IDENTIFICATION OF NONLINEAR NEUROMECHANICAL PROPERTIES OF THE HUMAN WRIST JOINT

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INTRODUCTION
Improper joint resistance after stroke can be a result of alterations in tissue visco-elasticity, muscle activity and neural reflexes [1]. Long term effects of stroke on joint dexterity are believed to result from the interplay between these three components. Discriminating between these components is therefore essential for understanding the etiology of the clinical phenotypes and for improvement of therapy. During functional movement these passive, active and reflexive components contribute to joint resistance in a highly nonlinear way, making interpretation of their combined role to joint impedance difficult. Muscle viscoelasticity and reflex gains change with the actual state, i.e. joint angle, angular velocity and muscle force. It is not clear to what extent viscoelasticity and reflex gains relate to these states. The goal of this study was to investigate the nonlinear characteristics of joint viscoelasticity and reflex gains by application of continuous position perturbations of which the amplitude was systematically varied. Different levels of joint torque were also applied to examine any changes in amplitude nonlinearity with muscle activation.

METHODS
Seven healthy subjects were included in this study. We used a piece-wise linear model approach in selected operating points of the nonlinear domain, defined by a combination of displacement amplitude and level of joint torque. A change in operating point that results in a change of the linearly estimated model parameters indicates nonlinear behavior. A ramped version of Pseudo-Random Binary Sequences (rPRBS, Fig. 1) has been used, allowing for changes in perturbation amplitude, while keeping velocity and inter stimulus interval constant. Frequencies up to approximately 11 Hz were suitable for system identification analysis. The shape of the signal also allowed for time domain analysis of the EMG signal. Continuous position perturbations of the wrist joint were performed using a single axis haptic manipulator (PoPe, TU Delft) [2]. The measurement protocol consisted of 36 rPRBS sequences consisting of four different amplitudes (0.5, 1, 2, 4 deg) and three voluntary contraction levels (0, 1, 2 Nm). Subjects were instructed to hold an average level of contraction using visual feedback. Conditions were repeated twice and ordered randomly, resulting in three datasets for each operating point. For each amplitude-torque condition, a physiological model [2] was fitted onto the corresponding

Frequency Response Function (FRF) between joint torque (model input) and angle (model output). The physiological model consisted of an intrinsic viscoelastic element and a reflexive pathway (Fig. 2) and was fitted on two datasets separately. Mass and activation dynamics were assumed, and estimated, constant over all conditions. Damping (B), stiffness (K), velocity dependent reflex gain (k_v) and short latency time (t_d) were separately estimated for each condition. The third dataset (2nd repetition) was used for validation of the model. For validation purposes regarding the reflexive parameters we checked the EMG response for the short latency reflex (M1) in a time window of 20 to 50 ms in response to individual ramps within the signal [3]. The M1 was divided by input amplitude to make it comparable with reflexive gain parameters from the parameter estimation.

RESULTS
Frequency domain analysis showed high coherence for all conditions, justifying the linear analysis. The model fitted well to the measured FRFs, and high VAF values (84 +/- 8%) indicated that accurate descriptions in the time domain were obtained. Similar VAF values (83 +/- 8%) were also obtained for the validation dataset. Estimated muscular and reflex parameters were highly repeatable over the first two sets. Group averages of the stiffness, damping, reflex gain and EMG response are presented in Figs. 3 and 4. Stiffness significantly increased with voluntary torque level and significantly decreased with angular displacement in the 0 Nm condition (Fig. 2, left). Damping significantly increased with torque level and significantly decreased with angular displacement, for all voluntary torque levels (Fig. 3, right). Reflex gain significantly increased with contraction level but did not significantly change with perturbation amplitude for higher torque levels (Fig. 4, left). However, inspection of EMG signal revealed a significant decrease in the short latency reflex gain with amplitude of perturbation and a similar increase with contraction level.

![Figure 1: The first seconds of a rPRBS perturbation signal.](image-url)
DISCUSSION
An increase in muscle activation is known to result in a stiffer, more damped joint, mostly due to cross-bridge turnover. Intrinsic resistance during the initial phase of movement is expected to be mainly determined by short range stiffness, likely explaining the higher stiffness for smaller amplitude [4], as seen in the 0 Nm condition (Fig. 3, right). This suggests the presence of cross-bridges in the resting (0 Nm) case, as previously reported by Hill [5]. It was expected that damping would increase with amplitude, as cross-bridges were expected to resume in cyclic turnover beyond their short range elastic limit inferring viscous like behavior. We do not have an explanation for the observed decrease in viscosity with joint displacement.

The increase of reflex gain with contraction level was also found in literature [6]. Possible explanations would be increased motor neuron pool sensitivity with increased supraspinal drive or an increased alpha-gamma co-activity. Furthermore, the estimated reflex gain based on EMG analysis ($M_1$) decreases with perturbation amplitude, although this decrease was only seen in the resting condition. Therefore it does not validate the reflexive model parameter $k_v$. It seems to imply that velocity dependent reflex gain ($k_v$) is either not sensitive enough for this type of change, or that the $M_1$ response is not solely related to the obtained reflexive model parameter.

A full understanding of the nonlinear behavior of passive, active and reflexive components is a prerequisite for the assessment of their contributions to movement disorders, and consequently targeted therapy. Therefore, future work mainly consists of modeling and validation of these nonlinearities, by connecting the now identified operating points using nonlinear physiological models. It also requires the investigation of effects of other (functional) measurement conditions. Angle, angular velocity, inter-stimulus interval, as well as the combinations of these conditions, are subject to current research.

CONCLUSIONS
It was concluded that muscular and reflex properties changed significantly with amplitude of joint displacement and voluntary contraction level. This nonlinear behavior of the neuromuscular system is important for the individual study of passive, active and reflexive contributions to joint impedance.

ACKNOWLEDGEMENTS
This work was supported by grants from ZonMW (grant 89000001), het Revalidatiefonds, Revalidatie Nederland and VRA, and is part of the EXPLICIT-stroke project.

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