Comparison of Force Matching Performance in Conventional and Laparoscopic Force-Based Task

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Laparoscopic instruments have limited haptics feedback. Hence, novices tend to exert excessive force which leads to tissue trauma. In laparoscopic surgery, no external information is available on the magnitude of excessive force. Therefore, novices should be trained to accurately perceive their own force output. This study analyzed the force perception of 18 novices in the absence of external information, by comparing the isometric force matching performance of index finger (i.e. used in conventional procedures) in extended arm posture with that of laparoscopic instrument in a force-based probing task. The study also examined the effect of handedness on force perception. A contra-lateral force matching paradigm was employed to analyze the matching performance of the novice subjects. Interestingly, matching error was found to be lower for laparoscopic instrument. An effect of handedness was visible for laparoscopic instrument only. The dominant hand overestimated the forces of non-dominant hand. The results can be used as a performance metric to evaluate the force perception of novices in laparoscopic force skills-training tasks.

INTRODUCTION

Direct palpation with fingers is used to explore the abnormal tissues in conventional surgery, but in laparoscopic surgery (LS) tissues are probed with laparoscopic instrument (LI). LI's are long and they provide remote access to surgical site. Haptics feedback is reduced in LS due to the usage of long LI's (den Boer et al., 1999; Perreault & Cao, 2006; Picod, Jambon, Vinatier, & Dubois, 2005). As a result, novices are unable to quantify the forces and tend to exert large probing forces on tissue. Many intra-operative errors in LS are due to the exertion of large forces (Joice, Hanna, & Cuschieri, 1998; Tang, Hanna, & Cuschieri, 2005; Way et al., 2003). Novices cannot always exert forces within the safety force range (Picod et al., 2005) and there is no clear information on accuracy of forces that they exert. It is very hard to infer the extent of trauma caused by the exertion of large forces unless a tissue injury or tear is clearly visible (Anup & Balasubramanian, 2000; Marucci et al., 2000; Ottermo et al., 2006; Reissman, Tiong-Ann-Teoh, Skinner, Burns, & Wexner, 1996). Thus, matching error of force is a crucial measure of performance evaluation in LS (Xin, Zelek, & Carnahan, 2006). Unfortunately, research in LS thus far have not studied the discriminability in terms of matching error using LI and finger. In this paper, we have used contra-lateral force matching paradigm to analyse the matching error between LI and finger in the absence of external information.

In contra-lateral force paradigm, a reference force is produced by an index finger or a LI and is matched with a force generated by a contra-lateral index finger or a LI. Numerous research works have focused on contra-lateral force matching for proprioception and force control (Cafarelli & Bigland-Ritchie, 1979; Carson, Riek, & Shahbazpour, 2002; Gandevia & McCloskey, 1977a, 1977b; L. Jones, 2003; Park, Leonard, & Li, 2008; Walsh, Taylor, & Gandevia, 2011). Perception of force in contra-lateral paradigm depends on many parameters. First, a common finding in this paradigm is that the force is perceived relative to the maximal force generating capacity. Second, matching performance depends on the muscle groups. L. Jones, 2003, reported an overestimation of matching forces by the elbow flexors with index fingers as reference and an underestimation when forces were matched by the index fingers with elbow flexors as reference. However, accurate matching of reference forces is possible only when matching is between similar muscle groups (L. A. Jones, 1989). In LS, surgeons or novices control the probing forces with both the upper limbs. That is in certain situations they apply a probing force with their left hand and exert same or different magnitude of force in their right hand. Therefore, the primary purpose of the present study was to investigate the matching performance between LI and index finger using contra-lateral force paradigm.

Handedness has an impact on contra-lateral force matching tasks (Park et al., 2008; Shergill, Bays, Frith, & Wolpert, 2003). The matching error is more when dominant - hand matches the force of non-dominant hand (Park et al., 2008). In laparoscopy, handedness is one of the important factors influencing the task performance (Elneel, Carter, Tang, & Cuschieri, 2008). Many studies have explored the effect of handedness on laparoscopic position and navigation skills (Grantcharov, Bardram, Funch-Jensen, & Rosenberg, 2003; Hanna et al., 1997; Nieboer et al., 2012; Suleman et al., 2010) and have concluded that right handed surgeons can perform better than left-handed . But these studies did not examine the effect of handedness on force-based tasks. Accordingly, our secondary objective was to examine the effect of handedness on LI and index finger modalities in force -based task.

Probing is considered as one of the important force-based task. It is a substitute for direct palpation in LS. Probing is a fundamental to many complex laparoscopic tasks. In past, several probing experiments have been conducted using finger and LI to identify texture, shape and compliance (Bholat, Haluck, Murray, Gorman, & Krummel, 1999; MacFarlane, Rosen, Hannaford, Pellegrini, & Sinanan, 1999; Ottermo et al., 2006), and shown that finger is better in compliance discrimination. But these studies were restricted to compliance discrimination. In our study, we analyse the force perception ability of novices in conventional (finger) and laparoscopic (LI) force-based probing task.

MATERIALS AND METHODS

Subjects

Eighteen healthy novices (13 Male and 5 Female; mean age: 28.1 ± 6.5 years; weight 69.5 ± 8.36 Kg; height 175 ± 5.22 cm) without any disorders voluntarily participated in the experiment. 10 subjects were right-handed and 8 were left-handed (Oldfield, 1971). Subjects had no prior information on the nature of the experiment.

Apparatus

Tekscan™ Model A201 Flexi Force Piezo Resistive force sensor, with sensing area diameter 9.53 mm, thickness 0.208 mm was used for sensing the force exerted by the subjects. The force matching experiment was conducted separately for finger and LI. For force matching with LI, a wooden T-shaped structure (Figure 1) was used for mounting the LI's. A separate rectangular wooden block was attached to the base of the T-shaped structure at an elevation of 40º from the base. For finger force matching task, a rectangular base and an elevated base was used as shown in (Figure 2A). The force sensors were mounted horizontally in a straight line on these elevated rectangular wooden blocks for both the experiments.

Experimental Procedure

A contra lateral isometric force matching paradigm was adopted to match a set of target reference force levels. Visual feedback was provided only for the reference arm which exerted the reference forces and not for the experimental arm that matched the reference forces. The visual feedback consisted of a change in colour (red to green) when the target force level was reached. The target reference force levels were delivered randomly.

Force matching task with LI consisted of two phases. During the first phase of the experiment subjects were instructed to reach the reference force level by exerting isometric force on the sensors using the LI held in their dominant hand (DH). When subjects reached the target reference level a visual feedback was delivered. Subjects were then instructed to match the magnitude of the reference force without visual feedback using the LI held in their contra-lateral hand i.e. with non-dominant hand (NH), while maintaining the reference force in their DH -LI. When subjects were confident of applying an isometric flexion force that matched with the reference force level, a verbal indication was given to the experimenter. The reference and matched force data were recorded for 5secs simultaneously.

In the second phase of isometric force matching experiment, subjects were instructed to reach the reference force using the LI held in their NH, and match the magnitude of the reference force by the LI held in their DH. The LI was held in a standard predefined posture (Figure 2B) with arms flexed for exerting both reference and matching forces. The angle between elbow flexor and shoulders were approximately 90°. In the finger force matching task, the isometric forces were exerted in an extended arm posture (Figure 2C). Proper care was taken to ensure that only index fingers were used to exert force on the force sensor. The experimental procedure and data recording mechanisms were similar to that of LI force matching task.

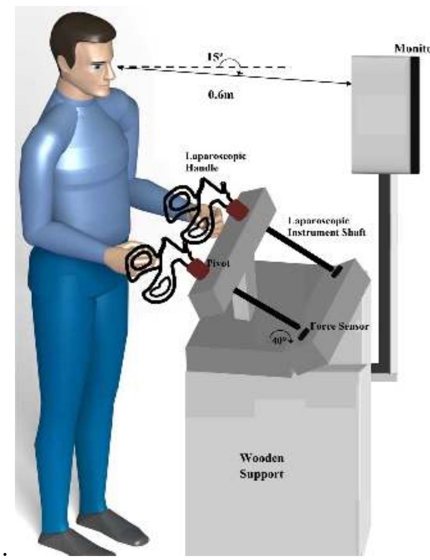


Figure 1. A animated model depicting force matching procedure with laparoscopic instrument.

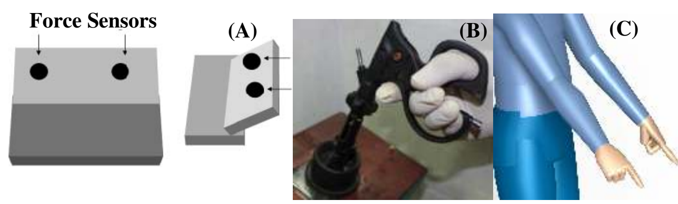


Figure 2.(A) Experimental set-up showing front and lateral view of finger force matching. (B) Posture during laparoscopic instrument force matching. (C) Posture during extended arm finger force matching.

EXPERIMENTAL DESIGN

In all the experimental conditions no attempts were made to assist the subjects in matching the reference force, and no feedback was given on the values of the matched force. A time gap of 30 minutes was provided in between the experimental conditions (LI and finger), and a time gap of 5 minutes was provided between consecutive force matching (DH and NH) tasks.

Data were sampled at a rate of 20 Hz. The target allowable force range was set to ±0.1N that allowed subjects to deviate from the target by a constant force of. There were five trials for each modality, and a total of 6 (*force levels:* 1.5N to 11.5N) ×2 (*hand conditions*: dominant hand and non-dominant hand) ×2 (*modality conditions:* laparoscopic instrument and bare finger) ×5 (*trials*) =120 experimental trials. In order to reduce order and carry over effects, the modalities, hand conditions and reference force levels were assigned randomly to all the subjects. Subjects performed all the experiments in standing position. Same group of subjects participated in all the experimental conditions.

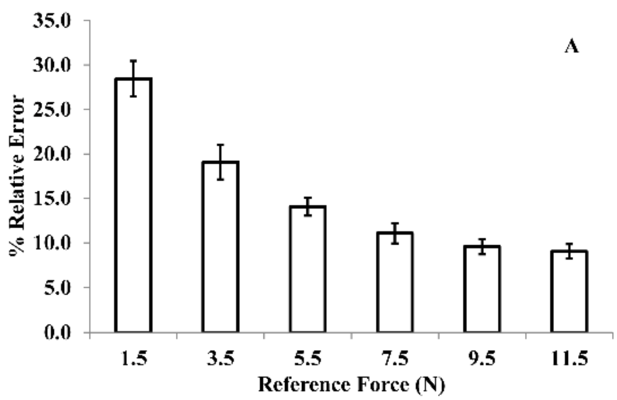
DATA ANALYSIS AND STATISTICS

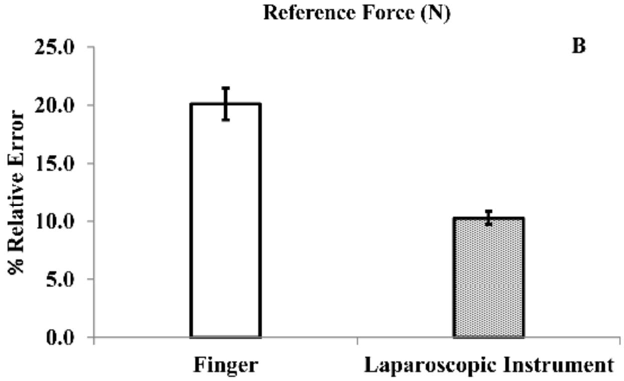
The precision and accuracy with which the reference forces (F_{Ref}) were matched (F_{Match}) was analyzed in terms of the relative and constant errors. The average % target difference $(|F_{Ref}-F_{Match}|)/F_{Ref})*100$ between the reference and matching forces constitute the relative matching error (%RME). The %RME accounts for accuracy of matching. But %RME ignores the direction of difference. Hence, constant errors (CE) were calculated ($F_{Ref}-F_{Match}$) to analyze the direction of difference i.e. the degree of underestimation (undershoot) and overestimation (overshoot) of reference forces. If CE is positive, it indicates an underestimation and a negative CE indicates overestimation. Three way repeated-measures ANOVA's were used on %RME (6×2×2) and CE (6×2×2) separately with within-subject factors as force, hand , and modality. The dependent variables were % RME and CE. Only significant ($p \leq 0.05$) main effects and interactions were reported.

RESULTS

Relative Error

Significant main effects were observed for force (F (2.55, 43.38) = 33.693, $p < .001$, η^2_p= 0.665, *Greenhouse-Geisser*) (Figure 3A) and modality (F (1, 17) = 45.242, $p <$ .001, η^2_p= .727) (Figure 3B). The %RME was found to be lowest (M = 9.02, SE = .811) at 11.5N and highest at1.5 N (M = 28.43, SE = 2). The interaction between hand and modality was significant (F (1, 17) = 10.839, p = .004, η^2_p = 0.389). We also performed a paired sample t-test as a follow up to examine the effect of handedness.





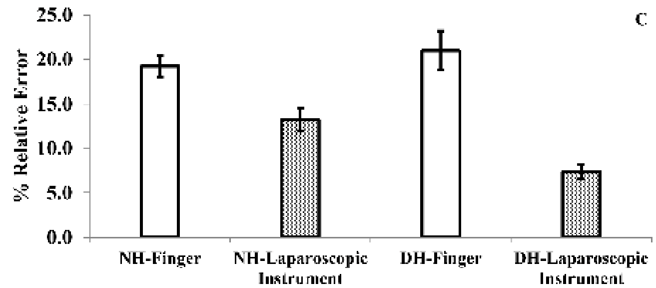


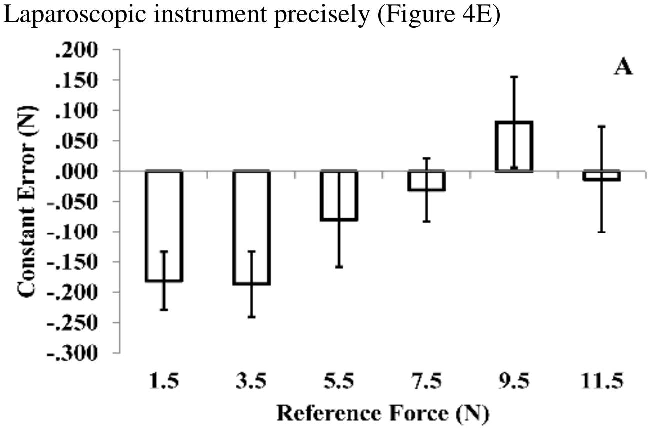
Figure 3. (A) %RME of force. (B) % RME of Modality. (C) %RME of hand as a function of modality.

The results showed a significant effect of handedness on %RME, when matching was performed with laparoscopic instrument. The %RME was lower for DH (M = 7.34, SE = .82) and higher for NH (M = 13.23, SE = 1.30) conditions of laparoscopic instrument, and the difference between the pair was found to be statistically significant (t (17) = -3.148, p = .006) (Figure 3C).

Constant Error

ANOVAs on CE as dependent variable showed significant main effects of force (F (5, 85) = 3.082, p = .013, η^2_p = .153), hand (F (1, 17) = 30.799, $p < .001$, η^2_p = .644), and modality (F (1, 17) = 6.068, p = .025, η^2_p = .263). Post-hoc bonferroni corrections on force revealed that the subjects overestimated the reference force at 1.5, 3.5, 5.5, 7.5 and 11.5N, and underestimated at 9.5N (Figure 4A). DH overestimated the reference force and NH underestimated the reference force (Figure 4B). Effects of modality showed that laparoscopic instrument (M = .02, SE = .03) attempted to match the reference force with minimal error, and finger (M = -.15, SE = .06) overestimated the reference force (Figure 4C). However, fluctuations during force matching were more in laparoscopic instrument.

The interaction between force and hand was significant (F (3.49, 59.42) = 2.864, p =.037, η^2_p = .144, *Huynh-Feldt*). The DH overestimated the reference force at all levels (see Figure 4D). NH underestimated the reference force at higher force levels (5.5-11.5N), and overestimated the lower reference forces (1.5 and 3.5N).There was also significant interaction between hand and modality (F (1, 17) = 15.035, $p < .001$, η^2_p = .469). The DH-Finger overestimated the reference forces of NH-finger. Whereas, DH –Laparoscopic Instrument attempted to match reference forces of NH-Laparoscopic instrument precisely (Figure 4E)



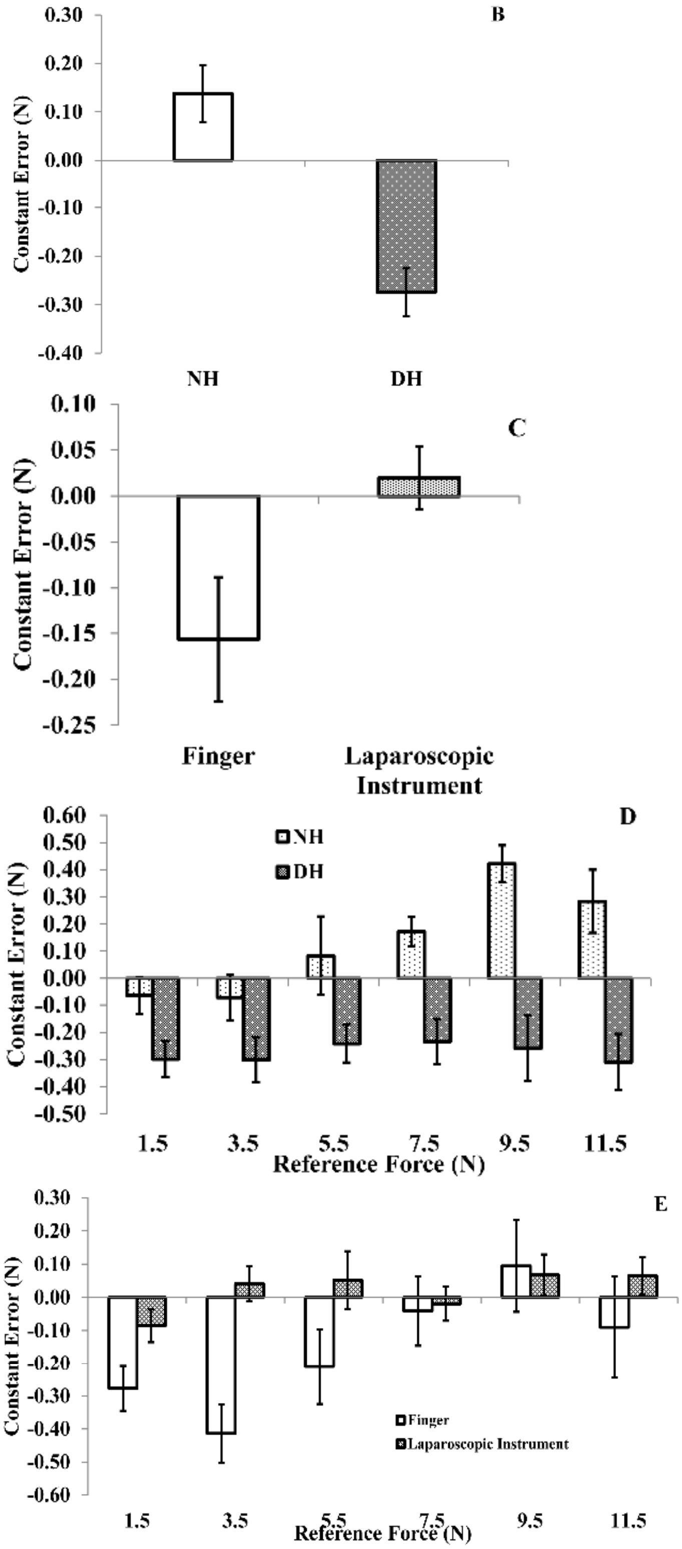


Figure 4.(A) CE of force (B) CE of modality. (C) CE of hand as a function of modality. (D) CE of hand as a function of force. (E) CE of modality as a function of hand.

DISCUSSION

The main purpose of the present study was to compare the force matching errors of laparoscopic instrument (LI) and index finger in flexed arm posture (i.e. used in conventional procedures) and to examine the effect of handedness on matching errors. Findings from this study showed that the matching performance was significantly better in laparoscopic instrument, and effect of handedness was clearly visible in the force matching performance of laparoscopic instrument only. The %RME in LI was 10.28%, which was comparatively less than finger (20.10%). The % RME was found to be inversely proportional to the reference forces. This indicates that subjects were able to perceive and match the reference forces more accurately at higher force levels. However, no major difference was found in %RME at higher force levels.

The reason for low %RME in LI could be due to the posture and the muscle groups involved in matching. Force matching through LI involves finger flexors, forearm and elbow flexors. Further, finger flexors have lower force control error with finer balance of force(L. Jones, 2003). In LI, the combination of the flexed five fingers of hand with forearm and elbow flexors could have affected the subject's force matching performance. The flexed five fingers have finer force control compared to index finger flexor. In addition, the strong grip established with flexed five fingers provides greater balance and control while exerting forces. Further, in direct finger force matching only index finger flexor is responsible for exerting and controlling the force. Another possible factor that may account for low matching error in LI is the pivot mechanism. The pivot acts as a LI holder, and is responsible for yaw and pitch motion. Though there was no displacement involved during force exertion, the pivot provides a guide way for LI. That is the LI shaft passes through the pivot and tip of the instrument shaft exerts force on the sensor. Our finding of matching error in LI being better compared to finger contradicts with earlier studies on compliance which have shown that finger is better compared to LI (Bholat et al., 1999; MacFarlane et al., 1999; Ottermo et al., 2006). The reasons for this contradicting result could be due to: a) the static probing, b) the fact that compliance discrimination study did not employ contra-lateral isometric force matching paradigm, in which same category of muscles were involved in exerting both the reference and matched forces, and c) absence of compliant objects. Effect of handedness on %RME was observed for LI only. The %RME of DH-laparoscopic instrument was found to be 7.32%. This shows DH is capable of controlling the reference forces compared to NH. However, no effect of handedness was observed for finger.

Constant errors revealed that reference force was underestimated at 9.5N and overestimated at 1.5 -7.5N. The modality wise force matching performance of LI shows that the when performing isometric force matching, LI attempted to match the reference force with maximum accuracy and precision, whereas finger overestimated the reference force. Interestingly, there was no effect of handedness on %RME of finger. This could be due to lower levels of matching. Overall results on handedness suggest that DH overestimated, and NH underestimated the reference force levels. This observation is in agreement with the finger force perception study (Park et al., 2008; Shergill et al., 2003). Further, DH applied greater force and NH applied lesser force at higher force levels. But at lower levels of force excessive forces were applied by DH, whereas NH attempted to match the reference force. However, in modality wise comparison DH-Laparoscopic instrument was more precise compared to NH-Laparoscopic instrument.

Overall results on handedness, considering both RME and CE show that force perception was better with DH, specifically in LI. Therefore, novices should take appropriate precautions to avoid intra–operative errors, while performing complex force-based laparoscopic tasks with their NH. Specifically, novices have to be extra cautious on tissue manipulation tasks that demand exertion of small magnitude of forces. In conclusion, the modality wise matching performance was better in LI with lower force matching errors. Further, novices applied excessive force at lower force levels. Dominant hand overestimated the reference forces of non-dominant hand. Novices have to be trained in applying precise and accurate forces in both their dominant and non-dominant hand. Thus, force-skills training curriculum should focus on improving the force perception ability and hand skills of novices. In future, we plan to test force perception and hand skills of surgical residents and experts. Further, in this study we have explored only the matching errors involved in static probing of LI, but the matching errors for basic laparoscopic tasks (grasping, pulling etc.) need to be explored. Furthermore, the force matching performed by LI was with a standard posture employed in most of the laparoscopic surgeries; force matching performance with different hand postures warrant a separate study.

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