Research article

Effects of wrist position on reciprocal inhibition and cutaneous reflex amplitudes in forearm muscles

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ABSTRACT

In the leg, amplitudes of cutaneous reflexes and reciprocal inhibition are significantly affected by joint and limb position. Comparatively little is known about such modulation in the arm. In this study, amplitudes of reciprocal inhibition (from median nerve stimulation near elbow) and cutaneous reflexes (from median or superficial radial nerve stimulation at the wrist) were measured in forearm muscle extensor carpi radialis with the hand pronated or neutral during graded voluntary activation. Significant correlations with muscle activation were found for reciprocal inhibition and cutaneous reflex amplitudes at both positions. Only cutaneous reflexes from superficial radial nerve were modulated by wrist position. This study reveals that effect of limb position is nerve-specific in cutaneous reflexes and not significant on reciprocal inhibition in the arm. This has implications for measurement and study design in those who have mobility and motor activation challenges (e.g. neurotrauma) that affect hand function.

1. Introduction

Human spinal excitability has been studied by measuring amplitudes of cutaneous and muscle afferent (Hoffmann (H-)) reflexes and reciprocal inhibition during different motor tasks. Amplitudes of these evoked responses reflect the excitability in different spinal-mediated neural pathways, but can all be modulated by factors such as task and background muscle activation. Some studies also suggest joint and limb position can affect reflex amplitudes.

Significant effects of joint and limb position on H-reflex amplitude have been observed in both arm and leg muscles. Baldissera et al. measured flexor carpi radialis (FCR) H-reflex amplitudes at five different joint positions between wrist pronated and supinated positions [1]. With controlled stimulus inputs (evoking similar efferent motor response amplitudes), FCR H-reflex amplitudes decreased when the wrist was rotated from the pronated to the supinated position. The mechanisms of this change are not clear but the authors suggested it may due to the ensemble altered afferent input at different positions. Effects of limb position on modulation of H-reflex amplitudes were also found in leg muscles. Soleus H-reflex amplitudes decreased when changing postural from lying to sitting, to standing due to increased

pre-synaptic inhibition at the Ia afferent alphamotoneuronal synapse [2–5].

Currently, the extent to which joint position may modulate reciprocal inhibition and cutaneous reflex amplitudes is not well understood, especially in arm muscles. Although reciprocal inhibition and cutaneous reflexes are mediated by different spinal pathways from H-reflex, altered afferent feedback from different joint positions may affect reflex amplitude. Evans et al. found altered middle or late latency cutaneous responses in first dorsal interosseous muscle during finger isometric contraction and grip task [6]. Similar results were also found in the late-latency cutaneous response in other hand muscles by Nakajima et al. [7]. Those results suggested the modulation of cutaneous reflex amplitudes is sensitive to behavioral context. It is possible that upper limb joint position could affect cutaneous reflex amplitudes in arm muscles. Compared to other spinal mediated reflexes, the modulation of reciprocal inhibition between arm muscles have received less attention. Several studies found reciprocal inhibition of the tibialis anterior muscle to soleus muscle is modulated by the posture of the task. During dorsiflexion, a stronger inhibitory effect was found while standing compared to sitting [8]. With the same background muscle activation, the amount of inhibition decreased from standing to walking
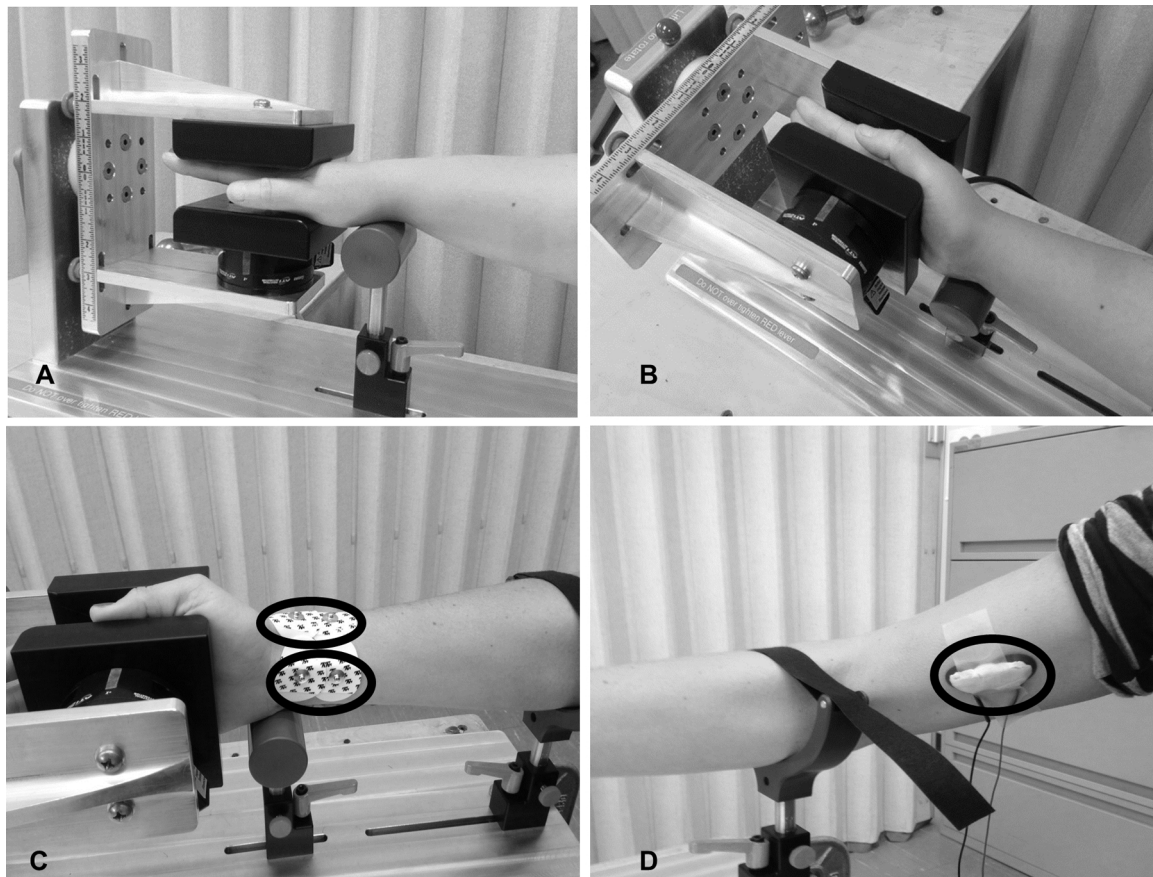
Fig. 1. Experimental set-up and stimulation locations.
Fig. 1 A and B illustrate the pronated and neutral wrist positions used during measurements. Fig. 1C and D show the stimulation locations during the test. The top circle in Fig1C indicates the superficial radial (SR) nerve stimulation location, the bottom one indicated the median nerve (MED) stimulation location. The black circle in Fig1D indicates the stimulation location for evoking reciprocal inhibition (RI).

to running [9]. Although the effects of joint position on reflex amplitudes were not the main research question for those studies, these results suggest that altered joint position and associated changes in afferent feedback may modulate motor output demands of the task [8], which is reflected in excitabilities in cutaneous reflexes and reciprocal inhibition pathways.

Modulation of excitability in neural pathways is commonly measured at different levels of muscle contraction. During static tasks, reflex amplitudes scale almost linearly with motor neuron recruitment from the targeted pool. This type of regulation was defined as "automatic gain compensation"[10], and was suggested to ensure reflexes are scaled to the motor output during specific non-locomotor motor tasks. By comparing the relation between background muscle activation and reflex amplitudes, the modulation of neural excitabilities during different motor tasks [11], pathological conditions [12] or intervention [13] can be studied.

Background muscle activation changes amplitudes for H-reflex [14,15], reciprocal inhibition [9,16–18] and cutaneous reflexes [19,20] in the leg. In clinical populations where motor output is compromised, such as after stroke or incomplete spinal cord injury, participants may be unable to perform refined motor tasks at certain joint positions and may require adaptation of the experimental approach [21,22]. Therefore, investigating the potential effects of joint position on reciprocal inhibition and cutaneous reflexes in the arm muscle will not only reveal the modulation mechanisms in the upper limb neural pathway but also has critical application for control in clinical studies.

The purpose of this study was to explore the effects of wrist position and level of muscle activation on reciprocal inhibition and cutaneous reflex amplitudes in wrist extensor carpi radialis (ECR) muscle. We

hypothesized that joint position would have similar effects on reciprocal inhibition and cutaneous reflex amplitudes

2. Methods

2.1. Subjects

In accordance with the Declaration of Helsinki, twelve healthy, young (24 ± 1.8 years old) participants without any neurological impairment or muscular injuries in their upper limbs participated with written in a protocol approved by the Human Research Ethics Board at the University of Victoria.

2.2. Electromyography (EMG)

EMG data from extensor (ECR) and flexor carpi radialis (FCR) and biceps and triceps brachii muscles were collected the right arm of each participant. After cleansing the skin with rubbing alcohol swabs, disposable surface electrodes (Thought Technology Ltd., Quebec, Canada) were placed in bipolar configuration over the target muscle bellies. EMG signals were amplified ($\times 5000$), bandpass filtered using a 1st order filter from 100 to 300 Hz (GRASS P511, Astromed-Grass Inc.) and sampled at 2000 Hz through a customized LabVIEW program (National Instruments, Austin, TX). This procedure involves some signal loss at lower frequencies but allows for effective amplifier response during evoked potential studies [20–22].

2.3. Electrical stimulation

In both reciprocal inhibition and cutaneous reflexes trials, stimulation was applied using a Grass 88 stimulator with SIU5 stimulus isolation and CCU1 constant current units (Grass Instruments, Astro-Med, Inc. West Warwick, RI, US). The method for evoking reciprocal inhibition was similar to earlier studies which stimulated the antagonist muscle nerve and measured the difference between the background and conditioned EMG in the target muscle [12,23]. Stimulation was applied to the median nerve just above the elbow under the curve of the biceps brachii with a single 1.0 ms pulse. To ensure stimulation was non-noxious, the intensity was set at 1.2 times motor threshold, defined as the lowest stimulation amplitude that evoked a direct muscle response (M-wave) in FCR. In cutaneous reflexes trials, trains of 5×1.0 ms pulse at 300 Hz were applied to the superficial radial (SR) and median (MED) nerves at the wrist with the intensity set as 2 times radiating threshold (RT) which evoked clear reflexes while not considered to be noxious by the subjects [24,25]. RT was defined as the lowest intensity at which a sensation of radiating paresthesia could be evoked in the innervation territory of the nerve. Here, MED nerve innervates the lateral portion of the palm (thumb, index, and half of the middle finger), and SR nerve innervating the dorsal surface of the hand towards the index finger and thumb. Stimulation electrode locations and experimental set-up were illustrated in Fig. 1. For both reciprocal inhibition and cutaneous reflex trials, 20 sweeps of stimulation were applied in each trial.

2.4. Procedures

Participants were seated in a chair with back support. The right forearm and wrist were supported and constrained with straps to a customized device which helped maintain shoulder extension at ~ 140 and elbow flexion at $\sim 50°$. Muscle activation during maximal contraction (EMG$_{MAX}$) in wrist extension was measured at two different wrist positions, pronated and neutral, over 2 attempts (1 min break in between, EMG$_{MAX}$ was held for 3–5 s). During the EMG$_{MAX}$ test, ECR muscle activity was rectified and averaged using a custom-written LabVIEW program. The averaged values were presented as bar graphs and updated every 25 ms. Participants were instructed to do wrist extension with maximal effort to generate an ECR EMG signal as large as possible. According to each participant's ECR muscle EMG$_{MAX}$, feedback was presented on the computer screen and four attempted contraction levels (10%, 15%, 25% and 50 of EMG$_{MAX}$) were calculated for each wrist position. During the reciprocal inhibition and cutaneous reflexes trials, twenty sweeps of data were triggered pseudo-randomly every 1.5–3 s (reciprocal inhibition trials) or 2–3 s (cutaneous reflex trials). Both responses were examined under two wrist positions and four different levels of muscle contraction in ECR. During each trial, the corresponding contraction level was presented as a target with the ECR EMG bar graph feedback. Participants were required to attempt to match their ECR EMG to the target between stimulations. FCR, biceps, and triceps brachii muscle EMG levels were monitored by the experimenter to ensure there was no co-contraction during the test.

2.5. EMG and reflex analysis

All the EMG data were analyzed offline with customized MATLAB programs (Version R2011b, The Mathworks, Natick, MA, USA). EMG signals were rectified and low-pass filtered using 4th order Butterworth filters at 100 Hz. Muscle activation during maximal contraction (EMG$_{MAX}$) was calculated as the average over a 10 ms window around the peak of each trial. The mean of two attempts was used for each participants EMG$_{MAX}$ for each joint position.

Fig. 2 shows typical responses to reciprocal inhibition and cutaneous stimulation. Reciprocal inhibition was measured as the difference between the mean pre-stimulus background EMG$_{MAX}$ (from a 20 ms window before stimulation onset) and the mean of the maximum
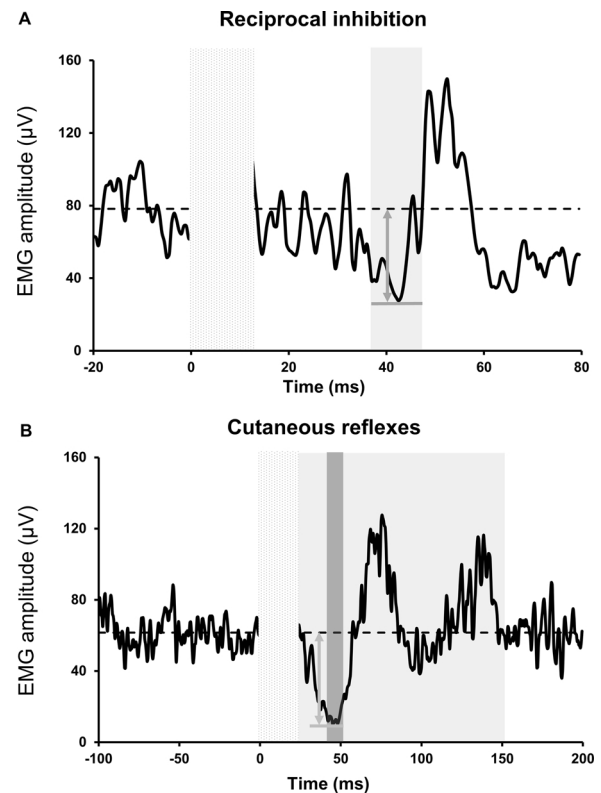

Fig. 2. Typical muscle responses during reciprocal inhibition and cutaneous stimulation trial.

A. Typical muscle response to reciprocal inhibition. The stimulation artifact was removed from the graph. There was a 20 ms window of data recorded before stimulation onset. Shaded area indicates the RI response, a 10 ms window around the lowest value that was used for data analysis at the latency around 30ms–40 ms.

B. Typical cutaneous reflexes. The stimulation artifact was removed from the graph. There was a 100 ms window of data recorded before stimulation onset. Dark grey area indicates the early latency cutaneous reflex, a 10 ms window around the lowest value that was used for data analysis at the latency around 50ms–75 ms. Light grey indicates the area used for calculating net reflex, which is averaged cumulative reflex EMG in a 150 ms window.

inhibition (from a 10 ms window around the post-stimulus minima with a latency ~ 30 ms). Cutaneous reflexes were determined as the difference between EMG amplitudes during the early latency window (50–75 ms post-stimulation) and prestimulus background EMG. Net cutaneous reflexes were determined from the average cumulative reflex EMG after 150 ms (ACRE$_{150}$). All reflex variables were normalized to the ECR EMG$_{MAX}$ for each participant obtained from the corresponding joint position condition.

2.6. Statistics

Mixed linear model analysis was performed using commercial statistical software (SPSS 20, Chicago, IL) to evaluate the effects of the wrist joint position and background EMG on reflex amplitudes. Paired t-tests were used to compare the EMG$_{MAX}$ between joint positions for each participant. The level of statistical significance was set as $p \leq 0.05$.

3. Results

3.1. EMG$_{MAX}$

Fig. 3 shows average EMG$_{MAX}$ of ECR muscle during wrist extension. There was a significant effect of joint position ($p = .019$). Averaged
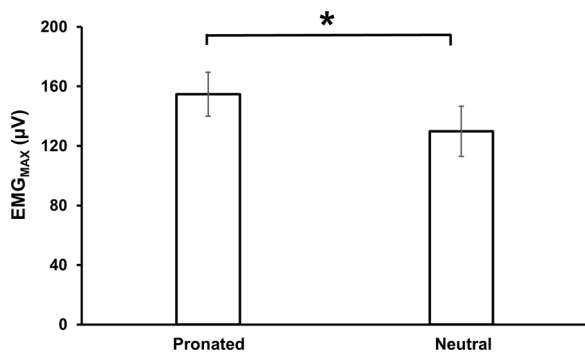
Fig. 3. Maximal muscle activation (EMG_{MAX}) of extensor carpi radials (ECR) during extension at two different wrist joint positions.
EMG_{MAX} at pronated position (154.69 ± 51.23 μV) was significantly higher compared to neutral position (129.79 ± 58.51 μV). Data was averaged across 12 participants and each bar represents the mean +/− one standard error of the mean, * indicates significant difference (p < 0.05).

EMG_{MAX} at wrist pronated position (154.69 ± 51.23 μV) was 19% higher compared to the neutral position (129.79 ± 58.51 μV). Eight out of twelve participants showed higher EMG_{MAX} with the wrist pronated position.

### 3.2. Reciprocal inhibition

The normalized amplitudes of reciprocal inhibition (% of ECR EMG_{MAX}) for all conditions are presented in Fig. 4. Larger (p = .027) inhibition was found at higher muscle activations for both joint positions. Average inhibited EMG amplitude decreased from 0.4% to −13% at wrist pronated position, and from 0.0% to −8% at wrist neutral position. There was no significant effect of joint position (Fig. 4).

3.3. Cutaneous reflexes

Early latency and net reflex amplitudes for MED cutaneous reflexes are shown in Fig. 5A and B, respectively. While no effect of wrist position was found, at both wrist joint positions early latency reflexes (p = .027) and net reflexes (p = .047) were significantly reduced with increasing background muscle activation. With increased background muscle activation, the normalized early latency MED cutaneous reflex
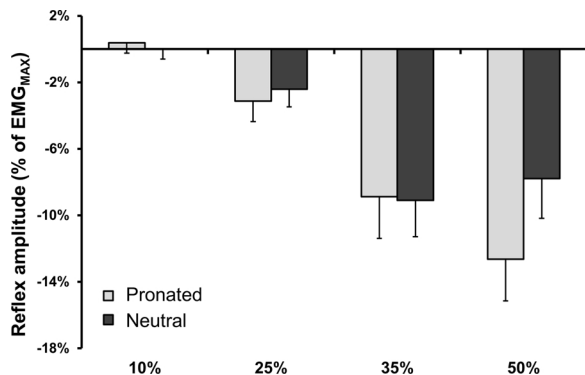
Fig. 4. Amplitudes of reciprocal inhibition at different levels of ECR muscle activity.
The inhibitory amplitude was larger with higher background EMG. The X-axis represents four different levels of background ECR muscle activation at 10%, 25%, 35% and 50% of EMG_{MAX} under the corresponding wrist position. The Y-axis represents the percentage of reflex amplitude to the EMG_{MAX} of ECR muscle. Dark grey bars represent reflex amplitudes at wrist neutral position, light grey bars represent reflex amplitudes at wrist pronated position. Data were averaged across 12 participants and each bar represents mean +/− one standard error of the mean.
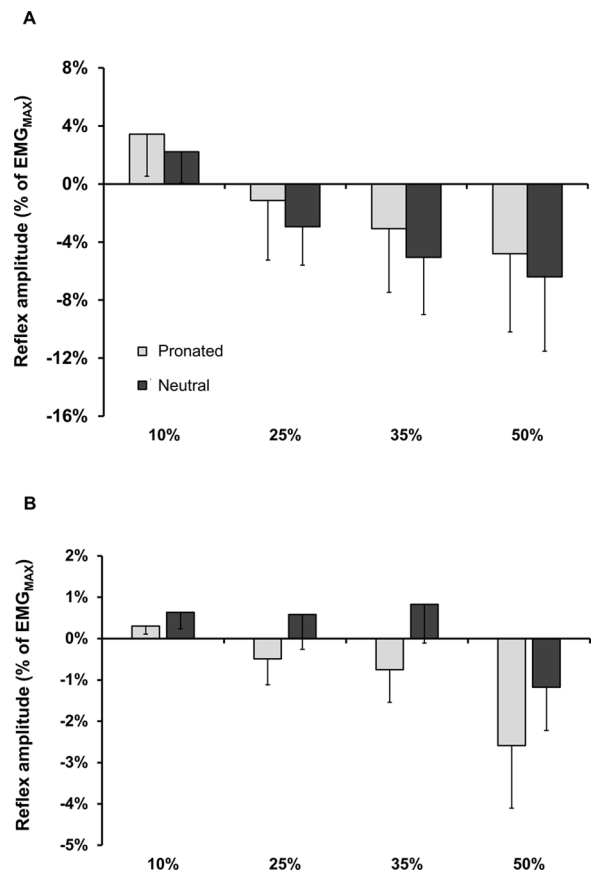
Fig. 5. Effect of muscle activation level and wrist joint position on (A) early latency and (B) net reflex of median nerve cutaneous reflexes.
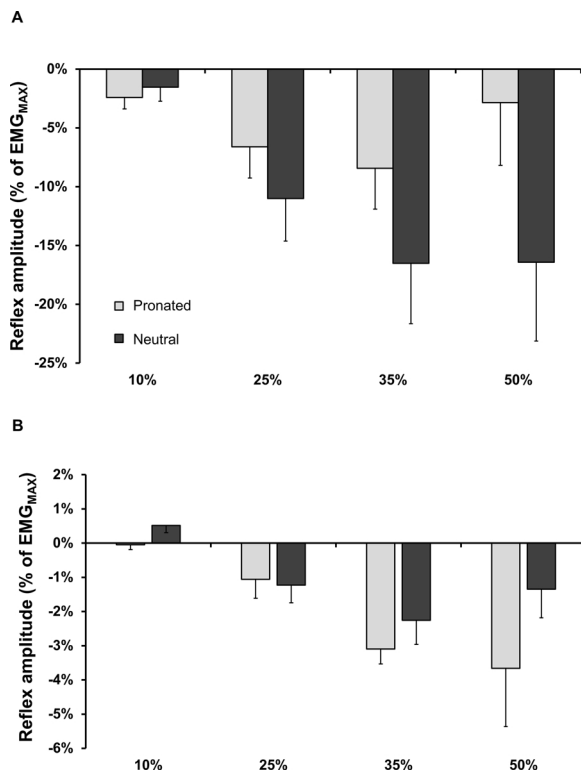The X-axis represents four different levels of background ECR muscle activation at 10%, 25%, 35% and 50% of EMG_{MAX} under the corresponding wrist position. The Y-axis represents the percentage of reflex amplitude to the EMG_{MAX} of ECR muscle. Dark grey bars represent reflex amplitudes at wrist neutral position, light grey bars represent reflex amplitudes at wrist pronated position. Data were averaged across 12 participants and each bar represents mean +/− one standard error of the mean.

amplitudes changed from 3.4% to −4.8% at the pronated position and 2.2% to −6.4% at the neutral position (Fig. 5A). Net reflex amplitudes decreased from 0.3% to −2.6% and from 0.6% to −1.2% at wrist pronated and neutral positions, respectively (Fig. 5B).

For SR nerve cutaneous reflexes, the size of the inhibition at early latency (p = .019) and net reflexes (p = .000) were greater with larger background muscle activation, but no significant effect of wrist position was found for early latency reflexes. Decreased early latency reflex amplitudes were found at wrist neutral position (from −1.5% to −16.4%, Fig. 6A). However, the effect of wrist position was only significant for net reflex amplitudes (p = .013) and the size of inhibition was greater when the wrist was pronate, which decreased from 0.0% to −3.7% with increased background muscle activation, as shown in Fig. 6B.

4. Discussion

The main purpose of this study was to explore the effect of joint position on modulation of reciprocal inhibition and cutaneous reflex amplitudes at different levels of muscle contraction. Both reciprocal inhibition and cutaneous amplitudes scaled with increasing muscle activation levels while the effect of wrist position was observed only for cutaneous reflexes evoked from SR nerve.

A

B

Fig. 6. Effect of muscle activation level and wrist joint position on (A) early latency and (B) net reflex of superficial radial nerve cutaneous reflexes.
The X-axis represents four different levels of background ECR muscle activation at 10%, 25%, 35% and 50% of EMG_{MAX} at the corresponding wrist position. The Y-axis represents the percentage of reflex amplitude to the EMG_{MAX} of ECR muscle. Dark grey bars represent reflex amplitudes at wrist neutral position, light grey bars represent reflex amplitudes at wrist pronated position. Data were averaged across 12 participants and each bar represents mean +/− one standard error of the mean.

4.1. Modulation with joint position

Joint position modulated spinally-mediated reflexes in several previous studies. Soleus H-reflex amplitude decreased when posture changed from lying to sitting to standing [2,3], likely due to changes in Ia presynaptic inhibition (PSI). Baldissera et al. found H-reflex amplitudes in FCR muscle were lower when the forearm was supinated compared to pronated [1]. They suggested that the H-reflex pathway to FCR motor neuron is influenced by the changes in the afferent feedback accompanying forearm rotation. The mechanisms were not clearly identified, but putative excitatory contribution of the homonymous stretch reflex should be ruled out since the FCR muscle length is shorter in pronation than in supination. These results are unlikely due to effects from Golgi tendon receptors since all the tests were performed with muscles relaxed.

Here we did not find a significant effect of joint position on reciprocal inhibition amplitude from FCR to ECR muscle. There is evidence suggesting that the inhibitory reflex (~30–40 ms latency) we investigated is mediated via a disynaptic spinal pathway since the Ia reciprocal inhibitory interneuron innervates the α-motor neuron directly [26]. As PSI does not affect α-motor neuron excitability directly [27], it is possible that due to different neural pathways, the effect of joint position on reciprocal inhibition is not as strong as it is on PSI. Lack of joint position effects has been found for reciprocal inhibition of lower limb muscles. Kido et al. compared reciprocal inhibition in soleus and tibialis anterior muscles during standing and walking and found a weaker task-dependency but a stronger speed-dependence in reciprocal inhibition [9]. Although this study was not designed to test the effect of

ankle joint angle on soleus H-reflex specifically, the authors did compare the reciprocal inhibition at matched EMG level during standing and walking, as well as the inhibition amplitudes across 16 phases in the gait cycle. No significant differences were found between all those variables. These results suggest that ankle joint angle also has little effect on the level of reciprocal inhibition between TA and SOL muscles.

Somewhat unexpectedly, we found cutaneous reflexes from the two nerve sites were modulated differentially with wrist position. SR cutaneous reflexes showed significantly increased inhibitory net reflex amplitudes at the wrist pronated position while amplitudes were relatively unchanged for MED cutaneous reflexes. Previous studies suggest cutaneous reflex amplitudes are highly task-dependent and nerve-specific in both arm and leg muscles. Depending upon the motor task, such as standing vs. walking [28], static vs. arm cycling [20] or static vs. leg cycling [29], cutaneous reflex amplitudes change dramatically at similar EMG levels. Differential reflex modulation was found in the same muscle when stimulating the nerves that innervating different skin area [6,7,19,30]. These types of task- and nerve-dependency of cutaneous reflexes have their functional significance and has been discussed in previous studies, especially in locomotion tasks [31]. In manual tasks, Evans et al., tested cutaneous reflexes from first dorsal interosseous muscle while performing isolated finger or grip maneuvers in eight different tasks [6]. Long-latency excitatory responses were significantly lower during isolated finger tasks. Similar results were found by Nakajima and colleagues [32] when comparing long latency cutaneous reflexes in intrinsic human hand muscles while performing isometric abduction with different fingers and when producing a pincer grip task. Results showed that the magnitude of peak EMG around ~60–90 ms latency was larger when the stimulation was applied to the homotopic digit that performed the motor task. Although not the explicit focus of their work, we interpret these earlier findings as indicators that cutaneous reflex modulation is stronger in muscles that are more functionally relevant for the task performed.

It is possible that the different joint positions used here could induce biomechanical and afferent input changes. Horri et al. examined five wrist muscle tendons at different joint angles and positions in cadavers and found the moment arm of extensor carpi ulnaris tendon significantly decreased when the forearm rotated from neutral to pronated positions [33]. Rugy et al. found an increase in FCR activity and a decrease in flexor carpi ulnaris (FCU) activity as the forearm rotated from supinated to pronated position [34]. They suggested that different joint positions might not only induce biomechanical changes but also tuned the motor commands to the muscles around the joint.

Here, differences in cutaneous reflex modulation could be due to the specific sensation and muscle functions MED and SR nerve generated and their relation to the motor task. Activation of SR nerve generates sensations in the dorsum of the hand, back of the thumb, index and middle finger. On the contrary, at the level of the wrist, the MED nerve innervates the skin of the palm side of the thumb, index and middle finger as well as the thumb flexor muscles. While participants contracted their ECR muscle at the required level, stimulation at SR nerve produced sensation within the muscles directly involved in the task. Additionally, different from the purely cutaneous sensory SR nerve, MED is a mixed nerve with both muscle and cutaneous sensory afferents and motor fibers. Studies showed that electrical stimulation in mixed nerve and cutaneous nerve activate different motor cortical areas [35]. Since the afferent feedback from these two nerves convey through different ascending pathway, it is likely that different afferent composition between MED and SR cutaneous stimulation may affect the spinal interneuronal networks differently, this despite some common activity during rhythmic motor output [20]. Therefore, the functional difference between MED and SR nerve may relate to their different modulations such that SR cutaneous reflex amplitude during wrist extension task is likely more sensitively modulated by changes in the wrist joint position.

Higher EMG_{MAX} in ECR muscle and stronger inhibitory net reflex in

SR cutaneous reflexes were found at the wrist pronated position. It is possible that altered EMG$_{MAX}$ was a methodological confound caused by the displacement of electrodes on ECR muscle fibers with change in wrist position. However, since all the reflex amplitudes were normalized to the EMG$_{MAX}$ at the corresponding position this potential confound is unlikely. In addition, the effects of possible movement of the surface EMG between wrist pronation and supination position have been excluded in Baldissera and colleagues' study. A control experiment were performed by using wire electrode in FCR muscle which confirm that changes in H-reflex amplitudes related to altered wrist position [1].

We suggest that altered sensory feedback at different wrist position plays a major role in modulating ECR motor neuron excitability and SR cutaneous reflex amplitudes. One possible source of change in afferent input is load-related feedback. Although the forearm and wrist were supported during this experiment, extending the wrist at the pronated position requires wrist extensors to contract to overcome the weight of the hand. Studies in leg muscles showed that load-related sensory inputs play important role in locomotor and postural control [36]. Walking with partial or whole body weight support can alter the phasic cutaneous reflexes modulation in the lower leg muscle [37,38]. Bastiaanse et al. also found load-dependent background muscle activity in leg extensor muscles during walking. In these studies, load-related sensory input was changed by changing total body weight (e.g. using body weight support to remove weight) or by applying external loads, but not by changing joint position. There is lack of corresponding investigations on the effects of load-related afference on cutaneous reflexes in the arm muscles during static task.

Despite that, we suggest that our results correspond with the above studies in leg muscles implying that load-related afferent input may play a role in the modulation of spinal interneuron excitability in the upper limb.

4.2. Modulation with muscle activation

Reciprocal inhibition and cutaneous reflexes amplitudes were both enhanced with increased ECR muscle activation. Proportional increases in reflex amplitudes with background activation was first emphasized by Marsden et al. by measuring stretch reflexes in flexor policis longus muscle during thumb movement. Marsden and colleagues defined this phenomenon as "automatic gain compensation" where reflex gain increases in proportion to the number of active motor neurons. This functionally ensures that reflexes remain appropriately scaled to the motor task [39,40]. Matthews provided more examples of automatic gain compensation during tendon vibration induced force and inhibitory reflex in elbow flexors. Matthews suggested that reflex regulation without automatic gain compensation would tend to be too powerful when pre-existing muscle contraction was weak, and too feeble when muscle contraction was strong [10]. Here, muscle activation level had a significant effect on the amplitude of both reciprocal inhibition and cutaneous reflex in ECR muscles regardless of joint position. As different from rhythmic or locomotion movement [20,30], this background EMG dependency suggests that during static contraction, background muscle activation affects interneuronal excitability relatively equally and makes a strong contribution to reflex amplitudes.

5. Conclusion

Joint position has a significant effect on SR but not MED cutaneous reflexes in ECR muscle. This effect of joint position in cutaneous reflex amplitude is thus nerve-specific. Amplitudes of cutaneous reflexes in arm muscles are likely more sensitive modulated in task-related muscles. As with related observations in the leg, amplitudes of reciprocal inhibition and cutaneous reflexes increased with background EMG in forearm muscles during tonic contraction regardless of joint position. In future studies that investigate the modulation of neural pathways, the effect of wrist joint position should be considered when measuring

maximum muscle activation and SR cutaneous reflexes. Changes in joint wrist position have less effect on reciprocal inhibition and MED cutaneous reflexes amplitudes, which has relevance for choosing tools and approaches for assessments in clinical populations with limited upper limb range of motion and motor output.

Conflict of interest statement

The authors declare that they have no conflict of interest regarding the publication of this paper.

Acknowledgments

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