\gamma m s}$ |
| Golgi tendon organ (GTO) feedback        | $H_5 = K_g e^{-\gamma g s}$ |
| Activation dynamics                      | $H_6 = \frac{1}{s^2 + \frac{K_p}{\tau_{st}} + 1}$ |

The parameters of the model can be divided into several groups; parameters describing the NMS physiology, most of which are assumed to be independent of the NMS task setting; only the intrinsic muscle stiffness and the proprioceptive gains are assumed to vary with task setting. Actual non-linear properties of muscle include increased stiffness of the muscle at higher activation levels; it is assumed that with a position task most subjects will apply some co-contraction, effectively increasing the muscle stiffness. Furthermore, the gains of the NMS position and velocity feedback through the muscle spindles and the force feedback through the Golgi tendon organs are assumed to vary. For the muscle spindle feedback gains, it is assumed that the ratio of rate and proportional feedback, $K_v/K_p$ is constant. Table 2 and 3 provides an overview of the parameters.

Notice that both Table 2 and 3 includes averaged parameter values found in literature (except for proprioceptive parameters) e.g., Vlugt de (2004), Schouten (2004), Lam et al. (2005); Lam (2009), and Lasschuit et al. (2008). The proprioceptive parameter lower and upper bounds, Table 4, are derived from an open-loop stability analysis; only parameter variations that result in a stable combination of NMS and manipulator are considered.

We used the “Delft” neuromuscular model here since it was readily available, and widely used. Note that the method proposed here is not limited to this model alone, other models, e.g. Sentouh et al. (2009), if they define...
a neuromuscular feedback loop and explicitly modeled manipulator, can also be used.

2.2 Position, Relax and Force Task

The position task and force task are the two extremes within which the NMS system settings must lie. For a force task, a positive Golgi tendon organ feedback is expected, and a negative muscle spindle feedback. For the position task, muscle spindle feedback is positive, resulting in an effectively stiffer NMS, and a slight negative Golgi tendon organ feedback is applied.

2.3 Test signals

To identify the properties of the NMS, a test signal, in the form of a force disturbance, is commonly applied to the manipulator. For this simulation, we will use a test signal based on the work of (Damveld et al., 2009). This test signal has a measurement time of 20.48 [s], and the eight sine component frequencies are an integer multiple (1, 3, 8, 18, 40, 88, 190 and 408 times respectively) of the base frequency of 1/20.48 ≈ 0.0488 [Hz]. A random set of start phases is chosen for the sines, and the signal is created to yield a low peak-to-average amplitude ratio. The cut-off frequency is varied following the reduced power method Mugge et al. (2007); McRuer et al. (1965). When the reduced-power method is applied, the power in the high-frequency sine components is scaled to 10% of the power in the low-frequency sine components. An example is given in Figure 3. The number of full-power components will be varied, and the effect of the test signal on the NMS behavior will be evaluated.

3. END-POINT VARIANCE METRIC

Variations of the test signal described above will now be evaluated for suitability in exciting the NMS. The principal idea is that the test signal needed for identification of NMS parameters should not significantly influence its measured process. In particular, the effect of the test signal on the chosen setting of the neuromuscular system should be minimal. It is assumed that in a natural control task setting, the NMS system setting can be based on the FT, PT or RT setting, and variation between those settings in the model is achieved by modifying a number of parameters in the model. Table 3 shows the fixed parameter values, which we selected from literature Vlugt de (2004); Schouten (2004); Lam (2009); Lasschuit et al. (2008). The parameters varying with degree of either FT or PT setting are given in Table 4. The bounds for these parameters were determined on the basis of stability analysis of the combined NMS and manipulator system. The parameters are jointly and linearly varied over their possible range, in a simulation in which the described test signal was applied. However, as an exception the muscle spindle velocity and proportional feedback parameters are kept at a constant ratio, resulting in a fixed time constant for the muscle spindle feedback \( \tau = K_p^0/K_v^0 \), see Table 3.

In the course of an experiment, either for one of the elementary tasks (PT, FT, RT) or an experiment in which a subject performs another task with the manipulator, any test signal force applied on the manipulator will result in movement of the manipulator. With the disturbance signal defined above, this movement is limited to approximately 0.5 deg excursion of a side stick. Note that these movements are mostly in a frequency range above that of the main control task, and that interference with the main control task is normally limited. To investigate the sensitivity of the neuromuscular system setting, simulations with the parameter variations defined above will be evaluated for the different test signals defined in Section 2.3. The resulting endpoint variance, expressed as the manipulator position variance for the PT and the manipulator moment variance for the FT, with parameter variation is then visualized in a plot and evaluated. In this case the position gain \( K_p \) is varied from its lower bound to its upper bound, see Table 4, and all other parameters are kept constant. With an appropriate test signal, the endpoint variance will be relatively insensitive to the setting of the neuromuscular system, so that a subject is free to use any NMS setting and not encounter settings for which the combined NMS and stick system exhibit increased variance in response.

4. RESULTS

Figures 4 and 5 show the results of varying the \( K_p \) parameter for respectively position task and force task behavior. This variation is shown for all different bandwidth choices of the forcing function signal, with either 1, 2, etc. signals in the high shelf, and remaining signals in the low shelf, until the highest-bandwidth signal, with sines at all frequencies of equal intensity. An acceptable test signal is a signal where the endpoint variance is relatively insensitive to the chosen \( K_p \) setting of the NMS. In case of the position task, the test signals with the highest frequency content (6, 7, 8) result in the highest three lines. These show a high endpoint variance, and a pronounced minimum, indicating that with these signals only a limited adjustment of the \( K_p \) is possible. The test signal with 5 frequencies in the high shelf also shows a pronounced minimum, but this time at a high \( K_p \) gain. The 1 . . . 4 test signals allow for a wider range in \( K_p \) adjustment.

For the force task, the 1, 2, and 3 test signals exhibit a pronounced minimum at fairly high \( K_p \) gain, but with the exception of these three signals, all others allow a fairly wide adaptation of \( K_p \) without large changes in endpoint variance. It can be seen that for the position task, a bandwidth of 0.39 [Hz] gives a wide range of possible \( K_p \) settings. For the force task, the bandwidth of 1.95 [Hz] is a good compromise which is near the natural frequency of the activation dynamics, although several other test signals also exhibit a low sensitivity to \( K_p \) settings. In case the tendency of the neuromuscular system setting is not known, a compromise test signal should be chosen, e.g., the signal with 4 sines in the low shelf.

5. CONCLUSION

This paper presents a model analysis of the effects of test signal choice on the adaptation range of neuromuscular feedback. The method indicates that the use of a reduced-bandwidth test signal is essential for allowing a wide range of adaptation of the NMS feedback gains. For situations
Table 2. Task independent parameters.

| Parameter (Lower bound;Upper bound) | Value | Dimension |
|-------------------------------------|-------|-----------|
| Activation dynamics                 |       |           |
| Natural frequency $\omega_0$ (5;20) | 13.823 | rad/s     |
| Damping $b$ (0.1) | 0.7071 |           |
| Arm dynamics                        |       |           |
| Inertia $I_{ARM}$ (0.005;0.025)     | 0.01  | Nms$^2$/rad |
| Neural transport delay $\tau_d$ (0.005;0.055) | 0.025 | s         |
| Hand grip dynamics                  |       |           |
| Damping $B_g$ (0;5)                 | 2     | Nms/rad   |
| Stiffness $K_g$ (50;500)            | 165   | Nm/rad    |

Table 3. Task dependent parameters.

| Parameter (Lower bound;Upper bound) | Value | PT | RT | FT | Dimension |
|-------------------------------------|-------|----|----|----|-----------|
| Intrinsic muscle feedback           |       |    |    |    |           |
| Damping $B_i$ (0;5) $B_i^0$         | 1     | 1  | 1  |    | Nms/rad   |
| Stiffness $K_i$ (0;30) $K_i^0$      | 11    | 10 | 9  |    | Nm/rad    |
| MS feedback                         |       |    |    |    |           |
| Position gain $K_p$ (-30;30) $K_p^0$ | 9     | $10^{-10}$ | -6 | Nm/rad |
| Velocity gain $K_v$ (-5;10) $K_v^0$ | 2     | $10^{-10}$ | 3  | Nms/rad |
| GTO feedback                        |       |    |    |    |           |
| Force gain $K_f$ (-20;20) $K_f^0$   | -1.5  | $10^{-10}$ | 1.5 | -  |

Table 4. Varying parameters with lower and upper bound.

| Proprioceptive parameter | Lower bound | Upper bound | Dimension |
|--------------------------|-------------|-------------|-----------|
| $K_p$                    | -10         | 30          | Nm/rad    |
| $K_v$                    | -1          | 5           | Nms/rad   |
| $K_f$                    | -5          | 15          | -         |

where position task behavior is expected, the bandwidth of the test signal should not exceed 0.39 Hz. When force task behavior is expected, a somewhat wider bandwidth can be maintained. Choosing a high bandwidth for the test signal, which might be desired from an identification standpoint, strongly limits the range of NMS feedback gains that results in a “comfortable” setting: too high or too low feedback gains will results in an increase in endpoint admittance, thus results obtained with these signals might not accurately reflect the NMS setting that is chosen for the task; the setting is mainly determined by the choice for the test signal.

In this paper, we limited ourselves to the variation of $K_p$ alone. A further extension of the work includes investigating the sensitivity of the endpoint variance to the variation of a combination of neuromuscular settings, and evaluation of the effect of different disturbance signals on the quality of the estimated parameter sets. Our current work focuses on the experimental validation of these calculations, using protocols for measurement of position and force tasks, and...
evaluating the effect of test signal properties on the range of NMS feedback parameters applied by subjects. A second focus of future work is the identification of neuromuscular system properties in the presence of an unrelated control task, i.e. when the neuromuscular test signal is added to the stick while the subjects are intent on another (e.g. manipulation, vehicle control) task with the control device.

Using this procedure, one can select a test signal that has a minimal influence on the settings of the neuromuscular system, and thus allows identification of an operator’s undisturbed neuromuscular settings during a specific task. These model calculations should actually be performed for each experiment in which neuromuscular system properties are determined, since the manipulator properties may also influence the optimal test signal selection.

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