Human force reproduction error depends upon force level

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ABSTRACT

For optimal haptic tele-manipulation system design, it is important to understand the accuracy and limitations of human force perception. Previous research demonstrated that humans generate higher forces when asked to reproduce an externally applied force; these studies proposed that the nervous system attenuates feedback from self-generated forces. The goal of this study was to determine how accurately subjects reproduce self-generated forces with the same hand over a broad range of force levels. Subjects (n=10, all right handed) had to generate an onscreen target force with visual support and subsequently reproduce the same force without visual support with their right hand against a static handle equipped with a force sensor. Six force levels (10 to 160N) were each presented randomly for eight repetitions. Subjects generated too high forces for lower force levels ($\leq 40N$) and too low forces for higher force levels ($\geq 130N$). Our results support force-dependent sensory integration and demonstrate that attenuated feedback of self-generated forces is not the sole factor in force reproduction errors.

Keywords: Attenuation, Force reproduction error, self-generated forces, haptic tele-manipulation systems, sensory integration

1 INTRODUCTION

In situations where human judgement is wanted, but human presence is undesirable such as in hazardous environments (e.g. nuclear power plants), haptic tele-manipulation systems provide the solution. The human operator controls a slave (e.g. remote robot arm), via the master (e.g. joystick) while haptic information of the forces at the slave is fed back to the human operator. Yet, the delicate nature of most tele-manipulation tasks complicates proper execution using tele-manipulation systems, leading to accidents. The accuracy and limitations of human force perception is a critical factor in optimizing man-machine interaction.

Humans perceive forces using Golgi Tendon Organs (GTO) that detect forces in the muscles and tactile sensors that detect deformations of the skin due to forces. When multiple sensors provide redundant information, the central nervous system integrates the information, using the accuracy of the sensorsy information as a weighting factor [3], [4], [6], [8]. To interact with the environment, humans generate forces using their muscles. Next to the externally applied forces, also self-generated forces are detected by the force sensors and will affect the external force estimate. The *efference copy* (motor commands used to generate forces with the own body), provides additional information that might correct for this extra sensory information [1] or can be used in the integration process to improve the force estimate.

In literature, it has been demonstrated that humans generate higher forces at the fingertip when asked to reproduce an externally applied target force up to 10N [5], [7]. It has been proposed that the nervous system attenuates feedback from self-generated forces, i.e. humans perceive self-generated forces to be lower than externally applied forces [5]. Bays and Wolpert [1], proposed a model that, using the efference copy, predicts the *reafference feedback* (sensory feedback due to self-generated forces), which is attenuated by subtracting it from the actual sensory feedback.

Walsh et al. [7] suggest that the *force reproduction error* (FRE, force difference between target and, in a subsequent trial, reproduced force) depends on a constant component (i.e. offset) and a force-level-dependent component (i.e. gradient). The FRE diminished when subjects self-generated the target force using their other hand, which is in accordance with Bays and Wolpert's model, but also diminished when subjects matched higher externally applied force levels (up to 75 % of their maximum voluntary contraction), which is not captured by the model as concluded by Walsh [7]. Walsh et al. [7] proposed that the gradient is generated due to an enhancement of reafference when receiving the target force, i.e. humans are more sensitive to self-generated reaction forces than to the externally applied force. Jones and Hunter [2], demonstrated that subjects generated relatively higher forces for low force levels with diminished FREs for high force levels when matching isometric contraction levels of the other arm on the basis of equal sensation. These previous studies present the FRE when matching externally generated targets or when targets are self-generated by the other arm. In tele-manipulations systems, however, humans often have to reproduce forces in the same way as performed before (e.g. in training sessions).

The goal of our study was to determine how accurately subjects reproduce self-generated forces over a broad range of force levels, from 10N to 160N, with the same hand. If only attenuation of self-generated forces causes the FRE, then self-generating both the target and the reproduction force should result in correct force estimates and no FRE. Therefore, attenuation of self-generated forces as proposed by Bays and Wolpert [1] does not affect the FRE in our experiment. We hypothesize that the accuracies of the force perception sensors change with force level and that subsequent sensory reweighting will affect the FRE. We expect that subjects will generate too high forces for force levels near 10N and too low forces for force levels near 160N. The results of this study will indicate whether attenuation of self-generated forces is the sole factor in force reproduction tasks. In addition, the results may have an impact on the design of haptic tele-manipulation systems. Knowledge of the human force perception can be utilized in scaling environmental forces to and from the human operator, e.g. preventing damage to the hazardous environment by presenting the environmental force in a range where the operator's FRE is smallest.

2 MATERIALS AND METHODS

Subjects Ten healthy right-handed males, aged 27.1 (SD 1.37), participated in the experiment. All subjects provided written informed consent prior to participation and the study was approved by the local ethics committee.

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Experimental setup Figure 1 shows the experimental setup with a subject in front of a monitor exerting forces to a handle with its right hand. Subjects performed two types of trials:

- a reference trial, where the subject generated an onscreen target force with visual support
- a reproduction trial, where the force of the reference trial was reproduced without visual support

The visual support consisted of target indicators and an indicator bar, see Fig. 1. The subjects were instructed to operate a foot switch that triggered a force measurement (0.3s with a sample rate of 500 Hz) when the bar was aligned with the target indicators (reference trial) or when they thought to have matched the reference force (reproduction trial). After operating the foot switch, subjects were instructed to maintain the force for at least one second (timed onscreen) to prevent the force to change during the measurement.

Experimental protocol The maximum voluntary contractions (MVC) before and after the experiment were used to check for fatigue. To prevent impact during the MVC trials, subjects were instructed to build up to their maximum force in three seconds. Visual feedback of the applied force as well as the maximum force from the previous trial was shown. The maximum force per trial was calculated using a moving average filter (time window: 100ms). Three trials were performed and the maximum force of the trials were averaged to obtain the MVC.

The experiment started with a training session to familiarize the subject with the setup and the protocol and consisted of five reference trials followed by eight alternating reference and reproduction trials at a force level of 20N. The next trial started when the force on the handle was back to zero. Subjects were instructed not to let go of the handle between a reference and reproduction trial.

In the experiment, the subjects had to perform alternating reference and reproduction trials of six force levels (10, 40, 70, 100, 130, 160N), which were randomly presented eight times each. Resulting in a total of 96 trials (6 force level x 2 trial type x 8 repetitions.

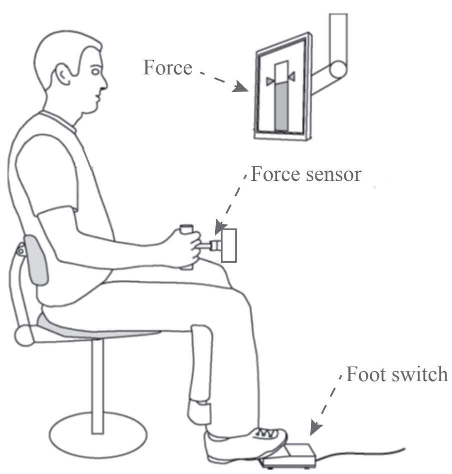

Figure 1: Experimental setup. The subjects were seated in front of a monitor and held a handle, equipped with a force sensor (ATI mini 45, calibration SI-145-5, sensitivity 1/8N), in their right hand with their right arm at an elbow angle of approximately 90 degrees. Visual support consisted of an indicator bar and target indicators. The indicator bar showed the force applied by the subject scaled to the target force, resulting in the same visual support for all force levels with the target indicators at 100%.

Data analysis The force measurements during the reference and reproduction trials were averaged over the 0.3 s measurement and the repetitions. To obtain the FRE, the target force is subtracted from the averaged reproduced force and the relative FRE is obtained by dividing the FRE by the corresponding target force. Repeated-measures ANOVA was used to test for effects of force level on the FRE and on the relative FRE, with $\alpha = 0.05$.

To check if the FRE and relative FRE differed significantly from zero, separate one way t-tests were performed. The α was corrected using Bonferroni correction. To measure the effect of fatigue, a paired t-test was performed between the MVC before and after the experiment. Statistical analysis was performed in IBM SPSS Statistics 20.

3 Results

The MVC results from Table 1 indicate that there was no effect of fatigue on the results ($t(9) = 0.014$, $p = 0.989$).

The small variance within subjects demonstrate that the tasks was repeatable, see Fig. 2A.

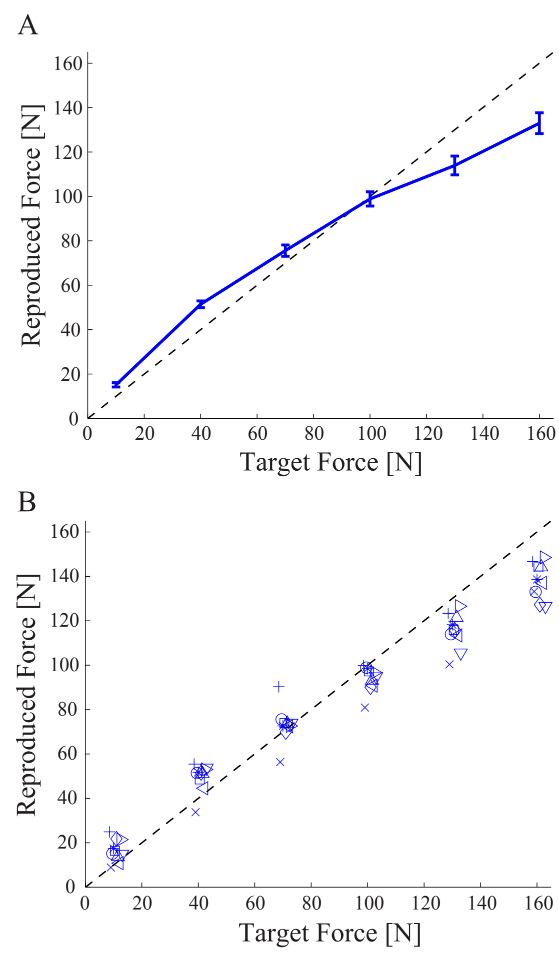

Figure 2: A, reproduced forces of a typical subject. Dashed black line: target forces; Errorbars: Standard error across trials. B, Averaged reproduction forces of all subjects. Dashed black line: target forces; Markers: different subjects. Nine out of ten subjects, generated higher forces for force levels below 40N and generated lower forces for force levels of 130N and up.

Table 1: Maximum voluntary contraction per subject and group average. MVC B: before experiment; MVC A: after experiment; Diff [N]: MVC A - MVC B; Diff [%] = Diff [N] / MVC B.

Subject	MVC B [N]	MVC A [N]	Diff. [N]	Diff [%]
1	321.4	323.0	1.6	0.5
2	338.6	300.9	-37.7	-12.5
3	304.0	260.3	-43.7	-16.8
4	372.8	402.8	30.0	7.5
5	368.8	369.3	0.5	0.1
6	279.9	280.0	0.1	0.1
7	422.4	409.1	-13.3	-3.2
8	298.0	370.3	72.3	19.5
9	382.3	302.3	-80.0	-26.5
10	340.9	409.0	68.1	16.7
mean	342.9	342.7	-0.20	0.06

Table 2: Force reproduction error. Per force level the mean FRE, standard error of FRE across subjects, mean relative FRE and standard error of the relative FRE across subjects; p-value: significance level of one way t-test. The α of the t-test is Bonferroni corrected to 0.008.

Force [N]	Mean [N]	SE [N]	Mean [%]	SE [%]	p-value
10	6.52	1.59	65.2	15.9	0.002
40	9.74	1.98	23.6	4.9	0.001
70	3.44	2.57	4.5	3.7	0.198
100	-5.32	1.81	-5.9	1.8	0.015
130	-13.59	2.50	-11.2	1.9	<0.001
160	-20.88	2.49	-13.8	1.6	<0.001

The variance of the force estimates between subjects is largest for 130N and 160N. The results show that there is an effect of force level on the FRE ($F_{5,45}=76.739$, $p<0.001$), see Fig. 3A. There is also an effect of force level on the relative FRE ($F_{5,45}=24.655$, $p<0.001$), see Fig. 3B. Subjects generated too high forces for force levels up to 40N (10N: p=0.002, 40N: p=0.001) and too low forces for force level above 130 N (130N and 160N: $p<0.001$), with the crossover point between 40N and 130N see Fig.3A and table 2. At 10N, the relative FRE and the range of force estimates between subjects is largest, see Fig.3B, for higher force levels, 40N until 160N, the relative FRE and the variance between subjects decreases.

4 Discussion

In this study we analysed the effect of force level on the force reproduction error when reproducing self-generated forces using the same hand. As hypothesized, an effect of force level on FRE was found. Subjects generated too high forces for force levels up to 40N and too low forces for force levels of 130N and up. The cross-over point was comparable for all subjects, see Fig. 2B, suggesting that the MVC does not affect the location of the cross-over point. The group average MVC results demonstrate that there was no fatigue during this experiment.

Force reproduction error Our results for low force levels (up to 40N) are in accordance with previous studies where subjects generated too high forces at the fingertip when matching externally applied target forces up to 10N [5], [7]. However, our findings when using the same hand are not in accordance with findings where the FRE diminished when subjects had to self-generate the target force, up to 10N, using their other hand [7]. Apparently human force perception depends on the way the forces are experienced, i.e. which sensors obtain useful information to be used in the reproduction phase.

Subjects generated too low forces for force levels of 130N and up, which is not in accordance with previous findings where the FRE diminished at higher externally applied force levels (up to 75% MVC) [7] and when matching higher contraction levels (up to 85% MVC) of the biceps muscle of the other arm [2]. It was found that subjects generated too low forces at higher force levels, when only tactile sensors were used to perceive the externally applied force [7], indicating that the CNS uses information from all available sensors to estimate the applied force.

Possible mechanisms Up to now, the discussion focused on the FRE, but more important is the mechanism behind the FRE. The model of Bays and Wolpert [1] proposed that the CNS attenuates self-generated feedback to estimate the sensory feedback due to external influences. In this study, both the target and reproduction force are self-generated using the same hand. Attenuation of self-generated feedback as proposed by Bays and Wolpert [1] does not affect the FRE in our experiment, which, if only attenuation of

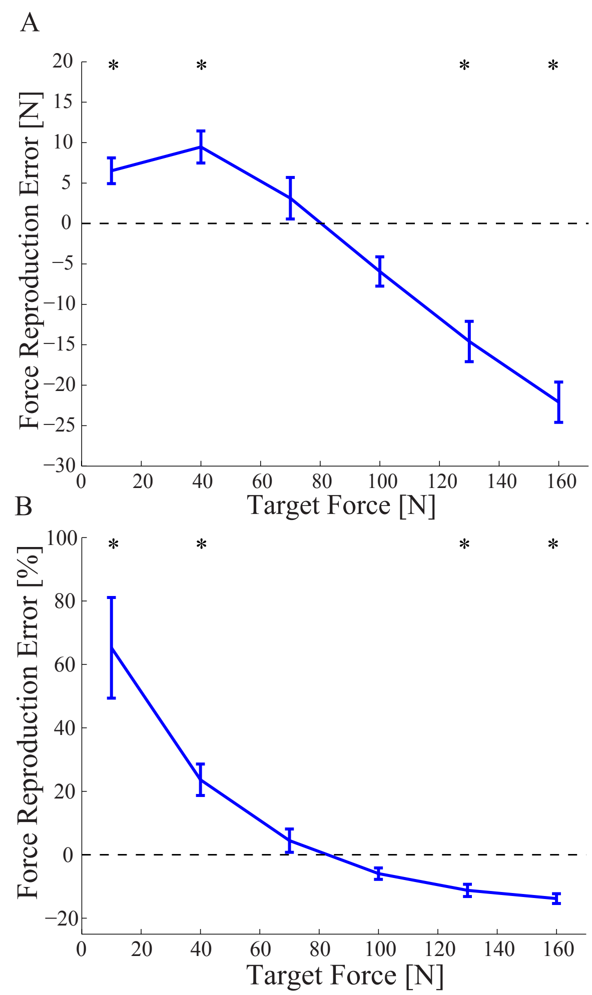

Figure 3: A, The mean FRE of the group as a function of the target force levels. Errorbars: Standard error across subjects. There is an effect of force level on the FRE. The outcomes of the t-tests are presented in table 2. B, The mean FRE of the group relative to target force (FRE/targetforce). Errorbars: Standard error across subjects. The FRE and relative FRE for four force levels differed from zero (stars).

self-generated forces causes the FRE, should result in correct force estimates. However, in this study we found a force level dependent FRE, indicating that attenuation of self-generated forces is not the sole factor in force reproduction tasks.

Walsh et al. [7], demonstrated that the FRE consists of a constant component (theoretical FRE at zero Newton) and a force-dependent component (gradient of the slope). He proposed that the force-dependent component is due to an enhancement of reafference when receiving the externally applied target force. Assuming that the CNS does not change the sensitivity of the force sensors between the reference and reproduction trial in this study and the force-dependency of FRE is caused by an enhancement of reafference in the target (reference) phase, we should find no force-dependent component. Yet, in our study we did find a force-dependent component, indicating that an enhancement of reafference is not the cause of the force-dependent component of the FRE.

We suggest that the CNS uses all available information from both force sensors and reafference (or efference copy), to estimate the experienced force using multi-sensory integration. We hypothesize that the different force sensors are more sensitive, and thus more accurate, at different force levels and the accuracy of the sensors changes over force level. The change in accuracy will bias (under- or overestimating) the force estimate of that sensor. The CNS weights the sensors using their accuracy as proposed in Bayesian decision theory [4], [8]. If we assume that sensors are unbiased and accurate at the force levels they are sensitive for and inaccurate and biased for higher/lower force levels, the total force estimate would be weighted towards the estimate of the accurate sensors, but still be biased by the estimate of the inaccurate sensors. The FRE as previously found for low force levels [7], [5], can be explained assuming the sensitivity of the GTO and tactile sensors are for high and low force levels respectively and will bias the force estimates at higher or lower force levels, resulting in too high forces at low force levels (GTO) and too low forces at higher force levels (tactile). At low force levels, tactile sensors will have an accurate estimate and will be weighted higher than the inaccurate and biased estimate of the GTOs, but the total estimate will be biased towards the GTO estimate. Subjects generated too low forces for higher force levels and showed an increasing variance with force level when perceiving the externally applied forces using only tactile sensors (Walsh et al. 2011, Fig. 5B), which might give an indication of the force sensitivity of tactile sensors.

Further research is needed to provide a better overview of the behavior of the force sensors and how the efference copy contributes to the sensory integration process.

Impact for tele-manipulation systems In tele-manipulation systems, the master and slave transmit forces between the human operator and remote environment.This study provides useful information about the accuracy of the human force reproduction capabilities, which can be used to scale forces from and to the human operator. The controller might scale the forces from the environment to force levels, where humans perceive the force more accurately. On the other hand, the forces generated by the human controller can be corrected to the intended ones. Consequently resulting in more accurate and safer tele-manipulation systems.

The relative FRE, Fig. 3B, shows that humans are most sensitive to forces between 70N and 100N, having correct force estimates and small variance between subjects. Humans are least sensitive to low force levels, near 10N, so scaling up low environmental forces might improve the human performance. The variance between subjects for low forces makes it difficult to accurately correct the force applied by the human, but for high force levels this might be a good option.

Although we can improve the human performance, further research is needed into the effect of force scaling on control effort and mental load.

5 Conclusion

In this study we analysed the effect of force level on the force reproduction error of humans when generating both the target and reproduction force with the same hand. We found that force level affects the force reproduction error and subjects generate higher reproduction forces for force levels up to 40N and lower reproduction forces for force levels of 130N and up. Our results support force-dependent sensory integration and show that attenuation of self-generated forces is not the sole factor in force reproduction errors.

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