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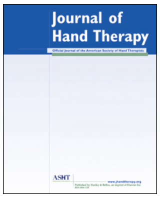

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Scientific/Clinical Article

A long-term effect of distal radius fracture on the sensorimotor control of the wrist joint in older adults

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ABSTRACT

Introduction: Sensorimotor control can be disturbed because of pain and trauma. There is scarce comprehension about which component of the sensorimotor system would benefit the most from treatment in distal radius fracture (DRF).
Purpose of the Study: The purpose of this study was to determine whether the sensorimotor control of subjects with a history of DRF impaired compared with healthy subjects. If so, which component of the sensorimotor system is most affected.
Methods: Nine healthy participants and 11 participants with a DRF history executed posture and reproduction tasks in interaction with a robotic wrist manipulator. A posture task with force perturbations assess sensorimotor control. Position and force reproduction tasks assessed sensory feedback. Electromyography recorded the muscle activity to study the motor part of the sensorimotor system.
Study Design: Cross-sectional case-control.
Results: The results showed that the motor responses to the perturbations during the posture task did not differ significantly, whereas the position reproduction did significantly differ between the 2 groups. Moreover, participants with a DRF history did not adapt to the changed dynamics of the environment during the posture task, whereas the controls did.
Discussion: The results of this study imply that processing of sensory position feedback is impaired in people with a DRF history while sensorimotor control during a posture task is unaffected. A possible explanation for these results is that different neural networks are involved during reproduction and posture tasks.
Conclusions: A history of DRF is related to disturbed processing of sensory feedback of the sensorimotor system, especially the Joint Position Sense, which leads to an impairment in detecting a changed environment and adapting to it. Impaired Joint Position Sense and thereby the inability to adapt adequately to a changing environment should be taken into account during the rehabilitation of patients with DRF.

Introduction

A distal radius fracture (DRF) in the lower arm is one of the most common fractures.[1,2] DRF leads to pain, a diminished range of motion, and lower grip strength, up to 4 years after fracture.[3] Besides a loss of grip strength and restricted range of motion, impaired sensorimotor control can be related to DRF as well.[4] The sensorimotor system is a complex subcomponent of the comprehensive motor control system of the body. It incorporates all the afferent, efferent, central integration and processing components involved in maintaining functional joint stability.[5] In this complex feedback system, proprioception, that is, the afferent information, takes up a prominent part.[6-8] Proprioception consists of joint position sense (JPS), kinesthesia, and force sense,[5,8] which are derived from sensory nerve endings in skin, joint capsules/ligaments, Golgi tendon organs, and muscle spindles.[7] In musculoskeletal disorders, proprioceptive information can be disturbed because of multiple causes including pain, effusion, trauma, and fatigue, involving both peripheral and central pathophysiological changes of the nervous system.[8,9] Disturbed proprioception is likely to have adverse effects on motor control and the regulation of muscle stiffness. Although proprioception plays an important role in sensorimotor control, other parts of the sensorimotor system (ie, efferent motor control and central integration) might be impaired as well due to trauma.

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Therefore, when 1 component of the sensorimotor system is impaired, the other components might be affected as well.

From a mechanical perspective, the sensorimotor system affects the combined behavior of our limbs that have elastic, viscous, and inertial properties. Key concepts in biomechanical engineering to describe these properties are stiffness (the extent to which an object resists elastic deformation in response to an applied force, ie, the ratio between force change to the displacement change), damping (an influence within or upon an oscillatory system that has the effect of reducing or preventing its oscillations, ie, the ratio between generalized force and generalized displacement velocity), and inertia (the resistance of a physical object, to change in its velocity, ie, the ratio between force change and displacement acceleration change). Joint stiffness and damping can be adapted through changes in muscle co-contraction and reflexive activity, whereas inertia is not affected by reflexive feedback or co-contraction. A relatively common representation of the sensorimotor dynamics is mechanical admittance, that is, the frequency response function of the causal, dynamic relationship between force (input) and position (output). At low frequencies, stiffness dominates the behavior, whereas at high frequencies, the admittance shows a decline dominated by inertia. Typically, subjects receive a maximal disturbance rejection task in which the goal is to minimize the effect of external disturbances to the best of their abilities. Examples of perturbation tasks are a position task in which a posture must be maintained and a force task in which a force must be maintained. Position tasks are best performed when disturbances are suppressed by resisting forces (low admittance), and force tasks are best performed by giving way to disturbances (high admittance). These tasks feel natural because they mimic daily life situations such as holding a cup of coffee on a bus ride (force task) or holding an umbrella in a storm (position task). The consistent motor control behavior these tasks elicit make them ideal to investigate the functionality of proprioceptive reflexes.[10,11]

Tailor-made rehabilitation techniques can be developed when it is known which component of the sensorimotor system causes the impairment of people with a DRF history. Rehabilitation using principles of sensorimotor control is already conducted in several hand therapeutic interventions[12,13] and more specific in patient with DRF.[14,15] However, despite some promising results of sensorimotor controlled based exercise programs for patients with chronic wrist problems,[13] there is scarce comprehension about which component of the sensorimotor system would benefit the most from treatment in DRF.

Purpose of the study

For a better comprehension of the functioning of the sensorimotor system after DRF, we formulated 2 research questions in this study:

1. Is the sensorimotor control of subjects with a DRF history impaired compared with healthy subjects?
2. If the sensorimotor control is impaired in patients with DRF, which component of the sensorimotor system is most affected? Proprioceptive afferent information, efferent motor information, or the integration of both?

Methods

Study design

The design of the study is a cross-sectional case-control study.

Participants

Twenty subjects participated in this study (Table 1), of which 11 subjects had a DRF history (at least 3 months since their last treatment at the moment of inclusion) and 9 controls had no history of hand or wrist injuries.

In the DRF group, subjects were included in the study when they were able to make a fist, and the range of motion of the wrist joint was at least 30° flexion to 30° extension. Subjects were excluded when suffering from carpal tunnel syndrome, other neurological diseases, or rheumatoid disease in the hand or wrist or when the pain score on the patient-rated wrist and hand evaluation (PRWHE)

Table 1
Population characteristics

DRF group

Number	Age	Sex	Length (m)	Weight (kg)	Evaluated arm	Dominant arm	PRWHE pain	PRWHE func.	DRF (years ago)	ORIF	Last treatment (y)
P1	55	F	1.6	77	Right	Right	8	36.5	2.5	Yes	0.4
P2	61	M	1.8	82	Right	Right	0	0	3	Yes	2.0
P3	59	F	1.7	59	Left	Left	16	17	1	No	1.0
P4	56	F	1.7	80	Right	Right	11	0	3	Yes	2.0
P5	57	F	1.7	60	Right	Left	0	0	2	Yes	2.0
P6	48	F	1.6	84	Right	Right	40	39	2	Yes	0.6
P7	55	F	1.6	80	Right	Right	26	19	5	Yes	4.1
P8	38	M	1.8	73	Right	Right	20	15.5	1.5	Yes	0.2
P9	46	F	1.7	61	Left	Right	16	4	5	No	4.0
P10	58	F	1.6	68	Left	Right	0	1.5	1.75	Yes	1.0
P11	53	M	1.8	72	Right	Left	8	1.5	4	Yes	3.0
Mean	53.3		1.7	72.4			13.2	12.2	2.8		1.8

Control group

#	Age	Sex	Length (m)	Weight (kg)	Evaluated arm	Dominant arm	PRWHE pain	PRWHE func.
P12	58	M	1.8	85	Right	Right	2	0
P13	54	F	1.7	67	Right	Right	0	0
P14	56	F	1.7	73	Right	Right	0	0
P15	59	M	1.7	80	Right	Right	0	0
P16	57	F	1.6	67	Right	Right	0	0
P17	56	F	1.6	67	Right	Right	0	0
P18	49	F	1.7	76	Right	Right	0	0
P19	55	F	1.6	54	Right	Right	4	0.5
P20	47	F	1.8	92	Right	Right	0	0
Mean	54.3		1.7	73.4			0.7	0.1

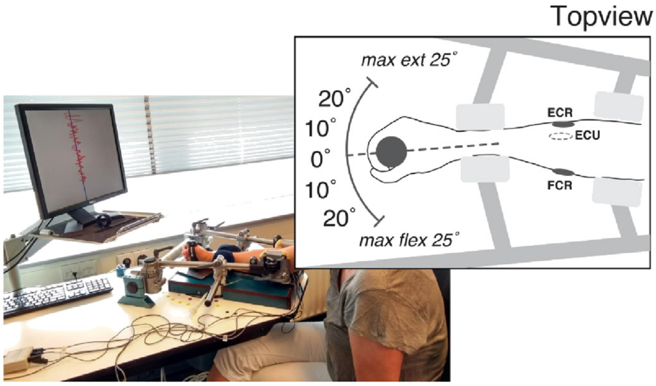

Fig. 1. Photo: typical posture of a participant during the experiment. The setup prevented movement of the lower arm. The depicted participant executes the position task: the participant grips the handle, whereas the reference position (straight line) and the actual position of the handle (sinusoidal line) are shown onscreen. *Top view*: schematic representation of the arm of the participant positioned in the RWM. The EMG electrodes of the extensor carpi radialis (ECR) and flexor carpi radialis (FCR) are indicated. The electrode of the extensor carpi ulnaris (ECU) is located at the ulnar side of the forearm and is therefore not visible. The angle of the wrist is 0° (neutral position). The movement range of the handle is shown with the black arc (25° flexion to 25° extension). The 4 angles which had to be reproduced during the position reproduction task are indicated. During the force reproduction task, the handle stayed in neutral position.

was higher than 40. The participants in the DRF group were all recruited by *Hand and Wrist Rehabilitation The Netherlands,* an organization with several hand and wrist rehabilitation centers in the Netherlands. In total, 187 former patients were approached for participation. Twenty-four former patients responded, of which 11 were included based on the criteria and random selection. The control group, having no history of hand or wrist injuries in the past 20 years, was matched with the DRF group by age and gender. Participants gave informed consent before participation, and the study was approved by the Human Research Ethics Committee of the Delft University of Technology.

Experimental setup

The sensorimotor system was tested with a robotic wrist manipulator (RWM), which applied small continuous torque or angle perturbations to the wrist.[16] With this device, the mechanical admittance was determined during position and force tasks, which is a reliable way to test the neuromuscular dynamics.[16-18] In a study by Van der Krogt et al[19] in a group of stroke patients, the test−retest reliability of the RWM was good (intraclass correlation coefficient 0.45-0.91 for passive parameters and intraclass correlation coefficient 0.88-0.99 for active parameters). This kind of research has been used to test several other disorders, such as stroke[20] and CRPS,[21] but it was never used in DRF.

The sensory part (proprioception) of the sensorimotor system was tested by measuring position and force feedback, with position and force reproduction tasks. The reflective activity of the motor part of the sensorimotor system was measured by muscle activity with electromyography (EMG). The integration of the sensory and motor part was tested with the RWM, by testing the capacity of people to adapt to changes in the dynamics of the environment imposed by the RWM (perturbations).

Participants were seated comfortably with their lower arm in the device, as shown in Figure 1A, such that the lower arm was not able to move. The elbow angle was left free. The participant held the handle of the device such that extension and flexion in the wrist joint were the only movements possible in the lower arm (Fig. B).[16]

Participants executed 5 tasks in a fixed order, as shown in Table 2. Two types of tasks were performed: reproduction tasks, in which an angle or force had to be reproduced, and perturbation tasks, in which an angle or force had to be maintained while small continuous perturbations were applied. The participant was instructed, and each task was practiced. When different conditions were present within 1 task, the trials were presented in random order. All perturbation trials lasted 26 seconds.

Maximum voluntary contraction (MVC)

Maximum (MVC) voluntary contraction measurements were performed before and after the experiment. The participant was asked to exert maximal isometric force on the handle in both flexion and extension directions, without using excessive grip force. During a single trial, which lasted 10 seconds, the participant was asked to produce maximal isometric force twice. The highest force was considered to be the MVC.

Position reproduction task

For testing 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 (20° flexion, 10° flexion, 10° extension, or 20° extension) and then held for 3 seconds (Fig. 1B). We chose a maximal angle of 20°, hence doing the test in a 40° range, to reassure the participants that the tests were done in an achievable and pain-free range of motion. Furthermore, this range of motion approximated the stable neutral wrist position as prerequisite for establishing proper long-term unconscious neuromuscular joint control for our daily functional demands.[13] The participant was asked to memorize the angle and reproduce it after moving the handle to the extreme of the other side. The

Table 2
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	None	No	n/a	0-12 s: position 12 s − end: force	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	Force	Minimize angle deviations
	Relax task	n/a	2	None	Yes	Angle perturbations	Position	Relax
	Force task	n/a	4	C	Yes	Angle perturbations	Position	Minimize force deviations

Overview of the task characteristics. Conditions: the conditions within 1 task, n/a means there is only 1 condition. Rep: the number of trial repetitions for every condition. Visual: the type of visualization as shown in Figure 2. During the position reproduction task and the relax task, no visualization 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 to 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.

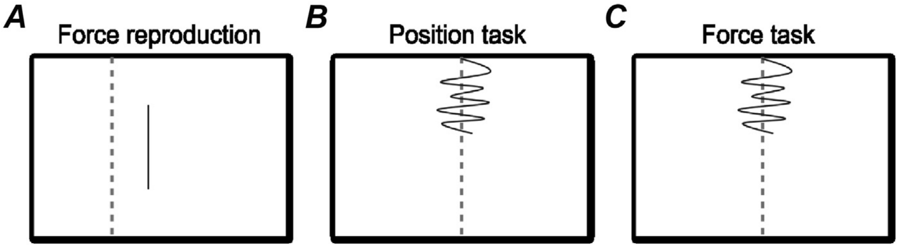

Fig. 2. Visualization on the computer screen. (A) Visualization during the force reproduction task. The dashed line represents the desired force. The middle of the screen represents 0 Nm. The solid line represents the current force, exerted on the handle by the participant. The solid line disappeared when the participant was asked to reproduce the force. (B) Visualization during the position task. The dashed line represents the desired position (zero deviation, which means that the hand is in neutral position). The solid line, propagating down, represents the position of the handle. The task was to keep the solid line on the dashed line by resisting the perturbations. (C) Visualization during the force task. The dashed line in the middle of the screen represents the desired force (0 Nm). The solid line represents the force on the handle. The task was to actively keep the solid line on the dashed line by giving way to the perturbations.

participant confirmed orally to have reached the memorized angle, and a 4 ms measurement of the angle was triggered, from which the mean was taken to obtain the measured angle θ_{meas}.

Force reproduction task

For testing the proprioceptive force feedback, a force reproduction task was executed. The handle of the RWM maintained a neutral position throughout this task. The 2 lines on the screen, as shown in Figure 2A, represented the current force exerted on the handle (represented by the solid line) and the desired force (represented by the dashed line). The participant was requested to match the desired force. This force was either 20% or 40% of the participants' MVC and had to be maintained and memorized for 3 seconds. After 3 seconds, the participant was required to relax the wrist completely. Two seconds after the wrist was relaxed, the solid line disappeared. The memorized force had to be reproduced without the visual feedback of the solid line. The participant confirmed orally to have reached the memorized force and a measurement of the force exerted on the handle for 4 ms was triggered, from which the mean was taken to obtain the measured force T_{meas}.

Position task

A posture task was executed to test whether DRF patients had impaired sensorimotor control of the wrist. The handle had to be maintained in a constant angle in face of small continuous torque perturbations. Visual feedback about the position of the handle was given as shown in Figure 2B. The task was to keep the solid line on the dashed line (see Fig. 1A) by resisting the torque perturbations through decreasing wrist joint admittance (ie, increasing joint stiffness). The applied torque perturbation was a continuous random phase multisine with frequencies from 0.1 to 30 Hz. Frequencies higher than 1 Hz had reduced power levels, according to the reduced power method[22] to evoke low-bandwidth control behavior while still enabling identification over the full bandwidth. The virtual dynamics of the environment imposed by the RWM changed by adjusting the values of the damping (b_e) and stiffness (k_e) across trials. These different virtual dynamics were used in 3 conditions:

1. Reference (low damping and low stiffness): b_e and 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 inertia was kept small at 0.0016 kgm^2. During practice, the deviations of the handle were scaled for each condition to a root mean square of about 1°, resulting in quasi-linear behavior enabling linear analysis.[23]

Relax task

The participants were asked to hold on to the handle and relax while angle perturbations were applied to the handle. No visual feedback was given onscreen. The applied angle perturbation was a continuous random phase multisine with frequencies from 0.1 to 30 Hz with reduced power on frequencies higher than 1 Hz, with a root mean square of about 1°.[22]

Force task

The subjects were asked to exert as little force as possible on the handle while angle perturbations were applied. This was best accomplished when the participant was being compliant, by increasing wrist joint admittance. The same perturbation signal as for the relax task was used. Visual feedback was given as presented in Figure 2C. The instruction was to keep the solid line on the dashed line.

Patient-rated wrist and hand evaluation

Before the experiment, subjects filled out the PRWHE, which is a validated questionnaire with 15 questions that measures pain in the hand and wrist and the difficulty of doing daily tasks.[24]

Signal recording

During every trial, the torque or angle perturbation, wrist joint angle, angle velocity, and interaction torque were recorded with a sample frequency of 2500 Hz. Furthermore, 3 differential electrodes (Delsys) recorded EMG of 3 muscles: flexor carpi radialis, extensor carpi radialis, and extensor carpi ulnaris. The EMG signals were 20 to 450 Hz band-pass filtered and pre-amplified and recorded at 1250 Hz by a separate system. EMG signals from the MVC trials were rectified and subsequently 1 Hz low-pass filtered. The maximum voluntary activation level was determined as the maximal activation level from the processed EMG signals during the MVC trials. EMG signals during all other trials were rectified, low-pass filtered at 6 Hz, and normalized to the maximum voluntary activation level.

Table 3
Reproduction tasks 2 × 2 statistical design

	Extension	Flexion
Angle reproduction task		
Angle		
10°	Ext 10°	Flex 10°
20°	Ext 20°	Flex 20°
Force reproduction task		
Force level		
20% MVC	Ext 20% MVC	Flex 20% MVC
40% MVC	Ext 40% MVC	Flex 40% MVC

Data analysis

The data were analyzed with MATLAB R2017b (The MathWorks B.V.).

Reproduction tasks

For the position reproduction task, the rectified difference between the desired and measured angle $\theta_{diff}$was calculated as a percentage of the desired angle:

$$\theta_{diff} = \left|\frac{\theta_{des} - \theta_{meas}}{\theta_{des}}\right| * 100\%$$

with θ_{des} the desired angle for the specific trial (10° or 20° extension or flexion) and θ_{meas} the measured angle.

For the force reproduction task, the rectified difference between the remembered and desired torque $T_{diff}$was calculated as a percentage of the desired torque for all trials:

$$T_{diff} = \left|\frac{T_{des} - T_{meas}}{T_{des}}\right| * 100\%$$

with T_{des} the desired torque (20% or 40% MVC extension or flexion) and T_{meas} the measured torque exerted on the handle as memorized by the participant. When the measured reproduction torque was lower than 0.1 Nm, it was assumed to be an early relaxation of the hand, and the data were excluded from the analysis.

Perturbations tasks

For every condition in the perturbation tasks, the recorded torque (T) and angle (θ) signals were averaged over the 4 trials. All signals were cut to the same length as the multisine of the perturbation signal (13 seconds). The signals were transferred to the frequency domain using the Fast Fourier Transform. The frequency response functions were estimated using the relevant cross-spectral and auto-spectral densities of the signals.

During the position task with torque perturbations, the human arm interacts with the handle in a closed-loop configuration. Therefore, the admittance ($H_{T\theta}(f)$), was estimated using a closed-loop frequency domain identification method[22,25]:

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

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

During the force and relax task with angle perturbations, the human arm interacts with the handle in an open-loop configuration. Therefore, the admittance ($H_{T\theta}(f)$) was calculated as follows:

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

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

Statistical analysis

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 2 groups were done on the means of the relative difference values, which were calculated across 6 trials for each angle/torque level, with a 2 × 2 repeated measures analysis of variance (ANOVA; Table 3): a mixed between-within subjects analysis of variance was conducted to assess the impact of the 2 groups on (1) position reproduction task across 2 directions (flexion and extension) and 2 angles (10° and 20°), and (2) force reproduction task, across 2 directions (flexion and extension) and 2 torque levels (20% MVC and 40% MVC). To test the relation between pain and the reproduction tasks, the Pearson correlation coefficient was calculated between the PRWHE pain score and the outcomes of the reproduction tasks. Furthermore, 3 repeated measures ANOVAs were performed for the position task reference condition to test if the DRF group reacted differently to the reference condition than the control group did, 1 test on the low (0-3 Hz), 1 test on the mid (4-10 Hz), and 1 test on the high (10-25 Hz) frequencies, which correspond to the frequency ranges primarily affected by stiffness, damping, and inertia, respectively. The magnitude of the admittance on the frequency points within these ranges was taken as the repeated measure, whereas the group was taken as the between-subjects variable. To test if the 2 groups reacted differently to the other conditions (high stiffness and high damping), a 2-way repeated measures ANOVA was performed for only the low frequencies, with the magnitude of the admittance on the low frequency points and the condition as within-subjects variables and the group as between-subjects variable. For the post-hoc, a Tukey High Speed Diesel test was used. A P value $\leq .05$ was considered significant.

Results

PRWHE and MVC

The DRF group had significantly higher pain scores on the PRWHE pain scale than the control group, $t\ (18) = 3.01$, $P = .008$. With a difference of 12.5 points, which is considered as clinically important.[26] 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 4. 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 muscle fatigue did not affect the results.

Position reproduction task

There was no significant interaction between group, direction and angle, $F\ (1,18) = .06$, $P = .81$. There was no effect for direction $F\ (1,18) = 0.008$, $P = .93$. There was a significant effect for angle, $F\ (1,18) = 17.24$, $P = .001$. No other interaction effects were found. The main effect comparing the 2 groups was significant, $F\ (1, 18) = 6.29$, $P = .02$, indicating a difference between the 2 groups when performing the position reproduction test, see Figure 3.

Table 4
MVC results

	MVC flexion		MVC extension	
	Mean (Nm)	SD (Nm)	Mean (Nm)	SD (Nm)
DRF	5.4	3.2	3.2	2.3
Control	7.3	2.9	4.5	1.2

Since the 20° condition introduced a bounded measure due to the restricted range of motion of the RWM, a second mixed between-within subjects analysis of variance was conducted to assess the impact of the 2 groups on θ_{diff}, across the 10° condition (extension 10° and flexion 10°). There was no significant interaction between group and direction, $F\,(1, 18) = .50$, $P = .49$. There was no effect for direction, $F\ (1,\ 18)\ =\ .05$, $P\ =\ .82$. The main effect comparing the 2 groups was significant, $F\,(1, 18) = 4.67$, $P = .045$.

No correlation was found between pain and any of the 4 conditions, which suggests that no influence of pain on the position reproduction task was found.

Force reproduction task

Twelve of 480 responses were excluded from the analyses since the reproduction torque was lower than 0.1 Nm. The reproduction responses of the extension torque reproduction task of P3, P7, and P10 were excluded from the analysis since these participants experienced considerable pain when exerting force in extension direction.

There was only a significant effect for force level, $F\,(1{,}15) = 12.66$, $P = .003$. No other interaction effects were found. The main effect comparing the 2 groups was not significant, $F\,(1, 15) = 3.87$, $P = .07$, indicating no difference between the 2 groups reacting to the force reproduction task (Fig. 4).

A correlation was found between pain and the extension tasks (20% and 40%). Therefore, a mixed between-within subject analysis of variance with pain as covariate was conducted. This resulted in a significant interaction effect for force level and group and a significant interaction effect for direction and force level. A significant main effect was found for pain, $F\,(1{,}14) = 9.18$, $P = .009$, but not for group, $F\,(1{,}14) = .04$, $P = .85$.

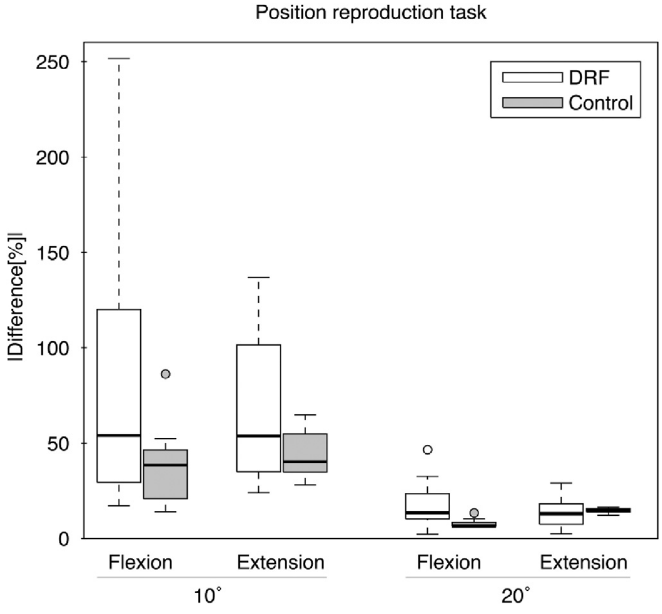

Fig. 3. Boxplots of the averaged values of the rectified difference between the desired and measured angle θ_{diff} per task and group. The DRF group (*white*) showed significantly greater θ_{diff} than the control group (*gray*).

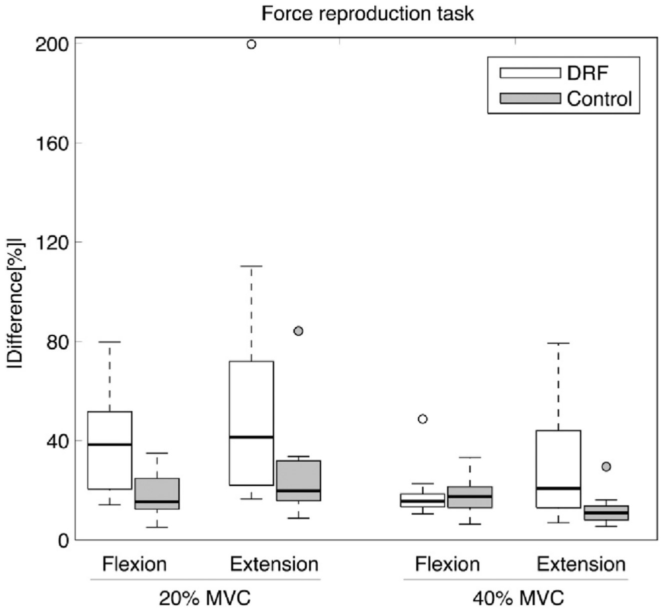

Fig. 4. Boxplots of the mean values of the rectified difference between the remembered and desired force T_{diff} per task and group. The DRF group (*white*) did not show significantly greater T_{diff} than the control group (*gray*).

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 was excluded, both due to low coherences (lower than 0.6). No significant differences between the 2 groups reacting to the position reference task were found for any of the frequency ranges (low, middle, and high). EMG levels during the reference position task are similar for both groups (see Fig. 5)

Regarding the effect of the 2 groups and the 3 conditions (reference, high damping, or high stiffness) on the admittance of the low frequencies, an interaction effect was found for group and frequency, $F\ (4{,}46)\ =\ 3.08$, $P\ =\ .03$ (Fig. 6). No other interaction effects were found, and no main effects were found. Because 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, but a marginally significant result was found between the high damping and reference condition.

Discussion

The findings of our study imply that a history of DRF is related to disturbed processing of sensory feedback of the sensorimotor system, especially the JPS, which leads to an impairment to detect a changed environment and adapt to it.

At first, we investigated whether people with a DRF history have impaired sensorimotor control compared with healthy participants. This was tested with the reference condition of the position task. It was assumed that if the 2 groups performed differently on this test that the sensorimotor system would differ between the 2 groups. However, no significant differences were found between the 2 groups in the 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.[10] During

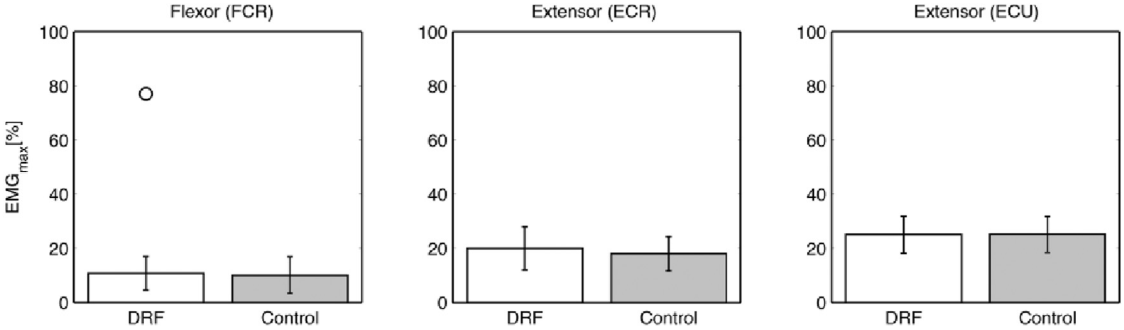

Fig. 5. Mean EMG levels of the DRF and control participants of the flexor carpi radialis (FCR), extensor carpi radialis (ECR), and extensor carpi ulnaris (ECU) during the reference position task The EMG levels are similar for both groups. The EMG levels are normalized to their respective maximum voluntary activations. For the FCR, the mean EMG level of P3 was considered an outlier.

these tasks, the coherences were high for both groups, indicating a low noise level and high linearity. This indicates that the position task was well executed. The lack of a significant difference could be explained in 2 ways: either DRF does not influence the sensorimotor system at all, which is in contrast with the expectations, or several parts of the sensorimotor system are influenced by a DRF but are compensated for by other parts of the sensorimotor system.

Specifically, an impaired sensory part was expected in people with a history of DRF compared with healthy subjects. The sensory part of the sensorimotor control system was assessed in this study with reproduction tasks. A significant difference was found between the 2 groups performing the position reproduction task, which indicates that position feedback is affected in people with a DRF history. This is in accordance with findings of Karagiannopoulos et al.[4] In our study, no significant differences were found for JPS scores between flexion and extension angles.

No significant result was found for the force reproduction tasks. However, the difference between groups showed borderline significance (see Fig. 4), especially for the 20% MVC tasks. The DRF group was small ($N = 8$) because 3 participants were excluded because of pain during the tasks. This could negatively impact the power of the statistical test. When pain was taken as covariate during the statistical test, there was a significant main effect for pain. This indicates that the found effects could be because of pain. Earlier studies have shown that pain can be a distorting factor in sensorimotor control.[9,13,27] However, 2 interaction effects were found, which makes it difficult to draw conclusions. The 40% MVC tasks show smaller differences between participants (Fig. 4) and a smaller difference between the 2 groups. This can be explained by the force reproduction error being dependent on the force level[28]: people underestimate high torques and overestimate low torques. In our study, the 40% MVC tasks were experienced as difficult by the participants.

Our analysis indicated that the motor part of the sensorimotor loop is not impaired in people with a DRF history compared with healthy participants. This was tested in this study by measuring the muscle activity during the position tasks. Karagiannopoulos et al[4] found significant differences in maximal EMG levels during a 30-second static maximum grip task between a DRF group and healthy controls. However, the normalized EMG levels of the DRF and control group during the position task (see Fig. 5) were similar in our study. This indicates that there were no significant differences in the motor part of the sensorimotor system between the 2 groups. However, the study by Karagiannopoulos et al[4] was conducted 8 weeks post DRF, investigating the acute effects of DRF on sensorimotor control, whereas in our study, sensorimotor control is assessed, on average, 2.8 years after DRF. Although there was an impairment in proprioception in the DRF group in our study, this did not lead to detectable feedback loop disturbances. Probably, impairment of the motor part of sensorimotor control will be mostly found in the acute phase but will be recovered after 1-year post DRF.

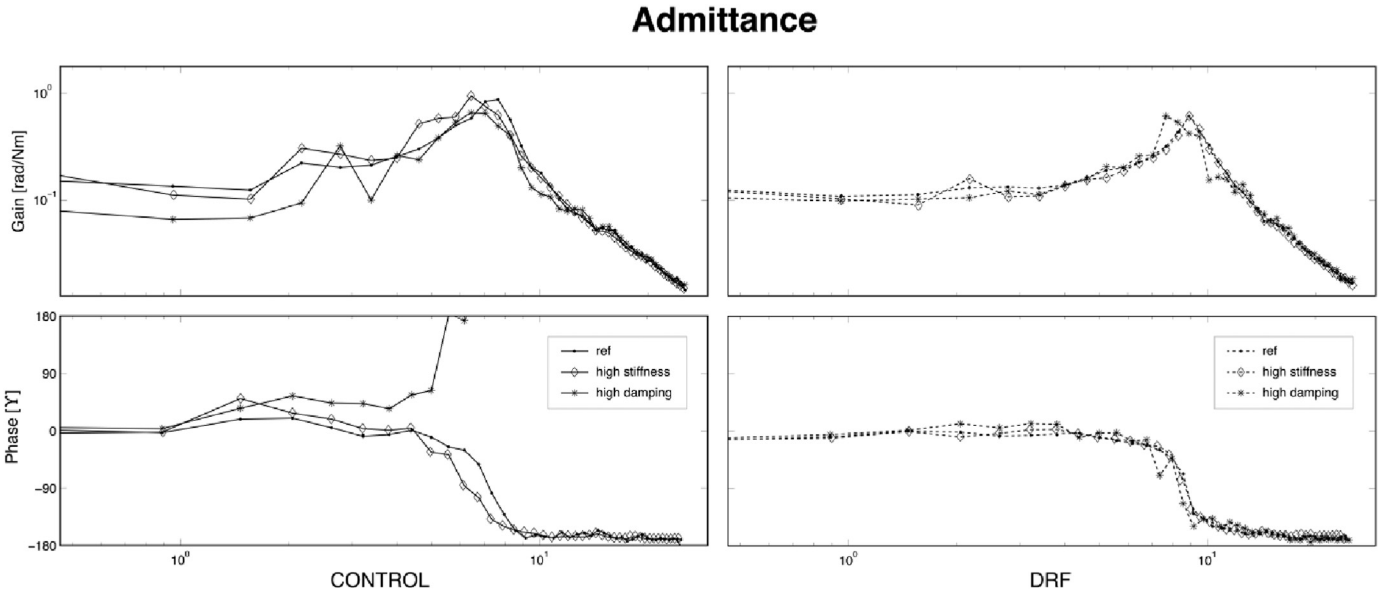

Fig. 6. Bode plot of typical estimated admittances (transfer functions describing the dynamic relation between force and position) during the position task of 1 control participant (solid lines, P19) and 1 DRF participant (dashed lines, P2) in 3 conditions: 1. Reference condition (ref, *circles*), 2. High damping (*stars*), 3. High stiffness (*diamonds*). Significant differences were found across the conditions for the control participants.

Finally, we investigated whether people with a DRF history could adapt to changed environmental dynamics like healthy participants. When resisting force perturbations, people use both intrinsic and reflexive impedance. 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.[29,30] In the control group, a significant main effect was found for condition, which implies that the control group reacted differently to the 3 conditions. This is presumably primarily the effect of the high damping condition because the difference when compared with the reference condition showed a borderline significance. This is in accordance with the study of De Vlugt et al[29] who showed that people increased their proprioceptive (muscle) length feedback gain in particular with higher environmental damping of the system. This reflex modulation due to a perturbation leads to a lower admittance and thus higher joint stiffness. Reflexive feedback introduces phase lags between perturbation and response due to inherent neural time delays. In Figure 6, this is shown for the control group, as the phase plot is rising (meaning a phase difference occurs) in the high damping condition. In the DRF group, this main effect of condition was not found, indicating that the DRF group did not adapt to the 3 conditions as the control group did. In the DRF group, this might be because of the fact that the primary reflex gain is attenuated by a cortical response due to pain.[9] In this respect, the DRF group is probably more likely to respond to the perturbations by co-contracting than by modulating reflexes to reduce the admittance. This was also seen in studies with people with low-back pain.[27]

Interpretation of the results

It seems contradictory that on the one hand, people with a DRF history perform worse on the position reproduction task, which is assumed to evaluate the sensory position feedback of the sensorimotor control system, and are unable to lower their admittance in response to changed environmental dynamics to deal with the force perturbations, while on the other hand, this does not influence sensorimotor control in general position tasks. There are several interpretations that could explain the found results. At first, the proprioceptive feedback which is used during the position task might originate from a different source than the feedback used during the position reproduction task.[31] The proprioceptive feedback used in reflexes during the position task is assumed to arise 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, some literature suggests that ligaments in the hand and wrist give proprioceptive feedback as well, especially during extreme positions.[7,32,33] 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 is useful in reproduction tasks, while this information is inconsequential during the position task. In this way, the position reproduction task could be affected while the position task is not. Ligament ruptures and injuries are often associated with DRFs,[34] increasing the plausibility of this theory.

This theory of involvement of mechanoreceptors at the ligaments, however, does not explain why people with a DRF history do not adjust their reflex gains to adapt to changed environmental dynamics. Therefore, a second possible explanation for the found results is that different neural processes are involved in position control and position reproduction, like found before between position and movement control.[35] 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 at least partly only monosynaptic.[29] Most likely, people with a DRF history did not use their wrist for a long time due to surgery or immobilization. This leads to decreased cortical activity in the sensorimotor cortex of the immobilized hand due to plasticity of the brain.[9,36] 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 may explain why people with a DRF history are unable to adjust their reflex gains to adapt to changed environmental dynamics. In this regard, pain can act as noise disturbing the signal processing, leading to an impaired sensory motor control of the wrist joint,[13,27,31] as we saw that the DRF group experienced significantly more pain than the control group.

Limitations of the study

We did not perform a power analysis to calculate the number of subjects to be included. Each measurement took up to 60 min. Hence, due to time constraints and feasibility of the study we chose to measure 10 subjects for each group. Despite the small sample size, we found some clear differences between the groups.

In the DRF group, there was a heterogeneity considering pain levels and the history of DRF. It can be hypothesized that longer pain duration might result in larger neuroplastic cortical changes, which might threaten the internal validity. However, in additional analysis, we did not find a correlation between history of DRF and either pain level ($r = 0.09$) or function level ($r = -0.20$).

In all controls, the dominant hand was assessed, whereas 64% of the DRF group had a fracture on their dominant side. Chronic pain complaints may be maintained by persistently abnormal cerebral motor control in both dominant and nondominant side.[37] Hence, we do not expect that not matching hand dominancy hampers the main results of our study.

During the position reproduction task, hardware stops were present during the test, due to the use of the RWM. This means that the handle of the RWM could only move between 25° extension and 25° flexion. This bound led to lower variances during the 20° reproduction tasks, which could have influenced the data. An additional statistical test was therefore done for only 10° reproduction tasks, which resulted in a significant difference between the 2 groups as well. This indicates that this limitation of the RWM did not substantially impact the test results.

The force task could have given additional information about adaptation to changes of environment dynamics, but the perturbation held too much power at high frequencies, which resulted in subjects (DRF and controls alike) getting demotivated. Moreover, participants had little time to practice the task and learn to perform it properly, so the force task was excluded from the analysis.

In this study, sensorimotor control was divided into a sensory, motor, and integration component, and we tried to test those components by testing the position and force feedback, muscle activity, and adaptation, respectively. However, these 3 parts include more aspects, for example, vision in the sensory part and (central) motor commands in the motor part. Therefore, the conclusions of this study have to be interpreted with care. Moreover, this study did not research a cause and effect relation between DRF and sensorimotor control.

Clinical recommendations

It has been stated that early conscious proprioception or JPS training is a prerequisite for establishing proper long-term unconscious neuromuscular joint control for our daily functional demands.[12,13,38] The data of our study indicate that rehabilitation after DRF should also focus on sensorimotor control exercise of the wrist as proposed by Karagiannopoulos.[14] Activating patients should enhance sensorimotor function.[39] In this regard, valid assessment of impaired sensorimotor function, that is, loss of JPS or kinesthesia would be necessary to evaluate rehabilitation progress in this respect. Although some efforts have been made,[40-42] the challenge remains to establish a feasible, affordable, and accurate measure for both JPS and kinesthesia in the clinical setting.[13]

As mentioned in the Introduction section, the sensorimotor control system affects a combined behavior that has elastic, viscous, and inertial properties. This behavior can be expressed by the admittance. Admittance may generally depend on numerous factors, including muscle activation, load or weight bearing, loading conditions, position or posture of the system (such as joint angle), interface properties between the human body and the contacting surface, task, learning and training, and physiological conditions such as wellness, fatigue, and possible existence of various pathologies.[11] In this respect, variation in the exercises applied, for example, isometric or dynamic, isolated or open kinetic chain, conscious or unconscious, all applied in different environmental contexts might contribute to a more clinically dynamic stable wrist joint.

Conclusions

We conclude that sensory position feedback in the wrist joint is disturbed in people with a history of DRF compared with healthy subjects. This disturbance influences the adaptation to changed environmental dynamics during position tasks. However, sensorimotor control during posture tasks with small deviations stays intact. An explanation for these results is that sensory feedback used in cortical processes is disturbed, whereas peripheral reflexes are still intact. The latter though is in DRF less reactive than for controls. Impaired JPS and thereby the ability to adapt adequately to a changing environment should be taken into account during the rehabilitation of patients with DRF besides mobilizing and strengthening exercises.

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1. To meet inclusionary criteria patients needed to
  a. have a ROM arc of 70 degrees
  b. be able to make a fist
  c. have a ROM arc of 30 degrees and be able to make a fist
  d. have a ROM arc of 60 degrees and be able to make a fist

2. During perturbation the DRFx group demonstrated
  a. loss of adaptation in posture control
  b. identical adaptation to the control group
  c. diminished adaptation in posture control
  d. hyper-adaptation compared to the control group

3. The motor component was measured by
  a. EMG
  b. videography
  c. a CHT
  d. goniometry

4. The authors postulate that
  a. posture tasks require more neural stimulation than reproduction tasks
  b. different neural pathways are involved in reproduction and posture tasks
  c. reproduction is a central nervous system function, whereas posture is a peripheral function
  d. posture and reproduction share the identical neural networks

5. The authors conclude that DRFx has a great capacity to disrupt sensory feedback, adversely altering position sense
  a. not true
  b. true

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