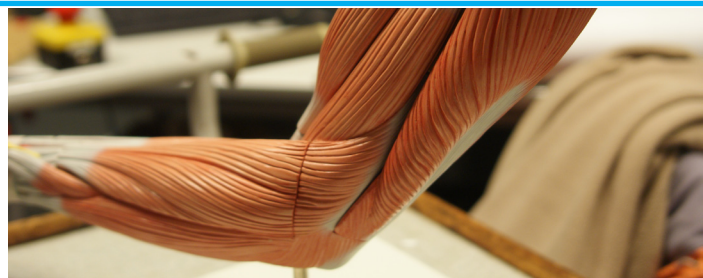


Master Thesis

# Recovery of reflexes at the elbow after surgery on severe brachial plexus injuries



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# Recovery of reflexes at the elbow after surgery on severe brachial plexus injuries

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## Abstract

The goal of this study is to quantify the recovery of spinal reflexes at the elbow after neurosurgical intervention in patients with brachial plexus injuries. So far, main focus was on the recovery of muscle force and little on sensory- and reflex system. As reflexes play an important role during normal movement, it is of interest to determine to what extent reflexes have been restored after surgery. Arm admittance (dynamic relationship between displacements in a response to forces) at endpoint level (hand) was estimated using force perturbations in two directions (horizontal) applied by a two-joint robotic manipulator. Three different task instructions were used to provoke different intrinsic and reflexive behavior, being a position task (PT), a relax task (RT) and a force task (FT) where the subject was required to minimize hand displacements, not react to the perturbations and minimize force deviations (being compliant) respectively. Ten patients with brachial plexus lesions participated in this experiment and were suffering from varying degrees of arm dysfunction. All had successful recovery for the biceps (MRC grade 3 and higher) after surgical nerve repair of the n. musculocutaneous. Estimated intrinsic and reflexive parameters were compared to those of a control group (n = 10, age and sex matched). The task instructions had great influence on the admittance, especially between the PT and RT. In all patients, reflexive activity was found corresponding to assumed muscle spindles (velocity- and position feedback) and Golgi tendon organ (force feedback) function. For the PT, the difference in parameters between patients and control subjects was largest. Overall, patients exhibit more intrinsic stiffness at the shoulder and elbow than the control subjects, an indication of co-contraction, and less reflexive feedback at the elbow. There are two possible explanations for this: 1) The intrinsic and reflexive properties did not recover to the combination as before the injury and are not cooperating correctly, and 2) The patients are relying more on intrinsic control than on reflexive control (different control strategy). Whereas the control group uses an energy efficient approach, i.e. less intrinsic and more reflex activity, the patients appear to use a more maximal activation approach resulting in co-contraction. It is possible that the exercises performed during rehabilitation

which focus on muscle force do not provoke enough reflexive behavior. More research, e.g. experiments that are designed to disable co-contraction, is needed to verify if the use of co-contraction is learnt or a necessity. Conclusion: reflexes do recover after surgery to severe Brachial plexus injuries, the amount of reflex function is less or less effective than for the control group.

## **1. Introduction**

The Brachial Plexus is a complex nerve bundle located in the neck, which innervates the arm. Brachial plexus injuries result in partly or total loss of arm function. Two causes for brachial plexus injuries exist, obstetric (during birth) and traumatic (due to accidents, e.g. motorcycle accidents). The focus of this study is on traumatic injuries. After the trauma the nerve (axon) distal to the injury perishes. Sometimes, the proximal part grows back again through nerve sheaths, into the arm. If the nerve recovery does not occur spontaneously, surgery is performed to reconnect the nerves sheaths and allow the nerves to re-innervate the arm muscles. The goal of surgery is improving functionality by restoring voluntary muscle force. One common surgical intervention aims to repair the nerves to the elbow muscles, biceps and triceps, to regain some elbow function (flexion of the elbow). The success of surgery is measured by the amount of muscle force that is returned. Not much is known about the recovery of sensory feedback and proprioceptive reflexes. Reflexes give information about the mechanical state of the muscles (length, velocity and force) and play an important role in the control of posture and movements (Burdet et al., 2000). Given the importance of reflexes during movements and the motion disorders often present in patients with brachial plexus injuries, it is desirable to obtain knowledge about the functioning of the reflexes in these patients. Due to the surgical preference, the focus of this study is to quantify the recovery of spinal reflexes at the elbow after neurosurgical intervention in patients with severe brachial plexus injuries that were successfully operated on. Intrinsic, i.e. muscle visco-elasticity, and reflexive, i.e. feedback from muscle spindles (MS) and Golgi Tendon Organs (GTO), properties of the arm can be derived from the arm admittance by using a model fitting procedure (De Vlugt et al., 2003b). In this study the arm of the subject was exposed to perturbations applied by a robotic manipulator. The subject was asked to perform different tasks to provoke different reflexive behavior. From the reactions to these perturbations the intrinsic and reflexive properties were estimated and compared with a control group to determine the level of recovery of reflexes.

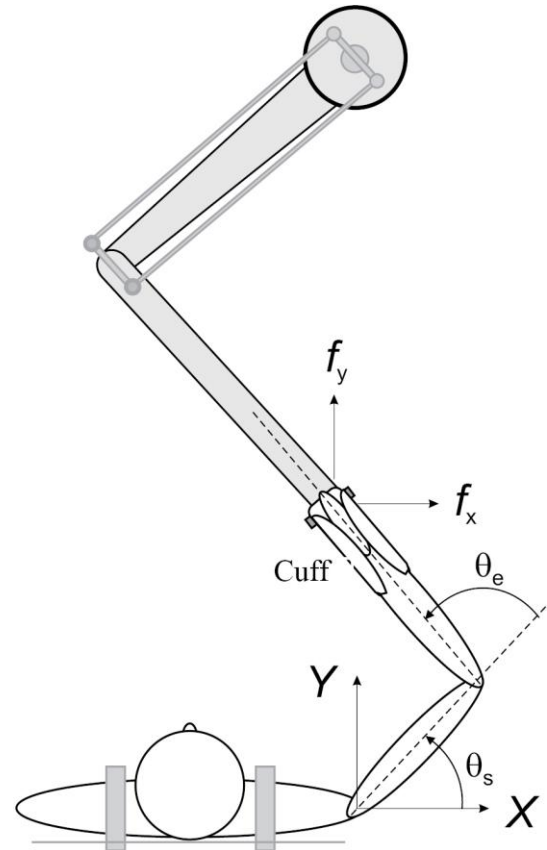
## 2. Materials and Method

### 2.1 Apparatus

The mechanical admittance of the arm at endpoint level (hand) in the horizontal plane was estimated from the measured reaction force, hand displacement and the applied force perturbations (see further). For this purpose, a planar two-joint robotic manipulator was used (De Vlugt et al., 2003), as shown in Figure 1. The manipulator acted as a mass-spring-damper system and will hereafter be referred to as the environment. Subjects were strapped into a car bucket seat. A four-point seat belt was used to constrain movements of the trunk. To compensate gravitational forces, the elbow was suspended by a cable mounted from the ceiling causing the arm to almost remain in a horizontal position (Figure 1). The wrist joint was immobilized by a lightweight cuff fitted onto the lower arm, leaving the fingers free to move. The handle was free to pivot around its vertical axis. Subjects were asked to maintain a firm grip onto the handle. At the palmar side of the hand, the cuff made tight contact with the handle without any play so subjects with less or no hand function were able to perform the tests.. Handle position was derived from measurements of the angles of the manipulator's arm using optical angular encoders (Heidenhain ROC417, 17 bits per 360 deg.). The force applied by the subjects onto the handle was measured using strain gauges (range -300 to 300 N). External force disturbance signals were generated off-line and imposed on the handle. Forces were defined in the Cartesian (X-Y) subject frame (Figure 1). Handle displacements, hand force and external disturbance were measured with a sample frequency of 250 Hz. EMG recordings from nine muscles were made using bipolar surface electrodes (2 cm inter electrode distance, 2 Delsys Bagnoli 8 systems). The important joint rotations of consideration were: elbow flexion / extension and horizontal shoulder adduction / abduction. The following muscles were measured: Biceps short head (shoulder adductor, elbow flexor, two joint); triceps lateral part (elbow extensor, single joint); triceps long head (shoulder adductor, elbow extensor, two-joint); anterior deltoid(shoulder adductor, single joint); posterior deltoid (shoulder abductor , single joint); extensor carpi radialis (extensor wrist); flexor carpi radialis (flexor wrist); latissimus dorsi (extensor, adductor, transverse extensor and internal rotator for shoulder joint) and pectoralis major (flexor and extensor humerus). EMG signals were measured with a sample frequency of 2000 Hz, full-wave rectified, low pass filtered at 20 Hz (Butterworth 3<sup>rd</sup>-order) and then re-sampled at 250 Hz for further analysis.



**Figure 1.** Experimental setup. The two joint manipulator was used to apply continuous force perturbations in two directions ( $f_x$  and  $f_y$ ) onto the subjects hand. The manipulator acted as a mass-spring-damper system. The subjects arm was held in horizontal position by a rope mounted from the ceiling and the wrist joint was immobilized by a cuff fitted on the lower arm. The subjects were asked to perform three tasks.



## 2.2 Subjects and protocol

Ten patients with brachial plexus injury (all male, all right handed) mean (standard deviation, SD) age of 38 (11,4) years, length and weight of respectively 182,6 (5,2) cm and 81,2 (6,4) kg with varying degrees of arm dysfunction participated in the study. Inclusion criteria were: 1) a successful recovery after neurosurgical procedure aimed to restore m. biceps function defined by a, MRC (Medical Research Council grading system), grade of 3 and higher, and 2) at least 1.5 years of rehabilitation. Patients were recruited from a database of the Neurosurgery department of the Leiden University Medical Center (LUMC) and all had surgery performed by one of the co-authors (MM) (Table 1). A control group, (all male, one left (double) handed), mean age of 34,7 (16,6) years, mean length and weight of respectively 187,6 (7,3) cm and 81,8 (5,9) kg was used to provide for normal results. The patients were indicated as ‘P’ and the control subjects as ‘C’. The study was approved of by the Medical Ethical committee of LUMC. All subjects signed an informed consent.

subject	Patient stats		Limb lengths (cm)			Arm orientation (deg.)	
	injury	surgery	$l_{\text{humerus}}$	$l_{\text{forearm}}$	$d_{\text{sh-handle}}$	$\theta_s$	$\theta_e$
P1	N: musculocutaneous and medianus. Ax: radialis	T: medianus (graft: 14 cm), musculocutaneous (graft 4,5 cm)	32	30	49	54/50/53	75/75/76
P2	A: C5 and C6	T: pectoralis and medialis – musculocutaneous. T: musculocutaneous antebrachialii lateralis – brachioradialis	35	36.5	47	40/52/52	97/70/79
P3	N: C5, C6 and C7	T: C5 – ADTS, C6 – PDTS, C7-C7	34	36	50	45/58/62	89/54/61
P4	N: C5 and C6, A: C7-T1	T: C5 – suprascapularis and axillaris. C6 – fasciculus lateralis, intercostals - medialis	35	38	50	39/40/45	99/86/90
P5	N: C5-T1	T: fasc. Lateralis and fasc. posterior	36	36	45	37/36/33	87/80/87
P6	N: C5. A: C6-T1	C5 – anterior division truncus superior	35	37	47	38/35/34	94/91/93
P7	N: C5, A: C6 and C7	C5 – anterior division truncus superior	30	30	65	49/48/56	85/74/68
P8	A: C5 – C7	T: intercostals 3 to 5 – musculocutaneous	28	31	50	43/47/52	76/60/57
P9	N: C5, A: C6-T1	T: intercostals 3 to 5 – musculocutaneous, T: C5 – truncus superior	27	33.5	47	45/42/48	81/74/71

**Table 1.** The injuries and the surgery performed on the patients, the humeral length ( $l_{\text{humerus}}$ ), forearm length ( $l_{\text{forearm}}$ ) and the distance from the shoulder to the handle ( $d_{\text{sh-handle}}$ ), and the arm orientation: shoulder angle ( $\theta_s$ ) and elbow angle ( $\theta_e$ ) during the tasks (PT/RT/FT). N: neurotmesis, Ax: axonotmesis, A: Avulsion and T: nervetransfer.

Clinical assessment prior to the measurements was performed by one of the co-authors (CM): 1) Recovery of the muscles were graded by the MRC grading system, 2) The maximal force in the muscle was measured using a dynamometer, 3) The Semmes-Weinstein monofilament test was used to test the skin sensation recovery, 4) The mobility of the arm was measured, and 5) The reflexes in the arm were tested using a reflex hammer. The results of the clinical tests are shown in Table 2. This table gives a complete overview of the, clinically measurable, effects of the injury and surgery on the functionality of the arm. For the experiment the handle position of the manipulator was adjusted so that the hand of the patient was right in front of the shoulder and the angle between the upper and lower arm was approximately 90 degrees. To calculate the shoulder and elbow angle from the measured manipulator angles, the limb lengths of the subject and the distance from hand to shoulder were measured by tape measure (see Table 1). During the experiments subjects were required to perform three tasks, being: 1) a position task (PT), i.e. minimizing the handle displacements as good as possible, 2) a relax task (RT), i.e. passive behavior (subjects were instructed to ‘do nothing’), and 3) a force task (FT), i.e. minimizing the force deviations (being compliant). For the PT a circle in which a dot, representing the reference hand position, had to be kept was visualized on a monitor in front of the subjects. A decreasing admittance is expected for the PT as a result of co-contraction and excitatory muscle spindle- (MS) and Golgi tendon organ (GTO) feedback. For the RT no co-contraction and little MS and GTO feedback is expected, resulting in a large admittance. During the FT the subjects behavior is compliant and a larger admittance than during the RT is expected. Reflexes are

expected to help increasing the admittance, this will result in no excitatory MS feedback and inhibitory GTO feedback. The expected effect of the task instruction on the admittance is shown in Figure 2.

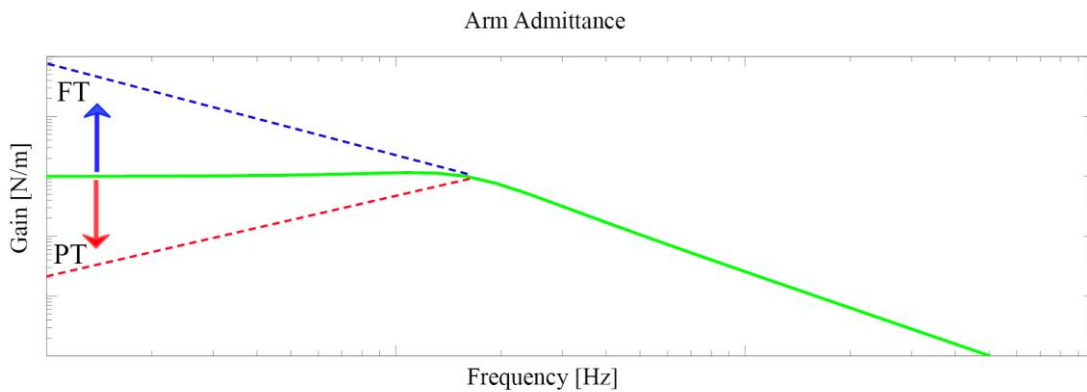
Subject	C <sub>average</sub>	P1	P2	P3	P4	P5	P6	P7	P8	P9
<b>Arm</b> (Dominant / injured)		R/L	R/L	R/R	R/R	R/L	R/L	R/R	R/L	R/L
<b>Strength</b> (max [Nm] (MRC))										
Exorotators										
0 degr elevation	144 (5)	94 (4)	50 (4)	30 (4)	0 (0)	7.5 (3)	0 (1)	0 (1)	25 (3)	0 (0)
90 degr elevation	211 (5)	100 (4)	30 (4)	20 (4)	0 (0)	29 (4)	0 (1)	0 (1)	30 (3)	9.7 (3)
Deltoid										
abduction	184 (5)	165 (5)	72 (3)	130 (4)	69 (2)	60 (4)	24 (1)	65 (4)	90 (2)	77 (3)
forward flexion	197 (5)	92 (5)	95 (4)	110 (4)	82 (2)	81 (4)	0 (1)	35 (4)	30 (2)	0 (2)
retroflexion	222 (5)	125 (5)	85 (4)	110 (4)	14 (2)	53 (4)	0 (1)	28 (3)	30 (2)	22 (2)
Biceps										
Triceps	249 (5)	155 (5)	57 (4)	110 (4)	105 (4)	31 (4)	39 (3)	65 (4)	70 (4)	48 (4)
Wrist extension	200 (5)	149 (5)	110 (5)	20 (3)	0 (0)	25 (4)	0 (0)	18 (3)	20 (1)	4 (2)
Wrist flexion	204 (5)	100 (4)	125 (5)	100 (5)	0 (0)	45 (4)	0 (0)	0 (3)	26 (4)	0 (0)
Finger extension	183 (5)	68 (4)	206 (5)	100 (5)	0 (0)	55 (4)	0 (0)	50 (4)	31 (4)	5 (1)
Finger flexion	(5)	(4)	(5)	(5)	(0)	(4)	(0)	(4)	(5)	(0)
Finger spread	(5)	(4)	(5)	(5)	(0)	(4)	(0)	(4)	(5)	(0)
Thumb opposition	(5)	(4)	(5)	(5)	(0)	(4)	(0)	(4)	(5)	(0)
<b>Sensibility</b> (right arm /left arm)										
Epaulet	283/283	361/361	431/456	361/283	361/361	361/431	283/361	361/361	361/431	361/431
Lateral side upper arm	283/283	361/361	361/431	361/283	361/361	361/431	283/361	361/431	361/431	361/431
medial side upper arm	283/283	361/361	361/456	361/283	361/283	361/665	283/361	361/361	361/431	361/431
lateral side lower arm	283/283	361/361	283/361	361/283	as/283	361/as	283/361	361/431	361/431	361/665
medial side lower arm	283/283	361/361	283/as	361/283	as/283	361/665	283/431	361/361	361/431	361/665
Hand, dorsum	283/283	361/431	283/361	431/283	as/283	361/665	283/361	361/431	361/431	361/as
Hand, palmar	283/283	361/361	283/361	431/283	as/283	361/665	283/361	361/361	361/431	361/as
<b>Mobility</b> (degrees)										
Shoulder elevation (a/p)	max	150/150	70/120	130/130	0/90	40/90	0/60	10/150	0/80	0/90
Scapula laterorotation	++	+++++	++++	+	+++	++	+	++	+++	-
Endorotation (0° abduction)	max	70	90	30	45	40	20	30	20	20
Exo rotation (0° abduction)	max	80	40	30	15	40	20	20	0	10
Elbow flexion/extension	max	150/10/0	150/10/0	130/0/0	150/20/0	150/0/0	110/30/0	150/10/0	150/20/0	150/30/-
Wrist flexion/extension	max	50/0/50	80/0/70	70/0/70	80/0/40	50/0/50	20/20	50/0/40	20/0/85	80/0/10
Finger flexion/extension	max	90/0/0	90/0/0	90/0/0	90/20/0	90/0/0	10/10	90/0/0	90/0/0	90/90/0
<b>Reflex (tendon taps)</b> (uninjured arm /injured arm)										
Biceps	+ / +	++ / +/-	+ / -	++ / +	+++ / +	++ / +	++ / +	++ / +/-	++ / +	++ / +
Triceps	+ / +	++ / ++	+ / +	++ / +	+++ / -	++ / +	++ / +	++ / ++	++ / -	++ / +
ECR	+ / +	++ / ++	+ / +	++ / +	+++ / -	++ / +	++ / -	++ / ++	++ / +	+ / -
ECU	+ / +	++ / ++	+ / +	++ / +	+++ / -	++ / +	++ / -	++ / ++	++ / +	+ / -

**Table 2.** Result of the clinical tests. (as)stands for not sensitive, (a/p) stands for active/passive. The value for Sensibility stand for the monofilament thickness(238 = monofilament 2.38)

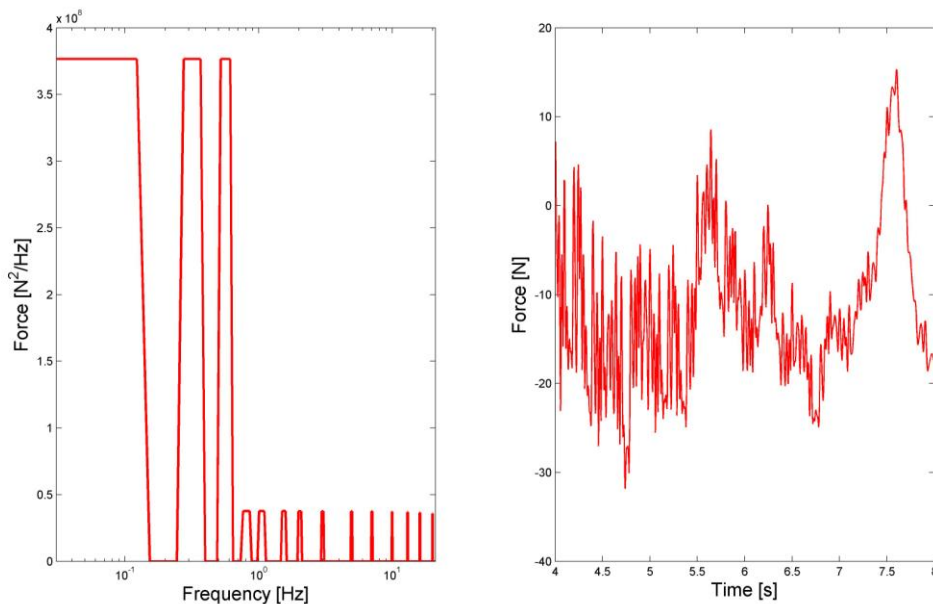
### Perturbation signal design

The applied force disturbance contained power between 0.01 to 40 Hz and was designed as a sum of sinusoids. For frequencies higher than approximately 3 Hz the contribution from reflexive feedback to overall endpoint admittance was negligible (Van der Helm et al., 2002). However, reducing the perturbation bandwidth would restrict the identification of the admittance to these input frequencies. To overcome this limitation, a reduced

power torque signal was used consisting of a high power band supplemented with a reduced power band, large enough to allow accurate identification, and small enough not to influence control behavior (Mugge et al., 2007). The high power band ranged from 0.01 to 0.75 Hz and the reduced power band from 0.75 to 40 Hz. To improve the signal to noise ratio, the power was distributed over alternating clusters (to reduce the number of sinusoids in the signal, but still disturb over the whole frequency range) of four adjacent frequencies that were linearly distributed in the high power band and logarithmically distributed in the reduced band. Figure 3 shows a realization of the perturbation signals.



**Figure 2.** Expected influence of the task instruction. The RT, green, is the base line. For PT, red, admittance is decreasing (increasing stiffness) and for FT, blue, admittance is increasing (being more compliant)



**Figure 3.** Example of the force disturbance signal used in this study. Left: autospectrum. Right: 4 second time sample.

## Measurement protocol

The power was equal in both x- and y-direction and was scaled to each task until the desired magnitude of 10 mm root-mean-square (RMS) Euclidean distance from the mean hand position was reached. The amount of reduced power needed, to identify neuromuscular properties, depends on the power level of the signal. The reduced power was set to 10%, 20% and 50% for the PT, RT and FT respectively. These prior adjustments also provided sufficient time to get the subject familiar with the different tasks. Each task was repeated ten times to evaluate consistency of the measurements. The power of the force perturbations were kept the same for all repetitions. Each trial lasted 35 s. The lumped impedance, amount of force needed for displacements, was calculated by dividing the standard deviation of the force by the RMS of the displacements, see Table 3.

subject		Lumped impedance [N/mm]										average
		1	2	3	4	5	6	7	8	9	10	
C	PT	1.06	1.13	1.12	1.47	1.67	1.45	1.26	1.41	1.26	1.07	1.29
	RT	0.18	0.19	0.17	0.18	0.18	0.19	0.17	0.19	0.19	0.19	0.18
	FT	0.19	0.12	0.11	0.17	0.14	0.11	0.11	0.12	0.15	0.11	0.13
P	PT	1.87	0.98	0.38	0.12	0.52	0.19	0.24	0.27	0.16		0.53
	RT	0.21	0.18	0.18	0.18	0.17	0.17	0.18	0.18	0.18		0.18
	FT	0.18	0.18	0.17	0.17	0.13	0.16	0.15	0.11	0.19		0.16

**Table 3.** Lumped impedance ( $std(Force)/RMS$ ) for the three tasks. For control subjects (C) and patients (P).

## 2.3 Identification and parameter estimation

The arm admittance at endpoint (hand level) describes the dynamic relationship between hand force and hand displacements and is expressed in the frequency domain as the Frequency Response Function (FRF). The arm admittance contains information about all the mechanisms involved, i.e. intrinsic and reflexive properties and inertia of the segments. The multivariable (2x2) admittance was estimated using a closed loop identification scheme (De Vlugt., 2003). In short, the recorded signals (force disturbance, reaction force and hand displacement) of which the first second was removed and the next 32,7 s ( $2^{13}$  samples at 250 Hz) were Fourier transformed, then the corresponding auto- and spectral densities were taken and combined to derive the estimated admittance FRF. The spectral densities were averaged over four adjacent frequencies, to reduce estimator variance. As the second step, model parameters were estimated by fitting an admittance model onto the FRF. Model fitting was applied over all frequencies present in the force disturbance signal up to 20 Hz which was the linear bandwidth of the manipulator. The coherence was provided as a measure of linearity with values ranging from zero (no linear correlation/severe noise) to one (perfect linear correlation and no noise).



nr	Parameter	Unit	Bounds (lb/ub)	nr	Parameter	Unit	Bounds (lb/ub)
Segmental mass				Acceleration feedback (spindels)			
1*	$m_{\text{humerus}}$	Kg	1/5	12	$k_{a,s}$	$\text{Nms}^2/\text{rad}$	0/5
2*	$m_{\text{forearm}}$	“	1/5	13	$k_{a,se} (=k_{a,es})$	“	0/5
3*	$m_{\text{end}}$	“	0.1 / 1	14	$K_{a,e}$	“	0/5
Viscosity				Velocity feedback (spindles)			
4	$b_s$	$\text{Nms}/\text{rad}$	0/10	15	$k_{v,s}$	$\text{Nms}/\text{rad}$	0/100
5	$b_{se} (=b_{es})$	“	0/10	16	$k_{v,se} (=k_{v,es})$	“	0/100
6	$b_e$	“	0/10	17	$k_{v,e}$	“	0/100
Elasticity				Position feedback (spindles)			
7	$k_s$	$\text{Nm}/\text{rad}$	0.2/100	18	$k_{p,s}$	$\text{Nm}/\text{rad}$	0/100
8	$k_{se} (=k_{es})$	“	0/100	19	$k_{p,se} (=k_{p,es})$	“	0/100
9	$k_e$	“	0.2/100	20	$k_{p,e}$	“	0/100
Hand Visco-elasticity (2x2 matrices)				Force feedback (golgi)			
10	$B_h$	$\text{Ns}/\text{m}$	10/500	21	$k_{f,s}$	-	-10/10
11	$K_h$	$\text{kN}/\text{m}$	5/30	22	$k_{f,se} (=k_{f,es})$	-	-10/10
				23	$K_{f,e}$	-	-10/10
				Activation cut-off frequency			
				24	$f_{\text{act},s}$	Hz	1.5/5
				25	$f_{\text{act},e}$	“	1.5/5
				Time delays			
				26*	$T_{ds}$	ms	20/33
				27*	$T_{de}$	“	20/45

**Table 4** Model parameters to be estimated. The subscripts refer to mono- and bi-articular joints: *s*: shoulder, *es*: two-joint and *e*:elbow. This set of parameters is used for all tasks separately (only the starred parameters are invariant). There are two constraints: the mass of the upper arm cannot be smaller than the lower arm mass and the time delay of the shoulder cannot be larger than the one of the elbow. (lb/ub) stands for lower bound/upper bound.

With  $f_m$  the discrete frequency in Hz (only frequencies that were present in the perturbation signal and averaged over four adjacent frequencies), with  $n_1 = 1$  and  $n_2 = 14$  (0.07 Hz to 20 Hz).  $\Gamma^2$  is the multiple coherence to both outputs, calculated separately for both outputs (De Vlugt et al., 2003a),  $H(f_m)$  the estimated arm admittance,  $H_{\text{mod}}(f_m(n), p)$  the FRF of the human model and  $p$  ( $n_p \times 3$ ) the parameter vector, with  $n_p$  the number (27) of parameters to be estimated per task, see Table 4. Three parameter sets corresponding to the three tasks were estimated simultaneously, where the mass and time delay parameters were kept identical, resulting in 71 parameters total. To limit the parameters to realistic values, upper and lower bounds were applied to the optimization (see Table 4). In addition, the following constraints were used between the parameters:  $m_{\text{humerus}} \geq m_{\text{forearm}}$  and  $\tau_{d,s} \leq \tau_{d,e}$ . Furthermore, a stability constraint was added restraining the Eigen-values of the model to be smaller than zero. The goodness of the model fit was provided by calculating the variance accounted for (VAF) between the hand positions  $X_h$  and the hand positions predicted by the model  $X_{h,\text{arm}}$ , according to:

$$VAF = \frac{\sum_{n=1}^N |X_h(t_n) - \hat{X}_{h,\text{arm}}(t_n)|^2}{\sum_{n=1}^N |X_h(t_n)|^2} \quad (2.2)$$

The predicted hand position was obtained by simulating the estimated model of the arm plus the environment using the force disturbance as input. A VAF value of 100% means that the model fully describes the measured system response and is equal to the real system. Lower values indicate to a bad model fit or the existence of noise.

## **2.5 Statistical analysis**

The differences of the parameters between the control group and the patients were tested for significance using a Student's Ttest ( $\alpha = 0.05$ ).

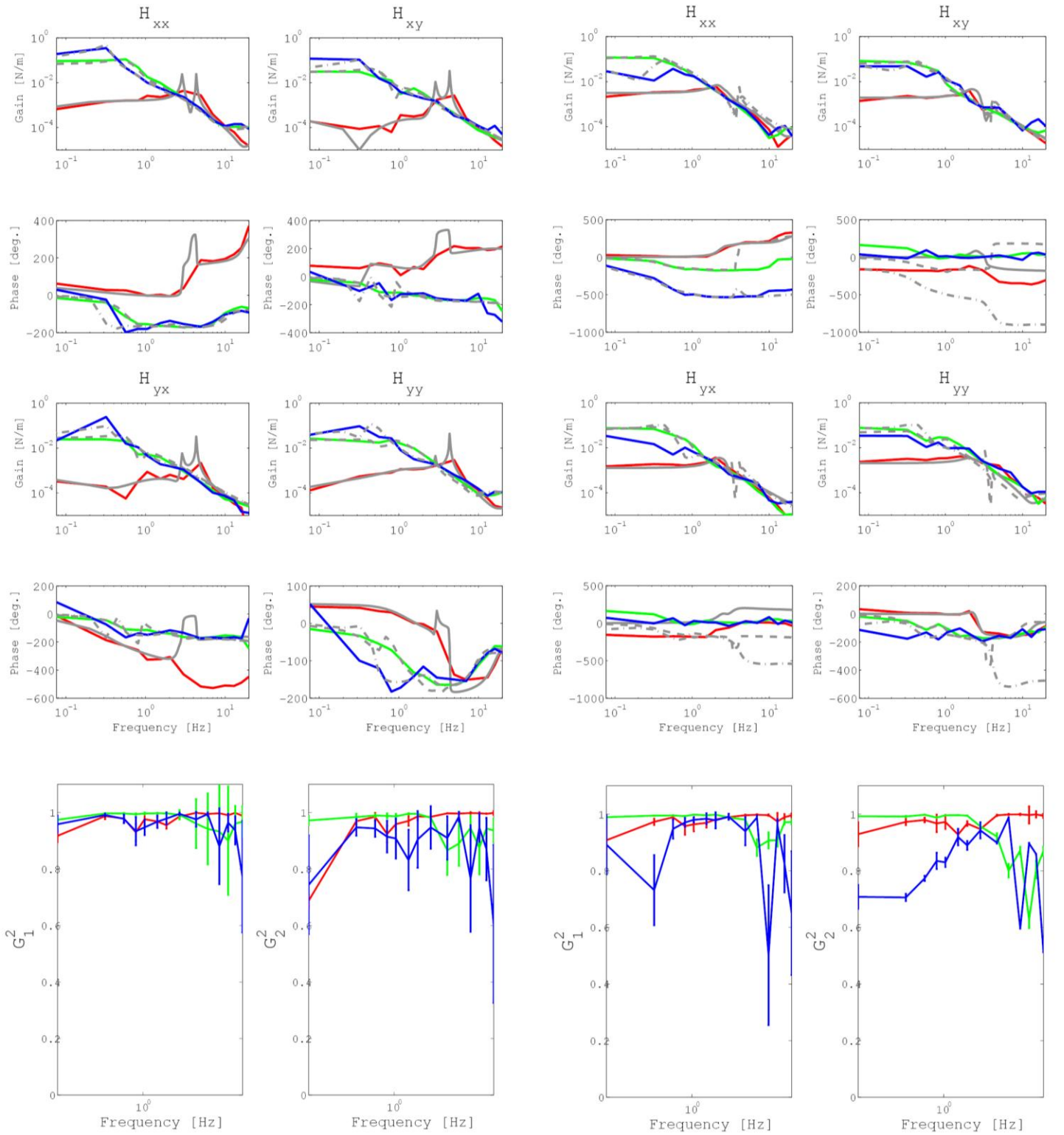
## **3. Results**

### **3.1 Clinical results**

The results from the clinical tests are shown in table 2. In the first column the average values of the control group are shown. All the patients showed a decrease of muscle force, even if the injury was less severe (more distal, e.g. P1). There was still reasonable good skin sensation, and proprioceptive reflexes for biceps and triceps in a response to tendon tapping in most of the patients.

### **3.2 Non parametric identification**

Figure 5 shows an example of the admittance FRFs and coherence of a control subject and patient (P2). The PT is shown in red, the RT in green and the FT in blue. Verbal inquiry from the subjects and observations during the experiments show that both control subjects and patients had difficulty performing the FT. One of the patients was not able to perform the tasks and was therefore excluded from the study. The shape of the FRFs resembles a second order system, with a phase going to approximately -180 degrees. In a number of trials the phase became positive, Figure 5. The admittance of the arm during a PT is lower than of the RT or FT (expectations in Figure 2). The difference between the RT and FT is less pronounced and for only four control subjects the admittance of the FT was higher than of the RT. The peaks were shifting between the tasks. There was a difference between the peaks of the control subject (PT: 3 Hz, RT: 0.6 Hz and FT: 0.3 Hz) and the patient (PT: 2 Hz, RT: 0.4 Hz and FT: 0.4 Hz). The patients generally had a higher admittance during the PT compared to the control group. For the RT and PT the coherence were 0.9. The coherence for the FT was 0.8 on average for control subjects and 0.6 to 0.8 on average for patients.



**Figure 5.** Estimated arm admittance and coherence. Left: Control subject C9, Right: Patient P5. The lines: Red: PT; Green: RT; Blue: FT; Gray: Parametric model fits (solid: PT; dashed: RT; dash-dot: FT)

### 3.3 Parameter estimation

The masses, time delays, hand visco-elastic parameters and the activation cut-off frequencies are provided in table 5. Because there was a lot of consistency between the subjects of the control group, only the average values of the whole group are shown. The values of the patients are the average over all ten trials.

Subject Parameter	Value (mean(SD))									
	C <sub>average</sub>	P1	P2	P3	P4	P5	P6	P7	P8	P9
m <sub>humerus</sub> [kg]	4.19(0.34)	4.12(0.30)	4.84(0.18)	4.64(0.61)	3.93(0.24)	4.79(0.32)	2.48(0.52)	4.47(0.38)	2.58(0.54)	2.11(0.50)
m <sub>forearm</sub> [kg]	3.45(0.28)	3.40(0.25)	3.99(0.15)	3.84(0.52)	3.24(0.20)	3.93(0.27)	1.99(0.43)	3.68(0.32)	2.11(0.48)	1.74(0.41)
m <sub>end</sub> [kg]	0.13(0.06)	0.10(0.03)	0.10(0.01)	0.10(0.10)	0.10(0.01)	0.10(0.01)	0.29(0.17)	0.12(0.11)	0.12(0.15)	0.29(0.14)
b <sub>h,PT</sub> [Ns/m]	23.7(47.3)	26.5(24.5)	28.1(7.9)	51.2(63.9)	92.1(27.6)	79.0(8.5)	43.7(16.0)	42.3(11.2)	154.3(72)	113.6(70)
b <sub>h,RT</sub> [Ns/m]	53.4(13.7)	56.6(4.8)	58.3(4.8)	50.4(20.8)	64.9(4.1)	59.8(13.8)	40.9(3.2)	63.3(6.6)	44.3(11.0)	46.7(14.4)
b <sub>h,FT</sub> [Ns/m]	52.3(28.1)	78.0(8.6)	66.7(8.6)	77.4(19.8)	59.0(13.4)	114.8(30)	56.7(14.5)	54.9(22.4)	50.9(18.6)	41.3(13.7)
k <sub>h,PT</sub> [kN/m]	23.7(2.02)	17.8(0.97)	20.7(0.45)	20.1(2.41)	9.3(1.44)	11.8(1.21)	5.0(0.25)	17.5(0.96)	9.8(3.85)	5.8(2.03)
k <sub>h,RT</sub> [kN/m]	8.05(0.79)	8.2(0.68)	13.0(0.83)	9.4(2.13)	8.7(0.61)	7.2(1.06)	5.0(0.18)	9.9(0.39)	5.0(1.41)	8.0(0.88)
k <sub>h,FT</sub> [kN/m]	6.89(1.38)	9.5(5.12)	9.6(3.22)	9.9(0.71)	8.8(1.09)	5.6(0.92)	5.3(0.59)	8.0(1.91)	5.0(0.18)	9.7(1.65)
T <sub>d,s</sub> [ms]	26.4(3.4)	20.0(1.0)	30.8(5.2)	23.4(4.5)	20.3(6.3)	32.5(4.5)	33.0(4.4)	29.3(5.5)	31.9(4.6)	23.3(5.1)
T <sub>d,e</sub> [ms]	34.1(3.2)	24.1(2.4)	39.8(7.2)	40.8(7.1)	27.3(9.1)	42.6(7.3)	43.1(6.6)	44.2(6.1)	43.7(2.5)	29.6(7.1)
f <sub>acts,PT</sub> [Hz]	2.16(0.43)	1.50(0.39)	2.76(0.64)	2.33(0.70)	1.51(0.20)	3.20(0.87)	2.68(1.10)	1.89(0.40)	1.80(0.67)	2.01(1.10)
f <sub>acts,RT</sub> [Hz]	2.29(1.08)	1.98(0.58)	1.86(1.31)	1.84(1.10)	1.86(0.20)	2.02(0.37)	1.73(1.06)	3.61(1.47)	1.61(0.52)	2.10(1.55)
f <sub>acts,FT</sub> [Hz]	2.82(1.33)	2.79(1.62)	4.72(1.71)	4.46(1.49)	1.97(1.30)	1.55(0.22)	1.50(0.25)	3.92(1.55)	1.55(0.36)	1.50(1.09)
f <sub>acte,PT</sub> [Hz]	2.42(0.74)	2.28(0.78)	4.25(1.03)	1.96(0.49)	2.08(1.35)	2.15(0.75)	3.83(1.33)	1.50(0.04)	3.65(1.27)	2.86(1.01)
f <sub>acte,RT</sub> [Hz]	1.95(0.55)	2.44(1.24)	4.98(1.23)	2.32(1.31)	1.50(0.96)	2.51(1.18)	4.33(0.87)	1.75(0.69)	1.52(0.32)	1.79(1.30)
f <sub>acte,FT</sub> [Hz]	1.91(1.00)	2.37(1.45)	1.50(0.01)	2.29(1.68)	1.50(1.16)	2.75(1.47)	1.50(1.54)	1.86(1.12)	1.69(1.63)	2.47(1.36)

**Table 5.** Estimated parameters. Mass and time delays (were kept identical over the tasks), hand visco-elastic parameters and activation cut-off frequencies.

The intrinsic and reflexive parameters of the control group and the patients are shown in figure 6. The model estimates, gray lines, are shown in figure 5, the solid line for the PT, the dashed line for the RT and the dash-dot line for the FT. The estimated model was plotted using all the frequencies between 0 and 20 Hz. This is the reason there are more peaks in comparison with the FRFs.

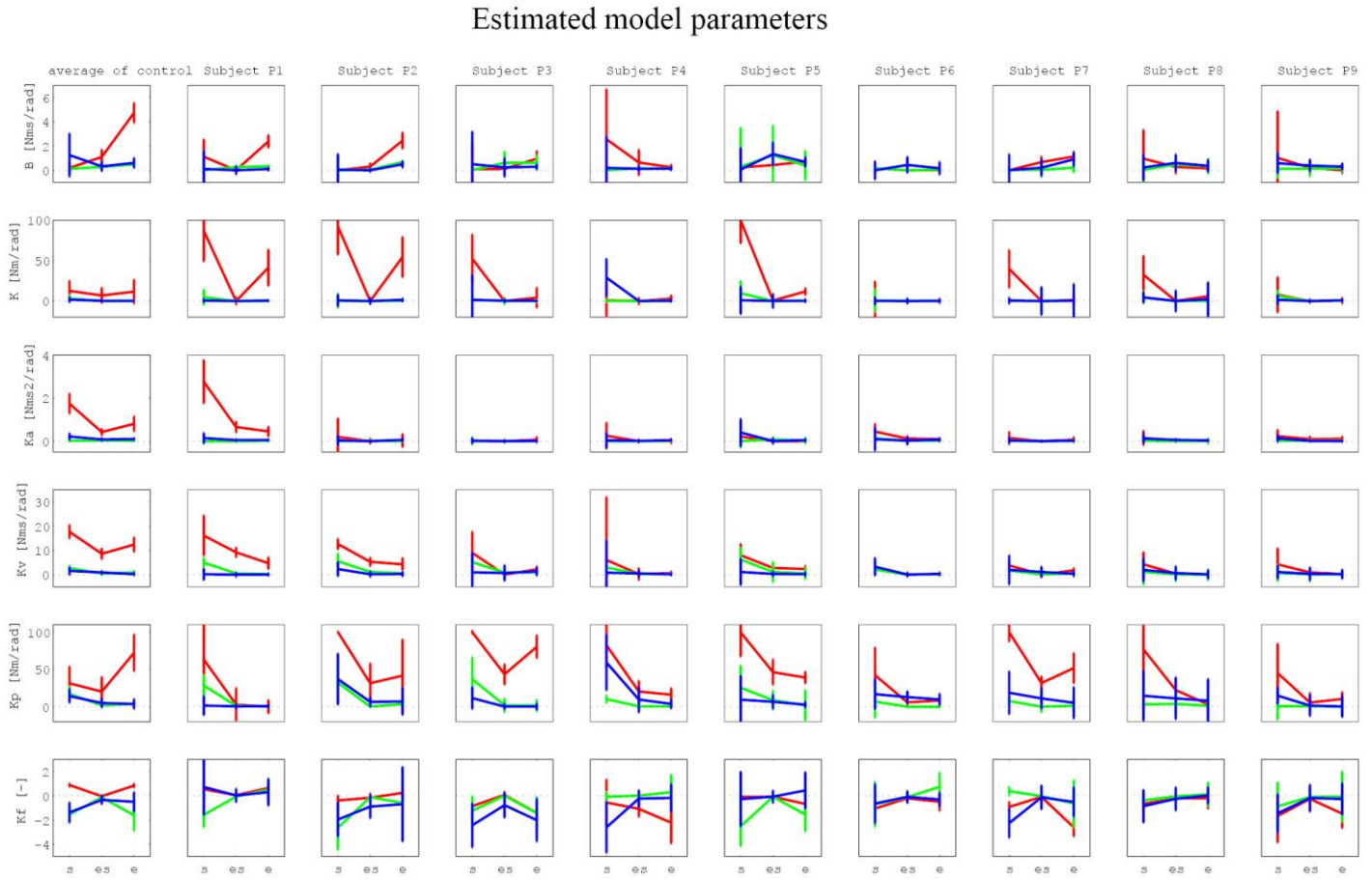
#### Control group

In the first column of figure 6 the average parameters of the control group are shown. For the PT the intrinsic stiffness was higher than for the RT and FT over all joints. Intrinsic damping was present at the elbow and at the two-joint, but not at the shoulder. MS reflex feedback was present, the acceleration and velocity feedback stronger at the shoulder and position feedback at the elbow. Force feedback was excitatory (see further) present at the shoulder and elbow. For the RT no intrinsic stiffness and damping were present and for the FT only damping at the shoulder. For both RT and FT there was little to no excitatory MS reflex feedback, and there was inhibitory force feedback present.

#### The extremes

Patient P1 had a less severe injury (Table 1) and good recovery (Table 2), and was expected to be comparable with the control group, see Figure 6. Differences were a significant higher intrinsic stiffness at the shoulder and elbow and lower intrinsic damping at the elbow for the PT. Reflexes were normal except the position feedback at the elbow, which was significantly lower and force feedback for the FT which was excitatory. Patient P6 had a very severe injury (Table 1) and poor recovery (Table 2), expected was to find little to no intrinsic and reflexive

properties. Figure 6 shows little intrinsic stiffness and damping for all tasks, but position feedback at the shoulder and force feedback at the shoulder and elbow were present.



**Figure 6.** The estimated intrinsic and reflexive model parameters. Average of the control group (first column) and all patients in the next columns. Colors: red: PT, green: RT and blue: FT.

#### *Patient group*

Comparing the average parameters of the patient group (not shown) with the average of the control group shows that for the PT the elbow damping  $B_e$ , the acceleration feedback at shoulder and two-joint  $K_{a,s}$  and  $K_{a,es}$ , all the velocity feedback and the force feedback at the shoulder and elbow  $K_{f,s}$  and  $K_{f,e}$  were significantly ( $p < 0.05$ ) lower than the for the control group. For all patients position feedback  $K_p$  was present. For the RT and FT this comparison gave no significant differences. For the RT this is expected, because this task is less dependent of the amount of muscle force. This gives an overall indication of the effects of injuries to the brachial plexus, because the patient group was not homogeneous individual analysis of the patients was done.

### *Subgroups*

The group is divided into three groups based on elbow function present, looking at both the biceps and triceps muscle based on the MRC scale, table 2. Group 1: P1 and P2 both have good elbow function, grade 4 or 5 for both muscles. Group 2: P3, P5 and P7 have moderate elbow function, grade 3 or 4 for both muscles. Group 3: P4, P6, P8 and P9 have little to no elbow function, because of one or both muscles missing muscle force. All groups will be compared with the average of the control group.

#### *Group 1: Good elbow function*

Both subjects have significantly less intrinsic damping at the elbow and more intrinsic stiffness at the elbow and shoulder during the PT, Figure 6. The two-joint components,  $B_{se}$  and  $K_{se}$ , are almost not present. The intrinsic parameters for the RT and FT do not differ much. In both subjects the reflex feedback looked normal, but for both there is less activity at the elbow. For the PT the velocity feedback at the elbow is significantly lower for both patients. For P1 there is no position feedback at the elbow and for P2 there is no acceleration feedback at all. The force feedback for the FT changed sign and was positive for P1.

#### *Group 2: Moderate elbow function*

For all subjects in this group there was little intrinsic damping and stiffness at the elbow and two-joint stiffness was not present. The intrinsic stiffness at the shoulder larger than that for the control group (for P3 and P5 significantly).

There is almost no, significantly less, accelerations and velocity feedback for elbow, two-joint and shoulder. For the PT Position feedback at the elbow and two-joint were normal, but significantly higher for the shoulder. The force feedback for the PT at the elbow and shoulder became inhibitory (switched sign) for all the subjects. The forced feedback for shoulder during the RT for subject P7 is significantly higher.

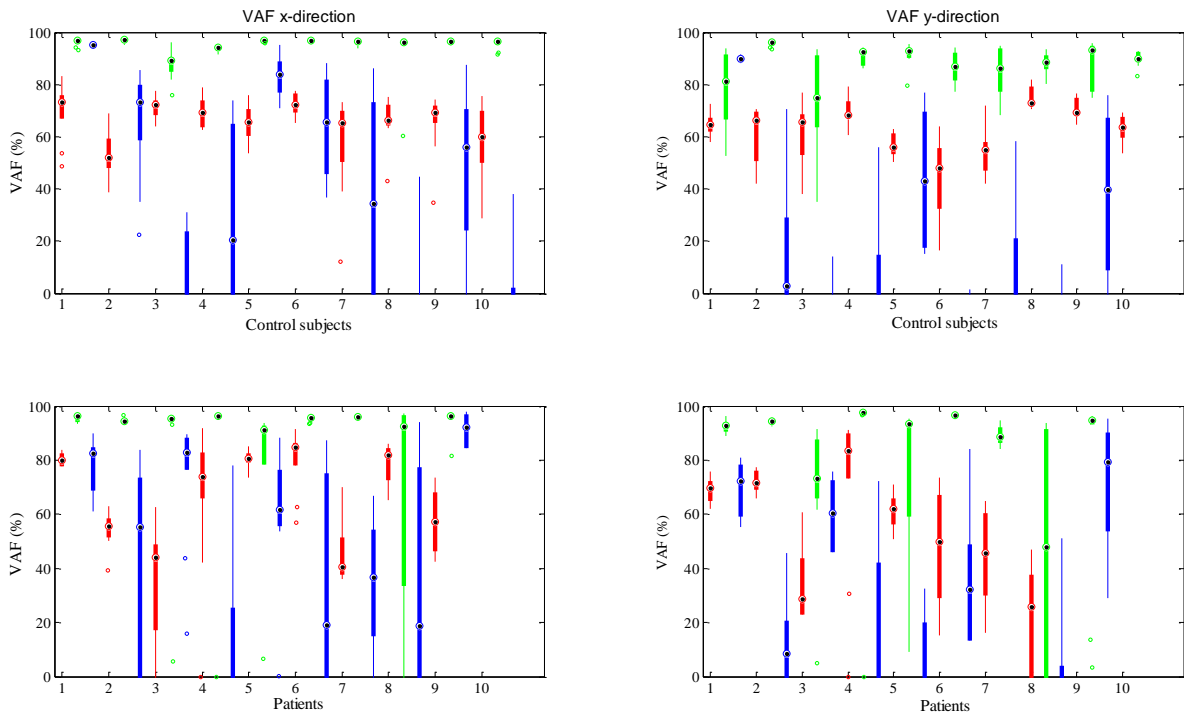
#### *Group 3: Little elbow function*

The estimated mass of the arm segments were significantly lower. There was little to no intrinsic damping and stiffness at the elbow and two-joint. For P8 intrinsic stiffness and damping at the shoulder were present, for P4 and P9 only damping. There was no acceleration and velocity feedback at the elbow and two joint for all patients, at the shoulder a little for P4, P8 and P9. Position feedback at the elbow was significantly lower, for the

shoulder it was higher. For all patients the force feedback for the PT was inhibitory (switched sign) for the shoulder and elbow. For P4 the force feedback for the two-joint is significantly lower.

### 3.4 Validation

The estimated model FRFs of the arm admittance, shown in Figure 5, capture a lot of the detail of the estimated FRFs. To see if the fits are correct the VAFs were calculated for the hand positions. The VAFs with standard deviation for the control group and patients are shown in Figure 7.



**Figure 7.** The VAFs with standard deviation for the different tasks. PT: red, RT: green and FT: blue. Left: VAF in the x-direction, Right: VAF in y-direction. Upper: Control group, Lower: Patients. Not visible VAFs are lower than zero.

On average the VAFs for the control group were: PT (x: 65% and y: 65%), RT (x: 95% and y: 85%) and FT (x: 2% and y: -55%). For the patient group: PT (x: 63% and y: 11%), RT (x: 86% and y: 80%) and FT (x: 20% and y: -30%). The standard deviations for the FT (control) and all tasks (patients) were large. Due to the position of the arm for the experiments (Figure1), the x-direction corresponds mostly with the shoulder and the y-direction mostly with the elbow.

### 3.5 Model sensitivity

A model sensitivity test was performed to analyze the effect of the force feedback pathway, because these parameters were the most difficult to explain. Of one control subject the estimated parameters corresponding to

all three tasks were used and fixated while the force feedback gains were varied between -2.4 and 1.5 (range force feedback in Figure 6). The force feedback of the two-joint is close to zero (PT: -0.08, RT: -0.13 and FT: -0.06) and is fixed on -0.09. The gains of the shoulder and elbow were kept the same during the variations. The force feedback was mainly effective on the lower frequencies (0 to 4 Hz), where it increases (decreasing stiffness) or decreases (increasing stiffness) the arm admittance depending on its value. For the higher frequencies there is no effect. For values below zero the force feedback is inhibitory. For values between zero and approximately one the force feedback is excitatory and above one it becomes inhibitory, Figure 8. This effect was present in all tasks, but the point where the force feedback becomes inhibitory changes (PT: between 0.9 and one, RT and FT: between 0.5 and 0.9).

## **4. Discussion**

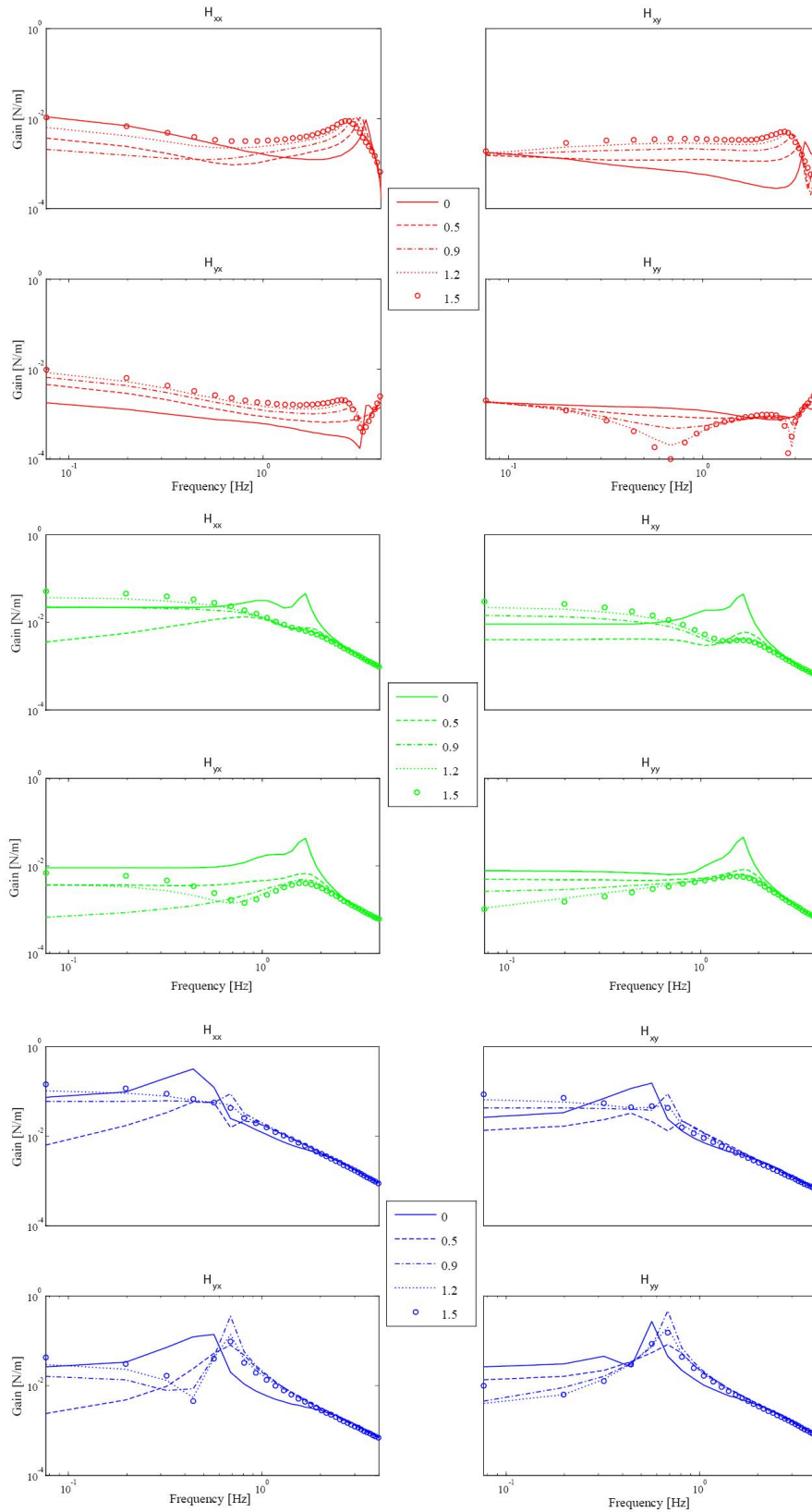
The aim of this study was to provide more insight in the functioning of the proprioceptive reflex systems after surgery in severe brachial plexus injured patients. The results indicated that reflexes recovered for all patients, still differences between the patients and control group were found.

### **4.1 Methodology**

Estimating the endpoint arm admittance using force perturbations using this manipulator was successfully done before on healthy subjects. Using the different task to provoke different control strategies was already proven useful for 1DOF experiments (Mugge et al., 2007, Mugge et al., 2010) and were used with success in this study, although the FT was difficult to perform and the corresponding parameter estimates were doubtful because the VAF for the FT was dramatically low. The use of frequency clusters and logarithmic scaling on the rest band left only few data points for parameterization. Despite the low amount of data points, good model fits were found. Good VAFs for the PT and RT, Figure 7, confirm that the model describes mechanical behavior of the arm well for these task conditions.

### **4.2 Clinical tests**

The clinical tests performed during this study give a good indication of the recovery of the patients. The maximal force measured was different between the patients and between the MRC grades (Table 2), which shows that the MRC grades are subjective and can only give an indication of the recovery. The MRC grades did correspond with the intrinsic parameters found for the elbow and the lumped impedance calculated (Table 3), so the grades gave a good indication of the recovery.



**Figure 8.** The effect of the force feedback on the arm admittance for the three tasks (gains between zero and 1.5). PT: red, RT: green and FT: blue.

### **4.3 Non parametric identification**

The effect of task description on control behavior is clearly visible for the PT and RT in Figure 5. For RT and FT the difference is less pronounced than found for the ankle and wrist joint (1DOF) where the difference between RT and FT is of the same magnitude as between the PT and RT (Mugge et al., 2007). A possible explanation can be that it is more difficult to perform a FT in 2DOF. In an earlier 2DOF study of the arm, subject had difficulty performing a FT and the difference between RT and FT were small (Lasschuit et al., 2008). The use of a cuff to immobilize the wrist joint makes it harder to feel the perturbations and thus harder to maintain a constant force on the handle (FT). Another explanation can be that it is hard to relax the arm during the RT when disturbed in two directions, and thus move with the perturbation performing a FT. But there was no clear evidence for either explanation. The higher admittance for patients, in comparison with the control subjects, during the PT indicated to a loss of intrinsic visco-elasticity that is related to active muscle force. The coherences for the tasks are good, the lower coherence for the PT and FT at the lower frequencies can be an indication for voluntary control behavior.

### **4.4 Parameter estimation**

#### *Control group*

The time delays and the activation cut-off frequencies for the PT of the control group correspond with earlier values of similar studies (De Vlugt et al., 2006). The estimated parameters for the control group were of comparable value over all subjects, which indicated that all subjects reacted similar to the tasks and perturbations. As expected the tasks provoked different intrinsic and reflex behavior. During the PT there is more reflex activity than intrinsic, which can indicate an energy efficient control behavior. Reflexes only provoke muscle activity in response to a perturbation, unlike co-contraction where the muscles are activated all the time.

#### *Patients*

The parameters found for the extremes of the patients group were consistent with the expectations (P1 comparable with the control subjects and for P6 little to no intrinsic and reflexive properties). Over the groups a decreasing intrinsic elbow damping and stiffness is found as expected, but even for the first group with good elbow function there was a significant decrease in damping. The significant increase in elbow and shoulder stiffness for the group with good elbow function indicates that more co-contraction is used. This increase in co-

contraction is found for all patients that had reasonably recovered their shoulder and elbow. When the elbow muscles (biceps and triceps) were graded MRC 4 or lower or uneven (e.g. biceps 4 and triceps 1), there is little to no elbow stiffness found (Table 2 and Figure 6). The biceps and triceps muscle have effect on the elbow and shoulder separately, but also on the two-joint. Two-joint stiffness was not present in any of the patients and damping only for some, which indicated that the biceps did not recover to its complete functionality. Stiffness at the shoulder was found for patients with a grade 2 or higher for the deltoids. An explanation can be that the arm position during the experiments resulted in small shoulder rotations, and smaller reaction forces are needed. For all patients MS and GTO feedback was found, which indicated that the reflexive pathways did recover after surgery. The group with little elbow function had no intrinsic properties at the elbow, but still reflexive properties were found. For these patients the triceps was absent or weaker than the biceps, which does not allow the patients to establish co-contraction. The biceps muscle is still able to react to reflexes. The force feedback during the PT switched from excitatory to inhibitory for all patients except P1. There is no clear explanation for this. For all patients the reflex activity is higher at the shoulder than at the elbow. A possible explanation for this is that the shoulder is closer to the neck (Brachial plexus) and it takes less time for the nerves to grow back to the shoulder than to the elbow, which might affect the functionality of the reflexes. Overall the patients seem to use more intrinsic stiffness, co-contraction, to resist the perturbation during a PT than control subjects. There are two explanations for this: 1) The intrinsic and reflexive properties did not recover to the combination as before the injury and are not cooperating correctly, 2) The patients use a different control strategy than the control group. Whereas the control group uses an energy efficient approach (sub maximal) the patients appear to use a more maximal approach resulting in co-contraction. It is possible that the exercises performed during rehabilitation which focus on muscle force do not provoke enough reflexive behavior. More research, e.g. experiments that are designed to disable co-contraction, is needed to verify if the use of co-contraction is learnt or a necessity. If it is learnt, there is a possibility that it can be unlearned.

#### **4.5 Validation**

For the RT good coherence and VAFs are found, what indicates that there is linear behavior and that the right model is used estimate the parameters. The coherences of the PT and FT are lower at the lower frequencies which can indicate voluntary control behavior. The VAFs for the FT were lower than of the PT and RT. Good coherence in combination with low VAFs indicate that not the right model was used though there was a linear relationship present. Voluntary control behavior was not taken into account in the model and can be a reason that the VAFs was high for the RT, lower for the PT and very low for the FT. For the PT (some) and the FT

voluntary control behavior can be expected. A possible explanation can be the use of low frequency perturbations, which can provoke this behavior. The subject is still able to react to the perturbations, unlike when using high frequency perturbations the movements become too fast to react. The VAF of the PT in y-direction of the patients can also be seen as the inability of elbow movement

#### **4.6 Force feedback sensitivity**

Positive values for the force feedback were expected to have an inhibitory effect. For the PT where an excitatory force feedback was expected, positive and thus inhibitory values were found for control subjects. With the sensitivity test insight in the functioning of the force feedback was found. Force feedback acts inhibitory for all used combinations (shoulder and elbow), except between zero and approximately one where it acts excitatory. This test was done for all three tasks to analyze if the other reflexes had influence in this behavior. The other combinations of intrinsic and reflexive parameters affected the range where the force feedback was excitatory. The force feedback therefore seems affected by the other reflexes. This properties of the force feedback were unexpected and a good explanation is not found.

### **5. Conclusions**

The experiment shows that there is a loss of intrinsic function for all patients with a brachial plexus injury, even patients with good recovery. For all patients both MS and GTO feedback was found, which indicates that reflexive pathways recover after surgery of severe Brachial plexus injuries. Overall the patients seemed to use more intrinsic stiffness, co-contraction, to resist the perturbation during a PT. There are two explanations for this: 1) The intrinsic and reflexive properties did not recover to the combination as before the injury and are not cooperating correctly, and 2) The patients are relying more on intrinsic control than on reflexive control (different control strategy). Whereas the control group uses an energy efficient approach, i.e. less intrinsic and more reflex activity, the patients appear to use a more maximal activation approach resulting in co-contraction. It is possible that the exercises performed during rehabilitation which focus on muscle force do not provoke enough reflexive behavior. There is no real proof to support either explanation. More research is needed to verify if the use of co-contraction is learnt or a necessity. Secondly the experiments show that the dynamic human response to perturbations is strongly influenced by task instruction. The tasks provoked different intrinsic and reflexive behavior, but all subjects had difficulty performing the FT. The method provided detailed information about the neuromuscular control system of the arm which can be used for thorough analysis of the remaining ability to control posture and movement and as a clinical tool for treatment evaluation in the future.

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## **References**

- Burdet E, Osu R, Franklin DW, Yoshioka T, Milner TE, Kawato M (2000) A method for measuring endpoint stiffness during Multi-joint arm movements. *J Biomechanics* 33(12): 1705-1709
- De Vlugt E, Schouten AC, Van der Helm FCT (2003) Closed-loop multivariable system identification for characterization of the dynamic arm compliance using continuous force disturbances: a model study. *J Neurosci* 122: 123-140
- De Vlugt E, Schouten AC, Van der Helm FCT (2003b) A force-controlled haptic device for movement control analysis of the human arm. *J Neurosci* 129: 151-168
- De Vlugt E, Schouten AC, Van der Helm FCT (2006) Quantification of intrinsic and reflexive properties during multi-joint arm posture. *J Neurosci* 155: 328-349
- Lasschuit J, Lam TM, Mulder M, Van Paassen MM, Abbink DA (2008) Measuring and modeling Neuromuscular System Dynamics for Haptic Interface Design. In: Proceedings of the AIAA modeling and simulation technologies conference and exhibit 18-21, August 2008, Honolulu Hawaii
- Mugge W, Abbink DA, Van der Helm FCT (2007) Reduced Power Method: how to evoke low-bandwidth behavior while estimating full-bandwidth dynamics. In: Proceedings of the IEEE 10<sup>th</sup> international conference on rehabilitation robotics, 13-15 June 2007, pp 575-581
- Mugge W, Abbink DA, Schouten AC, Dewald, JPA, Van der Helm FCT (2010) A rigorous model of reflex function indicates that position and force feedback are flexibly tuned to position and force tasks. *Exp. Brain Res* 200: 325-340
- Van der Helm FCT, Schouten AC, De Vlugt, Brouwn GG (2002) Identification of intrinsic and reflexive components of human arm dynamics during postural control. *J Neurosci* 119: 1-14