Force JND for Right Index Finger Using Contra Lateral Force Matching Paradigm

M. S. Raghu Prasad, Sunny Purswani and M. Manivannan

Abstract The paper aims at deriving the Just Noticeable Difference (JND) for force magnitude recognition between left and right index finger of human hand. The experiment involves establishment of an internal reference stimulus, using the left index fingers of the hand, by the subject, which is perceived and matched under contra-lateral force matching paradigm. A combination of virtual environment and a force sensor was used to derive the just noticeable difference for index-finger force application. Six voluntary healthy young adult subjects in the age group of 22–30 years were instructed to produce reference forces by left index finger and to reproduce the same amount of force by the right index finger, when the subjects were confident enough of matching same amount of force, the force values of the both the left and right index finger were recorded simultaneously for 5 s at 10 Hz. Five different trials were conducted for different force levels ranging from 2 to 5 N. The percentage real JND and absolute JND were derived for all the subjects. It was found that the Force-JND obtained was approximately 10 % across all subjects. Results also show that subjects tend to underestimate force at high force levels and overestimate at low force levels. The results obtained can be used as basic building block for the calibration of virtual reality based minimally invasive surgery related tasks and force based virtual user interfaces ranging from touch pad to assistive tools.

M. S. Raghu Prasad · S. Purswani · M. Manivannan (✉)
Haptics Lab, Biomedical Engineering Group, Department of Applied Mechanics,
IIT Madras, Chennai 600036 Tamil Nadu, India
e-mail: mani@iitm.ac.in

M. S. Raghu Prasad
e-mail: raghuprasad.m.s@gmail.com

S. Purswani
e-mail: sunny.purswani89@gmail.com

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1 Introduction

The Just Noticeable Difference (JND) is a measure of minimum difference between two stimuli necessary in order for human to differentiate between the two with certainty. Many researchers have focused on JND for force in human subjects but none of them have explored force JND for a single finger. Specifically the index finger force JND corresponds to the amount of differential sensation that an individual can negate while estimating the magnitude of a given stimulus.

In past, experimental results produced by various researchers have indicated the observable range of force JND to be between 5 and 10 %. Weber measured JNDs roughly 10 % in experiments involving active lifting of 907 g weights by the hand and arm [1]. Human force control and force resolution for the effective design of haptic interfaces was reported in [2] the study also emphasized the fact that humans are less sensitive to pressure changes (i.e. force changes, when contact area is fixed) when contact area is decreased. The JND was around 10 % for pinching tasks involving finger and thumb at a constant holding force [3]. A force matching experiment about the elbow, found a JND ranging between 5 and 9 % by Jones et al. [4]. Brodie and Ross [5] had obtained JNDs lying in the same range for tasks involving the active lifting of 2 oz. weight. These research works are focused either on whole limb/arm based weight estimation or finger-thumb based combinations. On the contrary, our study is primarily based on the single finger static force application of right index finger, without any involvement of any other muscle groups. Also, our study concerns the active force JND, rather than passive JND.

Various paradigms have been adopted in prior research works to obtain the force JNDs for various muscle groups. For example, Pang et al. [3] adopted one interval, two alternative forced-choice paradigms. On the other hand Jones et al. [4] utilized the method of contra-lateral force matching with generating force ranging between 15 and 85 % of the maximum voluntary contraction (MVC range: 169–482 N). An up-down transformed response rule (UDTR) paradigm, a modified form of staircase method, for both active and passive weight lifting procedures was put forth by Brodie and Ross [5]. But, most of these paradigms involve perception of force as well as movement, based on the apparatus being used for the respective experiments. Our experiment doesn't involve application of any of the conventional TSD (theory of signal detection)-based techniques due to absence of artificial external stimuli to match. The experiment involves establishment of an internal reference stimulus by the subject, which is perceived and matched by the homologous set of muscles of opposite limb, under the purview of magnitude estimation psycho-physics technique. This mechanism involves a controlled force variation and not the rate of change of the depth of skin-indentation in index-finger application [6, 7]. Moreover, the technique used here is responsive to the fact that people do not produce constant forces spontaneously unless they are artificially controlled [7, 8]. In our experiment, subjects gradually increased self-produced force to a peak value that is visually displayed and then contra laterally matched. The primary purpose of the study is to investigate the force perception of human right index finger using contra lateral matching tasks and to evaluate the % force JND for a range of forces.

1.1 Contra Lateral Force Matching Paradigm

A contra-lateral force matching paradigm is a typical method used by various researchers to study the force perception [9–13] it is a mechanism of matching forces generated by muscle group of the any of the limbs on one side of human body by using the same set of muscle group of the other side of the body. This matching action has been observed to involve CNS (Central Nervous System) and involves a small amount of lag in information exchange between the two sides when compared to the ipsilateral force matching paradigm, which involves matching action of muscle groups on the same side of human body. Contra-lateral force matching is a popular methodology for comparing force perception and control. A comparison of matching performance between ipsilateral and contra lateral finger force matching tasks and to examine the effect of handedness on finger force perception was conducted [14], the results from the experiment indicate that the absolute, rather than relative finger force is perceived and reproduced during ipsilateral and contra lateral finger force matching tasks [14].

2 Methods

2.1 Subjects

Subjects described here are 6 healthy members of the Indian Institute of Technology Madras community, age 26 ± 4.1 years, weight 69.5 ± 8.36 kg, height 172 ± 5.22 cm, hand length from the index fingertip to the distal crease of the wrist with hand extended 16.9 ± 1 cm, hand width at the metacarpophalangeal joints (MCP) level with hand extended 8.1 ± 0.6 cm. All subjects were pre-screened verbally for self-reported handedness, and history of visual, neurological, and/or motor dysfunction. All subjects gave informed consent. No subject was known to have any neurological and visual perception disorders. Five Subjects were right handed and one subject was left handed.

2.1.1 Apparatus

Each subject was comfortably seated on a chair facing a computer monitor and asked to place both of his/her upper limbs on a wooden table positioned at the same height as of the side support of the chair, thereby maintaining a correct symmetry with respect to the medial axis of the body. The angle made by the index finger with the shoulder joint was approximately 90°. Each subject was instructed to maintain a constant index-finger pressing posture during the course of the experiment. The monitor on which a visual feedback was given was placed 15° below eye level at a distance of 0.6 m away from the participant. Two Force Sensitivity Resistors (FSR) of Interlink ™ make were used as force sensors.

The two FSR's one each for left and right hands were mounted on a wooden board such that symmetry was maintained with respect to the hand positions. In order to avoid fatigue precautionary care was taken in positioning the FSR's in accordance with the participant's index fingers. The two square FSRs were connected to the Analog to Digital Converter embedded in a controller over a parallel voltage divider circuit with 1 KΩ loads each, under 5 V input supply as shown in Fig. 1.

3 Contra Lateral Force Matching Procedure with Visual Feedback

During each experimental trial, subjects were asked to reach a target force bar of constant thickness (0.15 N) by pressing left-index finger over a 2″ Square FSR (Resolution—0.01 N), which were calibrated for given range of application of force [15]. The touch surfaces of both FSRs possessed same texture and were devoid from presenting any tactile cues or spatial attenuation which could result in biased force sensation. Once the subject reached the target force level the background color of display changed as shown in Fig. 2, indicating the attainment of the target force. When the subject was able to maintain the target force level over a period of 4–5 s, he/she was instructed to press the similar FSR on the right side of the arrangement using his/her right-index finger and try matching the force, without any visual feedback. No information was given to the subjects about the matched force value attained by the right index finger. Once, subject assured that he/she had attained the same force on right-index finger, data was recorded for 5 s at a sampling rate of 10 Hz and the trial was completed. Each subject was presented with 4 different force levels of 2, 3, 4 and 5 N and each level was delivered 5 times, with equal a priori probability during the course of experiment, thereby making each experiment comprise of 50 trials. A constant target force range was set across all force levels which allowed subjects to deviate from the target by a constant force of 0.15 N (i.e. 7.5 % at 2 N; 5 % at 3 N; 3.75 % at 4 N and 3 % at 5 N) this window of 0.15 N has been chosen carefully, by keeping in mind the

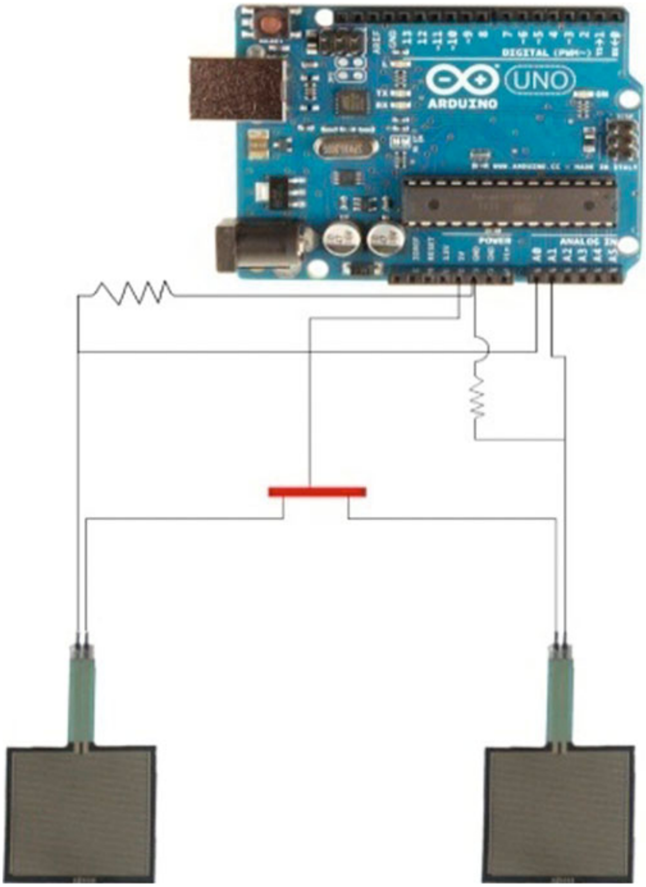


Fig. 1 Square FSRs are connected to the controller ADC

constant force error recognition results under visual feedback, as described in [8]. Subject was able to vary the force magnitude over the FSR, based on the calibration performed for electrical signal to force value conversion.

4 Data Analysis

Difference in force applied between the reference and matched value was calculated for the force-matched data across 6 subjects. The difference in real and absolute % force JND for each subject was computed separately. For a given reference force R_i and a matched force M_i the % real force JND for a single sample is obtained from Eq. (2) and the % absolute force JND is obtained from Eq. (3).

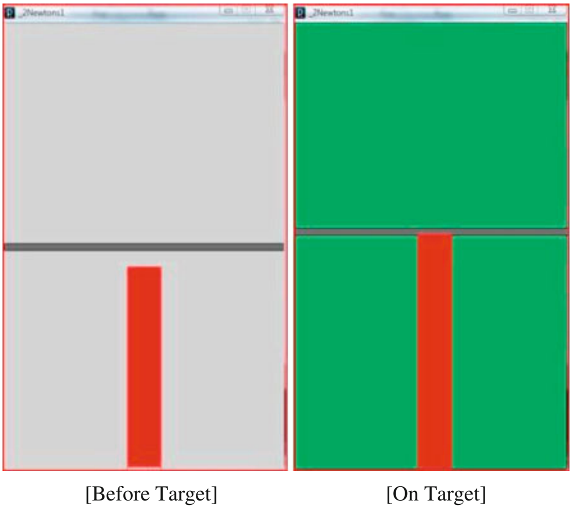


Fig. 2 Visual feedback

$$\% \, Force \, \mathrm{Real} \, JND = (M_i - R_i) \times 100/R_i \tag{2}$$

$$\% \, Force \, Absolute \, JND = Abs|(M_i - R_i) \times 100/R_i| \tag{3}$$

where i is the no:of of samples.

Similarly for 50 samples, average absolute % force JND and real % force JND per trial is computed using Eqs. (4) and (5).

$$\% \, Force \;\; Absolute \, JND = \frac{\sum_{i=1}^{50} |M_i - R_i| \times 100/R_i}{50} \tag{4}$$

$$\% \, Force \;\; \mathrm{Real} \, JND = \frac{\sum_{i=1}^{50} (M_i - R_i) \times 100/R_i}{50} \tag{5}$$

Parameters such as mean, standard deviation, standard error and variance were analyzed in detail to investigate the effect of change in % force JND across different subjects at different force levels ranging from 2 to 5 N. Table 1 summarizes the statistical analysis performed on the data set.

5 Results and Discussion

The absolute and real % force JND were obtained from each subject using contra lateral force matching paradigm. The distribution of % force JND values across subjects over various force levels in the graph, indicate that diversion of matched

Table 1 Mean, standard deviation (SD), standard error (SE) and variance (VAR) of the real and absolute % force JND across 6 subjects

Force level (Newton)	Mean % real force JND	Mean % abs force JND	SD % real force JND	SD % abs force JND	SE % real force JND	SE % abs force JND	VAR % real force JND	VAR% abs force JND
2	14.233	13.610	4.830	4.099	1.972	1.673	23.331	16.799
3	3.078	9.696	2.974	2.122	1.214	0.866	8.845	4.502
4	−4.996	7.856	2.418	2.825	0.987	1.153	5.846	7.980
5	−6.780	8.292	2.143	2.185	0.875	0.892	4.594	4.776

force values tend to contract as the force level increases. This indicates that subjects tend to produce similar static forces in a close range when the reference forces are high. Moreover, mean real % force JND values change sign between 3 and 4 N as illustrated in Fig. 3, which suggests that there exist certain set of force levels between this ranges, where subjects tend to match the reference forces most accurately, as per the contra-lateral force matching paradigm.

The pattern obtained from the average absolute % JNDs of each subject as shown in Fig. 4 indicate that at low force levels subjects tend to overestimate the reference forces and underestimate the reference force at higher force levels. Our

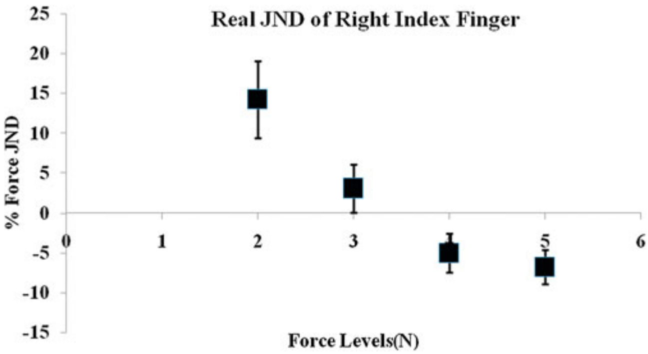


Fig. 3 Averaged real % force JND with mean and standard deviation

Fig. 4 Averaged absolute % force JND with mean and standard deviation

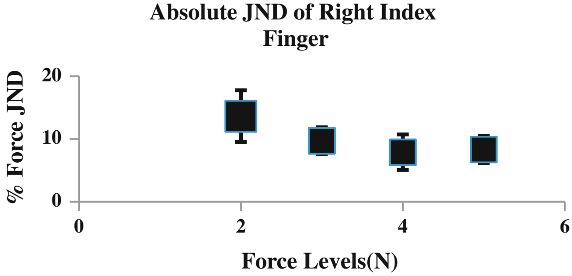
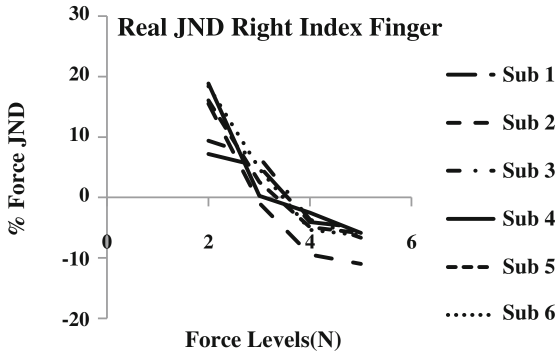


Fig. 5 Real value of % force JND of six subjects



main findings were: (1) The % force JND is larger for very small force intensity levels such as 2 N and decreases as the force stimuli increases to higher force levels such as 5 N, (2) The averaged absolute % force JND graph as illustrated in Fig. 4 follows Weber's law, (3) The decision making process of subjects took more time at lower force levels and response time was less for higher force levels.

The standard errors and standard deviations of the lower force JNDs were found to be greater than the JNDs (as shown in Fig. 4) of the higher force levels. This indicates that the subjects were more confident matching the reference force stimuli in their response to higher % force JNDs when compared to the lower force JNDs. The % force JND resolution was high at higher force levels compared to the % force JND resolution at lower force levels this indicates that the subjects were able to closely match the self generated reference stimuli by the left index finger with their right index finger at higher force levels.

Figure 5 Illustrates the real value of % force JNDs of all the subjects plotted across force levels ranging from 2 to 5 N. The graph shows that out of 6 subjects 2 subjects managed to attain lower % force JND at lower force levels. The absolute % force JND of all the subjects is shown in Fig. 6.

From our experiment we observed that absolute % force JND was roughly around 10 %, as shown in Fig. 7, when compared to JND obtained from active weight lifting

Fig. 6 Absolute value of % force JND of six subjects

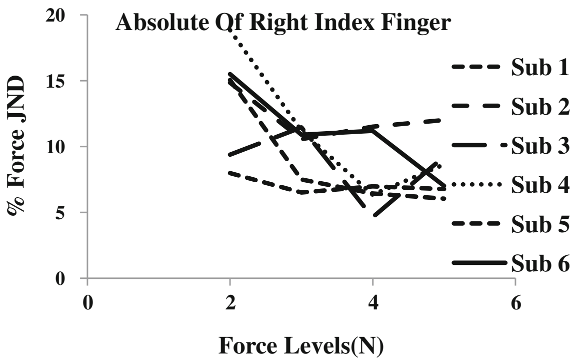


Fig. 7 Averaged % force JND of six subjects

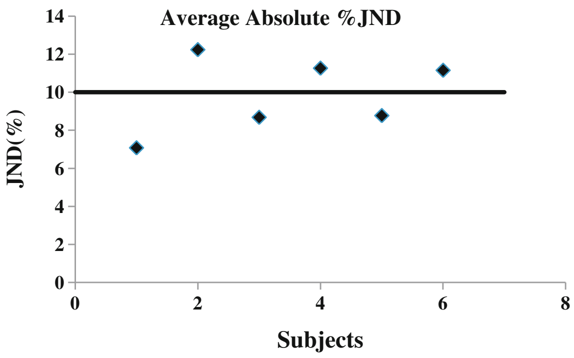


Table 2 Absolute % force JND across all subjects

Subject	2 N (%)	3 N (%)	4 N (%)	5 N (%)	Mean (%)
One	8	6.52	6.98	6.78	7.07
Two	14.85	10.567	11.51	12.02	12.24
Three	9.38	11.45	4.63	9.237	8.68
Four	18.84	11.22	6.36	8.64	11.26
Five	15.06	7.5	6.45	6.05	8.77
Six	15.5	10.9	11.2	7.02	11.15
Mean (%)	13.6	9.7	7.85	8.3	9.86 (net)

and force matching about the elbow. A number of significant elements, however, distinguish our paradigm from previous tasks reported in literature. Table 2 presents the complete set of absolute % force JND values obtained across all 6 subjects, during course of their individual experimental runs.

6 Conclusion

% Force JND experiment produced JND values for the static force increment task averaging out 10% approximately. These JND results have closely followed the Weber's law and have fallen in the allowable range of values obtained in past research works. These experimental results prove to be pivotal in establishing a force-based virtual environment which would be operated by force based tactile interface on real-time synchronization with the system. The present paper attempts to obtain the % force JND values for static force application, specifically using index finger. A contra-lateral force matching paradigm is adopted to obtain the matching forces and corresponding force JND's. Our experiment does not consider the displacement at the point of application of force and handedness during contra lateral force matching tasks.

The experiment involves use of a force sensitive resistor (FSR), as a force transducer for obtaining the force values and related parameters. Each subject performs 20 force-matching trials for four different force levels. Each trial involved matching left-index reference force window with the right-index finger by application of force over the FSR. The forces generated by the right and left index finger and the resulting % force JND supports the notion that cutaneous feedback from the contact surface of the FSR influences the perception of force within subjects [16]. Each subject performed experiment under identical conditions without bias. It was observed that the % force JND resolution at higher force levels were better when compared to the force resolution at lower force levels, indicating that the subjects responded positively to higher force stimulus.

Also, the nature of force matching for low and high force levels was observed to be on the lines of similar past research work involving contra-lateral force matching technique. The results obtained from the experiment using the described set of attributes, opens up scope for future work involving experimental validation of the same range of force JNDs in virtual laparoscopic surgery training environment. The experiment results and data provide a frame work to build an understanding of sensory and motor deficit to the physically challenged community. Moreover, the procedures we devise here can help us explore JNDs as they change during the course of recovery. Once this has been done, the development of adaptive rehabilitative environments tailored to patients' particular sensitivities can begin. Future work could be extended to providing calibrated framework for various force-based virtual user-interfaces (UI), ranging from touchpad to assistive surgical training tools and simulators.

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