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Design and Analysis of a Novel 5 - DoF Bimanual Laparoscopic Impedance Skills Trainer with Haptics Feedback

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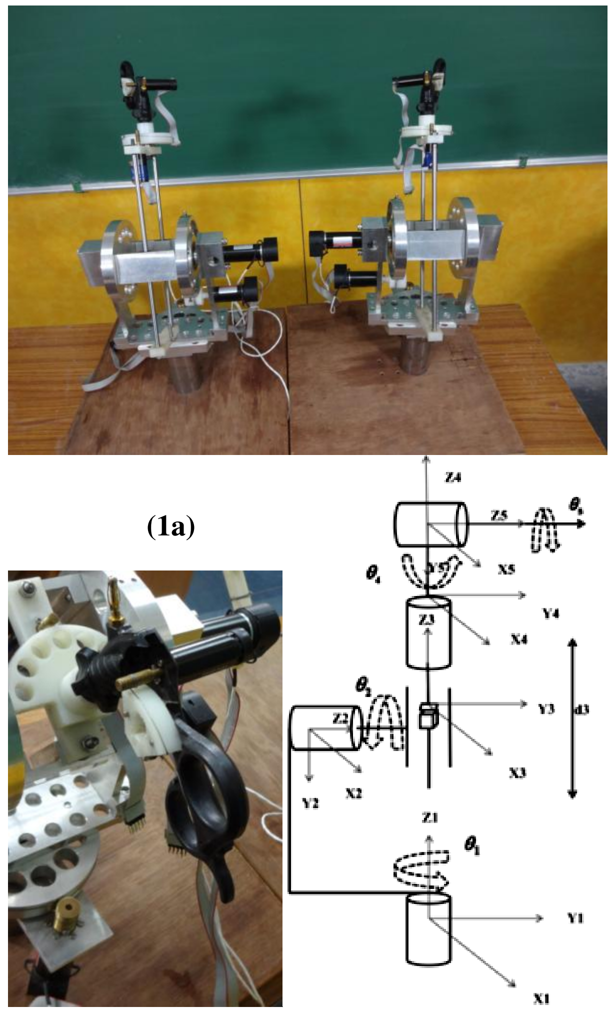
1 Background

Laparoscopic surgery has widely replaced open surgery due to the advantages it has for patients both during surgery and post-surgery recovery. Due to inversion and remote access to the surgical site, haptics feedback is altered with laparoscopic surgical instruments [1]. This leads to excessive exertion of force [2]. Many intra operative errors like tissue injury in laparoscopic surgery are due to texertion of large forces [2]. Over the years, virtual reality (VR) based laparoscopic surgical simulators with haptics feedback have been instrumental in teaching basic and advanced laparoscopic skills to residents and surgeons [3]. However, a major limitation in modern day VR based simulator training systems is that they do not effectively teach the bimanual impedance-based laparoscopic skills. Past studies on VR based laparoscopic training have captured the skills sets of residents and surgeons using force and psychomotor metrics [3,4]. However, till date none have explored the effects of experience on impedance based training. In this study, we analyze the impedance skills of residents and surgeons using custom developed novel bimanual laparoscopic skills trainer.

2 Methods

The design requirements for a typical haptic device are negligible friction, lightweight, no backlash, back-drivability, and low inertia. The 5- degree of freedom (DoF) device was designed in the accordance with the above requirements. Kinematically, the device can be described RRPRR serial manipulator (**Fig. 1a**). The first DoF is a revolute joint coupled to the base of the unit. This is responsible for the yaw (left-right) motion of the laparoscopic tool handle attached to the end effector (**Fig. 1b**). The second DoF is again a revolute joint coupled to the motor fixture link. This joint provides motion in the pitch (up-down) axes of the laparoscopic tool handle (**Fig. 1c**). Capstan drive mechanism is used in the yaw and pitch DoF to ensure negligible friction and backlash (**Fig. 1a**). In the present invention, the capstan drum, threaded pulley, cable, tensioning spring, stopper, and the motor together constitute the capstan drive mechanism. The cable used in our design is a thin steel cable connected to the outer surface of the capstan drum. A tensioning spring is tightly coupled to steel cable. A tightening screw is also mounted in the capstan drum which allows increasing the tension in the cable (**Fig. 2**). Further, a stopper is mounted on the capstan drum to restrict the motion of the capstan drum to -90° to 90° in the yaw and -70º to 80º in the pitch DoF's. The diameter of the capstan drum used in the yaw DoF is 120mm. This means that the torque on the motor shaft is enhanced by 12 times (**Fig. 2**). When the user initiates motion in the yaw axes the entire unit rotates in accordance with the user motion. The diameter of the capstan drum used in pitch is same 100mm. Therefore, the torque on the motor shaft is enhanced by 10 times the actual motor torque.



(1a)

(1b) **(1c)**

Fig. 1 (a) Bimanual laparoscopic simulator. (b) Gripper with capstan laparoscopic simulator. (c) Kinematic chain.

The third radial (or insertion) DoF is a prismatic joint which is responsible for linear (or In-Out) motion of the tool (**Fig. 1c**). The radial DoF consists of two linear ball bearing, two linear motion shafts and a dc motor coupled to a threaded shaft (**Fig. 2**) on which the steel cable is wrapped firmly. The fourth and fifth DoF's are revolute joints providing twist (roll) and gripping (opening and closing) mechanisms of the laparoscopic tool handle (**Fig. 1b**). The schematic diagram of the 5-DoF virtual reality based laparoscopic simulator with haptics feedback is shown in **Fig. 2**.

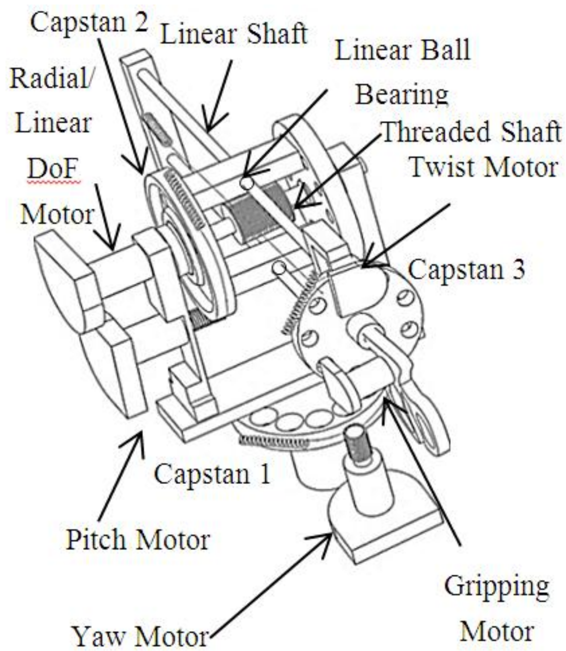


Fig. 2 Schematic diagram of 5-DoF haptic device

Again, the twist (or roll) DoF has a capstan drive mechanism to enhance the torque. In the twist DoF, torque is enhanced by 7 times the original motor torque (**Fig. 1b)**. Further, in our study, the impedance was calculated as the percent ratio of force to velocity. A 2 -way between subject's ANOVA was performed with independent variables as experience [3 levels: Novice (no laparoscopic experience), resident (< 3 years), and experts (>5years)] and handedness (2 levels: dominant hand (DH) and non-dominant hand (NH). There were 10 experts, 10 novices and 10 residents, with equal number of handedness in each group. The dependent variable was impedance. The task was to perform bimanual tissue exploration of a virtual reality based human anatomical model with 5 trials(**Fig. 3a**).

3 Results

The impedance based laparoscopic skills trainer was able to successfully differentiate the signatures of novices, residents, and experts. Significant effects were observed for both experience ($p = 0.021$) and handedness ($p < 0.001$) (**Fig. 3b**). Interestingly, it was observed that the impedance skills of residents were superior to that of experts and novices. Further, the DH of experts was found to have applied less impedance compared to NH ($p < 0.001$). The residents could impedance with their DH, this indicates that with DH, the residents carefully explored the tissue without applying excessive force or performing abrupt movements. Surprisingly, the NH of experts showed more impedance compared to NH of residents and novices (**Fig. 3b**). Further, a Wilcoxon signed rank test was performed to assess the effects of impedance between DH and NH. A significant difference was observed between DH and NH impedance skills in all the 3 groups ($p < 0.001$). However, the mean difference in % impedance between DH and NH was found to be more in the expert group ($p < 0.001$) (**Fig. 3b**).

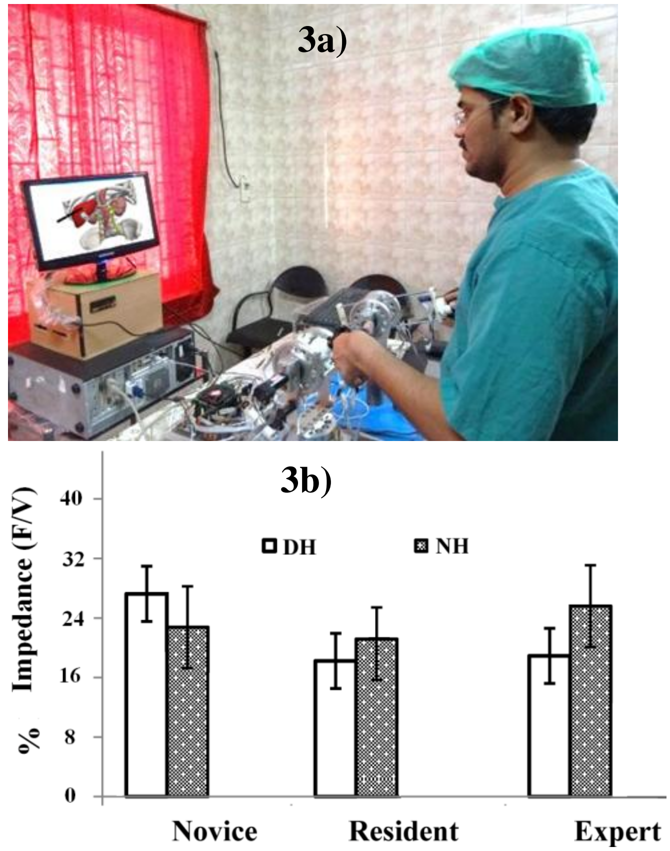


Fig. 3 (a) Subject performing tissue exploration task. (b) Effects of experience on impedance as a function of hand.

4 Interpretation

The simulator was proved to be an effective tool to objectively assess the effect of handedness on laparoscopic impedance-skills. Competency-based laparoscopic skills assessment curriculum should be updated to meet the requirements of bimanual impedance-based training. Our results indicate that though experts have more experience they need to enhance their impedance skills on a regular basis to avoid intra-operative errors during surgery.

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