A HISTORY OF DISTAL RADIUS FRACTURE DISTURBS PROCESSING OF SENSORY FEEDBACK WITHOUT INFLUENCING NEUROMUSCULAR CONTROL IN THE WRIST JOINT

Master thesis

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TU Delft

A history of distal radius fracture disturbs processing of sensory feedback without influencing neuromuscular control in the wrist joint

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CONTENT

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Abstract - A distal radius fracture (DRF) is one of the most common fractures, especially in older women. Previous research shows that a DRF disturbs sensorimotor functions even eight weeks after finished treatment, which could influence neuromuscular control. The neuromuscular system exists of a sensory, motor and integration part, which all interact with each other as a closed-loop system. This study researches if a history of DRF disturbs neuromuscular control and if so, which part of the neuromuscular control system is the origin of this impairment. Nine healthy participants and eleven participants with a DRF history (who finished their treatment 0.2 – 4 years ago) executed posture tasks and reproduction tasks with a wrist perturbator. A posture task with force perturbations was done to test neuromuscular control. Changed environmental dynamics were applied to test the adaptation of the participants during the posture task. A position and force reproduction task were executed to test sensory position and force feedback. To test the motor part of the neuromuscular system, muscle activity was measured during the tasks with electromyography. The responses to the posture task did not differ between the groups. The position reproduction task was found to be significantly different between the two groups. Moreover, people with a DRF did not adapt to changed environmental dynamics while control participants did. This implies that processing of sensory position feedback does not work properly in people with a DRF history while neuromuscular control during a posture task with small deviations is still intact. A possible explanation for these results is that different neural networks are used during reproduction tasks and posture tasks. It is concluded that sensory feedback which is used in cortical processes is disturbed in people with a history of DRF while peripheral reflexes are still intact.

1. Introduction

A distal radius fracture (DRF) in the lower arm is one of the most common fractures (Court-Brown & Caesar, 2006; Van Staa et al., 2001). Up to 25% of all fractures in the pediatric population and 18% in the elderly population is related to a DRF (Nellans et al., 2012). A DRF happens usually during daily life activities, sports or falling on an outstretched hand (Nellans et al., 2012). Low bone mineral density, age and gender are associated with a high risk for DRF; a high incidence of DRF is seen in older women (Vogt et al., 2002). DRF leads to pain, diminished range of motion and lower grip strength, up to four years after fracture (Brogren et al., 2011). These symptoms leave people with a reduced ability to perform their job and daily tasks, like cooking, cleaning or getting dressed. Residual impairment and pain will continue in up to 50% of women over 50 years old with a DRF, even after treatment is finished (Vogt et al., 2002).

Besides a loss of grip strength and restricted range of motion, impaired sensorimotor functions can be a result of DRF as well (Karagiannopoulos et al., 2013). Karagiannopoulos et al. (2013) found both sensory and motor deficits eight weeks after surgical or non-surgical treatment of DRF. Since sensorimotor functions are part of the neuromuscular control (NMC) system, it is likely that disturbed sensorimotor functions disturb NMC. The NMC system consists of the central nervous system, proprioceptors, muscles and the skeleton, which are the processor, sensors, actuators and linkage system of the system respectively (Lasschuit et al., 2008). The system can both make voluntary and involuntary movements and it can react to external disturbances. Impaired NMC can be the consequence of three things: impairment of the sensory part, of the motor part, or of the integration of the sensory and motor part. All parts of the NMC system interact with each other in a closed-loop configuration. Therefore, when one part of the system fails, the other parts are affected as well.

When NMC is impaired in people with a DRF history (defined as at least three months since their last treatment) and it is known which part of the NMC system causes this impairment, personalized rehabilitation techniques can be developed and evaluated. Several tests and rehabilitation techniques to improve NMC in people with a DRF history have already been suggested: Karagiannopoulos & Michlovitz (2016) show that Joint Position Sense (JPS) is a good measure for sensorimotor impairment. With this test, people were asked to reproduce a certain position of their wrist with their eyes closed. Röijezon et al. (2017) suggested a new test to assess sensorimotor function, but they did not use it on patient groups yet. Wollstein et al. (2017) highlighted that only testing JPS is not enough when testing NMC. They show significant differences between patients with a DRF and healthy subjects in wide-ranging sensorimotor tests and found improvements with a therapeutic protocol which focused on sensorimotor improvement. However, they emphasize that more research is needed to validate the results of their study.

To develop satisfying rehabilitation techniques, the underlying problems of impaired NMC should be researched. It should first be confirmed that NMC is indeed influenced by a DRF and thereafter, which part(s) of the NMC loop have most impact on this impairment. Therefore, two research questions are addressed in this study:

1. **Is the neuromuscular control of subjects with a distal radius fracture history impaired compared to healthy subjects?**
2. **If neuromuscular control of subjects with a distal radius fracture history is impaired, which part of the neuromuscular control loop is the origin of this impairment?**

To answer these questions, four hypotheses will be tested in which people with a DRF history and healthy subjects will be compared. At first, NMC will be tested in general. Second, the three aforementioned parts of the NMC system will be tested separately, which leads to the following hypotheses:

1. People with a DRF history have disturbed neuromuscular control in the wrist compared to healthy participants.
2. People with a DRF history have disturbed proprioceptive position and force feedback compared to healthy participants.
3. People with a DRF history have a disturbed motor part of the neuromuscular control system compared to healthy participants.
4. People with a DRF history do not adapt to an environment with changed dynamics while healthy participants do.

NMC (hypothesis 1) will be tested with the wrist perturbator (WP), which applies rotational force or position perturbations to the wrist (Schouten et al., 2006). With this device, the mechanical admittance can be determined during position and force tasks, which is a reliable way to test the neuromuscular dynamics (Lasschuit et al., 2008). This kind of research has been used to test several other movement disorders like stroke (Meskers et al., 2009) and CRPS (Mugge et al., 2016), but it has never been used with a DRF patient group. The sensory part of the NMC system (hypothesis 2) will be tested by measuring position and force feedback, with position and force reproduction tasks as done before by Karagiannopoulos et al. (2013). The motor part of the NMC system (hypothesis 3) will be tested by measuring muscle activity with electromyography (EMG). The integration of the sensory and motor part (hypothesis 4) will be tested with the WP, by testing the capacity of people to adapt to changed dynamics of the environment.

2. Methods

2.1. Participants

Twenty subjects participated in this study (Table I), of which 11 subjects had a DRF history and 9 controls had no history of hand or wrist injuries. In the DRF group, subjects were included in the study

TABLE I: PARTICIPANT DETAILS

DRF group												
#	Age	Sex	Length (m)	Weight (kg)	Ev. arm	Dom. arm	DRF?	Years ago	Last treatment (years)	Surgery?	PRWHE pain	PRWHE func.
P1	55,1	F	1,60	77	Right	Right	Yes	2,5	0,4	Yes	8	36,5
P2	61,1	M	1,80	82	Right	Right	Yes	3	2,0	Yes	0	0
P3	59,9	F	1,67	59	Left	Left	Yes	1	1,0	No	16	17
P4	56,0	F	1,73	80	Right	Right	Yes	3	2,0	Yes	11	0
P5	57,5	F	1,70	60	Right	Left	Yes	2	2,0	Yes	0	0
P6	48,9	F	1,65	84	Right	Right	Yes	2	0,6	Yes	40	39
P7	55,9	F	1,63	80	Right	Right	Yes	5	4,1	Yes	26	19
P8	38,1	M	1,75	73	Right	Right	Yes	1,5	0,2	Yes	20	15,5
P9	46,3	F	1,74	61	Left	Right	Yes	5	4,0	No	16	4
P10	58,0	F	1,60	68	Left	Right	Yes	1,75	1,0	Yes	0	1,5
P11	53,6	M	1,81	72	Right	Left	Yes	4	3,0	Yes	8	1,5
Mean	53,7		1,70	72,4				2,8	1,8		13,2	12,2
Control group												
#	Age	Sex	Length (m)	Weight (kg)	Ev. arm	Dom. arm	DRF?	Years ago	Last treatment (years)	Surgery?	PRWHE pain	PRWHE func.
P12	58,9	M	1,83	85	Right	Right	Yes	21	21	No	2	0
P13	54,4	F	1,69	67	Right	Right	No				0	0
P14	56,4	F	1,65	73	Right	Right	No				0	0
P15	59,8	M	1,73	80	Right	Right	No				0	0
P16	57,6	F	1,64	67	Right	Right	No				0	0
P17	56,2	F	1,64	67	Right	Right	No				0	0
P18	49,3	F	1,72	76	Right	Right	No				0	0
P19	55,3	F	1,64	54	Right	Right	No				4	0,5
P20	47,3	F	1,78	92	Right	Right	Yes	23	23	No	0	0
Mean	55,0		1,70	73,4							0,7	0,1

Participant details. ***Ev. Arm:*** *evaluated arm, the arm with the fracture in the DRF group.* ***Dom. Arm:*** *dominant arm.* ***DRF?:*** *Is a history of DRF present?* ***Years ago:*** *how many years ago did the fracture happen?* ***Last treatment:*** *how many years ago did the treatment end?* ***Surgery?:*** *was the DRF treated with surgery?* ***PRWHE pain:*** *pain score on the patient-rated wrist and hand evaluation (PRWHE). Scale ranges from 0 (no pain) to 50 (worst pain).* ***PRWHE func:*** *functionality score on the PRWHE. Scale ranges from 0 (no difficulty) to 50 (impossible to do activity).*

when the range of motion of the wrist joint was at least 30° flexion and 30° extension and when the subjects were able to make a fist. Subjects were excluded when suffering from carpal tunnel syndrome, other neurological diseases in the wrist or rheumatoid disease in the hand or wrist, or when the pain score on the patient-rated wrist and hand evaluation (PRWHE) was higher than 40. The participants in the DRF group were all recruited by the *Hand en Pols Revalidatie Nederland,* a hand and wrist rehabilitation centre in the Netherlands. In total, 187 former patients were approached for participation, from which 35 responded with 24 a positive response. In the end, only 13 former patients were available in the scheduled time, from which 2 cancelled the meeting due to illness. Participants gave informed consent before participation and the study was approved by the Human Research Ethics Committee TU Delft.

2.2. Experimental set-up

Participants were seated comfortably with their lower arm in the device as shown in Figure 1A, such that the forearm was not able to move. The elbow angle was variable. The hand held the handle of the device such that extension and flexion in the wrist joint were the only movements possible in the lower arm (Figure 1B). The device used was a WP, as described by Schouten et al. (2006), a position or torque controlled actuator which could apply torque or position perturbations.

Participants executed five tasks with different characteristics in a fixed order, as shown in Table II. Two types of tasks were possible: reproduction tasks, in which a position or force had to be reproduced, and perturbation tasks, in which a position or force had to be maintained while

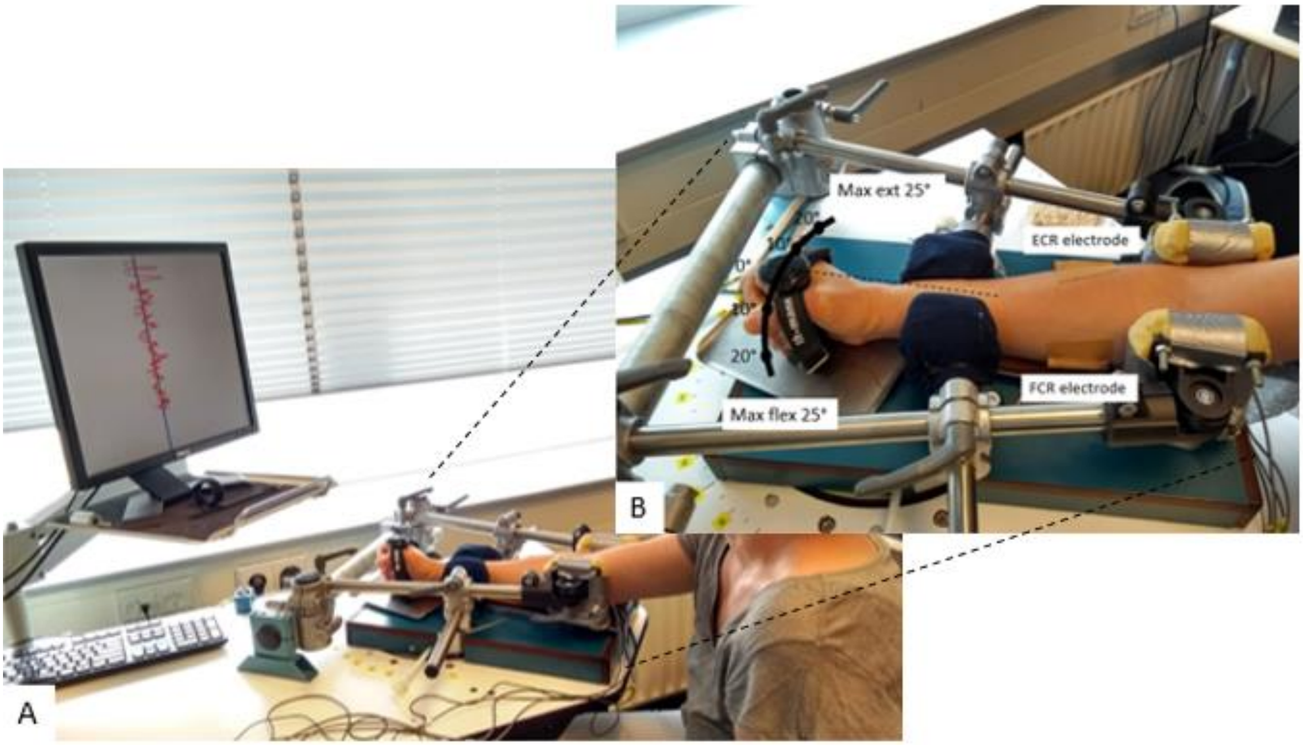

Figure 1: A) The typical posture of a participant during the experiment. The installation illustrated in the picture prevents movement of the lower arm of the participant. In this picture, the participant executes the position task: the participant holds the handle while the reference position (blue line) and the actual position of the handle (red line) are shown onscreen. The participant was asked to sit comfortably, which led to slightly different elbow angles between participants. B) the arm of the participant positioned in the WP. The EMG electrodes of the extensor carpi radialis (ECR) and flexor carpi radialis (FCR) are visible. The electrode of the extensor carpi ulnaris (ECU) is located at the unlar side of the forearm and is therefore not visible in this figure. The angle of the wrist is 0° (neutral position). The movement range of the handle is shown with the black line (25° flexion to 25° extension). The black dots on the black line show the four angles which had to be reproduced during the position reproduction task. During the force reproduction task, the handle stayed in neutral position. During the position task, the task was to keep the handle in neutral position.

TABLE II: TASK CHARACTERISTICS

Task type	Task name	Conditions	Rep	Visual	Arm visible?	Perturbations	Control mode	Task instructions
Reproduction	Position reproduction	1. 10° flexion 2. 20° flexion 3. 10° extension 4. 20° extension	6	n/a	No	n/a	0 – 12 s: position 12 s – end: torque	Reproduce remembered angle
	Force reproduction	1. 20% MVC flexion 2. 40% MVC flexion 3. 20% MVC extension 4. 40% MVC extension	6	A	No	n/a	Position	Reproduce remembered force
Perturbation	Position task	1. Reference 2. High damping 3. High stiffness	4	B	Yes	Force perturbations	Torque	Minimize position deviations
	Relax task	n/a	2	n/a	Yes	Position perturbations	Position	Relax
	Force task	n/a	4	C	Yes	Position perturbations	Position	Minimize force deviations

Overview of the task characteristics. ***Conditions:*** *the conditions within one task, n/a means there is only one condition.* ***Rep:*** *the number of trial repetitions for every condition.* ***Visual.:*** *the type of visualisation as shown in Figure 2. During the position reproduction task and the relax task, no visualisation was shown on the screen.* ***Arm visible:*** *no means that the arm was covered by a wooden board, to make sure that the arm and hand were not visible for the participant.* ***Perturbations:*** *the type of perturbation. During the reproduction type, no perturbations were applied.* ***Task instruction:*** *in short the task instruction which was given to the participant.*

perturbations were applied. Before each task, a brief introduction and explanation was given. The participant trained each task until it was clear by both the participant and researcher that the participant had understood the task completely. When different conditions were present within one task, the trials were presented in random order. All perturbation trials lasted 26 seconds.

2.2.1. Maximal Voluntary Contraction

Maximal voluntary contraction (MVC) measurements were done twice: before and after the experiment. The participant was asked to exert maximal isometric force on the handle in both flexion and extension direction, without using much grip force.

2.2.2. Position reproduction task

In order to test the first part of hypothesis two, about the proprioceptive position feedback, a position reproduction task was executed. The hand of the participant was moved passively by the handle to a certain angle θ and then held for 3 seconds (Figure 1B). The participant was asked to memorize this angle and move the handle maximally to the other side. Only when the wrist was flexed maximally, the program requested the participant to reproduce the memorized angle. The participant confirmed verbally to have reached the memorized angle cueing the researcher to trigger a measurement of the angle of the handle. The measurement consisted of 10 samples at a sample rate of 2500 Hz, from which

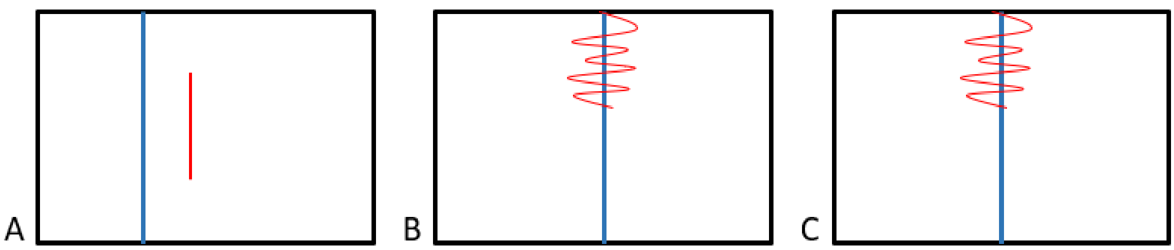

Figure 2: Visualisation on the computer screen. A) Visualisation during the force reproduction task. The blue line represents the desired torque line. The red line represents the current torque, exerted on the handle by the participant. The red line disappeared when the participant was asked to reproduce the torque. B) Visualisation during the position task. The blue line represents the desired position (zero deviation). The red line represents the position of the handle. The task was to keep the red line on the blue line. C) Visualisation during the force task. The blue line represents the desired torque (zero torque). The red line represents the torque exerted on the handle. The task was to actively keep the red line on the blue line.

the mean was taken to obtain the measured angle θ_{meas}.

2.2.3. Force reproduction task

In order to test the second part of hypothesis two, about the proprioceptive force feedback, a force reproduction task was executed. The handle of the WP maintained in neutral position during this task. The participant saw two lines on the screen as presented in Figure 2A. The participant was asked to bring the red line (which represented the current torque, exerted on the handle) and blue line (which represented the desired torque) together by exerting exactly the right amount of torque on the handle. This torque was either 20% or 40% of the MVC of the participant. When the two lines were brought together, the participant was asked to memorize this torque by maintaining it for 3 seconds. After 3 seconds, the participant was required to relax the wrist. Two seconds after the wrist was relaxed (no torque was measured on the handle), the red line disappeared. The participant was then asked to reproduce the memorized torque without the visual feedback of the red line. The participant confirmed verbally to have reached the memorized torque cueing the researcher to trigger a measurement of the torque exerted on the handle. The measurement consisted of 10 samples at a sample rate of 2500 Hz, from which the mean was taken to obtain the measured torque T_{meas}.

2.2.4. Position task

In order to test hypothesis one, a posture task was executed. The participants were asked to maintain the same position of the handle of the handle while force perturbations were applied. Visual feedback was given about the position of the handle as shown in Figure 2B. The task was to maintain the red line on the blue line (see Figure 1A). The applied force perturbation was a continuous signal consisting of random phase multisines with frequencies from 0.1-30 Hz (see Figure 3). Frequencies higher than 1 Hz had reduced power levels, according to the Reduced Power Method (Mugge et al., 2007), in order to evoke low bandwidth control behaviour while it still enables identification over the full bandwidth.

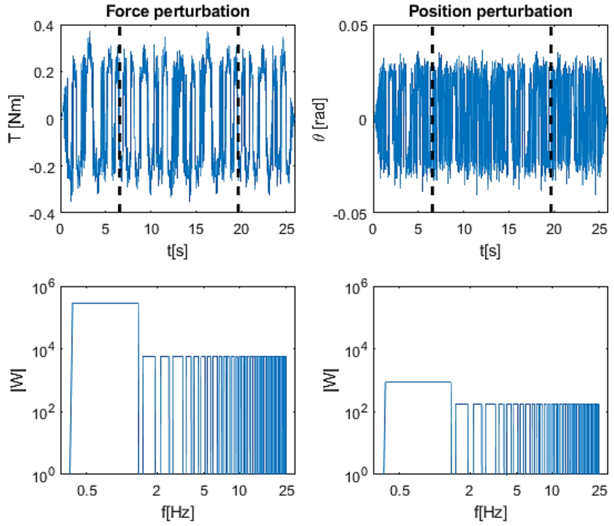

Figure 3: the perturbation signals of the force and relax task (right) and position task (left) in the time domain (upper) and frequency domain (lower). The part of the signal between the dashed lines in the upper graphs was used for analysis.

Regarding hypothesis four, different system dynamics were used in three conditions:

1. Reference (low damping, low stiffness): the damping of the system (b_e) and stiffness of the system (k_e) were set to 0.04 Nms/rad and 0.5 Nm/rad respectively.
2. High damping (and low stiffness): b_e and k_e were set to 1 Nms/rad and 0.5 Nm/rad respectively.
3. High stiffness (and low damping): b_e and k_e were set to 0.04 Nms/rad and 10 Nm/rad respectively.

The virtual intertia was kept small at 0.0016 kgm^2. Before the recording started, one test trial was used for each condition to scale the deviations of the handle until the standard deviation was about 1°, resulting in quasi-linear behaviour enabling linear analysis (Kearney et al., 1990).

2.2.5. Relax task

The participants were asked to relax while position perturbations were applied to the handle. No visual feedback was given onscreen. The applied position perturbation was a continuous signal consisting of random phase multisines with frequencies from 0.1-30 Hz with reduced power on frequencies higher than 1 Hz, with a standard deviation of about 1° (see Figure 3).

2.2.6. Force task

The subjects were asked to keep the force on the handle as low as possible while position perturbations were applied. This was best accomplished when the participant was being compliant. The perturbation signal was the same as for the relax task. Visual feedback was given as presented in Figure 2C. The task was to maintain the red line on the blue line.

2.2.7. Patient-Rated Wrist and Hand Evaluation

Before the experiment started, subjects had to fill in the PRWHE, which is a validated questionnaire with 15 questions. This questionnaire measures pain in the hand and wrist and the difficulty of doing daily tasks (MacDermid, Turgeon, Richards, Beadle, & Roth, 1998). The participants self-reported levels of wrist pain and function on a 11-point scale, from 0 (no pain/no difficulty) to 10 (worst pain/impossible to do activity). A total pain score was calculated by summing the scores of five questions about pain, resulting in a score from 0 (no pain) to 50 (worst pain).

2.3. Signal recording

During every trial, the force or position disturbance, position angle, angle velocity and interaction torque were recorded at 2500 Hz sample frequency. Furthermore, three differential electrodes (Delsys) recorded EMG of three muscles: flexor carpi radialis (FCR), extensor carpi radialis (ECR) and extensor carpi ulnaris (ECU). The EMG signals were pre-amplified, low-pass filtered at 450 Hz and high-pass filtered at 20 Hz, before being digitized at 1250 Hz by a separate system. The maximal activation level was determined from the EMG during the MVC trials, by taking the maximal level of activation from the rectified and low-pass filtered EMG at 1 Hz. The recorded EMG signals were rectified, low-pass filtered at 6 Hz and normalized to the maximal activation to compare the EMG between subjects.

2.4. Analysis

2.4.1. Reproduction tasks

For the position reproduction task, the absolute difference between the desired and measured angle was calculated for all trials:

$$\theta_{diff}(k) = |\theta_{des} - \theta_{meas}(k)|$$

with θ_{des} the desired angle (10° or 20° extension or flexion) and $\theta_{meas}(k)$ the measured angle in trial k.

For the force reproduction task, the absolute difference between the remembered and desired torque was calculated as a percentage of the desired torque for all trials:

$$T_{diff}(k) = |\frac{T_{des} - T_{meas}(k)}{T_{des}}| * 100\%$$

with T_{des} the desired torque (20% or 40% MVC) and $T_{meas}(k)$ the measured torque exerted on the handle as memorized by the participant in trial k. A response remarkably different from the individuals mean response was likely the result of a measurement error. When the reproduction torque was lower than 0.1 Nm it was assumed that the participant already relaxed its hand before the data was recorded and it was therefore decided not to include these data points in the analysis.

2.4.2. Perturbations tasks

For every condition, the recorded torque (T) and position (θ) signals were averaged over the four trials. All signals were cut to the same length as the multisine of the perturbation signal (13 s), see the dashed lines in Figure 3. The signals were transferred to the frequency domain using the Fast Fourier Transfrom (FFT). The frequency response function (FRF) was estimated using the cross-spectral densities of these signals. During the position task with force perturbations, the human arm interacts with the handle in a closed-loop configuration. Therefore, the admittance ($H_{T\theta}(f)$), which is defined as the causal relationship between torque input and position output (Mugge et al., 2007), was estimated using a closed-loop frequency domain identification method (Van Der Helm et al., 2002):.

$$H_{T\theta}(f) = -\frac{S_{D\theta}\,(f)}{S_{DT}\,(f)}$$

with $S_{D\theta}\,(f)$ the cross-spectral density of the external disturbance signal and the angle of the handle, and $S_{DT}(f)$ the cross-spectral density of the external disturbance signal and the exerted torque on the handle. Frequency averaging was applied over 8 bands. To check for linearity (which is assumed in the admittance estimate), the coherence was estimated:

$$\Gamma^2_{D\theta}(f) = \frac{|S_{D\theta}\,(f)|^2}{S_{DD}(f) * S_{\theta\theta}(f)}$$

with $S_{DD}(f)$ the auto-spectral density of the external force disturbance signal and $S_{\theta\theta}(f)$ the auto-spectral density of the angle of the handle.

During the force and relax task with position perturbations, the human arm interacts with the handle in an open-loop configuration. Therefore, the admittance ($H_{T\theta}(f)$) was calculated as the inverse of the impedance, which is defined as the causal relationship between position input and torque output:

$$H_{T\theta}(f) = \left(\frac{S_{T\theta}\,(f)}{S_{\theta\theta}\,(f)}\right)^{-1}$$

with $S_{T\theta}\,(f)$ the cross-spectral density of the position input and the torque output, and $S_{\theta\theta}\,(f)$ the auto-spectral density of the position input.

2.5. Statistical analysis

The preparation of the data was done with MATLAB R2017b while the statistical analyses were performed with IBM SPSS Statistics 24.0. Muscle fatigue was tested with a paired samples t-test, comparing the MVC values obtained before and after the experiment. Pain score and mean MVC differences were tested with a t-test. For the reproduction tasks, comparisons between the two groups were done on the means of the absolute difference values, which were calculated across six trials for each angle/force level, with a 2x2 repeated measures ANOVA (Table IV). Furthermore, three repeated measures ANOVA's were performed for the position task, to test if the DRF group reacted differently to the reference condition than the control group did on the low (0 – 3 Hz), mid (4 – 10 Hz) and high (10 – 25 Hz) frequencies, which correspond to the stiffness, damping and inertia lines respectively. The admittance on the frequency points was taken as the repeated measures while the group was taken as the between-subjects variable. To test if the two groups reacted differently to the conditions (high stiffness and high damping), a two-way repeated measures ANOVA was performed. For the post-hoc, a Tukey HSD test was used. A p-value of 0.05 was considered significant.

TABLE IV: REPRODUCTION TASKS 2X2 STATISTICAL DESIGN

Position reproduction task		
Side→ ↓Angle	Extension	Flexion
10°	Ext 10°	Flex 10°
20°	Ext 20°	Flex 20°
Force reproduction task		
Side→ ↓Force level	Extension	Flexion
20% MVC	Ext 20% MVC	Flex 20% MVC
40% MVC	Ext 40% MVC	Flex 40% MVC

TABLE III: MVC RESULTS

	MVC flexion		MVC extension	
	M (Nm)	SD (Nm)	M (Nm)	SD (Nm)
DRF	5.39	3.18	3.21	2.26
Control	7.31	2.86	4.48	1.23

3. RESULTS

3.1. PRWHE and MVC

The DRF group had significant higher pain scores on the PRWHE pain scale than the control group, $t(18) = 3.01$, $p = .008$. The mean MVC values of the DRF and control group did not differ for both the MVC contraction in flexion direction, $t(18) = -1.46$, $p = .16$, and in extension direction, $t(18) = -1.40$, $p = .18$, see Table III. No significant differences were found between the MVC values before and after the experiment in both flexion direction, $t(19) = -1.46$, $p = .16$, and extension direction, $t(19) = -1.05$, $p = .31$, which implies that no muscle fatigue was experienced by the participants.

3.2. Position reproduction task

The position reproduction task data was found to be normally distributed when using the Kolmogorov-Smirnov test except for the 20° flexion test in the control group. The assumption of homogeneity of variance was violated for all angles, but analysis of variance is reasonably robust against this violation since the group sizes are similar. Regarding hypothesis two, a mixed between-within subjects analysis of variance was conducted to assess the impact of the two groups, across two sides (flexion and extension) and two angles (10° and 20°). There was no significant interaction between group, side and angle, Wilks' lambda = .98, F(1,18) = .06, p = .81, partial eta squared = .003. There was no effect for side, Wilks' lambda = 1.00, F(1,18) = 0.008, p = .93, partial eta squared = .000. There was a significant effect for angle, Wilks' lambda = .51, F(1,18) = 17.24, p = .001, partial eta squared = .49. No other interaction effects were found. The main effect comparing the two groups was significant, F(1, 18) = 6.29, p = .02, partial eta squared = .26, indicating a difference between the two groups when reacting to the position reproduction test, see Figure 4.

Since the 20° tasks were bounded measures due to the design of the WP, a second mixed between-within subjects analysis of variance was conducted to assess the impact of the two groups on θ_{diff}, across the 10° tasks (extension 10° and flexion 10°). There was no significant interaction between group and side, Wilks' lambda = .97, F(1, 18) = .50, p = .49, partial eta squared = .03. There was no effect for side, Wilks' lambda = 1.00, F(1, 18) = .05, p = .82, partial eta squared = .003. The main effect comparing the two groups was significant, F(1, 18) = 4.67, p = .045, partial eta squared = .21.

No correlation was found between pain and any of the four tasks, which suggests that pain has no influence on the position reproduction tasks.

3.3. Force reproduction task

For 12 out of 480 responses, the responses were excluded from the analysis, since the reproduction

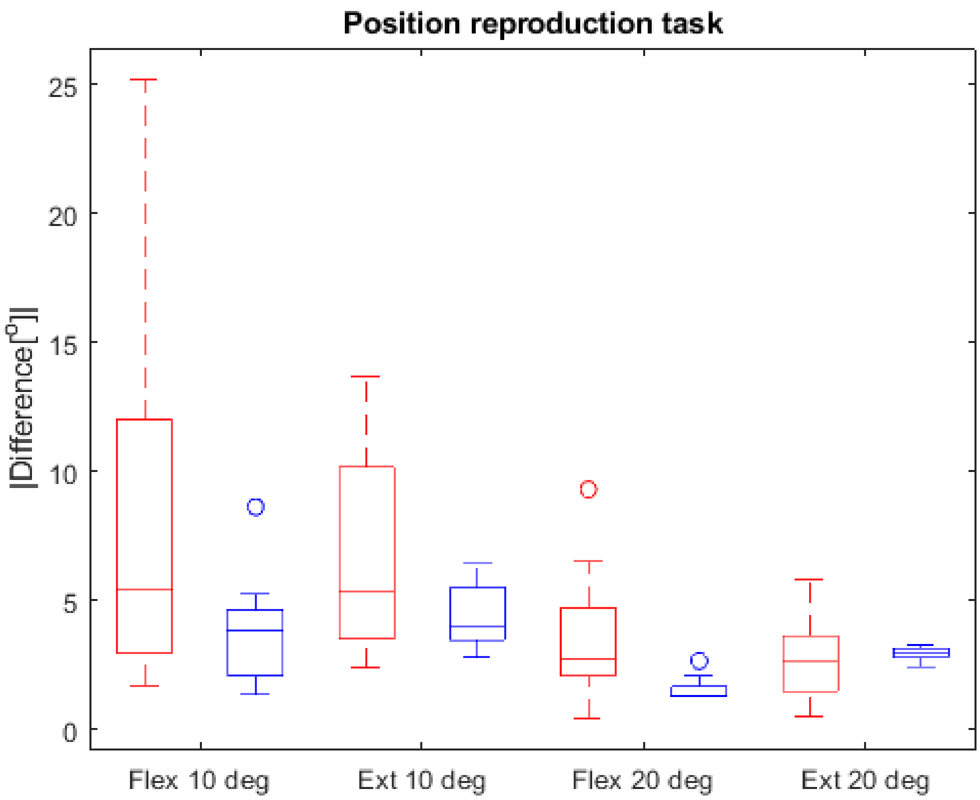

Figure 4: boxplot of the mean values of θ_{diff} per task and group. The DRF group (red) showed significantly greater differences than the control group (blue).

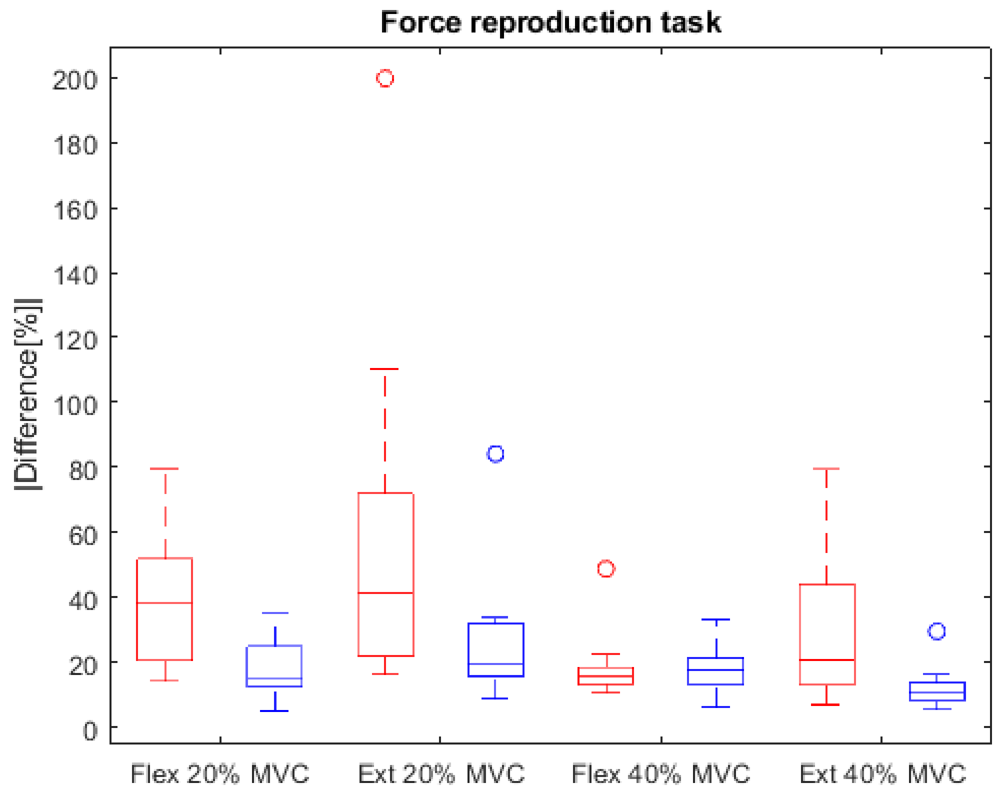

Figure 5: boxplot of the mean values of T_{diff} per task and group. The DRF group (red) did not show significantly greater differences than the control group (blue).

torque was lower than 0.1 Nm. Besides this, the reproduction responses of the extension force reproduction tasks of P3, P7 and P10 were excluded from the analysis since their data was unreliable due to pain when exerting force in extension direction.

The force reproduction data was found to be normally distributed except for the 40% flexion and 20% extension task in the DRF group and the 20% extension task in the control group according to the Kolmogorov-Smirnov test. The assumption of homogeneity of variance was not violated. Regarding hypothesis two, a mixed between-within subjects analysis of variance was conducted to assess the impact of the two groups on the force reproduction tasks, across two sides (flexion and extension) and two force levels (20% MVC and 40% MVC). There was only a significant effect for force level, Wilks' lambda = .54, $F(1,15) = 12.66$, $p = .003$, partial eta squared = .46, while no other interaction effects were found. The main effect comparing the two groups was not significant, $F(1, 15) = 3.87$, $p = .07$, partial eta squared = .21, indicating no difference between the two groups reacting to the force reproduction task, see Figure 5.

A correlation was found between pain and the extension tasks (20% and 40%). Therefore, a mixed between-within subjects analysis of variance with pain as covariate was conducted. This resulted in a significant interaction effect for force level and group, $p = .007$, and a significant interaction effect for side and force level, $p = .02$. A significant main effect was found for pain, $F(1,14) = 9.18$, $p = .009$, partial eta squared = .40, but not for group, $F(1,14) = .04$, $p = .85$, partial eta squared = .003.

TABLE V: STATISTICAL RESULTS FOR THE POSITION TASKS

Frequencies	F	Sig
Low (0-3 Hz)	F(1,16) = .09	No (p = .77)
Mid (4-10 Hz)	F(1,16) = 2.53	No (p = .14)
High (10.5-25 Hz)	F(1,16) = .91	No (p = .36)

3.4. Position task

P1 was excluded from the analysis, because of technical reasons. For the reference condition, P6 was excluded, for the high damping condition, P10

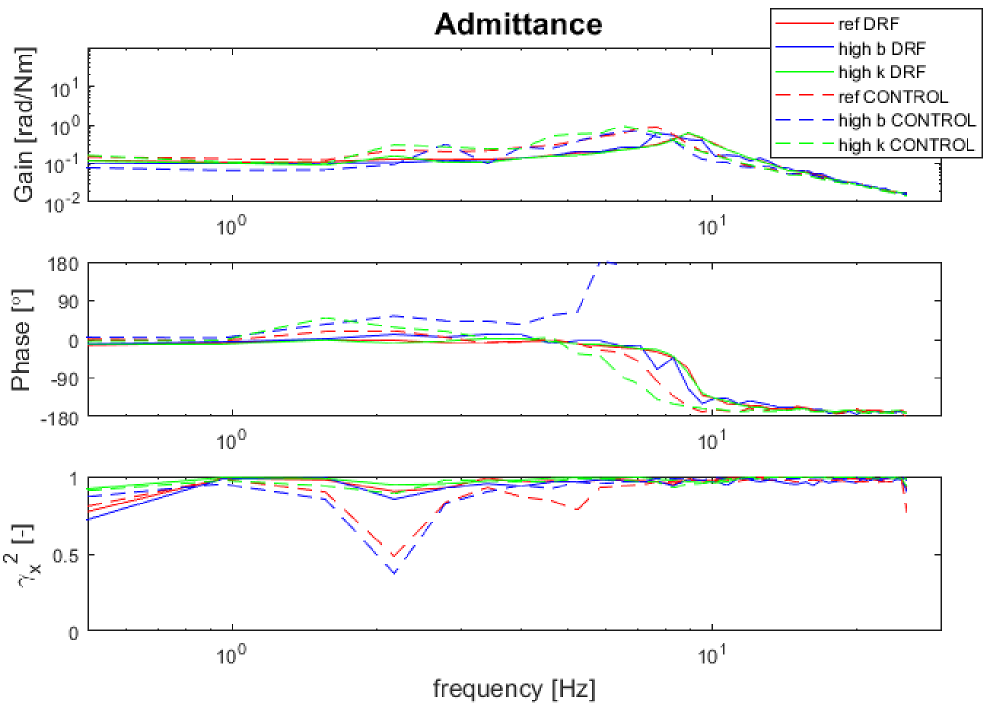

Figure 6: The typical transfer functions of the position task of one control participant (striped lines, P19) and one DRF participant (continuous lines, P2) in three conditions: 1. Reference condition (red), 2. High damping (blue), 3. High stiffness (green). Only the control participants behaved significantly different in the three conditions. No significant difference was found between the two groups in the reference condition.

was excluded, both due to low coherences (lower than 0.6). Regarding hypothesis one, the main effects of the repeated measures ANOVA to compare the two groups on the reference condition of the position task can be found in Table V for the low, mid and high frequencies. No interaction effects were found. It can be seen that no significant difference was found for any frequencies, indicating no difference between the two groups reacting to the position reference task, see Figure 6. Regarding hypothesis three, the EMG levels during the reference position task are presented in Figure 7.

Regarding hypothesis four, a two-way repeated measures ANOVA was conducted to compare the effect of the two groups and the three conditions (reference, high damping or high stiffness) on the admittance of the low frequencies. An interaction effect was found for group and frequency, Wilks' lambda = .79, $F(4,46) = 3.08$, $p = .03$. No other

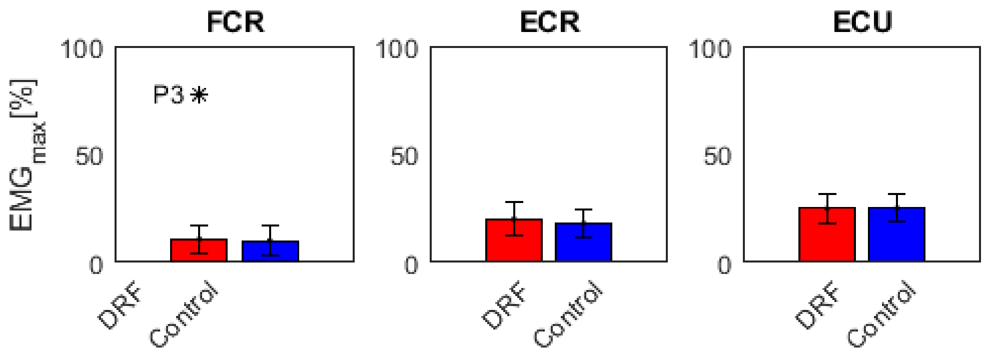

Figure 7: the mean EMG levels of the DRF (red) and control (blue) participants of the flexor carpi radialis (FCR), extensor carpi radialis (ECR) and extensor carpi ulnaris (ECU) during the reference position task. The EMG levels are similar for both groups. The EMG levels are normalized to the maximal voluntary contraction. A mean EMG level was derived from the part of the EMG signal which was used for the analysis in accordance with previous analyses. For the FCR, the mean EMG level of P3 was considered as an outlier.

interaction effects were found and no main effects were found. Since an interaction effect was found for group and frequency, a repeated measures ANOVA was conducted with condition as between-subjects variable for both groups separately. No interaction effects were found for both groups. A significant main effect was found in only the control group, $F(2,24) = 3.51$, $p = .046$. A Tukey HSD post hoc test showed that the high stiffness condition did not differ from the reference condition ($p = .98$), but a tendency towards significance was found between the high damping and reference condition ($p = .06$).

4. Discussion

The purpose of this study was to determine if a DRF influenced NMC and if so, which part of NMC system was influenced most. In order to fulfil this purpose, four hypotheses were tested. Only the second and fourth hypotheses were found to be true, which said that the sensory part of the NMC system was impaired in the DRF group compared to healthy participants and that people with a DRF history do not adapt to an environment with changed dynamics while healthy participants do. These findings imply that a DRF is related to disturbed processing of sensory feedback of the NMC system which leads to an impairment to detect a changed environment and adapt to it, without influencing NMC, an unexpected result. All hypotheses will now be discussed one by one in more detail.

4.1. Hypothesis 1: neuromuscular control

The first hypothesis was that people with a DRF history have impaired NMC compared to healthy participants. This was tested with the reference condition of the position task. It was assumed that if the two groups reacted differently to this test, that NMC would differ between the two groups. However, no significant differences were found between the two groups in the mechanical admittance of the reference position task, neither for low, mid or high frequencies. During the position task, all participants were stiffer than during the relax task, as expected (Mugge, et al., 2009). Besides that, the coherences were high for both groups, indicating a low noise level and high linearity. Hence, it was assumed that the position task is well executed. It is therefore expected that finding the non-significant difference does not result from a badly executed test, but might result from the absence of a difference. This could be the result of two things: either DRF does not influence NMC at all, which is in contrast with the expectations, or several parts of the NMC system are influenced by a DRF but are compensated for by other parts of the NMC system. In order to investigate this idea, the other hypotheses were tested as well.

4.2. Hypothesis 2: sensory feedback

According to the second hypothesis, an impaired sensory part was expected in people with a history of DRF compared to healthy subjects. The sensory part of the neuromuscular system was measured in this study with the proprioceptive position and force feedback. This hypothesis was tested with the reproduction tests. A significant difference was found between the two groups reacting to the position reproduction task, which indicates that position feedback is different for people with a DRF history and healthy people. This is in accordance with the study of Karagiannopoulos et al. (2013). Since the position reproduction task was executed with the WP, instead of with a goniometer, the data was more accurate, and more repetitions were done than in the study of Karagiannopoulos et al. (2013), which makes the data more reliable.

No significant result was found for the force reproduction tasks. However, looking at the results (Figure 5), it seems like there is a difference between the two groups, especially for the 20% MVC tasks. The p-value was very low ($p = .07$), which suggests a relation that the experiment did not sufficiently demonstrate. The DRF group was small (N=8) because three participants were excluded due to pain during the tasks. This could have influenced the statistical test. When pain was taken as covariate during the statistical test, there was a significant main effect for pain but not for group. This indicates that the found effects are rather an effect from pain than from the DRF. However, two interaction effects were found, which makes it difficult to draw conclusions. The

40% MVC tasks show smaller differences between participants (Figure 5) and a smaller difference between the two groups. This can be explained as follows: the force reproduction error is dependent on the force level (Onneweer et al., 2016): people underestimate high forces and overestimate low forces. The 40% MVC tasks were experienced as difficult by the participants. They had the feeling that they had to push the handle almost maximally, which could have made it easier to reproduce the force.

4.3. Hypothesis 3: muscle activity

The third hypothesis was that the motor part of the NMC loop is impaired in people with a DRF history compared to healthy participants. This was tested in this study by measuring the muscle activity during the position tasks. Karagiannopoulos et al. (2013) found significant differences in maximal EMG levels during a 30-s static maximum grip task between the DRF group and the healthy controls. However, when looking at the normalized EMG levels during the position task (see Figure 7) in this study, the EMG levels of the DRF and control group are similar. This indicates no differences between the two groups in the motor part of the NMC system. Besides this, no significant difference was found between the MVC values in both flexion and extension direction in this study.

4.4. Hypothesis 4: adaptation

The last hypothesis was that people with a DRF history could adapt worse to changed environmental dynamics than healthy participants. When reacting to force perturbations people use both intrinsic and reflexive stiffness. Previous literature shows that people adapt to changed environmental dynamics by modulating the length and velocity reflex gains, or by changing their intrinsic stiffness with co-contraction (De Vlugt et al., 2002; De Vlugt et al., 2001). In the control group, a significant main effect was found for condition, which implies that the control group reacted differently to the three conditions. This is presumably primarily the effect of the high damping condition, since the difference with the reference condition is almost significant ($p = .06$). This is in accordance with the study of De Vlugt et al. (2002) since this article shows that people increased their length feedback gain in particular with higher environmental damping of the system. In the DRF group, this main effect for condition was not found, indicating that the DRF group does not adapt to the conditions. This is possibly the result of the inability of people with a DRF history to detect changes in the environmental dynamics and adapt to this by modulating their reflex gains. Another possible explanation is that pain disturbs the ability to detect changes in the environment.

4.5. Interpretation of the results

Thus, only hypotheses two and four were found to be true, while NMC in hypothesis one was not influenced, which is against the expectations by previous studies (Hagert, 2010; Karagiannopoulos & Michlovitz, 2016; Karagiannopoulos et al., 2013; Valdes et al., 2014; Wollstein et al., 2017). It seems contradictory that on the one hand people with a DRF history perform worse on the position reproduction task which is assumed to measure the sensory position feedback of the NMC system, and are unable to lower their admittance to react to the force perturbations to adjust to changed environmental dynamics, while on the other hand, this does not influence NMC during general position tasks. There are several explanations which could be thought off to explain the found results. At first, the proprioceptive feedback which is used during the position task can come from a different source than the feedback used during the position reproduction task. The proprioceptive feedback used in reflexes during the position task is assumed to come from the muscle spindles in the muscles, which sense stretch length and velocity of the muscle, and the Golgi tendon organs in the tendons, which are sensitive to muscle force. However, previous literature shows that a current belief is that ligaments in the hand and wrist give proprioceptive feedback as well, especially during extreme positions (Hagert et al., 2016; Hagert et al., 2009; Petrie et al., 1997). During the position reproduction task, the deviations from the neutral position are much larger than during the position task. It is therefore possible that several ligaments are being stretched during the 10° and 20° tasks. The proprioceptive feedback from the mechanoreceptors in the ligaments are being used in memorizing the angle, while this information cannot be used during the position task. In this way, the position reproduction task could be influenced while the position task is not. Ligament ruptures and injuries are often associated with distal radius fractures (Geissler et al., 1996), which makes this theory plausible.

This theory, however, does not explain why people with a DRF history are unable to adjust their reflex gains in order to adapt to changed environmental dynamics. Therefore, a second possible explanation for the found results is that different neural processes are needed for position control than for position reproduction, like found before between position and movement control (Chew et al., 2008). For example, during the position reproduction task memory is needed to memorize the angle which has to be reproduced. Moreover, active motor commands are given from the brain to the muscles to make voluntary contractions to reproduce the memorized angle during the position reproduction task, while during the position task reflexes are used which are probably only monosynaptic (De Vlugt et al., 2002). Most likely, people with a DRF history have not used their wrist in a long time due to surgery or immobilisation. This leads to decreased cortical activation in the sensorimotor cortex of the immobilised hand due to plasticity of the brain (Weibull et al., 2011). With the peripheral reflexes still intact and decreased cortical activation of the affected hand, participants in the DRF group were able to execute the position task well in contrast to the position reproduction task. The adjustment of reflex gains is assumed to take place cortically as well, which can explain why people with a DRF history are unable to adjust their reflex gains in order to adapt to changed environmental dynamics

4.6. Limitations of the study

There were several limitations in this study. At first, two participants in the control group experienced a DRF more than 20 years ago. When executing the statistical tests again without these participants, similar results were found, except for the adaptation test. Without these participants, the control group did not show significant differences between the three conditions during the position task, $p = .099$. However, this was probably due to the small group size (N=7). This implicates that the effects found in this study are temporary for people who experienced a DRF, and may fade out over time. Second, the complexity, location and treatment of the fraction and other damaged structures due to the fraction were not taken into account in this study. Third, during the position reproduction task, hardware stops were present during the test, due to the use of the WP. This means that the handle of the WP could only move between 25° extension and 25° flexion. This led to lower variances during the 20° reproduction tasks, which could have influenced the data, since a significant interaction effect was found for angle. Therefore, a second statistical test was done for only the 10° reproduction tasks. This resulted in a significant difference between the two groups as well, which indicates that the limitation of using the WP can be neglected. Fourth, the force task could have shown more information about hypothesis four, but the force task turned out to be not well executed. All participants were stiffer during the force task than during the relax task, while this should be the other way around (Mugge, et al., 2009). This is probably the result of a badly designed perturbation signal. The power on the high frequencies was too high, which resulted in oscillations which were too fast to react to by the participant (see Figure 3). Besides this, the participant had little time to practice the task. Therefore, it was chosen to not include the force task in the analysis. Fifth, NMC was tested with a posture task with small deviations only, while NMC in general is a much broader concept. For example, motion control has not been taken into account in this study. Furthermore, in this study NMC was divided in a sensory, motor and integration part and tested individually by testing the position and force feedback, muscle activity and adaptation respectively. However, these three parts include more, for example vision in the sensory part and motor commands in the motor part. Therefore, care has to be taken when interpreting the conclusions of this study. At last, this study did not research a cause and effect relation between DRF and NMC. For example, sensory feedback could be disturbed as a result of DRF, but it is also possible that people with disturbed sensory feedback experience a DRF more often. The relation between NMC and DRF found in this study is therefore not necessarily a causal relationship.

4.7. Recommendations

Further studies should include or control the complexity, location and treatment of the fraction and other damaged structures due to the fraction in their studies to be sure that the DRF is the only cause of the investigated problems. Furthermore, further research should focus on the causal relationship between a DRF and NMC, for example by testing both the affected and unaffected wrist of all participants. Moreover, it is recommended to execute a well-executed force task in further research, since a force task could have given more complete information about the working of NMC in people with a DRF history. Besides this, further research should focus on the difference between peripheral and cortical processes after a DRF to validate the proposed theory in this study. At last, only non-parametric system identification has been performed in this study. Further research should also focus on parametric system identification, in order to identify physiologically relevant parameters (Mugge et al., 2009). When fitting a neuromusculoskeletal model to the experimental data, more information could be obtained about the underlying reason why the reproduction and adaptation tasks are found to be significantly different between the two groups while the other tests are not.

The results of this study can be used by hand physiotherapists. Their treatments should focus on specialised therapy for restoring proprioceptive feedback rather than focussing on the whole NMC system like proposed before (Röijezon et al., 2017; Wollstein et al., 2017). It is advised to be physically active with the affected hand to restore the functional activation levels in the sensorimotor cortex (Cirillo et al., 2009).

5. CONCLUSION

We conclude that sensory position feedback in the wrist joint is disturbed in people with a history of DRF, which influences the adaptation to changed environmental dynamics during position tasks. However, NMC during posture tasks with small deviations stays intact. An explanation for these results is that sensory feedback which is used in cortical processes is disturbed while peripheral reflexes are still intact.

6. APPENDIX

In this appendix, the responses of all participants for all tasks will be shown. Figure 8 shows the EMG levels of all participants during the reference position task. This is a more elaborate figure than Figure 7. Figure 9 until Figure 47 show the responses of P1 until P20, in accordance with Table I, of all trials of the reproduction tasks and the transfer functions of the perturbation tasks (position, relax and force tasks).

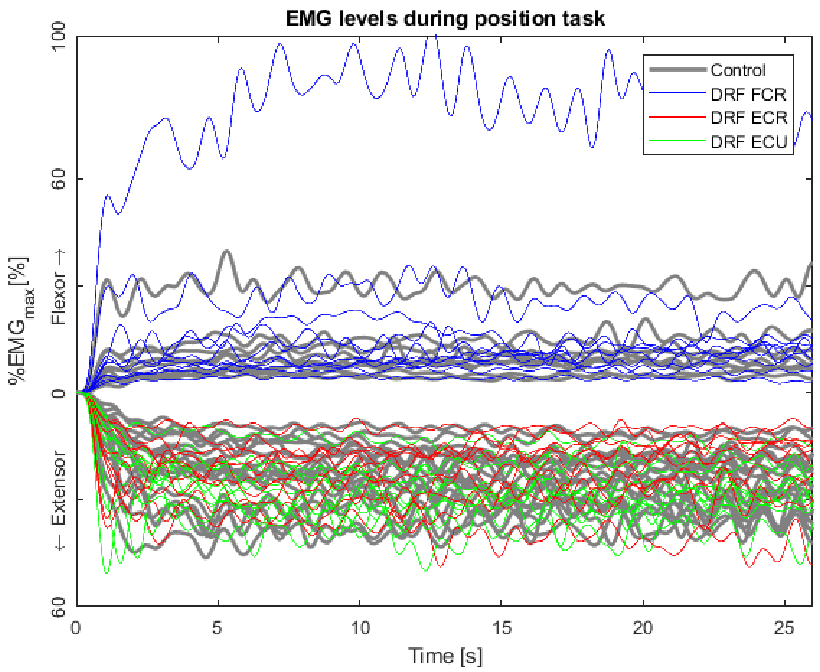

Figure 8: the normalized EMG levels of all participants during the position reference task, filtered with a 1 Hz lowpass filter. 0 shows no activity while 100 shows 100% of the MVC activity. Positive levels are the EMG levels of the FCR (blue). Negative lines are the ECR(red) and ECU (green) of the DRF participants. The thick grey lines show the muscle activity of the control participants. It can be seen that the EMG levels for both the DRF participants and control participants are similar.

P1

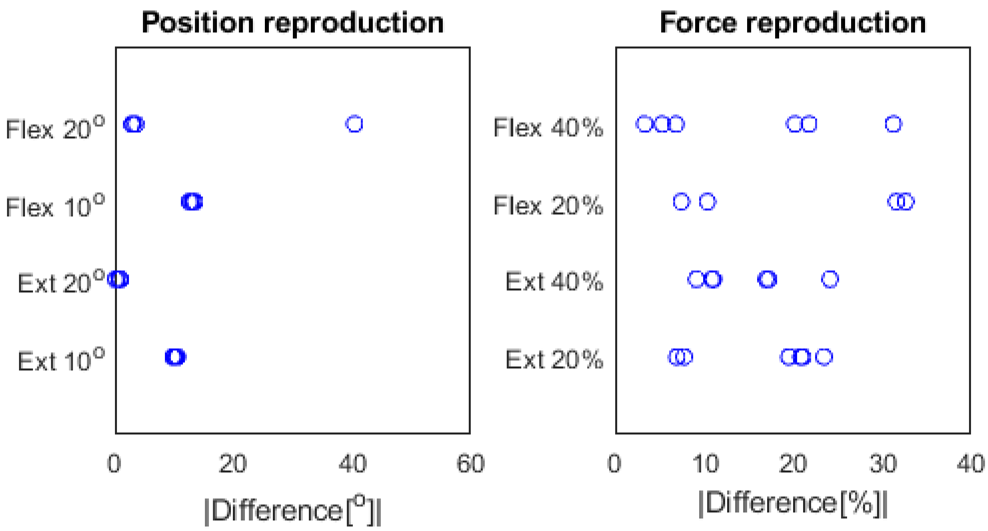

Figure 9: P1 position and force reproduction task responses.

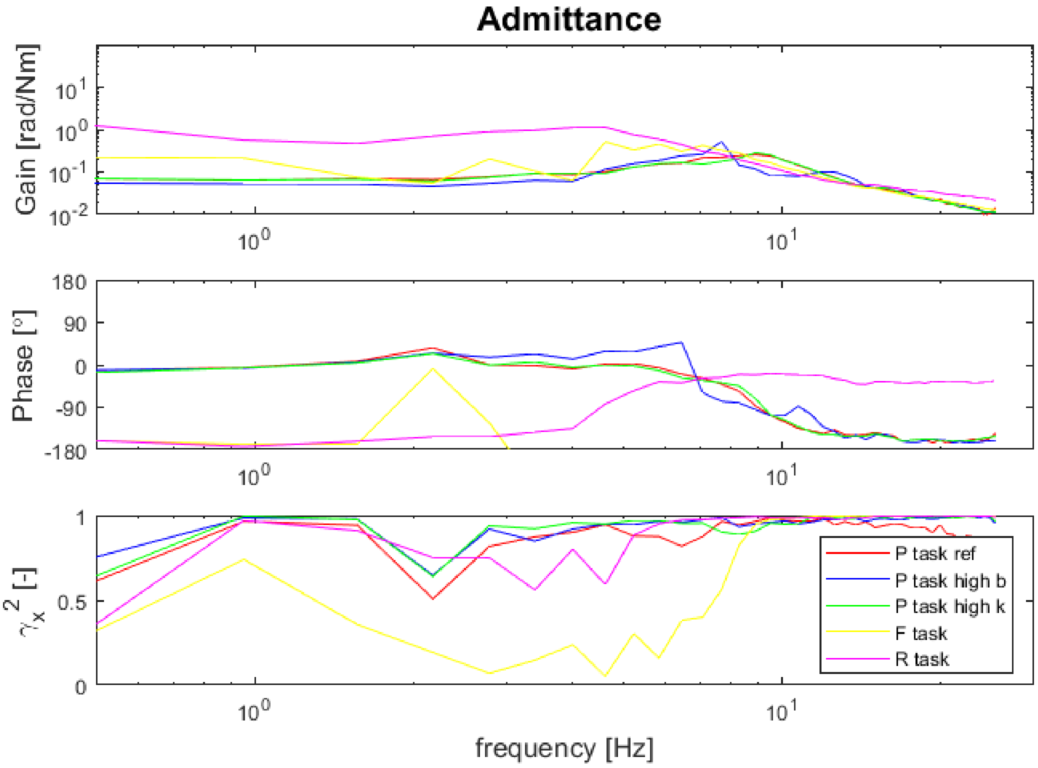

Figure 10: P2 responses to the position task (P) in the reference, high damping and high stiffness conditions, the force task (F) and relax task (R).

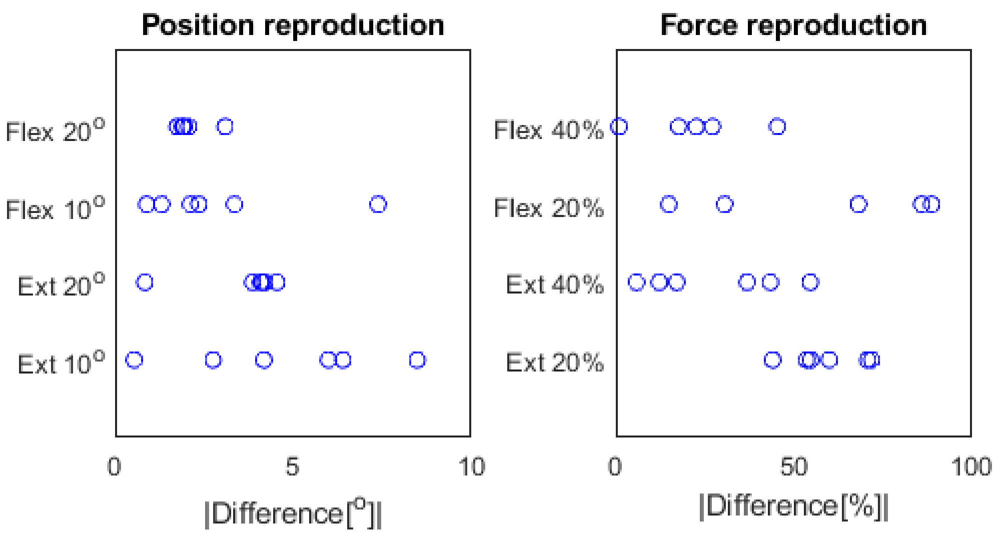

Figure 11: P2 position and force reproduction task responses.

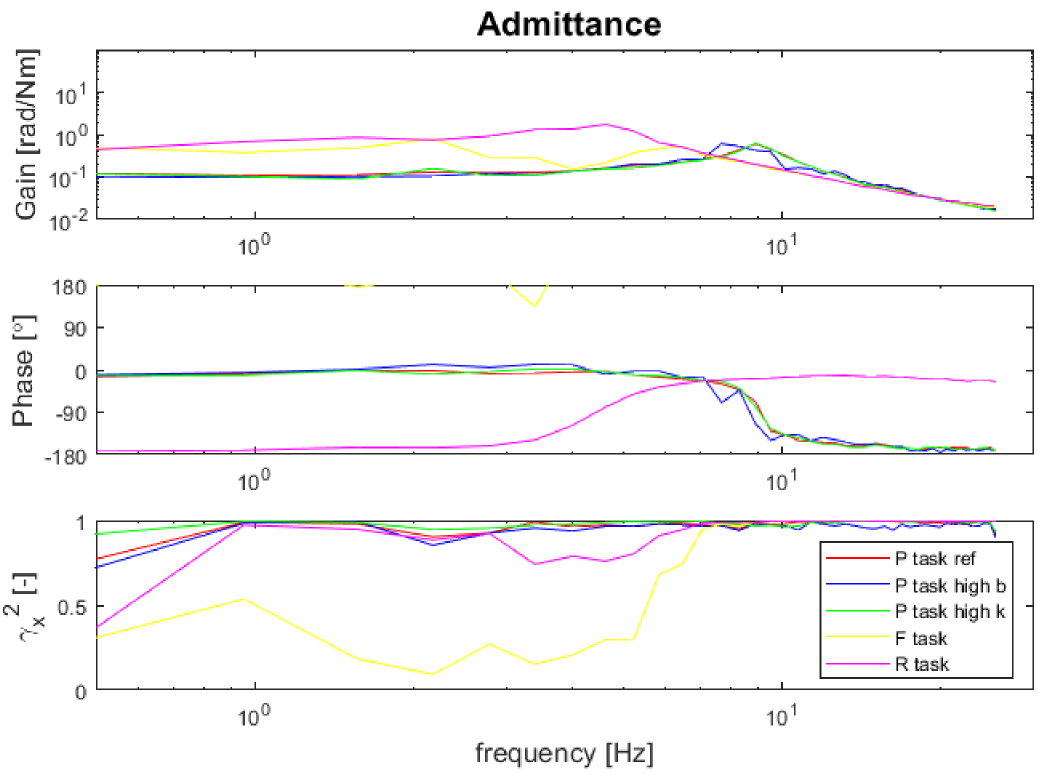

Figure 12: P3 responses to the position task (P) in the reference, high damping and high stiffness conditions, the force task (F) and relax task (R).

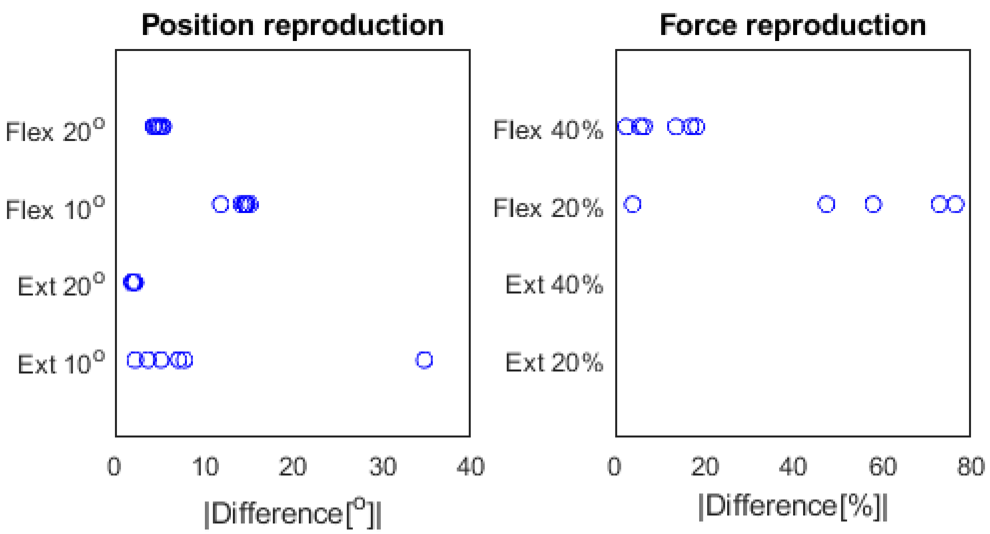

Figure 13: P3 position and force reproduction task responses.

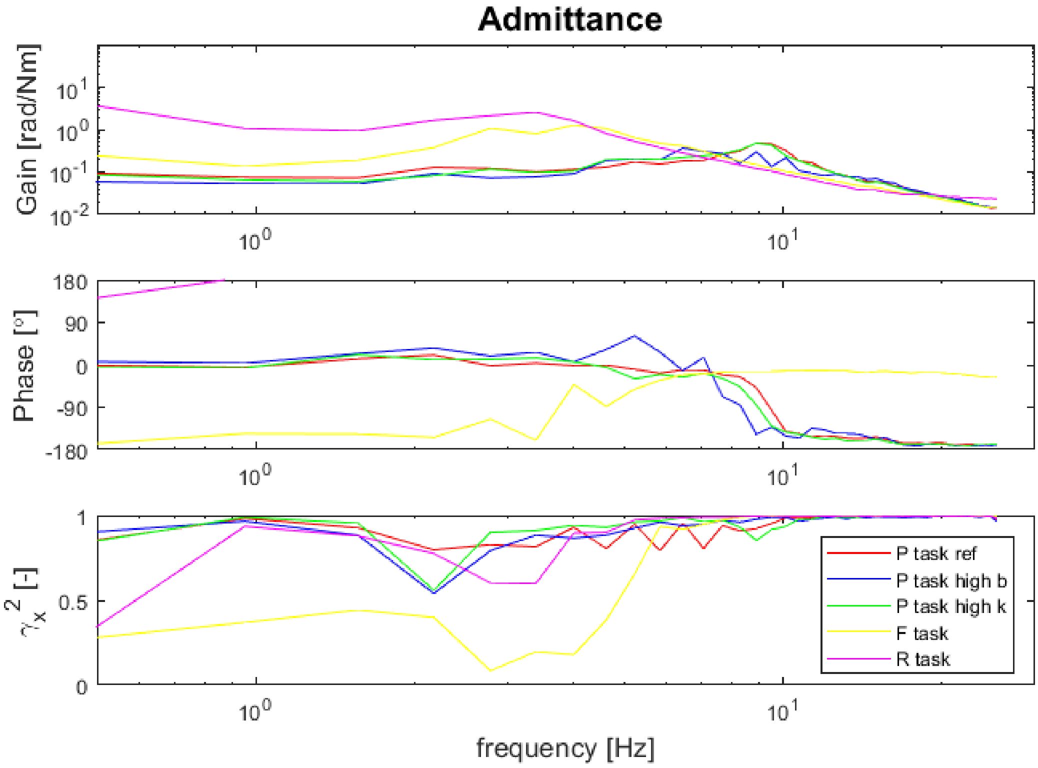

Figure 14: P4 responses to the position task (P) in the reference, high damping and high stiffness conditions, the force task (F) and relax task (R).

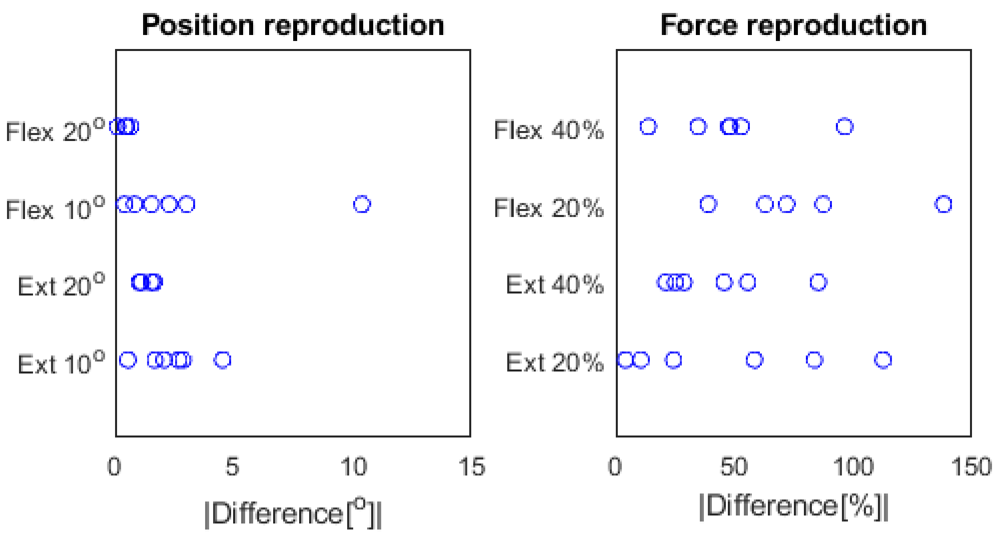

Figure 15: P4 position and force reproduction task responses.

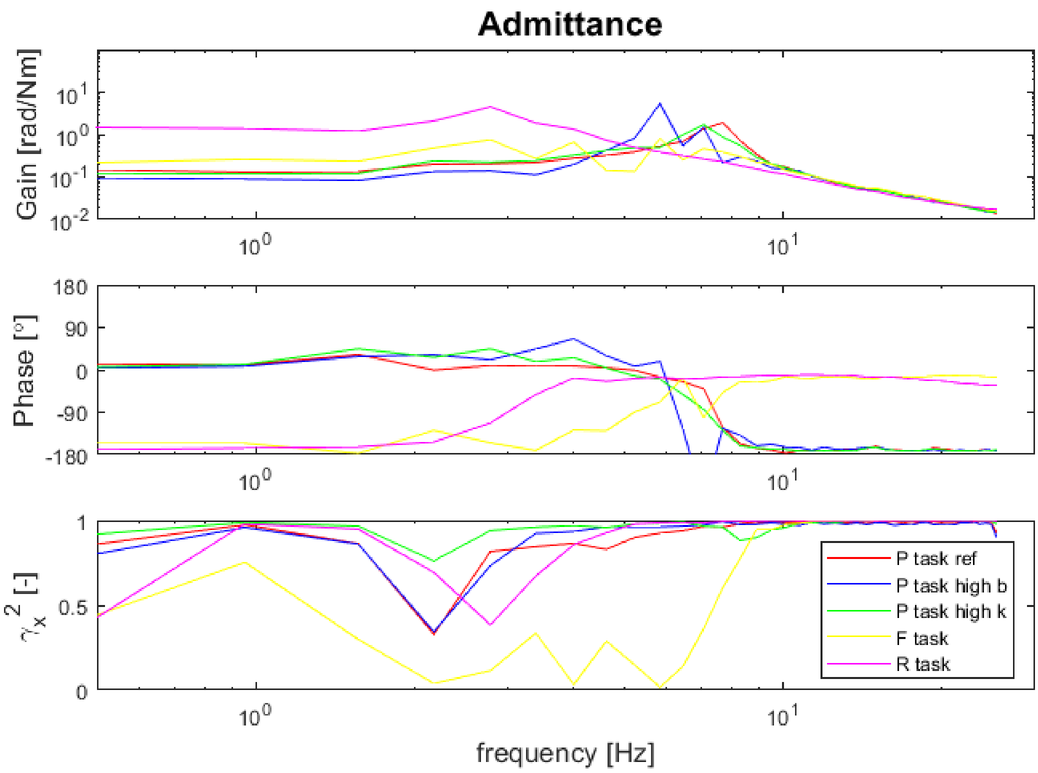

Figure 16: P5 responses to the position task (P) in the reference, high damping and high stiffness conditions, the force task (F) and relax task (R).

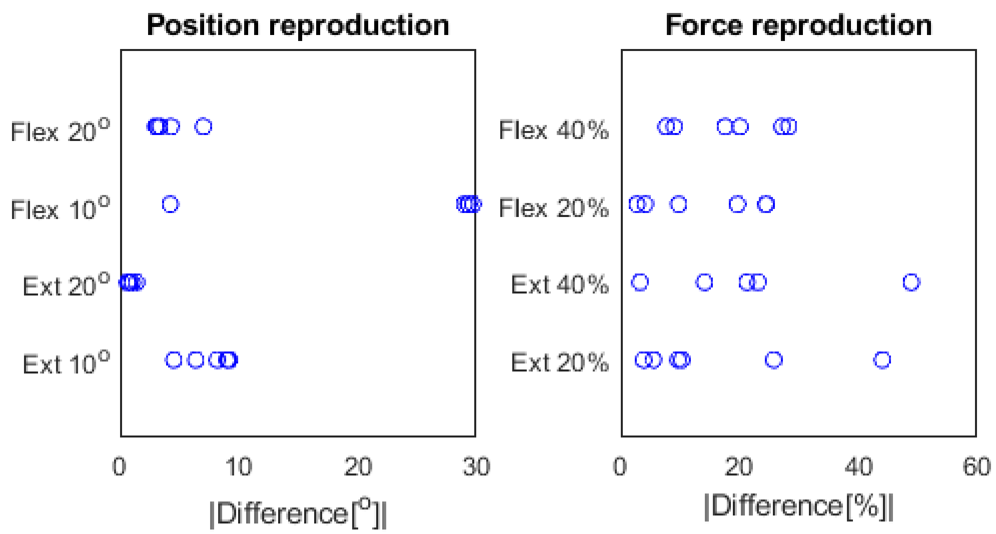

Figure 17: P5 position and force reproduction task responses.

P6

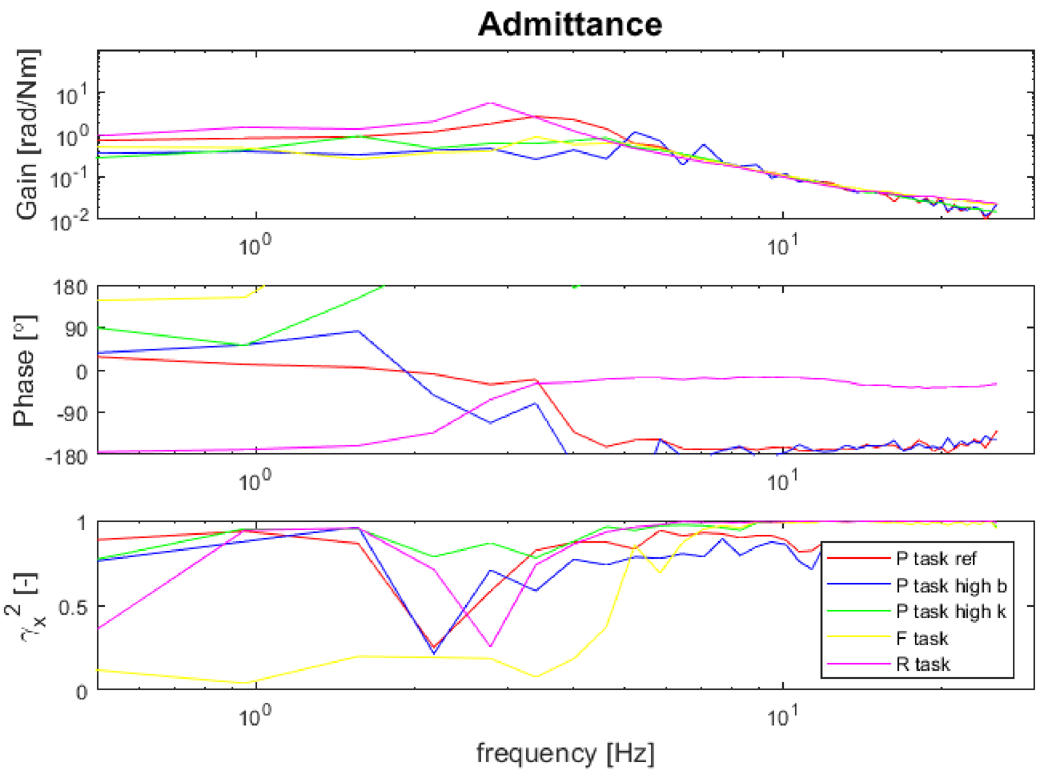

Figure 18: P6 responses to the position task (P) in the reference, high damping and high stiffness conditions, the force task (F) and relax task (R).

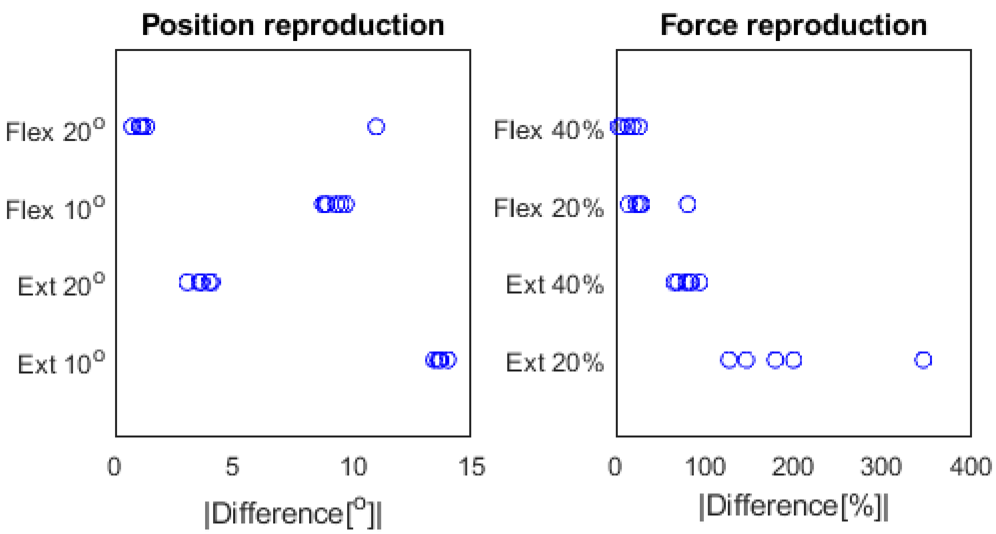

Figure 19: P6 position and force reproduction task responses.

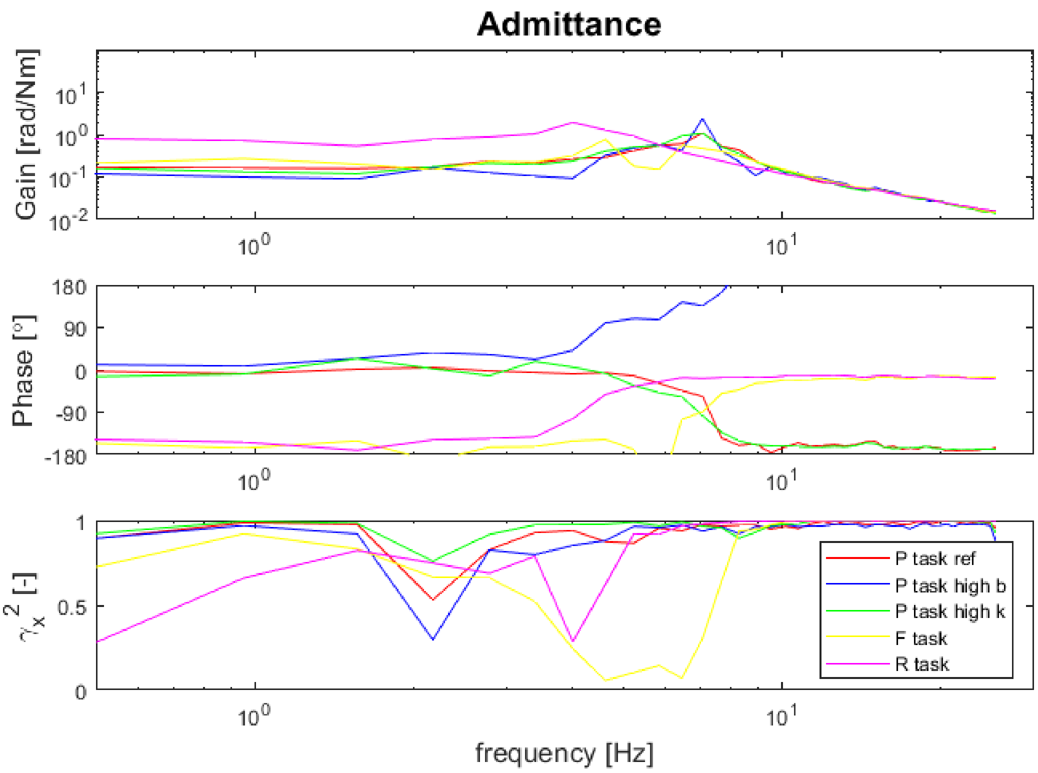

Figure 20: P7 responses to the position task (P) in the reference, high damping and high stiffness conditions, the force task (F) and relax task (R).

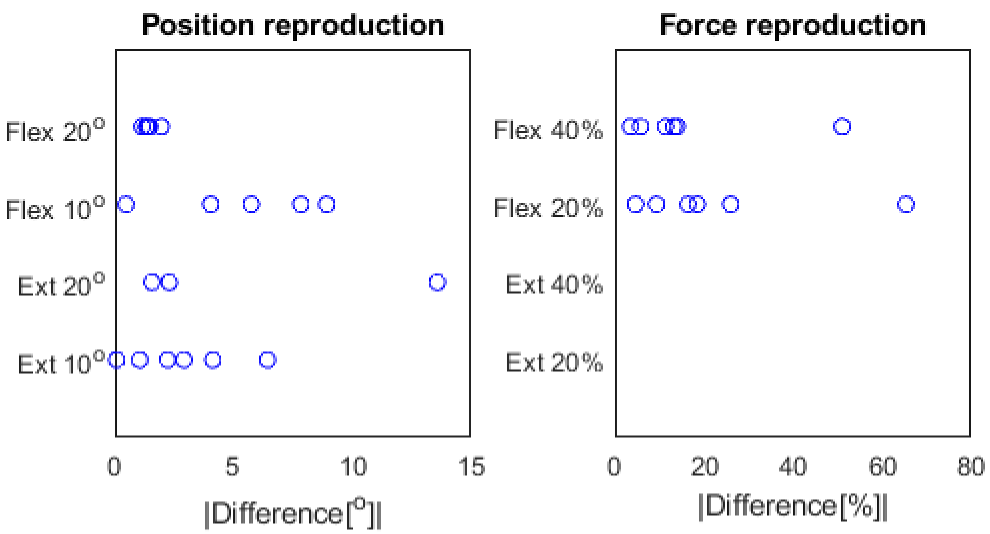

Figure 21: P7 position and force reproduction task responses.

P8

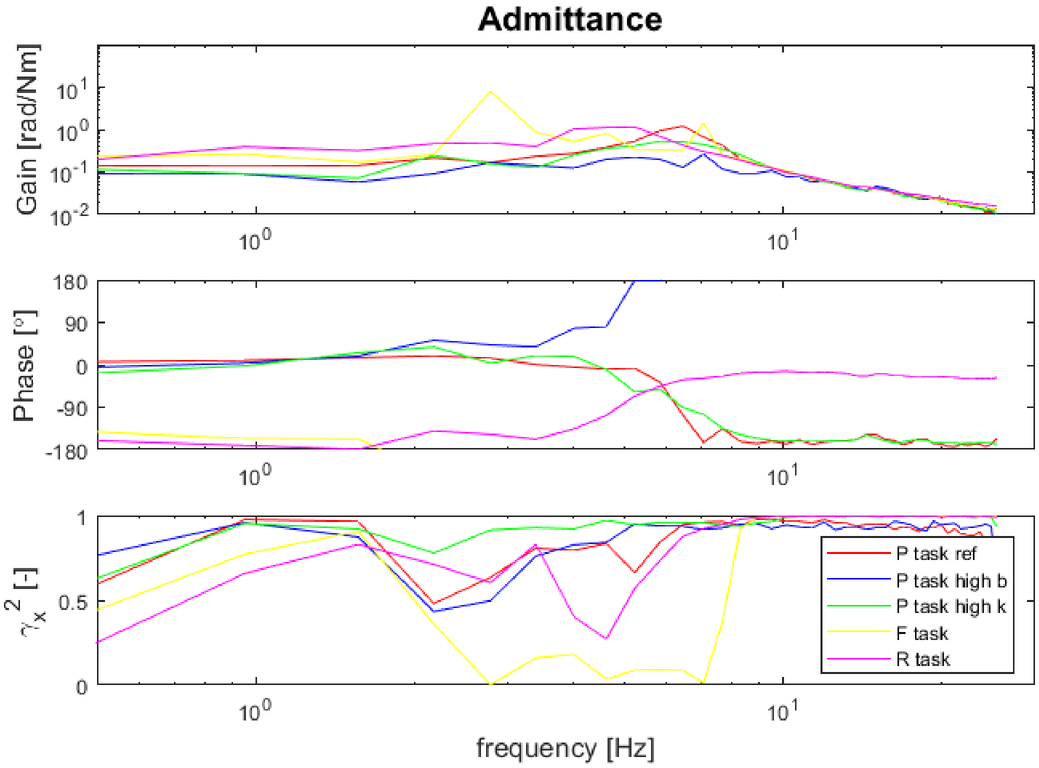

Figure 22: P8 responses to the position task (P) in the reference, high damping and high stiffness conditions, the force task (F) and relax task (R).

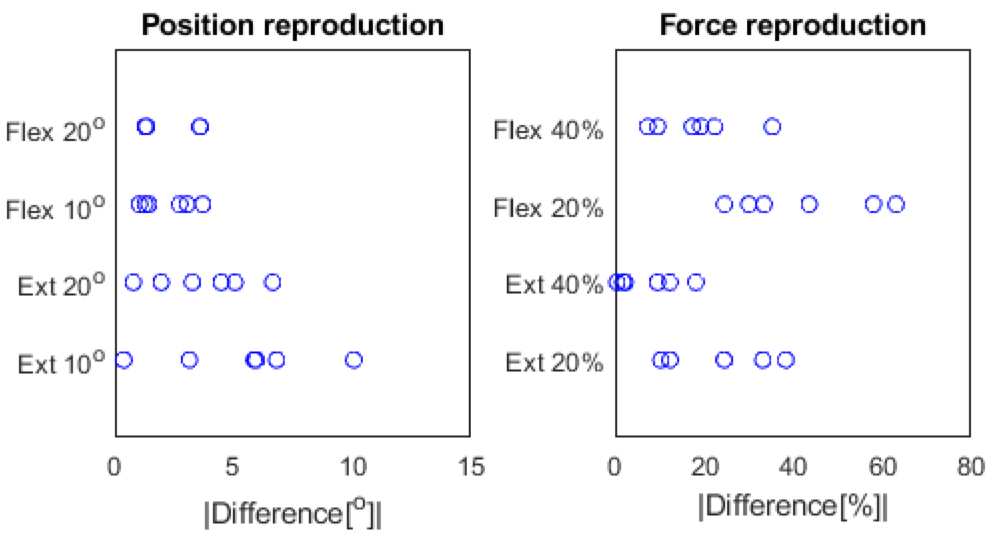

Figure 23: P8 position and force reproduction task responses.

P9

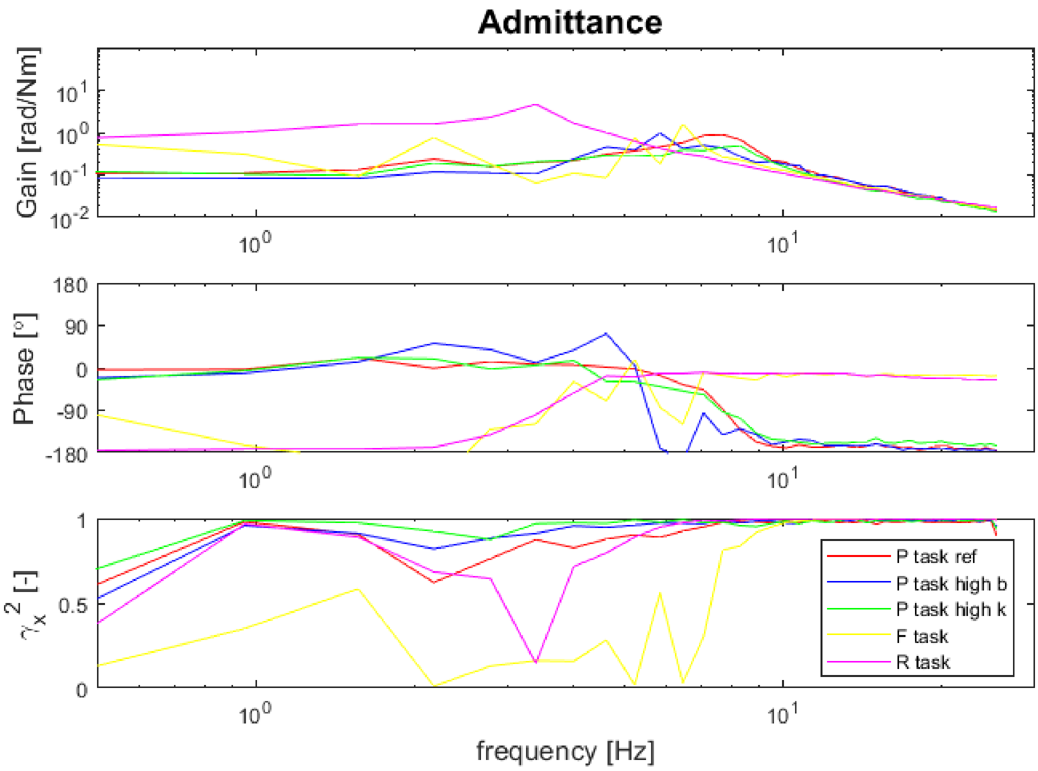

Figure 24: P9 responses to the position task (P) in the reference, high damping and high stiffness conditions, the force task (F) and relax task (R).

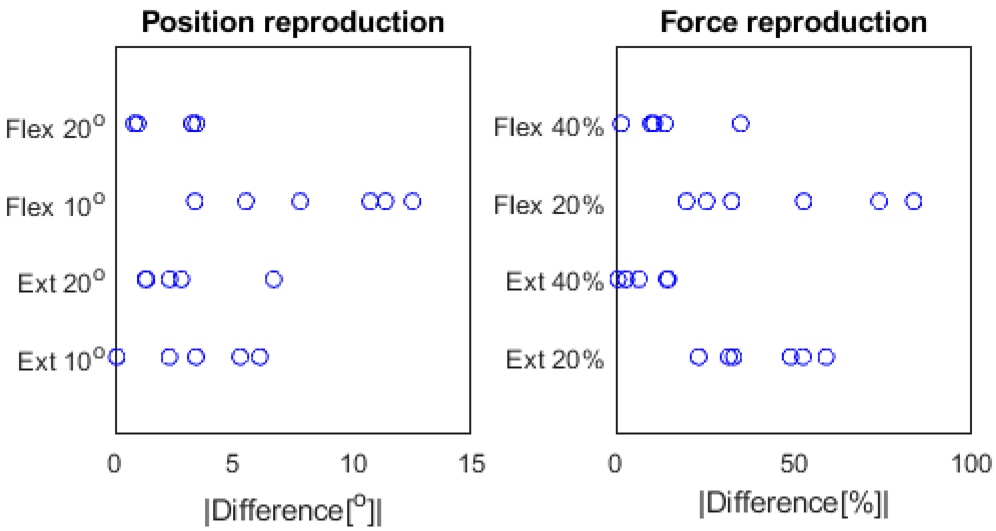

Figure 25: P9 position and force reproduction task responses.

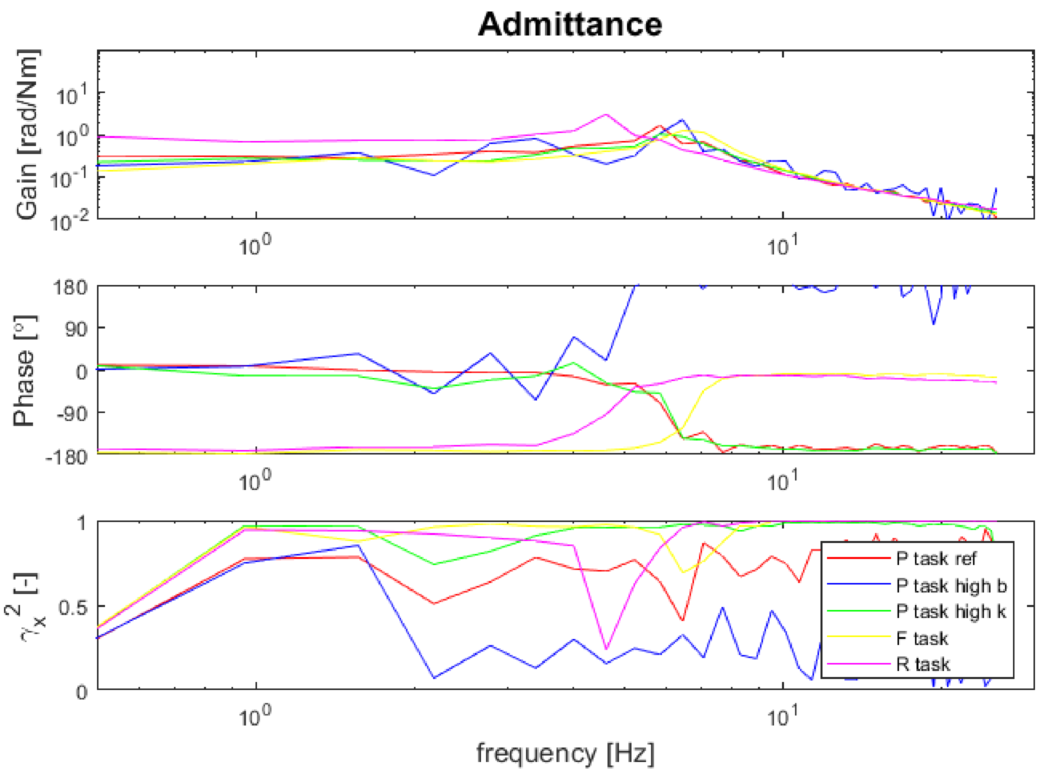

Figure 26: P10 responses to the position task (P) in the reference, high damping and high stiffness conditions, the force task (F) and relax task (R).

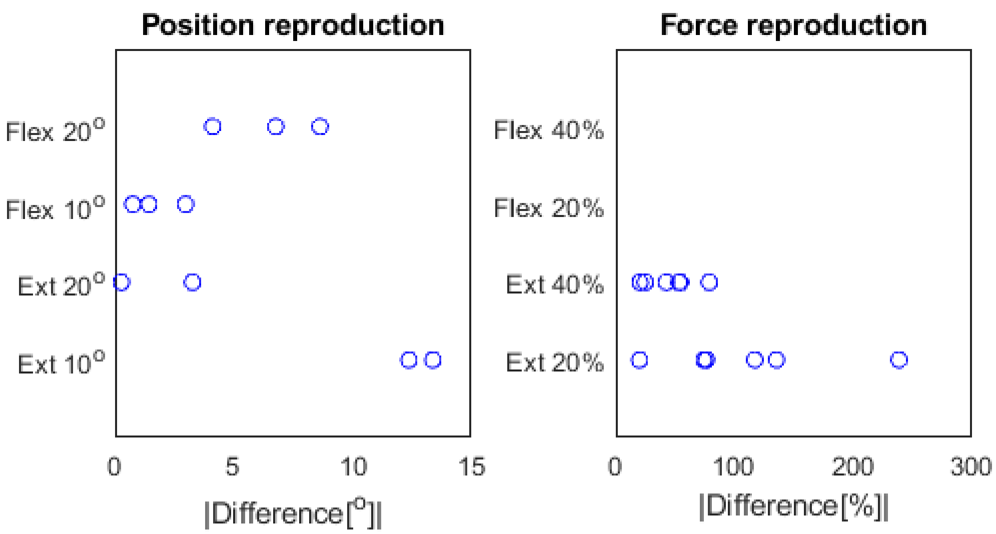

Figure 27: P10 position and force reproduction task responses.

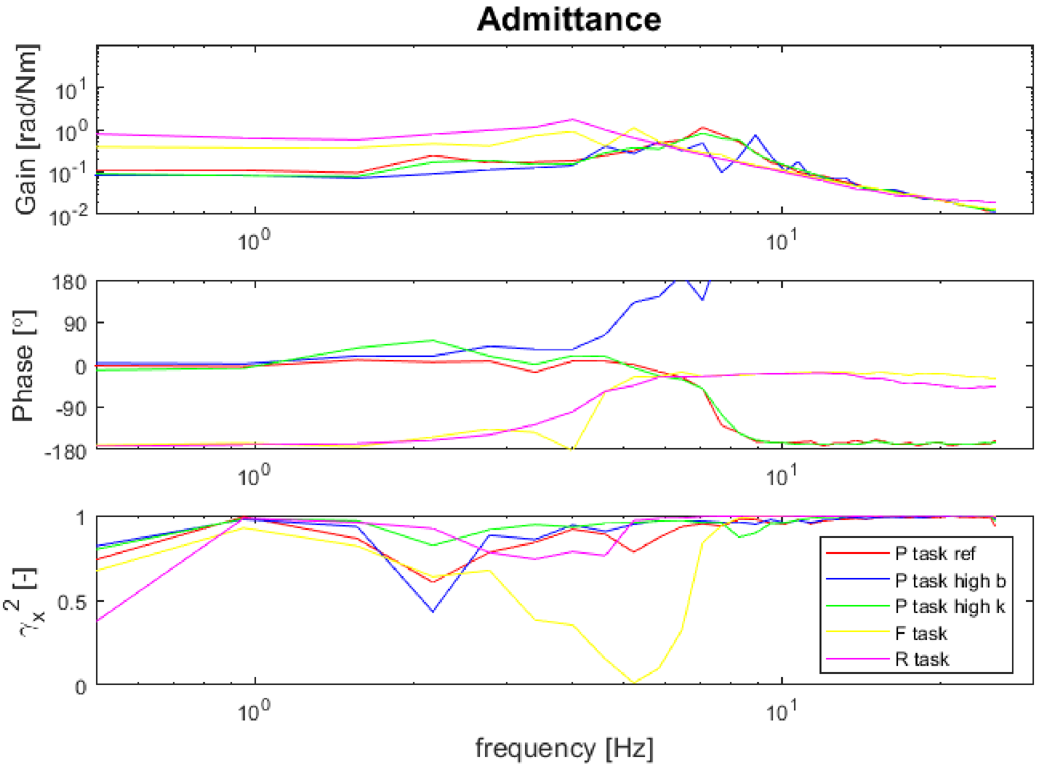

Figure 28: P11 responses to the position task (P) in the reference, high damping and high stiffness conditions, the force task (F) and relax task (R).

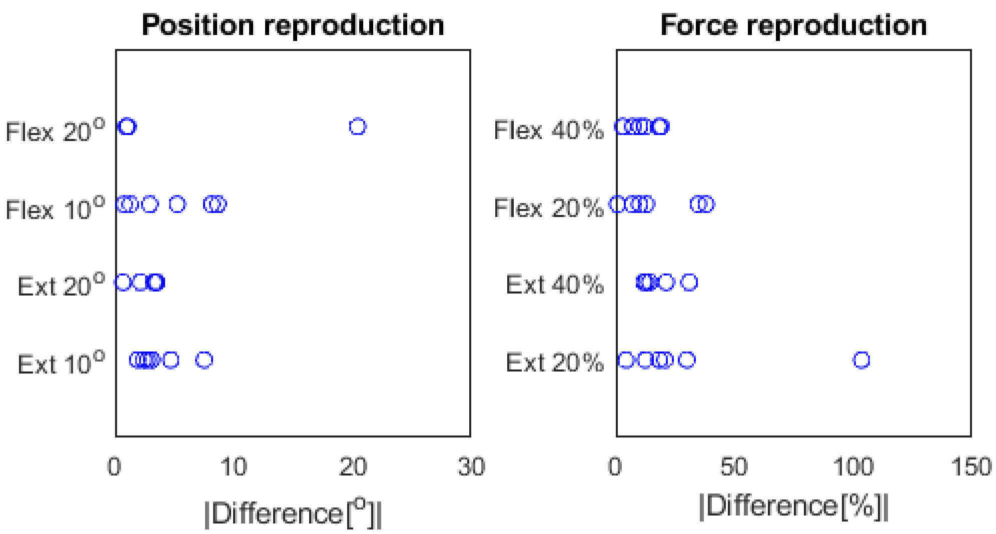

Figure 29: P11 position and force reproduction task responses.

P12

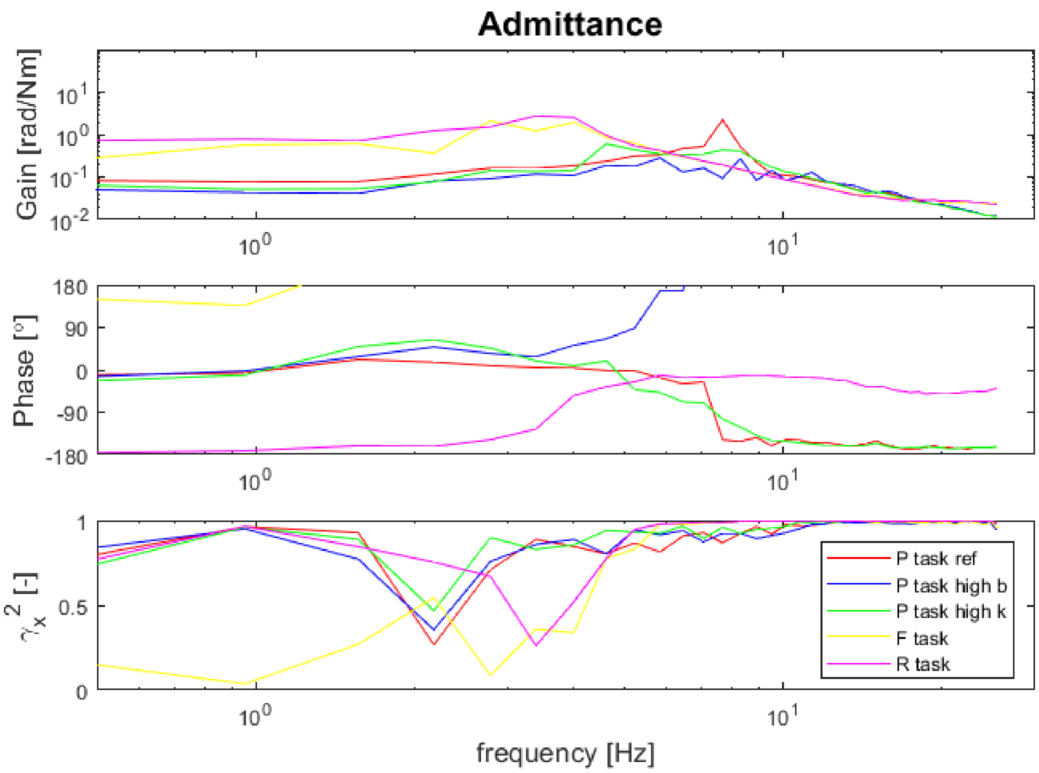

Figure 30: P12 responses to the position task (P) in the reference, high damping and high stiffness conditions, the force task (F) and relax task (R).

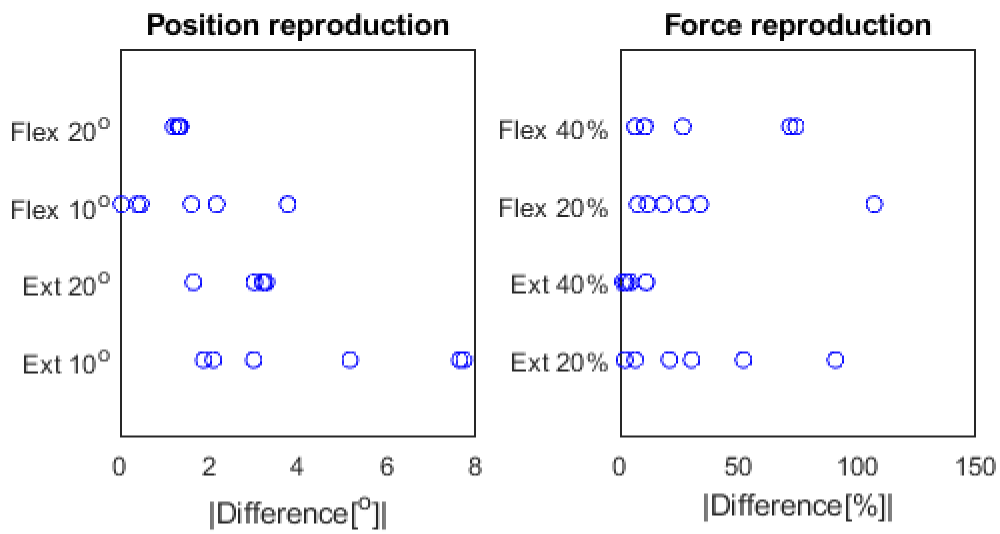

Figure 31: P12 position and force reproduction task responses.

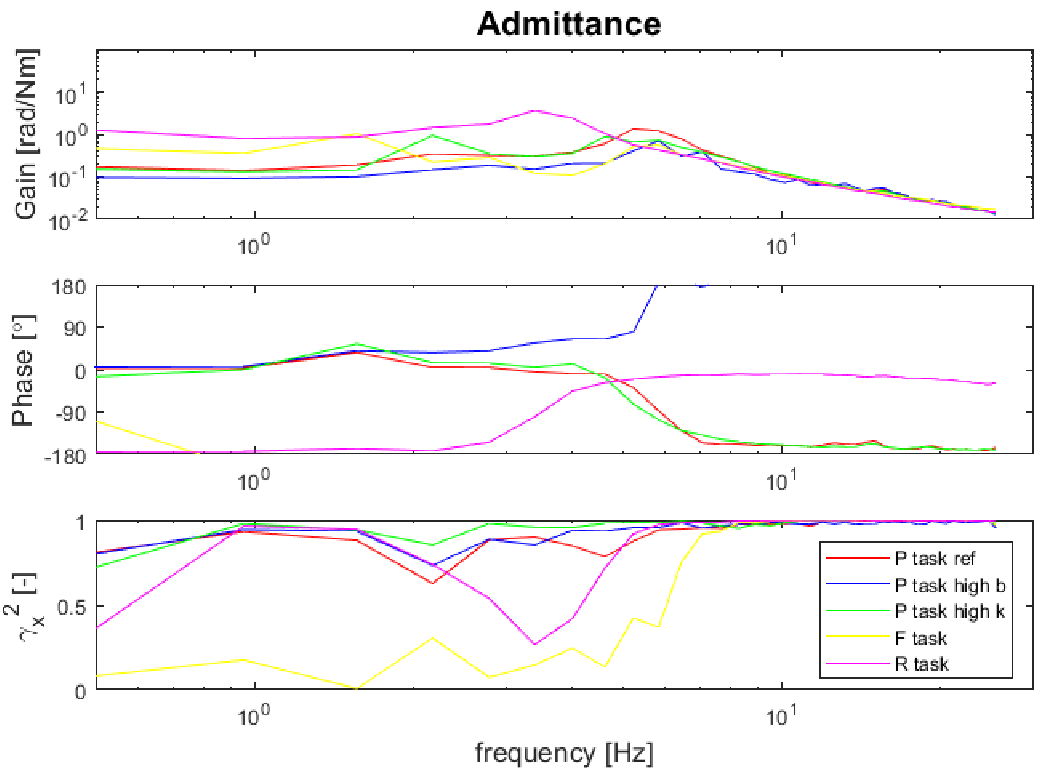

Figure 32: P13 responses to the position task (P) in the reference, high damping and high stiffness conditions, the force task (F) and relax task (R).

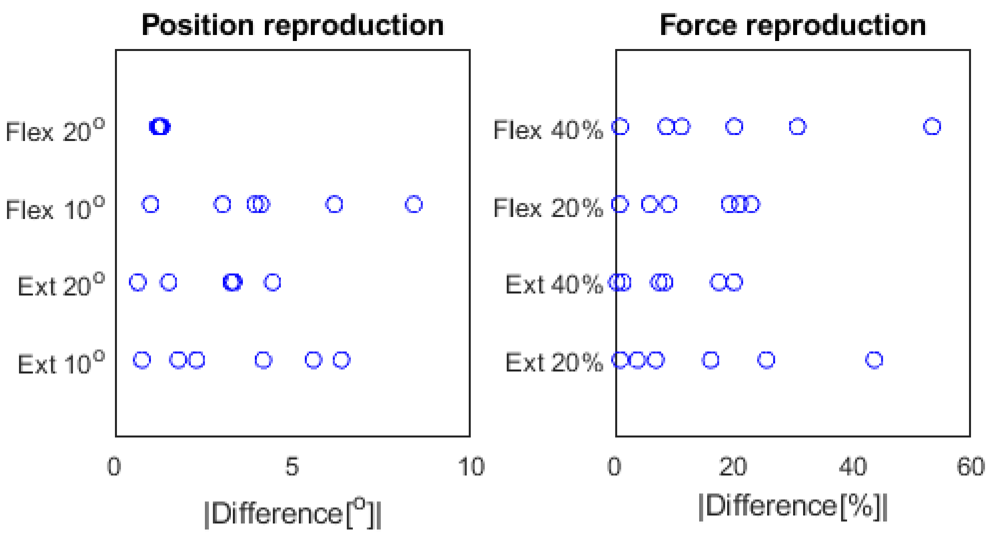

Figure 33: P15 position and force reproduction task responses.

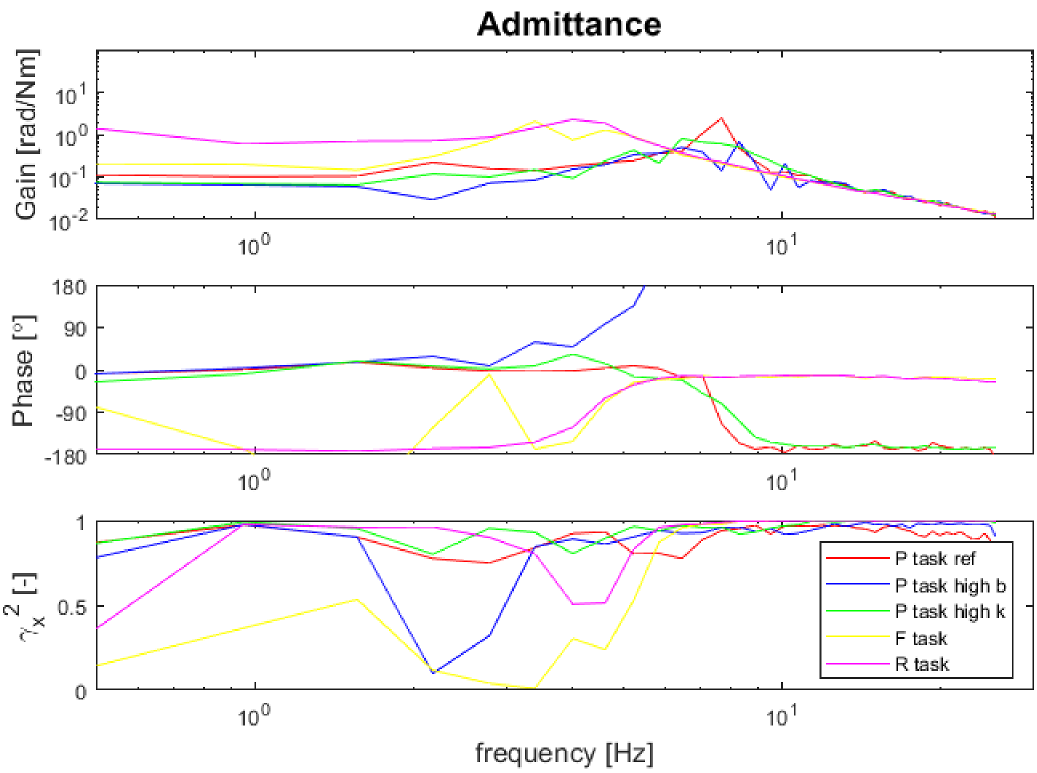

Figure 34: P14 responses to the position task (P) in the reference, high damping and high stiffness conditions, the force task (F) and relax task (R).

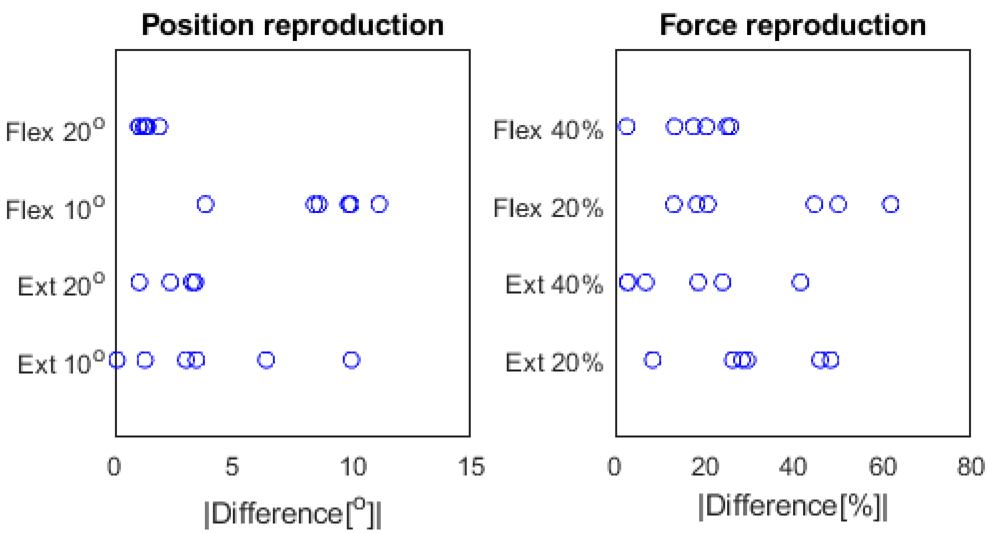

Figure 35: P14 position and force reproduction task responses.

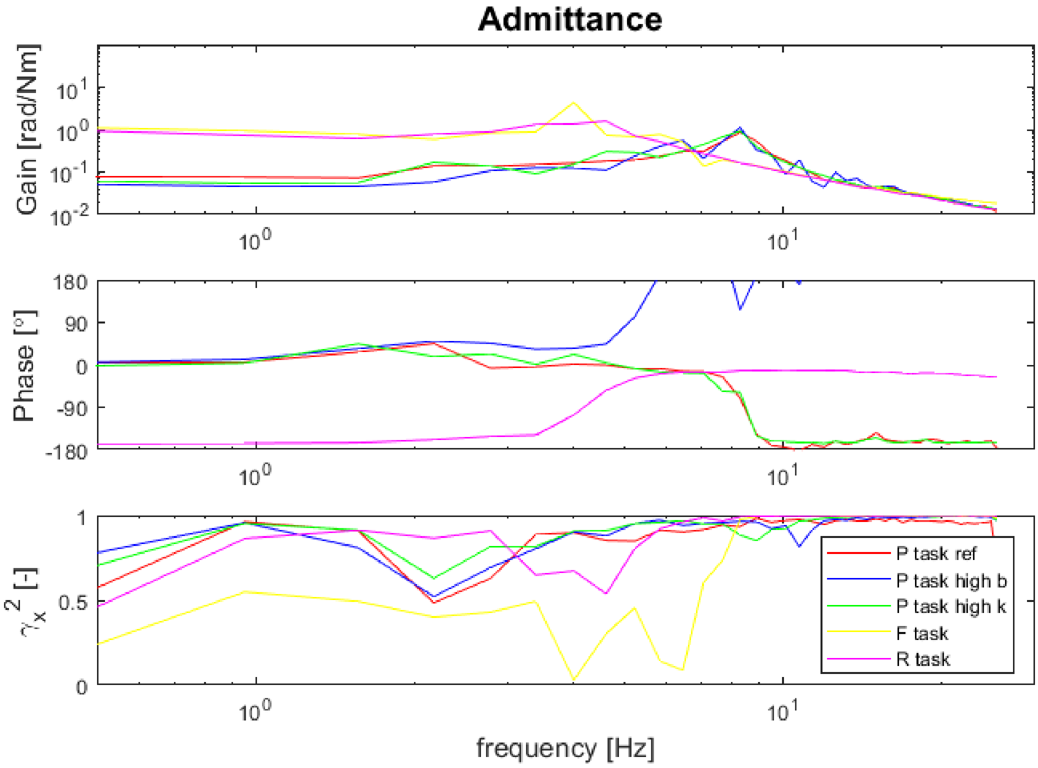

Figure 36: P15 responses to the position task (P) in the reference, high damping and high stiffness conditions, the force task (F) and relax task (R).

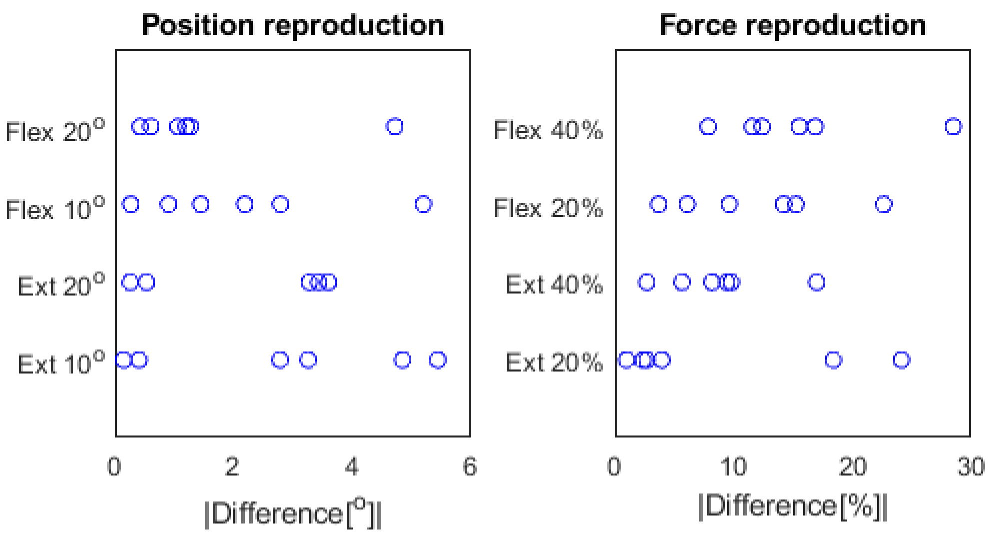

Figure 37: P15 position and force reproduction task responses.

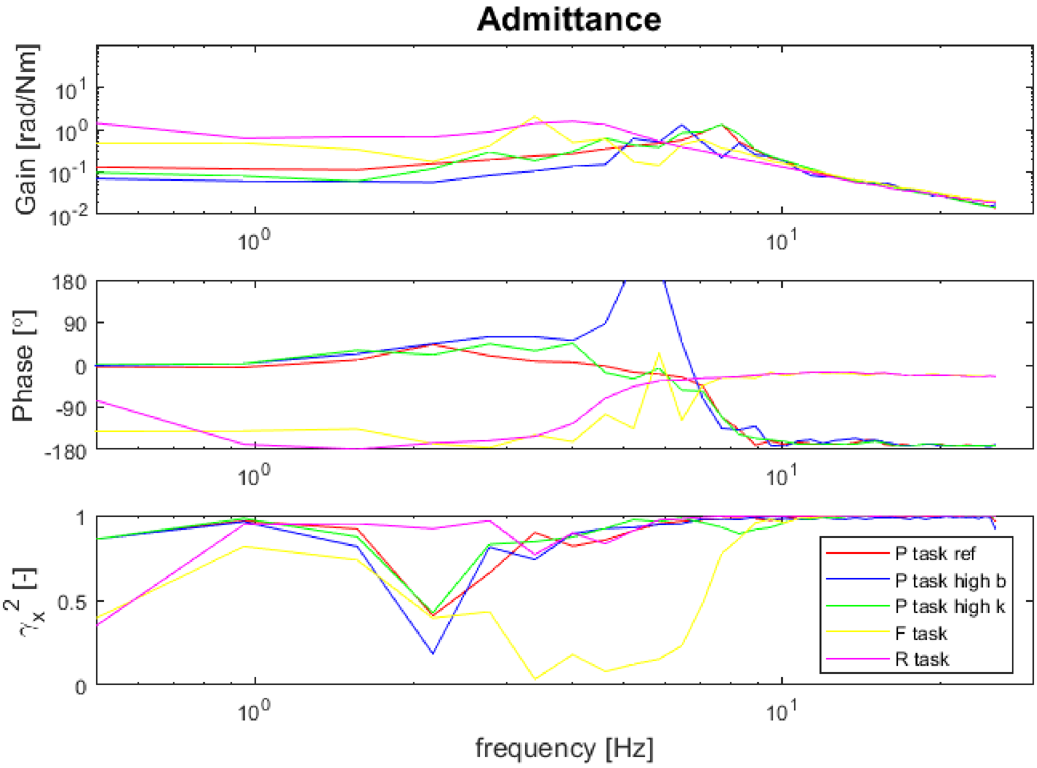

Figure 38: P16 responses to the position task (P) in the reference, high damping and high stiffness conditions, the force task (F) and relax task (R).

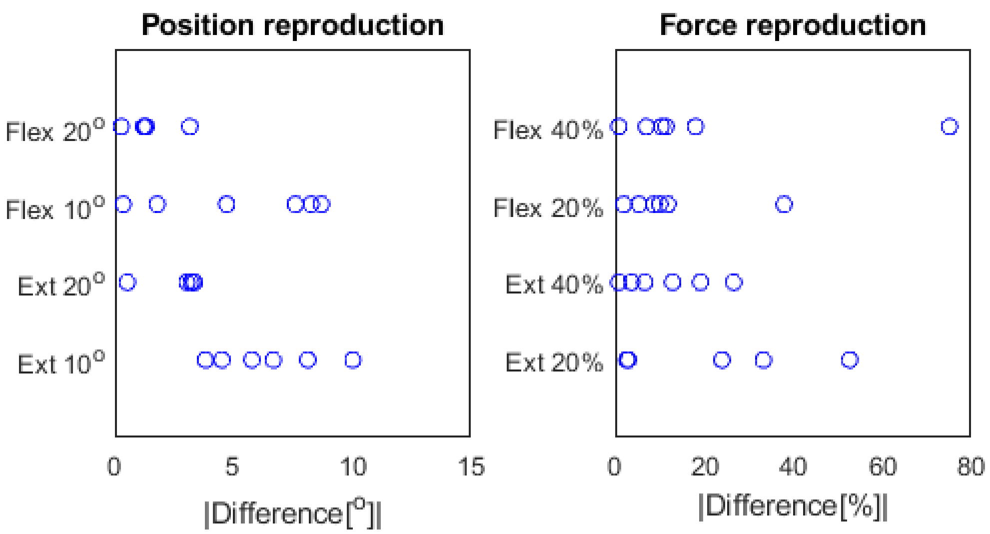

Figure 39: P16 position and force force reproduction task responses.

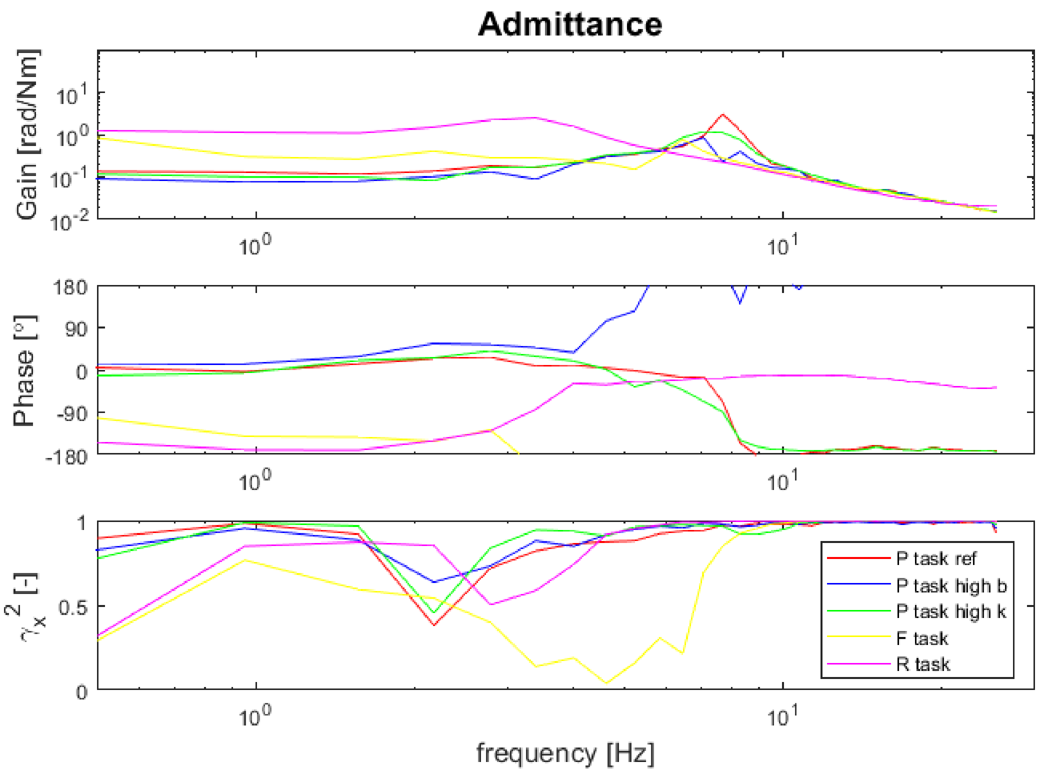

Figure 40: P17 responses to the position task (P) in the reference, high damping and high stiffness conditions, the force task (F) and relax task (R).

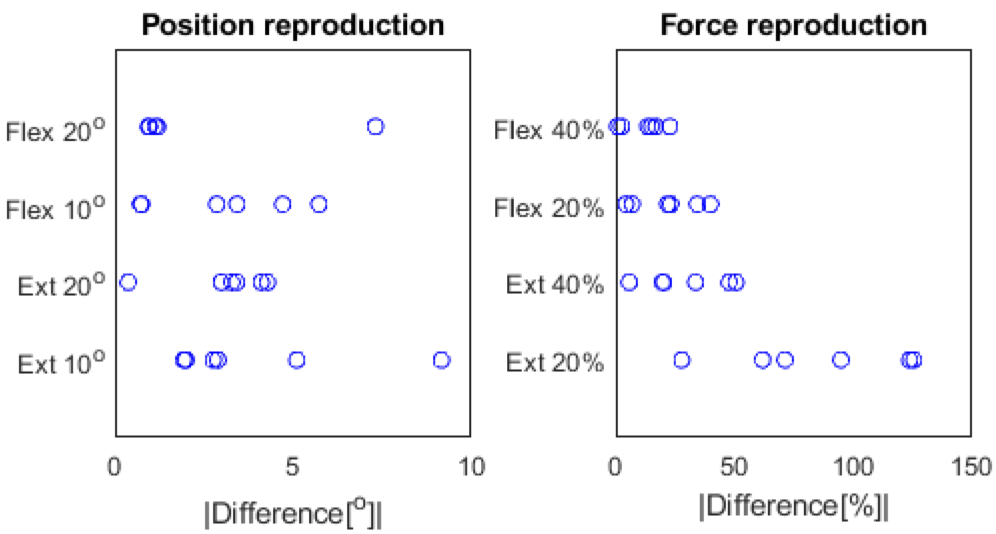

Figure 41: P17 position and force reproduction task responses.

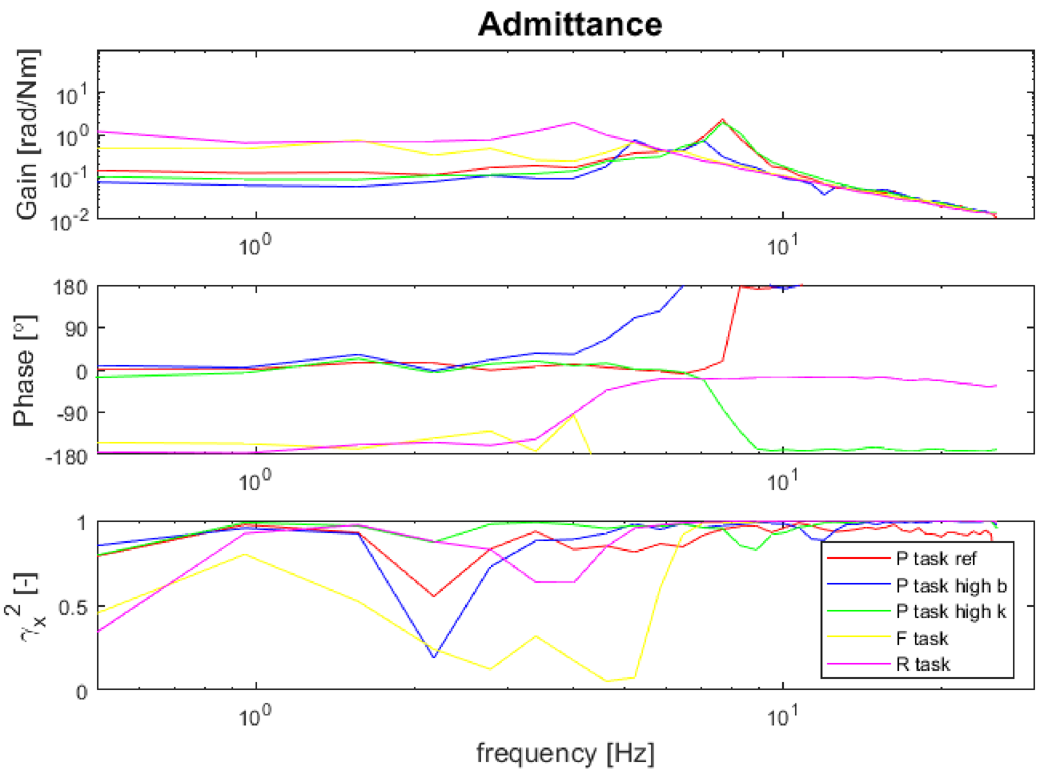

Figure 42: P18 responses to the position task (P) in the reference, high damping and high stiffness conditions, the force task (F) and relax task (R).

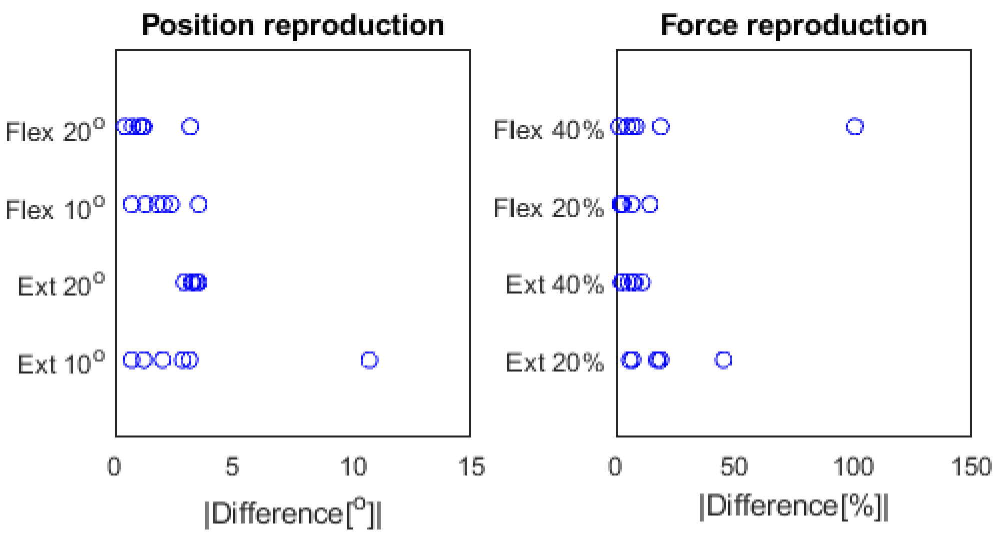

Figure 43: P18 position and force reproduction task responses.

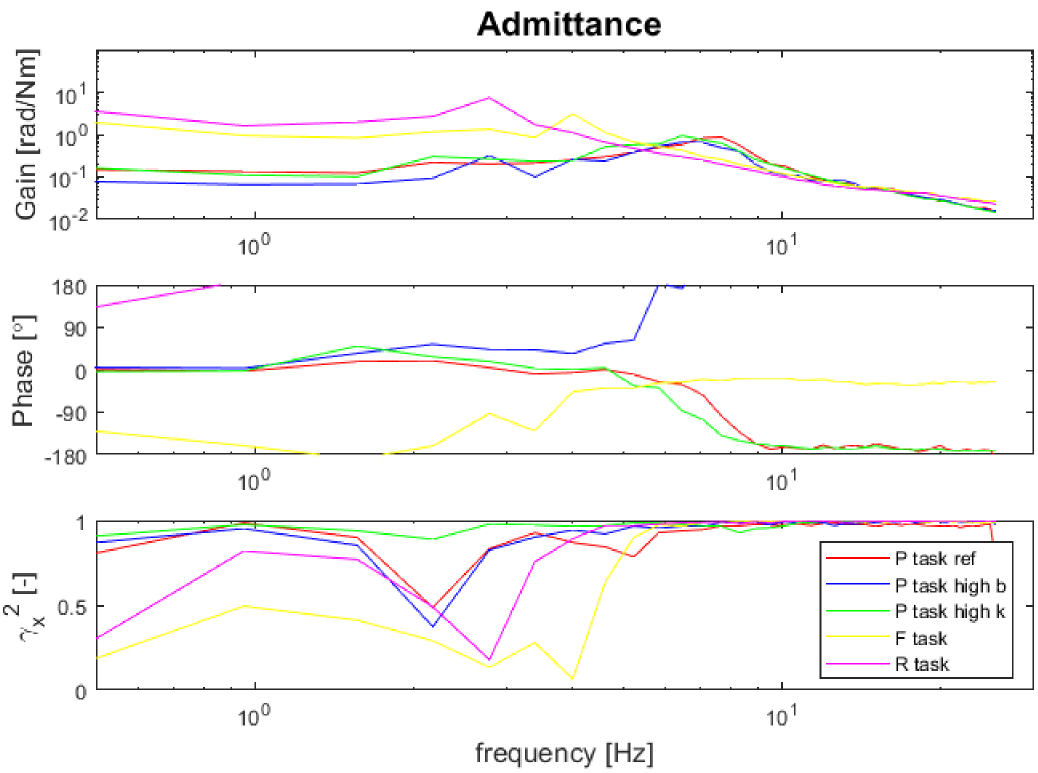

Figure 44: P19 responses to the position task (P) in the reference, high damping and high stiffness conditions, the force task (F) and relax task (R).

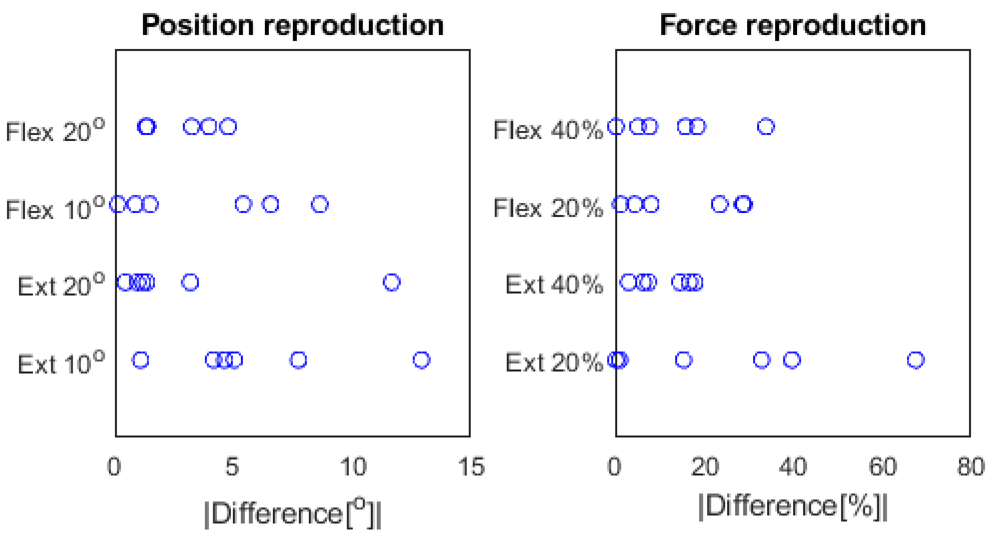

Figure 45: P19 position and force reproduction task responses.

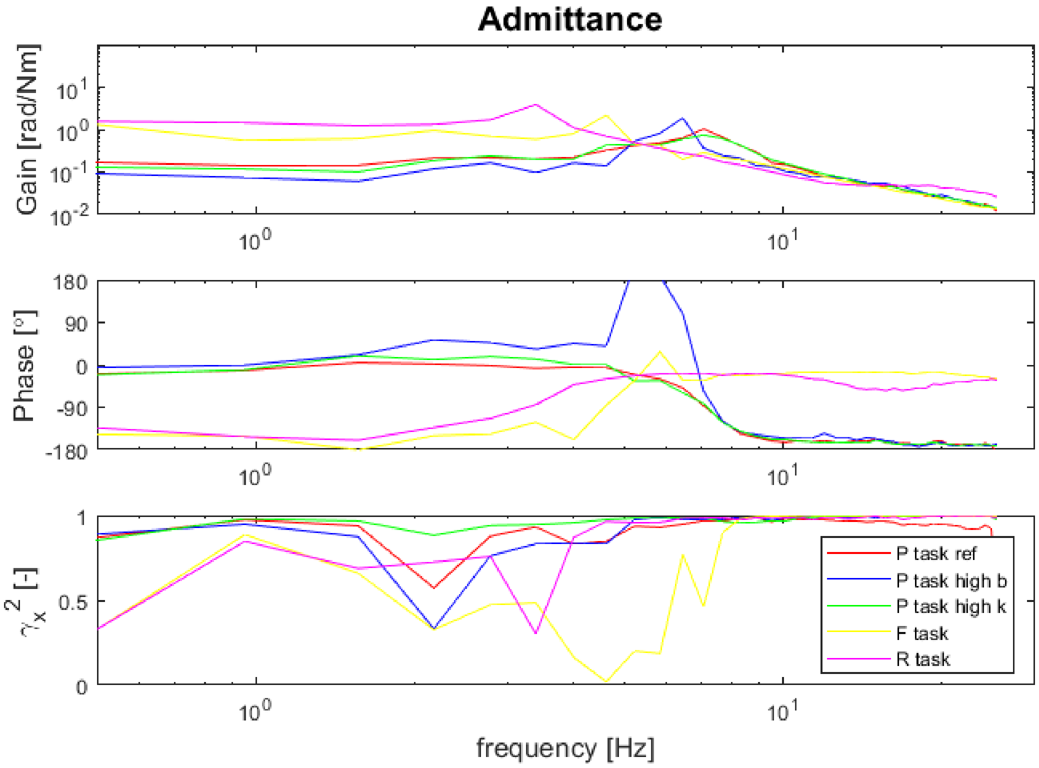

Figure 46: P20 responses to the position task (P) in the reference, high damping and high stiffness conditions, the force task (F) and relax task (R).

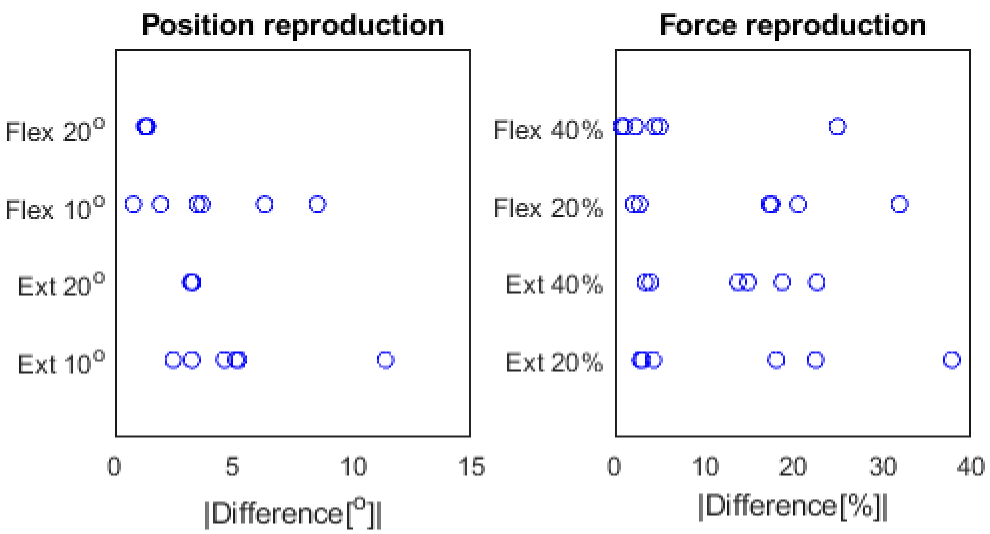

Figure 47: P20 position and force reproduction task responses.

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