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ORIGINAL ARTICLE

Improved force JND in immersive virtual reality needle insertion simulation

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Abstract
Haptic feedback in immersive virtual reality (IVR) systems is critical to enable a more intuitive and natural way of interacting with virtual objects. IVR-based haptic medical simulations such as needle insertion procedures have the potential to enhance clinicians' haptic expertise. This work is a preliminary study on the use and implementation of IVR for needle simulators. Although few studies have quantified haptic skills such as force Just Noticeable Difference (JND) with the single finger, none have measured the force JND as recommended in the standard needle insertion protocol in an IVR environment. The hypothesis of this study is that there will be an improvement of force perception in the IVR, compared to that of the non-immersive virtual reality (NIVR) which facilitates the use of IVR for medical simulations. This paper emphasized on two objectives: firstly, the development of the observer state model for both the IVR and NIVR and the theoretical analysis of the psychophysical measures in both of the environments. Secondly, measures of force JND with the three fingers and comparison of these measures in NIVR to that of the IVR using psychophysical study with the force matching task, constant stimuli method, and isometric force probing stimuli to validate the model. Twenty voluntary subjects performed the experiment in both of the environments. Mean force JND and standard deviation of the JND were found to be 9.12% and 3.75% in the NIVR and 5.91% and 3.65% in the IVR (p value < 0.0001) which are in the same range of JNDs found in the literature (5–10%) for the NIVR using a single finger. Surprisingly, the results showed a better force JND in the IVR compared to that of the NIVR. Also, a simple state observer model was proposed to explain the improvement of force JND in the IVR. This study would quantitatively reinforce the use of IVR for the design of various medical simulators.

Keywords Immersive virtual reality · Non-immersive virtual reality · Isometric probing · Force JND · Psychophysical study · Observer state model

1 Introduction

Immersive virtual reality (IVR) technologies have advanced rapidly in recent years with a wide range of applications, including health care (Riva 1997), aviation, gaming (Zyda 2005), manufacturing (Ong and Nee 2013), and military (Burdea and Coiffet 1994). The quantitative measures on the use and implementation of IVR for various applications are not well studied in the literature. This paper is a preliminary study on the use of clinical training simulations, especially needle insertion procedure in IVR.

Haptic feedback in IVR systems such as clinical training simulators is critical to enable a more intuitive and natural way of interacting with virtual objects. Haptic skills in needle insertion procedure for some critical cases such as epidural anesthesia are of great importance because the insertion forces vary depending upon the depth of penetration and type of the tissue through which the needle penetrates. Therefore, for high success rates, clinicians need expertise in accurate and precise haptic skills. With improper haptic skills, there is a high chance for clinicians to overshoot tissue layers and cause tissue damage; for example, the puncture of the sub-dural layer in epidural anesthesia can cause critical injury to patients. In Ready (1999), a survey of 2140 surgical patients resulted in a failure rate of 32% for thoracic

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needle procedures and 27% for lumbar epidural anesthesia procedures.

Training novices in haptic skills can improve the efficiency and confidence in needle procedures, which in turn improves patients' safety. Computer simulations of the needle insertion technique equip physicians to get trained in an administered environment that makes them familiar with both common and rare cases ensuring patients' safety (Taschereau et al. 2000). As most of the needle procedures are blind procedures, force discrimination is one of the major factors that affect the success rate and thereby increase the need for simulators. Although there are many needle simulators in the market, most of these simulators are rubber models that do not provide quantitative feedback to trainees.

A quantitative measure of haptic skills such as force just noticeable difference (JND) is a key factor which would help in the design and development of better needle simulators (Ravali and Manivannan 2017). In the study of psychophysics (Gescheider 2013), JND is a quantitative measure of perception in terms of minimum noticeable or detectable difference in the input stimulus, in this case, force JND, which is analogous to force resolution in the engineering field. Although few studies have measured the force JND during needle insertion procedures with the index finger alone, none has measured the force JND with the three fingers (index, middle, and thumb fingers) holding the syringe as suggested in the standard needle insertion protocol (Hungate 1969). Also, none has studied the effect of IVR on the force perception.

The hypothesis of this study is the improvement of force perception in the IVR, compared to that of the non-immersive virtual reality (NIVR). This paper is a preliminary study on the use and implementation of IVR for needle simulators, emphasizing on two objectives: firstly, the development of the observer state model for both the IVR and NIVR and the theoretical analysis of the psychophysical measures in both of the environments; and secondly, measures of force JND with the three fingers and comparison of these measures in NIVR to that of the IVR using psychophysical study with the force matching task, constant stimuli method, and isometric force probing stimuli to validate the model. The time taken to reach the target force was also measured in both the environments. Surprisingly, results showed that the immersive environment provides a better force JNDs compared to that of the NIVR.

2 Probing

Probing is a basic haptic task and is a substitute for direct palpation in many clinical tasks such as pushing, pinching, inserting, cutting, clipping, and sweeping. Probing is mainly classified into two types: active probing and passive probing.

Active probing is a combination of tactile sensing, kinesthetic sensing, and motor system. For example, stiffness discrimination is a complex task which is considered in the literature as a combination of displacement and force perception. This notion of stiffness discrimination is known as active probing (Raghu et al. 2015). Passive probing, on the other hand, is the probing without the finger movement where the kinesthetic sensing and motor system are inactive and have only tactile sensing; in other words, it involves force application by an instrument/device on the finger.

Active probing is further classified into isometric probing, isotonic probing, and isokinetic probing as shown in Fig. 1 where the external length of the muscle, tension developed, and the velocity of probing are constant, respectively.

Palpation is a complex task which involves the control of length, velocity, and force as shown in Fig. 2. For the study of the implementation of probing for clinical applications in IVR, a simplified task, isometric probing is proposed. The main motivation behind the isometric probing task is that it simpler than that of the palpation task. Considering the probing task as a control system with three inputs (length, velocity, and force), isometric probing is a control system with only one input (Golgi tendon organ) where the length of the muscle is kept constant and the velocity of probing is zero.

3 Prior work

Most of the force JND studies in the past focused on a single finger. In late 80's (Jones 1989) studied the contact force JND and found it to be 5–15% using contralateral force matching paradigm with a single finger. The JND for a pinching task involving thumb finger was determined to be between 5 and 10% (Tan Hong et al. 1995). Force matching JND of around 10% was obtained between left and right index finger of the human subject using a contralateral force matching paradigm (Prasad et al. 2013) in a 2D display. Allin et al. (2002) studied the effect of visual distortions on the force JND and measured it to be around 10% with the force feedback distortion below the level of the measured

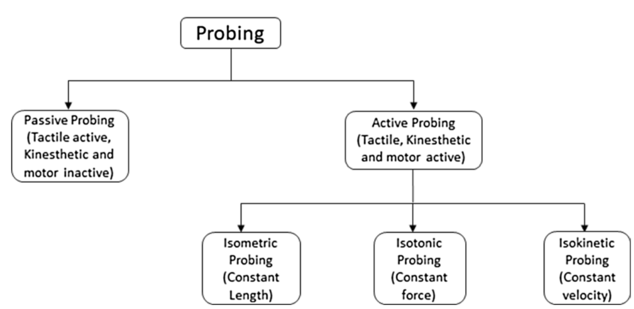


Fig. 1 Classification of probing

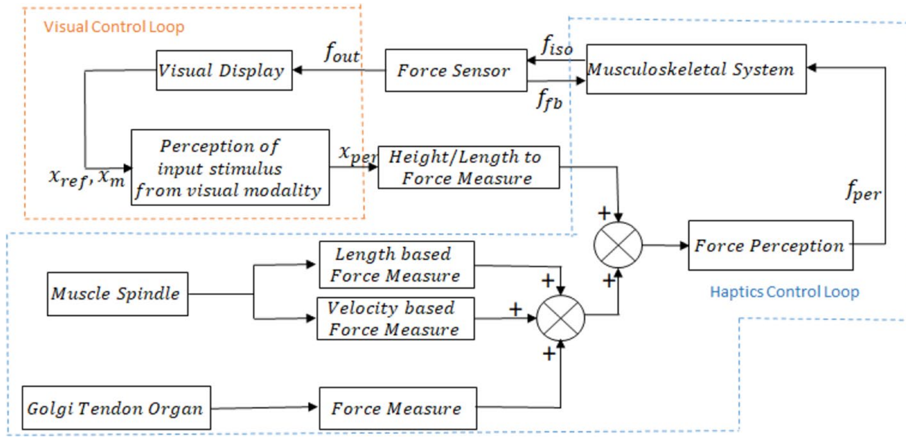


Fig. 2 Block diagram of the control loop for palpation in visual-haptic cross-modality (x_* represents the force measures in visual display and f_* represents the force measures in haptic loop. x_{per}, f_{per} are perception level measures and x_{ref}, x_m, f_{iso}, f_{fb}, and f_{out} are the physical measures)

threshold. Their experiment concluded that visual distortions, one of the behavioral strategies, in a 2D display helped in increasing the force detection up to 10% with the subject's awareness.

Few studies measured the force JND with multi-fingers. In early 90's Pang et al. (1991) performed a psychophysical experiment with one interval, two alternative forced choice paradigm and measured the force JND when the subject grasps two plates between the thumb and the forefinger. They used an electromechanical device using the force feedback, and they found a force JND of around 7% of the reference force. King et al. (2010) studied the force detection threshold of individual fingers (index, middle, ring, and pinky) and interaction of all four fingers and found it to be 33.5, 32.1, 33.5, 28.9 mN, respectively; however, they found lesser sensitivity with the ring finger (mean threshold of 43.6 mN). Bing et al. (2011) studied the effect of torque and force cues in haptic discrimination of the stiffness, force, and torque. Their findings concludes that the perceptual hierarchy of force and torque discrimination are integrated rather than being processed as a separate dimension of perception.

Although none has studied the force JND in IVRs, there are few psychophysical studies in the NIVR. Heyde and Häger-Ross (1998) measured general hand-eye coordination performance such as sorting objects according to their weights, lifting objects, and reaching the destination point through fields. Juan et al. (2012) performed an experiment to study the force JND of virtual texture and the effects of spatial and temporal texture force perception. Also, none has compared the psychophysical parameters of the IVR with that of the NIVR.

Few studies explored the effect of the immersive environment over the non-immersive environment. Raja et al. (2004) looked into the benefits of the immersive environment over the non-immersive environment with the help of a CAVE system and found that the immersive environment is most useful in viewing the data sets and also for performing tasks. Parmar et al. (2016) compared a desktop-based virtual reality (DVR) viewing metaphor and an immersive head-mounted display (HMD)-based viewing metaphor and their results concluded that there is a great advantage in terms of learning benefit pertaining to the evaluation of the HMD compared to that of the DVR.

The above studies have measured the force JND using a single finger and multi-fingers, and few studies have also explored the benefits of IVR compared to that of the non-immersive environments. Our focus is the measure of the force JND with three fingers as required in the standard needle insertion protocol in both the NIVR and the IVR and also a comparative study of the force JND in the NIVR to that of the IVR.

4 Observer model

For the design and development of the haptic-based IVR systems where human interaction is involved, the perception model is one of the basic steps to understand and quantitatively measure the force discrimination abilities. In our study, visual-haptic force perception is attained using the concept of isometric probing where there is no finger movement and has only isometric muscle contractions. The proposed models are built upon the assumption of an existing variance δ of force JND with the reference force during the matching task.

4.1 Observer response model

In the proposed model of the arm consisting of three fingers active, performing a force application without any finger movement, having only isometric muscle contractions in both the NIVR and the IVR as shown in Figs. 3 and 4, respectively.

The perceptual response R at any given time t is determined by

$$R = \begin{cases} \text{matched} & \text{if } \mathrm{RF} - \delta < \mathrm{MF} < \mathrm{RF} + \delta \\ \text{not matched} & \text{otherwise} \end{cases}$$

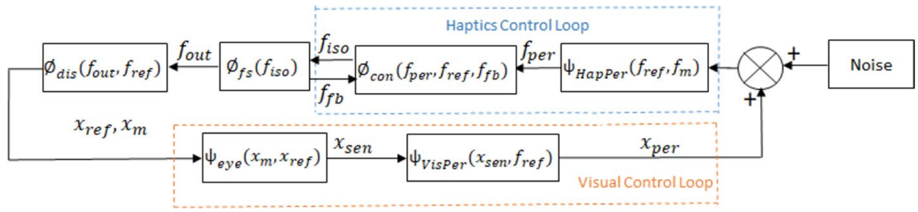


Fig. 3 State observer model of visual-haptic force perception in NIVR

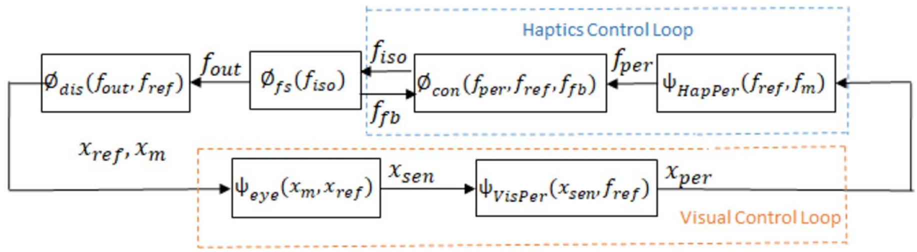


Fig. 4 State observer model of visual-haptic force perception in IVR

where RF is the reference force, MF is the matching force. δ is decided based on the variance of force JND.

The response time, t_r is determined by

$$t_r = t_{MF} - t_{OS} \quad \text{if RF} - \delta < \text{MF} < \text{RF} + \delta$$

where t_{MF} is the time taken to match the reference force, t_{OS} is the onset time.

4.2 Sensorimotor control model

The state vectors x_m, x_{ref} represent the matching force and reference force, respectively, in the visual display. The control mechanism $\phi_{con}(x_m, x_{ref})$ represents the forces that must be applied using the contralateral muscle contractions. The visual display transforms the force input into the visual progressive bars, $\phi_{dis}(f_{iso}, f_{ref})$. The transfer function of the force sensor is indicated as $\phi_{fs}(f_{iso})$, and f_{fb} is the feedback force from the force sensor (active touch). The sensory input to the eye $\psi_{eye}(x_m, x_{ref})$ determines the input stimulus information from the visual feedback. The perception of input stimulus and the feedback from the visual and the haptic modalities are determined by $\psi_{VisPer}(f_{des}, f_{iso})$ and $\psi_{HapPer}(f_{des}, f_{iso})$, respectively. The environment visual noise is contained in the NIVR which is mostly eliminated in the IVR.

The experimental results in the literature (Zwislocki 2009) from the cross-modal matching show that the stimulus intensity is directly proportional to the sensation magnitude with a nonlinear relationship. The logarithmic relation proposed by Fechner seems to be more appropriate than the power law which was previously used for the validation in case of audio-haptic matching experiment (Zwislocki 2009). Considering the same hypothesis, in our study where we have both visual and haptic modalities, we consider the comparison of IVR with the NIVR using Fechner's law. The Fechner's law (Gescheider 2013) is given as

$$\psi = a * \log(\phi)$$

where ψ is the sensation magnitude, ϕ the input stimulus.

The total stimulus intensity for both the NIVR and IVR, respectively, is

$$S_{T(\mathrm{NIVR})} = S + N_I + N_E$$
$$S_{T(\mathrm{IVR})} = S + N_I$$

where S refers to the signal intensity, N_I the internal noise intensity, and N_E the external environmental noise.

Considering the Fechner's law for both the environments,

$$\psi_{NIVR} = a * \log(S + N_I + N_E)$$
$$\psi_{IVR} = a * \log(S + N_I)$$

From the above equations, the sensation magnitude is always higher for the NIVR than that of the IVR as the external environmental noise N_E is unlike to have a negative value and is always positive which is indirectly indicating a higher value of the JND for NIVR than that of the IVR.

5 Psychophysical experiments for visual-haptic force perception in both the environments

In order to assess the subject's ability to discriminate forces, a standard psychophysical experiment using a constant stimuli force matching paradigm (Gescheider 2013) was conducted. The experiments aimed to measure the difference threshold (JND) of the subjects for visual-haptic force perception in both the NIVR and the IVR using the three fingers.

5.1 Method

The method of constant stimuli is one of the classical psychophysical methods where stimulus values are not related from one trial to the next trial and are presented in a random order to prevent the subject's prediction of next stimulus value, therefore reducing errors of habituation (known as muscle memory) and expectation. The force matching paradigm involves a reference force, and the subject is required to apply the same force as the reference force which is referred to as matching force. In this experiment, only a visual feedback of the matching force (force applied by the subject) is provided, and no external or simulated force feedback is presented. Although a cross-modality, the consideration of visual display as a feedback parameter for the force perception is taken from the literature Prasad et al. (2013) as mentioned in the previous section. The force sensor mounted on the wall measures the matching force as shown in Fig. 5. The schematic of the experimental setup as shown in Fig. 6 includes a visual display and a force sensor for the subject to match the quantized force applied by the subjects with the reference force. The Sensable Phantom™ is used only for the position rendering in the IVR experiment and not for any force rendering. In order to maintain the same experimental setup for both the environments, the phantom device has also been used in the NIVR experiment, but there has not been any input from the phantom device in this NIVR experiment.

5.2 Force measurement system and its calibration

In both the NIVR and the IVR experiments, a force sensitivity resistor (FSR) of 'Interlink TM 402 make' was used. The FSR was calibrated with known weights ranging from 5 g to 2000 g, and the calibration curve for 10 $K\Omega$ load with 5 V

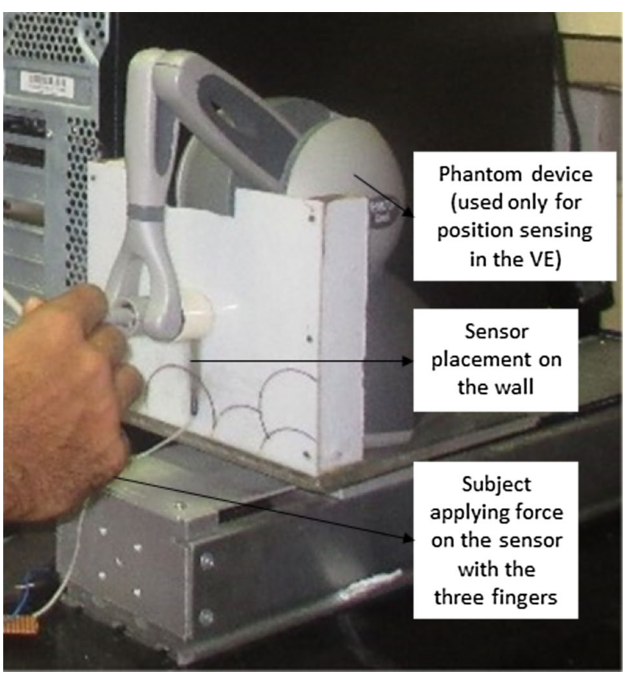


Fig. 5 Representation of a subject holding the end effector of phantom which is only used for the position tracking in the IVR and also representing the placement of Force Sensor on the wall

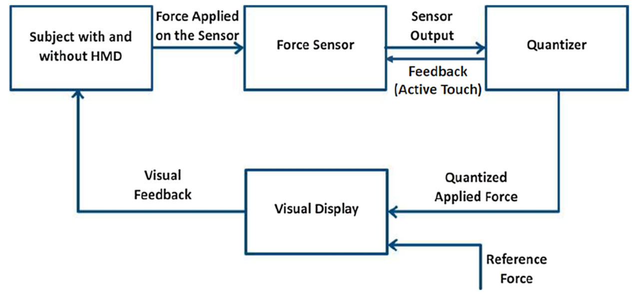


Fig. 6 Block diagram of the experimental setup

input supply is as shown in Fig. 7. The repeatability of the sensor was checked for five trials and found to be 2.4% of the full scale. The sensor is approximately linear in the range of forces used for this experiment. Although stated as a continuous resolution in datasheet (Electronic, Interlink), the resolution of FSR measured was found to be 0.05 N which was higher than that of the minimum resolution expected in our experiment (0.1 N). This minimum resolution is decided by considering the minimum force JND values found in the literature which is 5% and the minimum force applied by the subject in our experiment which is 2 N. As stated in the datasheet (Electronic, Interlink), FSR 402 has a hysteresis of 10%, but in our experiment, the subjects were asked to maintain the force for three seconds where the hysteresis of the sensor can be neglected. The data were collected at 20 Hz and a baud rate of 9600.

5.3 Participants

Twenty voluntary healthy subjects (ten males and ten females) with age ranging from 21 to 45 years, average weight 65.6 ± 10.3 kg and the average height of 156.4 ± 15.8 cm performed both experiments with informed consent. All participants were right-handed, and no subject was noted to have any visual (including the color deficiency) and

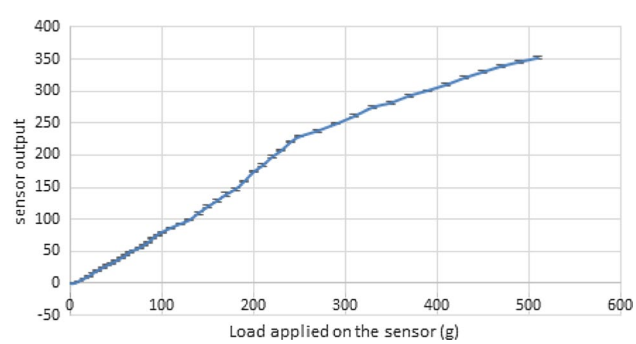


Fig. 7 Sensor calibration curve with a load of 10 $K\Omega$ for the voltage divider circuit and a supply voltage of 5V

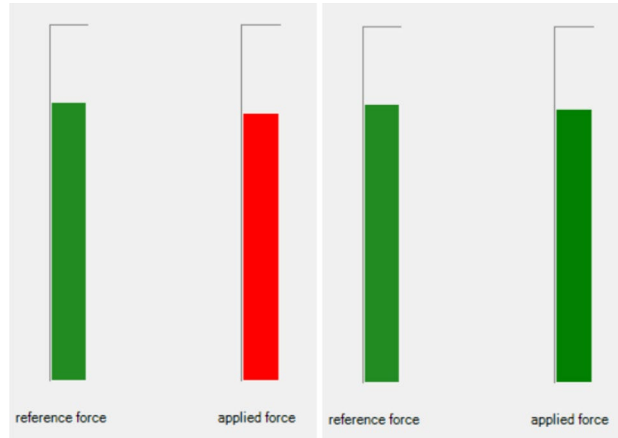
neurological perception disorders from pre-examined verbal self-report. They were naive for the objective of this study.

5.4 Experimental procedure

In both the NIVR and the IVR experiments, subjects were asked to hold the needle with the help of the three fingers and match the force applied on the sensor with the reference force shown on the visual display for three seconds. The time three seconds is considered just to make sure that the subject is not randomly attaining the reference force instead he/she feels the force applied. In both experiments, the FSR sensor was mounted on the side of the flat regular rigid surface and made sure that the subject's arm position matches with the height of the sensor placement. The subjects were comfortably seated on a chair facing the visual display and were asked not to take any support for the arms similar to that of the needle procedure. The horizontal and the vertical distance of the subject's shoulder joint to that of the sensor was maintained constant and was equal to 0.5 m and 0.22 m, respectively, and the lower arm was maintained at 90° with respect to the upper arm.

Subjects were familiarized with the protocol with a trial demo of the experiment until they were confident with their performance before the actual experiment. The GUI consisted of two vertical bars on the screen to indicate the reference force and the matching force and also included a start, next, stop, and save buttons. The color of the vertical bar changes when the matching force reaches the reference force as shown in Fig. 8. Subjects were asked to maintain the same force for three seconds. The experiments were repeated for four sets with twenty trials for each set, altogether involving eighty trials. The four sets include force from 2 N to 5 N with an increment of 1 N which are in the typical needle insertion procedure (DiMaio and Septimiu 2003). The maximum force sometimes may go little higher than 5 N but the average range of forces are being considered for this experiment. The reference stimulus was generated in a random order with uniform distribution for each trial under the constraint that each force is repeated for exactly twenty times to ensure that the results were not biased by muscle memory (van Polanen and Davare 2015). A relaxation gap of 2 min was provided for every twenty trials in order to avoid the effect of muscle fatigue. The entire experiment typically last about 30 min for each subject.

The only difference between experiments in non-immersive and immersive environments: In the NIVR experiment, the visual feedback was provided on a desktop screen with the 2D visual screen involving a GUI. The visual feedback in the IVR experiment was visualized on an HMD (Oculus Development Kit), and the environment was rendered in unity. Here, the environment included 3D immersive operation theater and a patient and a nurse for the enhancement of the IVR along with the GUI components which were similar to that of the NIVR as shown in Fig. 9. Not only the distance between the desktop screen and the subject in the NIVR is maintained as the same in the IVR by adjusting the distance between the first-person view camera and the GUI components but also the size of the progressive bars is maintained same in both the NIVR and the IVR.



(a) Before reaching target **(b)** After reaching target

Fig. 8 The visual feedback in NIVR on the display indicating both the cases of force applied by the subject before and after matching the reference force in red and green color, respectively. **a** Before reaching target, **b** after reaching target

6 Data analysis

The data collected from twenty subjects and twenty trials of four sets were analyzed with four parameters: mean force JND, the standard deviation of the JND, standard error and variance as mentioned in the literature for similar works Prasad et al. (2013) from the twenty trials for each set. For a given matching force (MF) and a reference force (RF), the real and the absolute mean force JNDs were obtained based on Eqs. 1 and 2, respectively. The standard deviation force JND was calculated from the standard deviation of the sixty samples that were collected for three seconds at a rate of 20 Hz in a single trial. The mean of means and the mean of standard deviation were obtained for twenty trials.

$$\%\ \text{Force Real JND} = \frac{\text{MF-RF}}{\text{RF}} * 100 \tag{1}$$

$$\%\ \text{Force Absolute JND} = \frac{\text{Abs }|\text{MF-RF}|}{\text{RF}} * 100 \tag{2}$$

This can also be considered as a force reproduction variance since we are using a matching task, but this can be compared

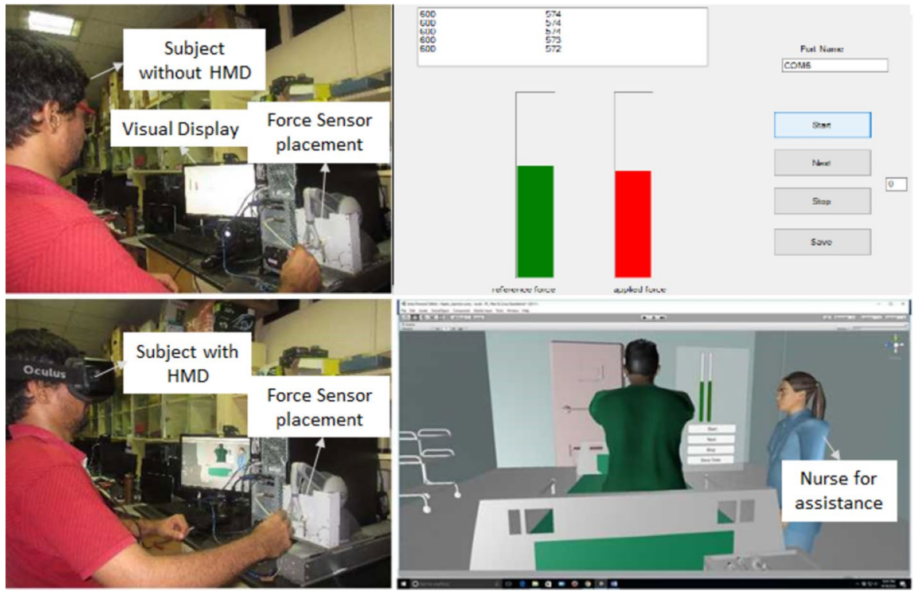


Fig. 9 The experimental setup in NIVR (top row) and IVR (bottom row) and the visual display (right column) with the subject performing the experiments (left column). The experiment view in the IVR is a first-person view where it has a patient and a nurse displayed on an HMD

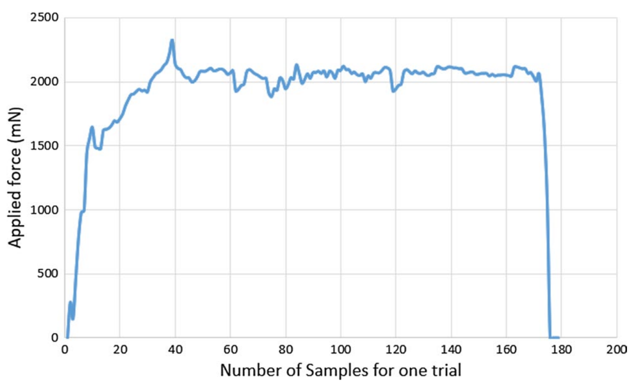


Fig. 10 Typical data collected for a single trial on a subject for the reference force of 2 N in NIVR

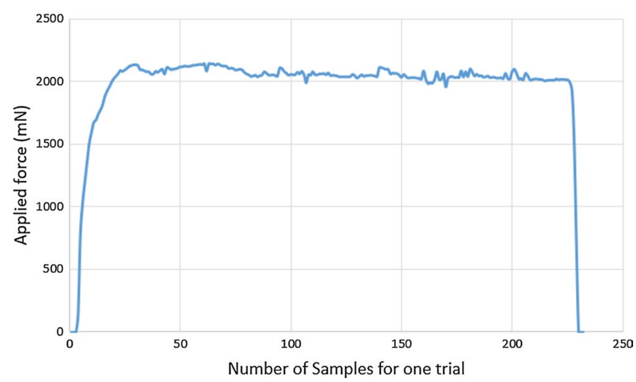


Fig. 11 Typical data collected for a single trial on a subject for the reference force of 2 N in IVR

with the earlier work which states it as a measure of JND in similar experiments.

The sample data with one trial for 2 N reference force in the NIVR and IVR is as shown in Figs. 10 and 11, respectively. The data indicate more fluctuations in matching the reference force for three seconds in the case of the NIVR compared to that of the IVR. The plot also indicates the overshoot in reaching the target force for 2 N (lowest force value). This overshoot occurred during the trial of 2 N just after the trial of higher forces such as 4 N or 5 N. These two sample data from the NIVR and the IVR are on the same subject for the same force value after the trial of 5 N.

7 Results and discussion

The real and the absolute mean force JND for twenty subjects were calculated from Eqs. 1 and 2. From the literature, although it is stated as force JND, visual-haptic JND can be a more appropriate term since it involves the force perception using both the visual and haptic modalities. The real standard deviation JND and the absolute standard deviation JND were computed considering the standard deviation of sixty samples of data collected in a trial. The mean of all the twenty trials for each reference force was computed for all the subjects in both the NIVR and the IVR. The comparison of mean and standard deviation force JND between the two environments by each subject is shown in Table 1. The table shows a higher force JND for NIVR when compared to IVR by all the twenty subjects.

Table 1 Comparison of mean and the standard deviation of force JND in both non-immersive and immersive environments by twenty subjects

Subject#	Absolute mean JND		Absolute standard deviation JND	
	NIVR	IVR	NIVR	IVR
1	7.73	4.54	3.66	3.09
2	8.14	4.14	3.35	4.00
3	9.29	5.56	3.94	3.26
4	7.56	8.5	3.47	3.03
5	7.62	8.15	4.08	3.09
6	10.3	4.58	2.97	4.41
7	10.55	6.13	4.40	3.41
8	9.56	5.58	3.86	3.66
9	8.43	5.15	3.51	3.06
10	7.82	4.84	3.78	2.87
11	9.57	5.91	3.98	3.05
12	8.61	6.1	3.61	4.55
13	9.15	4.37	3.8	3.87
14	8.99	6.97	3.23	5.14
15	10.52	7.03	3.66	4.40
16	11.03	4.62	3.95	3.68
17	10.03	6.01	3.96	3.8
18	9.71	6.77	3.64	3.6
19	10.1	6.38	4.11	3.71
20	7.85	7.04	4.10	4.09

The time taken in matching the reference force is shown in Fig. 12, and the error plot indicating the mean and the standard deviation of the time taken by twenty subjects for all the four different forces is shown in Figs. 13 and 14 for NIVR and IVR, respectively.

Table 2 compares the other parameters such as real mean JND, real standard deviation JND, standard error, and variance for both the environments by all the subjects.

The average mean force JND in non-immersive and immersive environments with twenty subjects are found to be 9.12% and 5.91%, respectively, which is in the range of JNDs reported in the literature (around 10%) for the NIVR using single finger force. Along with the mean JND, all the stated parameters have a better measure in the IVR when compared to that of the NIVR experiment. The mean force JND in both the environments followed Weber's law as observed in the literature for the single finger. Both the JNDs were less than 10% and this could be because of the three fingers providing a better grip when the force was applied. The one-way ANOVA analyzed the participants' ability to perceive force in both the NIVR and the IVR, which was the main goal of our study. Participants' mean performance in the NIVR was compared with their mean performance in the IVR. Overall participants performance for both the

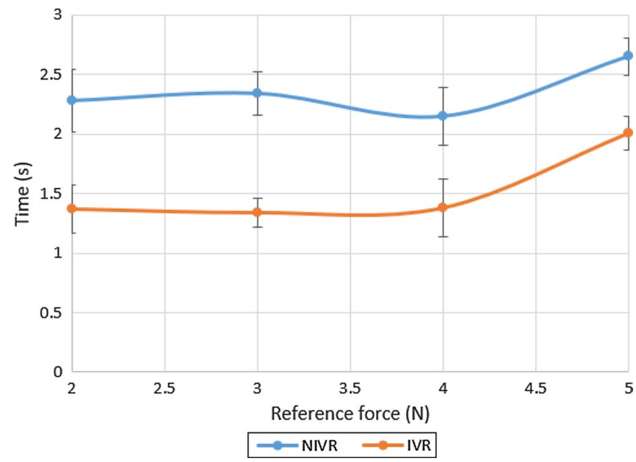


Fig. 12 Plot indicating the average time taken for twenty subjects to reach the target force

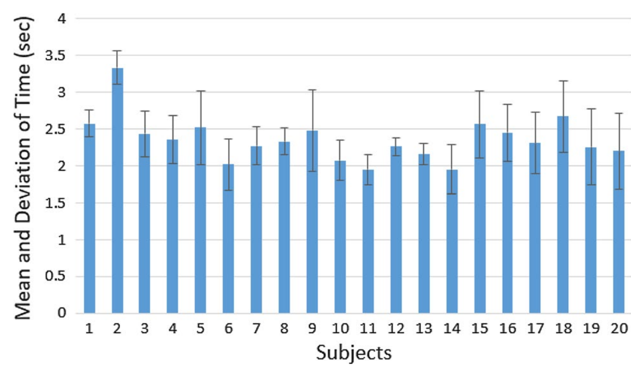


Fig. 13 Error plot indicating the mean and the standard deviation of the time taken in NIVR

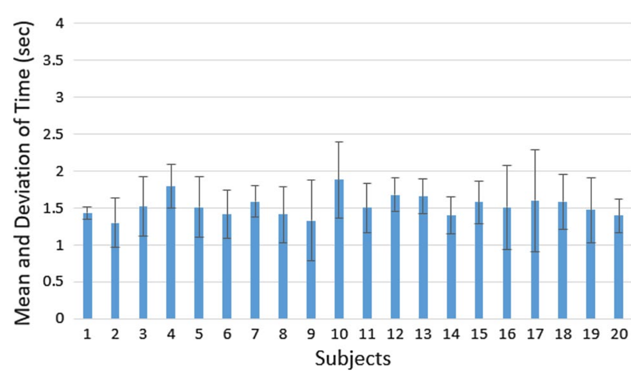


Fig. 14 Error plot indicating the mean and the standard deviation of the time taken in IVR

experiments is significantly different at the $p < 0.5$ level across four different forces (one-way repeated-measures ANOVA, $F(1, 38) = 4.09, p < 0.001$). Also, the time taken for matching the reference force is higher in the NIVR when compared to that of the IVR. Therefore, it is observed that

Table 2 Comparison of mean and the standard deviation of force JND and also standard error and variance in both non-immersive and immersive environments

Mean of parameters/environment	NIVR	IVR
Real mean JND (%)	3.86	2.43
Absolute mean JND (%)	9.12	5.91
Real standard deviation of the JND (%)	3.74	3.63
Absolute standard deviation of the JND (%)	3.75	3.65
Real standard error (%)	2.23	1.96
Absolute standard error (%)	1.68	1.40
Real variance (%)	13.98	13.17
Absolute variance (%)	14.06	13.32

JND in the IVR is better than that of the NIVR and this could be due to the 3D immersive display provided to the subject on an HMD as there is no other change in the two experimental setups except an HMD.

7.1 Possible reasons for the improved JND

The display resolution of Oculus is 1080 * 1200 and that of the display provided in the NIVR is 1920 * 1080 which is actually higher than the resolution of Oculus. Visual acuity for both the cases is within the limits. Also, the distance from the visual display in the NIVR is same as that of the distance adjusted in the IVR. Therefore, the resolution of visual display may not have affected the force perception in both the NIVR and the IVR. Both the experiments are performed by individual subjects on the same day with a gap of 30 min. In our experiment, it is also maintained that 10 subjects performed their first experiment in NIVR and then in the IVR whereas the other 10 subjects performed the experiment in the IVR as the first one and then in the NIVR. This is followed just to avoid any impact of the first experiment on the other. A preliminary check for the measure of the force JNDs for a varying distance of the progress bars in the IVR was performed on two subjects and found that there is no significant change in the result.

During the experiment, subjects reported a better stability of force in the IVR compared to that of the NIVR. It was also observed during both the experiments that overshoot of the force was occurring at a higher rate for lower force stimuli compared to that of higher force stimuli. Also, the time taken to reach the target force was lesser for lower stimuli compared to that of higher stimuli.

Horiuchi et al. (2017) studied the function of optical flow in the peripheral visual field for stable quiet standing. Their results have reported that the extent of postural sway was higher with the visual stimuli in the central visual field than that in the peripheral visual field, while using the DTD alone, and has no effects on the extent of postural sway with the visual stimuli in the peripheral vision while using the HMD. This study shows that the stability of the subject increases with the IVR.

The field of view (FOV) of the human eye, according to the psychophysical measures, is horizontal 240° and vertical 180°. The non-immersive virtual reality (NIVR)-based experiment has a desktop screen where the area of interest is just 20°, and the FOV of the human eye apart from this area of interest is considered as visual noise. In an immersive virtual reality (IVR)-based experiment, the FOV is 110° (Oculus rift being used for the experiment) and the area of interest is the entire FOV which is 110°. This shows that there is no visual noise in the IVR than that of the NIVR-based experiment.

With all the protocols followed for both the experiments and also from the literature (Horiuchi et al. 2017), it is observed that the improved force JND might be because of the visual noise present in the NIVR experiment which is mostly eliminated in the IVR experiment. A simple test with the same experimental setup as that of the NIVR with an enclosed display to reduce the visual noise was performed to check the impact of visual noise on the subject's perception. The test was performed on three subjects and found that the force JND was improved from 9.12% in the NIVR to 7.98% in the enclosed display test. This improvement in the force JND would support our hypothesis that visual noise might be one of the reasons for this improvement.

8 Conclusion and future scope

This paper was a preliminary study on the use and implementation of IVR for needle simulators, emphasizing on two objectives: firstly, the development of the observer state model for both the IVR and NIVR and the theoretical analysis of the psychophysical measures in both of the environments; and secondly, measures of force JND with the three fingers and comparison of these measures in NIVR to that of the IVR using psychophysical study with the force matching task, constant stimuli method, and isometric force probing stimuli to validate the model. A perceptual quantitative measure of force discrimination was measured and compared in the non-Immersive and immersive environments using constant stimuli force matching paradigm with isometric probing as input stimuli. From the results, we observe that the force JND is better/improved in the IVR compared to that of the NIVR where the visual display is the only difference in both the experimental setups. This experimental observation was also explained with a proposed state observer model where Fechner's law was employed. Along with the advantages of the IVR and the possibility of simulating different test cases, this study would also quantitatively reinforce the use of the IVR for the design and development of various medical training simulators. The limitation of this study is the assumption of the force perception of subjects with a corresponding visual feedback. This method is also assumed in the literature during the JND measurements. The future plan is to explore different dimensions of the force JND measurement by considering the force feedback and also with varying stiffness.

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