

Posture Maintenance of the Human Upper Extremity; Identification of Intrinsic and Reflex Based Contributions

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ABSTRACT

Neuromuscular stabilization has been investigated for the human upper extremity. Force perturbation methods have been applied to characterize the human joint resistance. Non-parametric identification was used to derive transfer functions describing arm admittance and neural feedback. Using parametric identification the intrinsic and reflexive contributions could be unraveled into physical model parameters. The intrinsic resistance is represented as joint stiffness and damping attributed to muscle co-contraction. The reflexive feedback is represented by neural feedback delays and gains.

Results show that the intrinsic and reflexive joint resistance vary strongly with experimental conditions and depend in particular on the task instructions, the perturbations, the posture and on the manipulator (payload) mass and damping. Within conditions consistent results are found within and between subjects.

In most cases a considerable part of the motion resistance was attributed to the intrinsic joint resistance apparently caused by muscle co-contraction. Reflexive feedback is primarily effective in the lower frequency range.

INTRODUCTION

In Aviation and Automotive research neuromuscular identification has been applied to gain understanding in human control, and to develop advanced human machine interfaces. Manipulator design and tuning is sometimes more of an art than a science. A prominent example of a case where the interaction between the manipulator and the pilot's arm was not foreseen is the General Dynamics F-16, in which the original design of the side-stick controller suffered from oversensitivity, which led to problems during high-speed taxi tests (*Hoh 1982*). A following redesign suffered from roll-ratchet problems (*Johnston 1988*). By using a model of the neuromuscular system that enables an analysis of the interaction between the manipulator and the pilot's arm while subjected to accelerations, that is, in a moving vehicle, such cases could be analyzed beforehand.

Other application areas for such a model are the analysis and design of so-called active manipulators (the active stick by Hosman 1988 or the "Assistive Aid" described by Morris 1988), in which an active servo element is used to provide feedback from the controlled system or from other sources such as threats in the environment. Another example is a haptic gas pedal assisting drivers with force feedback to maintain a safe distance to preceding vehicles. In designing the haptic gas pedal it was shown how drivers adapt neuromuscular control strategies to benefit optimally from the feedback applied through the gas pedal (*Abbink 2006, 2007a, 2007b, De Winter 2007, Mulder 2007, Mugge et al 2007*).

In the medical field neuromuscular identification has been applied to better understand movement disorders and to develop diagnostic tools (*Schouten 2001-2006, De Vlugt 2001-2006, Van der Kooij 1999-2007*). Research has always been done in close collaboration with academic medical centers, where we showed the proof of principle on small populations of patients. In recent years we focused on complex regional pain syndrome (*Schouten et al 2003*), Parkinson's Disease (*Schouten et al 2004*) and Stroke. In experiments used to investigate reflex gain adaptations to loading conditions it was found that, where normally the reflex magnitude varies considerably, within movement disorders the reflex magnitude is set at one end of the normal range. The overall finding is that movement disorders in general do not result from exaggerated reflexes per se, but emerge from malfunctioning mechanisms to rapidly adapt the reflex magnitude. Therefore we now develop (time-varying) methods to measure the temporal profile of the reflex adaptation of the spinal reflex loop in humans.

To maintain the hand at a specific point in space, humans need to control their muscles around the shoulder, elbow and wrist joints simultaneously. Joint resistance is produced firstly by *intrinsic muscle visco-elasticity* and secondly by *reflexive feedback*. The intrinsic muscle visco-elasticity depends on muscular (pre)tension. As described in common muscle models muscular damping and stiffness are roughly proportional to muscular activation. Pretensioning antagonist (opposing) muscle groups thereby provides a substantial intrinsic joint visco-elasticity. Reflexes result in additional compensatory muscle activation.

Obviously prolonged pretension consumes more energy than reflexive action. Pretension results in an instantaneous resistance while reflexive action is only effective after a significant neural delay. This difference enables a separate identification of the intrinsic and the reflexive resistance as shown in this paper.

The described research on human movement control and system identification has been carried out by the Delft Laboratory for Neuromuscular Control (NMC). This paper builds upon experiments published in earlier papers by the authors. A comprehensive overview of the applied methods is provided together with new results and a synthesis of results found with different postures and setups.

The main focus of the Delft Laboratory for Neuromuscular Control (NMC) is the quantification of neuromuscular properties in vivo during natural tasks. The rationale for the in vivo approach is, evidently, that identified properties can be related directly to normal motion behavior of the human or to the pathological movement behavior of patients. The counterpart of such an approach is that measurements are limited and certain quantities can not be measured at all. Figure 1 shows schematically the neuromuscular system in its functionally distinct parts. Accessible quantities that can be measured are displacement $\mathbf{x}_h$ and reaction force $\mathbf{F}_h$ at the hand (or other points of body interaction with the environment). The muscular activation $\mathbf{a}$ can be estimated using electromyography (EMG) which can be obtained routinely from most superficial muscles.

Our approach is twofold: first with haptic robots (manipulators) we apply mechanical perturbations and record motion and force, and second by parameterization of mathematical models we describe the data. The main challenge is to find an appropriate model that produces a unique set of parameters with a distinct physical meaning. Models are raised from pre-existing knowledge about subsystem physiology. These

models can lead us into a thorough analysis of whole system functioning and the role of its different parts.

SYSTEM IDENTIFICATION

With system identification basically one wants to elucidate the (dynamical) relationship between input and output channels of a system. Here, we discern four different aspects that are important to setup an identification study of the human motor control system:

- **Perturbations:** a manipulator is needed to apply some sort of mechanical perturbation signal. Here we make a distinction between force and position perturbations.
- **Behavioral Consistency:** as humans are highly adaptive a clear and unambiguous task instruction is required to minimize variations in system behavior during the performance of a motion task.
- **System identification:** force disturbances induce mutual interaction of the manipulator and the subject. Closed-loop techniques are required in that case to separate the neuromechanical properties of the human from the mechanical properties of the manipulator. Nonlinearity and time variance are also important issues.
- **Parameter estimation:** to interpret the results and compare cases the input-output relation should be described by a limited number of physiological meaningful parameters, like muscle visco-elasticity, neural time-delay, and reflexive feedback gains.

The above mentioned issues have to be addressed and are highly correlated as will be explained in the following sections.

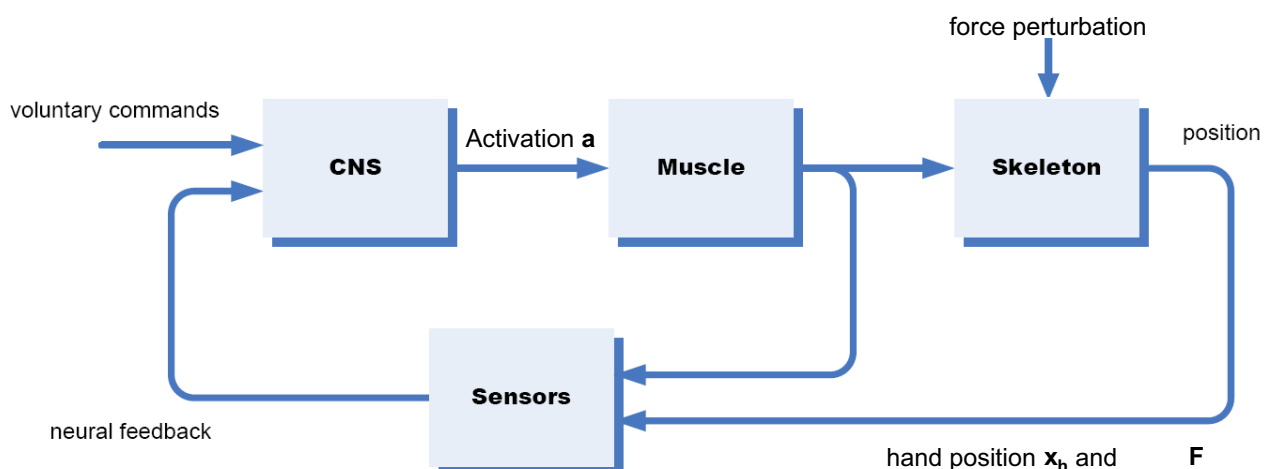


Figure 1. Schematic representation of the human neuromuscular control system. The different parts are: the central nervous system (CNS) that receives sensory input and controls the muscles, the muscles that convert neural activation signals into force, the skeleton on which muscle force and external forces are applied and the musculoskeletal sensors of which the muscle spindles and Golgi tendon organs are most relevant.

The need for perturbations

Without deviation there would be no progress. This statement, in a lesser philosophical sense however, is typical for system identification. To measure the behavior of any system, one should seek for some sort of stimulus that the system will react on. The reaction can mostly be measured in a laboratory setting such that the system under investigation can be analyzed from responses to those stimuli. An important criterion for successful identification is the persistence of the stimulus: does that part of the system express itself sufficiently in the measured response? Practically, there is much trial-and-error on this issue since identification implies that you are seeking for things that are unknown on forehand. The NMC Lab has followed this line of identification by application of different types of mechanical perturbations.

Past and ongoing research utilizes *force perturbations* applied by an actively powered manipulator, applied to hand or foot. In those cases, the subject is in control of its motion by the fact that the manipulator is a compliant load. Thus, force perturbations are ideal stimuli to perturb voluntary controlled limb motions where the controlling capabilities of humans are to be studied.

Random appearing perturbations

Transient perturbations such as ramp, step or impulse shaped forces or displacements provide simple and intuitive responses. However transient responses provide limited information and are hardly suitable for analysis in the frequency domain. In our research we have therefore focused on continuous perturbations. In order to identify reflexes rather than anticipatory actions, only unpredictable random appearing perturbations have been used. Several perturbation types were successfully applied including white noise, wide band noise and noise distributed over different frequency bands (e.g Figure 2). By perturbing only a limited number of frequencies effects of noise at intermediate frequencies has been eliminated. Furthermore by perturbing the motor and visual system at separate frequencies, motor and visual feedback have been separately identified in car following (Abbink 2006). Likewise Cenciari and Peterka (2006) separately identified motor and vestibular feedback in standing. Recent effort has been put into the optimization of perturbation signals with respect to the distribution of signal power over a limited bandwidth (Schouten et al 2008b, Mugge et al 2007). In general, the higher the input power the better the signal to noise ratio of the responses. Main criterion, however, is the limitation of power to avoid nonlinear behavior and discomfort. On the other hand, too low power may result in poor signal to noise ratios. A spectrum of about 0.5-20 Hz proved relevant for identification of neuromuscular models where the lower frequencies are most relevant for identification of feedback while the higher frequencies are most relevant for inertia, hand contact and intrinsic joint visco-elastic properties. A noteworthy point here is the dependence of the human reflex system on the bandwidth of the applied

perturbations (Van der Helm et al 2002, Schouten et al 2008b, Mugge et al 2007). Feedback is hardly effective for the higher frequencies and when high frequency perturbations are offered with large amplitudes they tend to elicit a rather unnatural behavior. Increasing perturbation bandwidth leads to reduced task performance resulting in a higher admittance during position tasks, and a lower admittance during force tasks. This undesired effect can be handled by reducing the amplitude of the higher frequencies to a level sufficient for identification but not dominating human behavior (Mugge et al 2007).

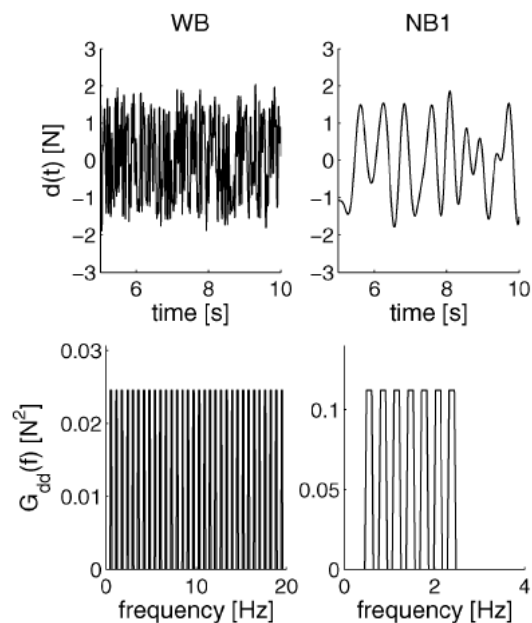


Figure 2. Random appearing perturbations consisting of multiple sinusoids (top); and their power spectral densities (bottom).

Force vs. position perturbations

Human upper extremities are specialized in reaching and grasping. Mechanically, the thorax functions as an inertial ground for the arms (and neck). During arm movements, disturbing forces from either the object that is grasped or internally from the movements of the thorax, require some sort of compensation strategy to minimize the deviations from the intended trajectory or postural position. For the upper extremities, force perturbations are the most natural stimuli for identification. The arm admittance (inverse of impedance/compliance or resistance) determines the response to the force perturbation. In case of a position task the admittance should be low, i.e. the deviations resulting from the force perturbations are small. The admittance is constituted by the intrinsic visco-elasticity from the muscles and passive tissues and by the inertia of the segments. Force perturbations have been shown to be effective for the analysis of arm posture control in the 1DOF and 2DOF case (De Vlugt et al 2002, De Vlugt et al 2006). The usage of force perturbations has been studied also in combination with force tasks. That is, humans were asked to hold a mean force level (or minimize variation) while the limb is perturbed.

moving. Admittance indeed does matter as high admittance will reduce the reaction force variations in response to the imposed force perturbations; ideally the admittance is very high. We called that compliance control and confirmed that humans are very well able to increase their admittance during such force tasks (Abbink 2006).

An experimentally interesting option that comes along with the usage of force perturbations is the study of human motion behavior in reaction to different types of mechanical environments (payloads) representing different mass, damping and stiffnesses (De Vlugt et al 2002, Schouten et al 2008). Stability and performance become important trade-off criteria when changing the stability margins by imposing additional damping or stiffness by the manipulator.

In a systematical sense, position perturbations (in contrast to force perturbations) separate limb motion from muscle forces that are normally causing the motion. That is, muscles are lengthened but the responding intrinsic forces (from visco-elasticity of the muscles and passive tissues) and reflexively mediated forces (from proprioceptors) do not have any influence on the joint motion as it is externally dictated by the robot. Apart from force control studies as mentioned above, this artificial separation has been exploited by many researches to identify both intrinsic and reflexive components, e.g. (Mirbagheri et al 2000, Mirbagheri et al 2001, Perrault et al 2001).

Haptic robots (or manipulators) are perfectly suited to apply mechanical perturbations (force or position). Figure 4 shows the first haptic manipulator of the NMC laboratory (Ruitenbeek and Jansen, 1984). Figure 4 shows a 2D manipulator (De Vlugt et al 2003) and Figure 5 shows a wrist manipulator which due to its limited motion range is very practical in a clinical environment (Schouten et al 2006).



Figure 3. The Proprio manipulator. The subject was seated in a chair while holding the handle of a hydraulic actuator. The subject was positioned in such a way that the elbow made an angle of 90 degrees of flexion. Force perturbation applied through the handle resulted in ante/retroflexion movements of the shoulder joint. To prevent drift and to motivate the subject the actual position of the handle was shown on the display.

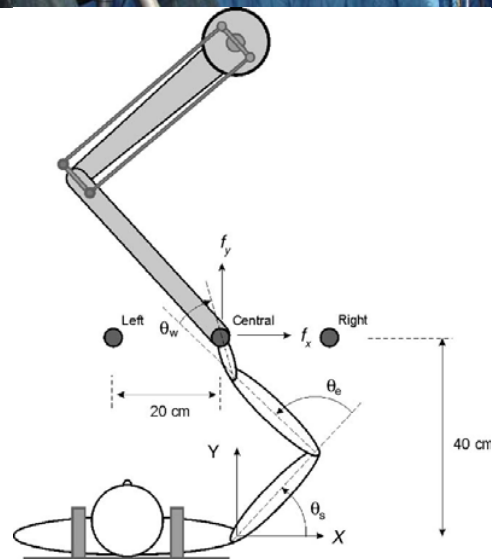


Figure 4. The Armanda manipulator (Photo and topview drawing). The subject held the handle and controlled the position or trajectory of the manipulator in the horizontal plane. The elbow was supported by a long rope connected to the ceiling. The two-joint manipulator (shaded) was used to apply continuous random forces in two directions (x and y) onto the subject's hand. The manipulator represented a virtual mechanical environment that consisted of a mass-damper-spring system in the horizontal plane. The different hand positions are shown by the shaded circles (Left, Central and Right).



Figure 5. Pope manipulator for testing wrist flexion.