2022 9th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob) | 978-1-6654-5849-8/22/$31.00 ©2022 IEEE | DOI: 10.1109/BIOROB52689.2022.9925461

Evaluation of Surgical Performance after Extended Laparoscopic Training using Physical Haptic Constraints

Noah Wright[1], Deborah Farr[2], Ann Majewicz Fey[1,2]

***Abstract*— Laparoscopic training often lacks an emphasis on proper grip of the instrument. Novices will often over-grip handle, restricting the thumb's range of motion and preventing them from pivoting the tool within their grasp. Limiting the thumb's range of movement can impact the force applied by the surgical instrument tips. We developed a passive and active constraint to prevent over-gripping. Initial experiments showed significant improvements in grip as well as task performance when evaluated using standard surgical training tasks. In this paper, we evaluate the effects of extended practice with these haptic constraints on skill acquisition. For this study, 12 novices were recruited to complete four trials consisting of three tasks each. Subjects were randomly assigned into a control group, a passive constraint group, and an active constraint group. The middle two trials were performed using the constraints but the first and last trials were conducted without constraints to measure lasting effects of using the constraints. The 3D movement of the instrument tips were measured with electromagnetic trackers and a custom sensing glove was used to measure finger tip position along the instrument handle. Metrics of path length, motion smoothness, depth perception, volume of motion, and velocity were computed from the instrument motion data. A score for each trial was also calculated and was derived from the task completion time. After a period of extended practice, the active constraint group had significantly less over-grip compared to the control group. This group additionally showed significantly lower volumes of motion. The passive constraint also showed consistently lower integrated jerk measurements through the trials indicating long-term benefits of the constraints.**

I. Introduction

Laparoscopic surgery is a minimally invasive surgery technique in which surgery is performed through long, thin instruments inserted into the abdomen, with an additional port for a viewing camera. Widely popularized in the early 1990's, laparoscopic surgery is used in a wide range of procedures including exploratory diagnostics, small organ and tissue removal, and repairing abdominal defects [1]. While this technique offers benefits to the patient in terms of better recovery and smaller incision size when compared to traditional surgery [2], it also represents a significant learning challenge for the surgical operator. Limited degrees of freedom of the instruments, non-intuitive tool motions due to the fulcrum effect and reduced depth perception from viewing the surgical field through a camera [3] all contribute to greater concentration and stress for the operating surgeon [4]. Additionally, laparoscopic surgery can prove to be uncomfortable for the surgeon and cause post-operative pain due to the awkward nature of handling these tools [5].

This work was supported in part by NSF #2109635. N. W. and A. M. F. are with the Department of Mechanical Engineering, The University of Texas at Austin, Austin, TX 78712, USA. A.M.F. and D.F. are with the Department of Surgery, UT Southwestern Medical Center, Dallas, TX 75390, USA.

(a) Passive Constraint (b) Active Constraint

Fig. 1: Laparoscopic constraints developed for this study included a passive constraint that physically prevents over-grip and an active version made of compliant material which increases resistive force feedback the more the finger over-grips the instrument

Much of the research related to laparoscopic instruments to date has centered on ergonomic studies which explore various factors of these instruments, including different metrics for surgeon comfort [6]–[8]. Different types of handles have also been explored and evaluated for differences in elbow angle, muscle activation, and performance in a variety of surgical training tasks [9], [10]. Many studies indicate benefits of tools with a pistol grip handle, particularly for certain instrument orientations [11], [12], but others have shown opposite results where pistol-grip handles lead to increased tissue damage and non-goal-directed movements [13].

As minimizing gripping forces and tissue damage is a critically important aspect of surgery, many research studies have also explored measuring gripping forces for different types of laparoscopic instrument handles or across expertise levels [14], [15]. Additionally, some have sought to solve this problem by developing sensors or training systems to monitor and potentially reduce excessive gripping force [16], [17].

An often overlooked aspect of laparoscopic surgical training is the proper positioning of the hand on the tool. Depending on the task, the ideal hand positioning may be different. For example, in tasks that require high force, palming the laparoscopic instrument has been shown to reduce overall workload in terms of muscle activity [18], whereas delicate tasks require a much finer grip [8]. In delicate tasks, such as in pediatric surgery, proper grip of the tool requires that only the fingertips are placed on the instrument handle. This allows the thumb to pivot the tool within the hand, giving the surgeon increased control on the amount of force applied to tissue. This is an important skill as the metal graspers can damage tissue if excessive force is applied [19].

In prior work, we developed an active and passive haptic constraint device to prevent novice surgeons from over-gripping laparoscopic instruments [20] (Fig. 2). This work showed significant improvement in finger positioning and task completion time for the passive constraint in a simple 1-hour long crossover study design. In this paper, we investigate the effects of extended training (i.e., 4 sessions over 4 weeks) on instrument handling and various performance metrics when completing standard laparoscopic training tasks.

II. Haptic Constraints for Laparoscopic Tools

In this section we briefly summarize the design of the laparoscopic haptic constraints and our preliminary evaluation results [20].

a) Passive Constraint Mechanism: The passive mechanism consists of a 3DOF knob (palm rest on spherical joint) which can also change height through a screw and thumb nut mechanism which can be adjusted to fit within the trainees hand. This mechanism is made of custom 3D printed parts and standard mechanical hardware.

b) Active Constraint Mechanism: The active constraint consists of a custom plastic 3D printed clip with a flexible silicone finger tray that was molded in-house using Ecoflex 30 (Smooth-On, Macungie, PA), in a custom 3D printed mold. Our particular constraint is designed specifically for the Johnson and Johnson Endopath line of surgical instruments that are commonly used at the UTSW surgical training center but the design can easily be modified to fit other similar instruments.

c) Preliminary Experimental Methods and Results: Twelve novice subjects were recruited in a cross-over trial design. Subjects performed two training tasks including the Fundamentals of Laparoscopic Surgery (FLS) Peg Transfer and Circle Cutting tasks three times each while under a pseudo-randomized experimental condition of control (i.e., no constraint), active, or passive constraint. This was done to ensure a balanced design of constraint conditions. Hand position with a custom sensing glove and task metrics of completion time and errors were recorded. The passive constraint condition not only showed statistically significantly lower over-grip, but also lead to decreased task completion time in both training tasks. This work was the foundational motivation for this current study where we aim to explore these effects further through extended practice with the haptic constraints on surgical skill transfer.

A. Subjects

A total of twelve novice subjects (ages 20-35, 5 female, and 7 male, 2 left-handed and 10 right-handed) were recruited for this study which was approved by the UT Austin Institutional Review Board. Informed consent was collected from all participants. At the conclusion of the study, all participants were compensated with a gift card. Participants had no medical background and were comprised of UT faculty and students.

(a) Passive Constraint on Tool (b) Active Constraint

Fig. 2: Laparoscopic constraints developed for this study included passive and active are shown attached to laparoscopic tool. Reproduced from [20].

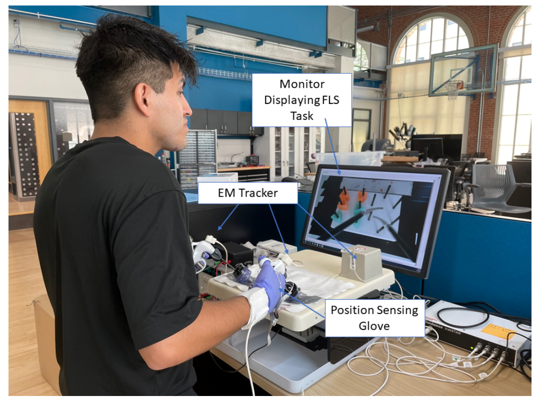


Fig. 3: Experimental Setup. The subject is wearing the custom sensing glove while performing the peg transfer task. A electromagnetic motion tracker is mounted onto each of the tool handles.

B. Experimental Tasks

Participants were asked to complete four trials with each trial consisting of the following training tasks chosen from the Fundamentals of Laparoscopic Surgery (FLS) Training Curriculum [21]:

1) Peg Transfer: Using two Maryland dissectors, six triangles are transferred from the left side of the board to the right side, then again in the opposite direction. If a triangle was dropped out of bounds, a penalty of 15 or 30 seconds was added depending on the section of the task (Fig. 6a).

2) Precision Cutting: Using a Maryland dissector and a pair of endoscopic scissors, a two-ply piece of gauze is cut following the shape of a printed circle. A penalty of 5 seconds was assigned for each centimeter of arc length cut outside of 2mm from the drawn circle (Fig. 6b).

3) Intracorporeal Knot: Using a Maryland dissector and a needle driver, the user must complete an intracorporeal knot with a suture through a penrose drain marked with two dots for the taperpoint needle to be inserted through. This task was modified from the FLS task to no longer include cutting the suture as switching instruments during the procedure can be difficult with the position sensing gloves. A 10 second penalty was

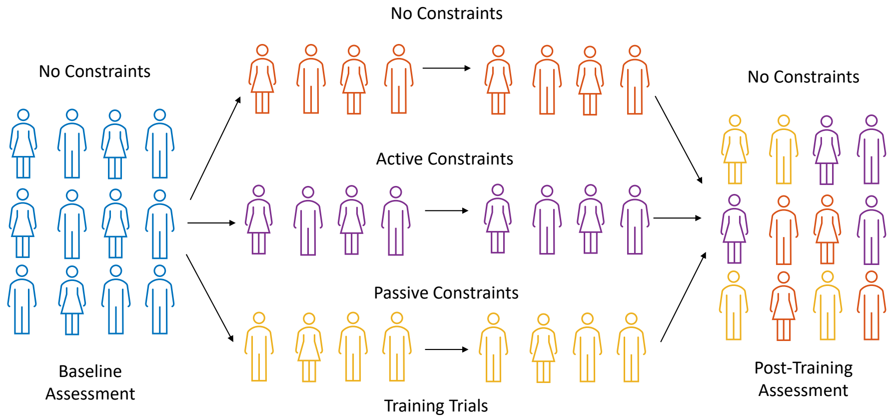


Fig. 4: Experimental Protocol. Twelve novice subjects completed a baseline trial with all using no constraints. For trials two and three, participants were randomly placed into one of three groups that used either the passive constraint, active constraint, or no constraint. For trial four, all participants again used no constraints to observe the differences in hand position.

applied if the knot slipped, 10 seconds if the penrose drained was not closed, 20 seconds if the knot came completely apart, and 5 seconds for every millimeter deviated from the marked dots. For all subjects, the needle driver was held in the right hand (Fig. 6c). These penalties were chosen as estimates of the additional time that would have been required to ensure that the mistake would not have been made.

Tasks were chosen from the FLS program as it is a validated educational program for MIS that has been endorsed by the American College of Surgeons. Each task was performed once per trial and were assigned in the order listed above for all trials due to the variance in difficulties of the tasks. Participants were not allowed practice with the instruments prior to testing. The first trial acted as a baseline trial with all participants wearing the position sensing gloves while using unmodified instruments. The second and third trials had the subjects randomly divided into groups that either used the passive constraint, active constraint, or no constraint as seen in Figure 4. It is important to note that for the intracorporeal knot task, because an in-line needle driver is required, no constraint was used with that instrument regardless of the assigned group. However, constraints were still attached to the Maryland dissector if the subject was not in the control group. Upon completion of the second and third trials, the subjects undertook a fourth trial where all subjects wore the sensing gloves and used no constraints. Additionally, the subjects partook in a post-test analysis immediately following the fourth trial after completion of the standard three tasks. The post-test task involved completing another incorporeal knot on simulated bowel tissue as seen in Figure 6d. This introduced new obstacles such as having to complete the knot in a different direction and having the surgical medium capable of movement.

In order to create a simulated environment for laparoscopic surgery, all participants performed each task inside of a box trainer containing an internal camera that displayed video onto a monitor as seen in Figure 3. Each trial was completed

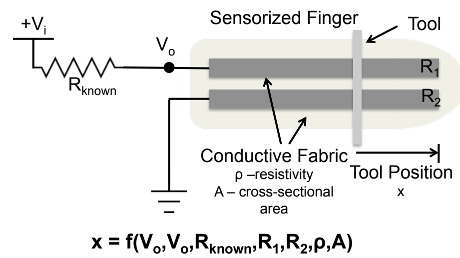


Fig. 5: Custom Finger Position Sensing Glove Schematic. This sensor uses conductive fabric to measure contact with metal pads on the instrument handles. Voltage measured from the sensor changes as a function of finger position along the tool. A calibration is required to correlate minimum and maximum sensor voltages based to each subjects finger anatomy. Reproduced from [20]

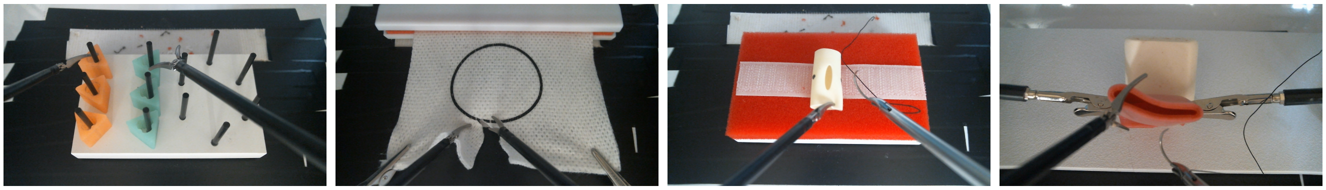
.

an average of 6.5 days apart depending on participant needs for a total of approximately 4 weeks of extended practice. This spacing between intervals was chosen as it allows a small window for participant scheduling that limits interference with the results in the event that a trial needed to be rescheduled. Additionally, this can help to reduce user frustration that may be caused by more frequent training.

C. Data Collection

There were three categories of data in consideration: time, hand position, and the kinematics of the instrument tip. All data was collected using LabVIEW 2020 SP1 and processed into usable metrics with MATLAB 2020A.

Hand position was measured by using a voltage sensing glove. The glove is configured with two parallel lines of conductive fabric on each finger that result in a voltage drop when current is passed through the two lines. Depending on the location of this connection, the voltage drop will vary. By attaching conductive foil tape to the handles of the instrument, the position where contact is made can be deduced through the linear relationship between the minimum and maximum voltages of each finger (Fig. 5).



(a) Peg Transfer (b) Precision Cutting (c) Intracorporeal Knot and Suture (d) Post-test Task

Fig. 6: Each of the experimental tasks performed during each trial. Each subject completed the tasks in the same order of peg transfer, precision cutting, then incorporeal knot.

Tool position was collected using an Ascension 3D Guidance trakSTAR electromagnetic tracker with sensors mounted to the instrument handle via a custom 3D-printed mount. Using a rigid body transformation, the instrument tip position can be inferred from the position and orientation of the handle.

D. Objective Measurements

There have been numerous studies on the development of objective measurements for determining laparoscopic skills proficiency. These measurements give insight into both where the user is moving the instrument, and how they are moving the instrument. Finally, because these metrics are generalized performance metrics using instrument tips, a lumped analysis can be done regardless of instrument types and surgical task for the purpose of comparing the constraints used.

- Path Length: This is the total distance travelled by the instrument tip in respect to all three dimensions [22].

$$PL = \sum \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$$

- Volume of Motion: This metric refers to the volume of an ellipsoid defined by the standard deviations along three dominant axes of motion. These new axes of motion are calculated by using principal component analysis on the observed position data [23].

$$VM = 4\pi/3 * (STD1 * STD2 * STD3)$$

- Depth Perception: This is the distance travelled along the vertical axis. When measured this gives insight into how well the user is performing in a 3D environment while viewing through the 2D display. This is similar to the path length but represents a more focused aspect of the distance travelled [23].

$$DP = \sum \sqrt{\Delta z^2}$$

- Score: This is determined by collecting the total completion time for each trial and adding penalties based on the participant errors described before.

- Motion Smoothness: The time integrated squared jerk provides an accumulated measurement for how smooth and continuous the movements of the user are during each trial. In order to compensate for the different time to completion for each participant, each measurement is divided by the trial time [24].

$$J = \sqrt{1/2 \int_0^T j^2 dt}$$

- Velocity: This metric shows the pace of the user during each task. When observed in combination with motion smoothness, it can give insight into how delicate the movements are during experimentation [23].

- Normalized Finger Position: This metric indicates the position of each respective finger on the tool with 1.0 representing the finger tip and 0.0 as the finger base.

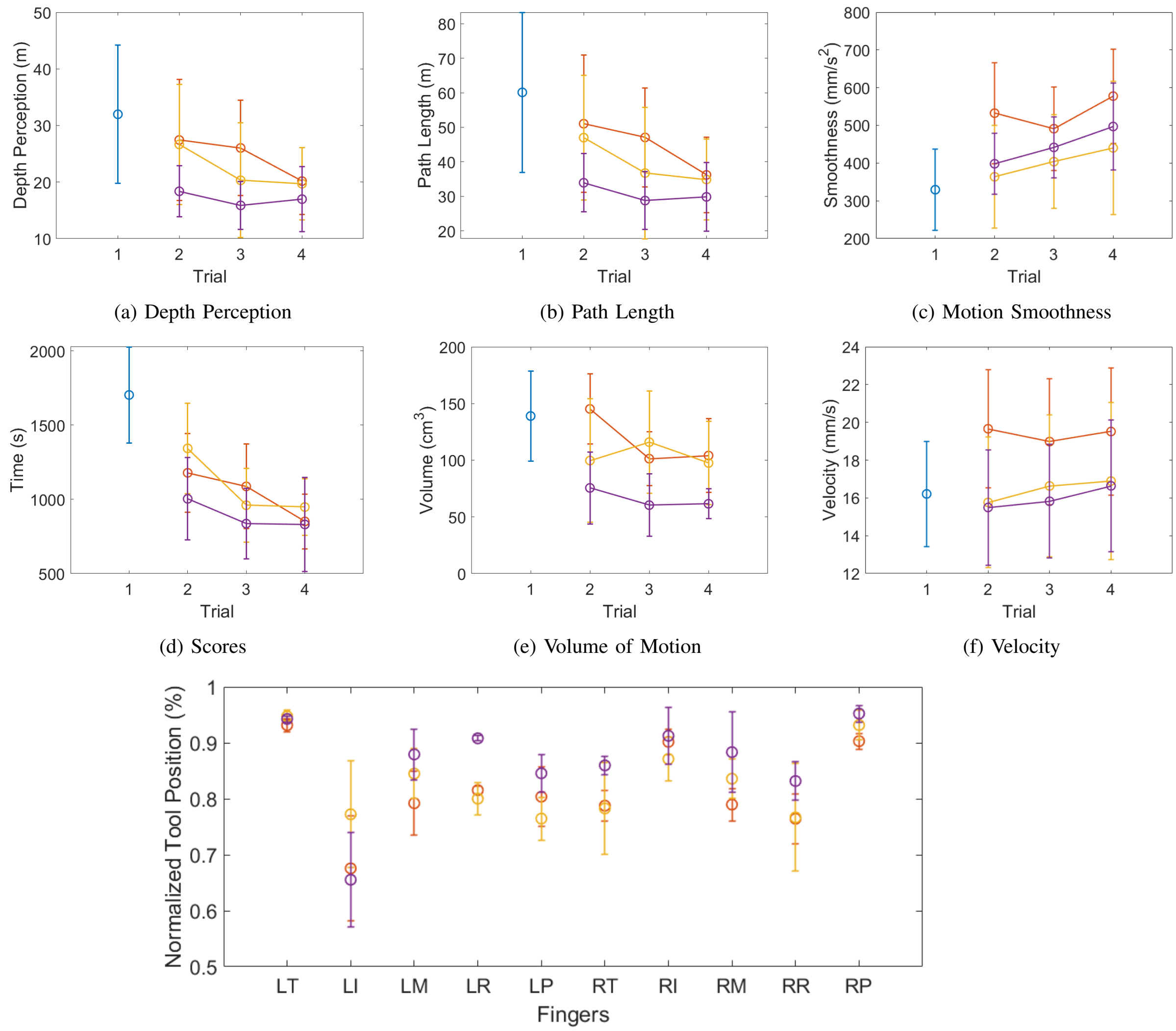
TABLE I: Statistical Analysis Summary for Trials 2, 3, 4

Source	Prob > |t|	
	Active Constraint	Passive Constraint
Path Length	.0556	.6309
Volume of Motion	.0151	.0965
Depth Perception	.1376	.1977
Motion Smoothness	.0792	.0338
Score	.1934	.2203
Velocity	.1179	.1405
Normalized Finger Position	1.069e-05 (N,P) < A	

For many of these metrics, there are difficulties in defining a threshold of proficiency that determines when one is assigned the status of an expert (i.e the ideal path length). Nonetheless, given that each participant will only complete four training trials, it can be expected that there is sufficient deviation from these theoretical barriers that we can focus on the difference between groups.

III. Results and Discussion

Score, path length, depth perception, volume of motion, and motion smoothness were all evaluated through the three trials after intervention with the constraints. Hand position



(a) Depth Perception (b) Path Length (c) Motion Smoothness

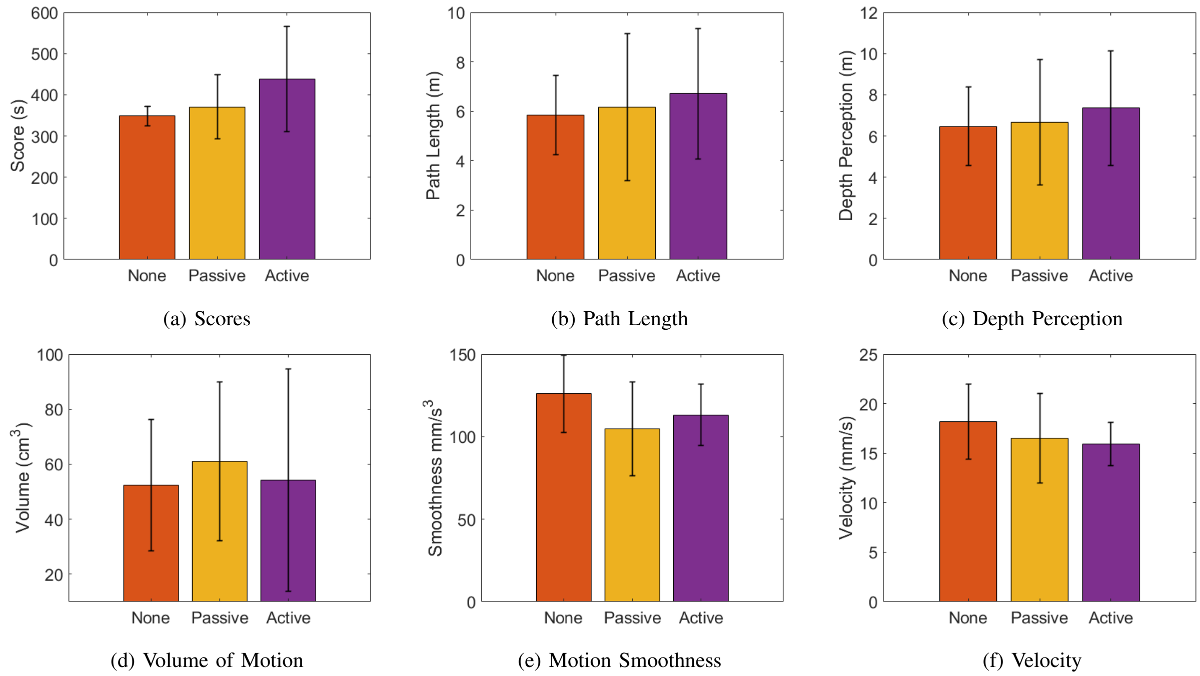
(d) Scores (e) Volume of Motion (f) Velocity

(g) Normalized Finger Position

Fig. 7: The results from each metric measured. Depth perception, path length, motion smoothness, and scores are displayed as the total of each individual task metric. Velocity, volume of motion, and finger position are shown as the averages of each individual task metric. Baseline: ——— , No Constraint: ——— , Active Constraint: ——— , Passive Constraint: ———

was solely evaluated at the end of the experiment in the fourth trial. Results from the course of the experiment are shown in Figure 7. Depth perception, path length, motion smoothness, and scores were analyzed by collecting the summation of results from each task, thus, receiving a total for each trial. Volume of motion, velocity and normalized finger position results, however, are depicted by the averages over each of the three tasks. A linear mixed model was fitted to evaluate the effect between each constraint group against the collective kinematic data through the second, third, and fourth trials, once intervention with the constraints had occurred. P-values collected from the constraint group fixed effect were approximated using the Satterthwaite's method. Statistical results comparing the constraint group fixed effect are displayed in Table I. Normalized finger position and all post-testing data were analyzed using a one-way ANOVA between groups. R Version 4.1.1 was used to study the linear mixed effect models while MATLAB was used to analyze the results from the ANOVA tests.

The active constraint proved successful in preventing over-grip as a result of the training. Finger position was significantly higher meaning that the user held the instrument closer to the fingertips (P = 1.069e-05). This contradicts our former study where the passive constraint prevented over-grip during usage. This could indicate that the active constraint is more effectively used to treat over-grip over an extended training period while more soundly transitioning the skills obtained when the user eventually returns to using no constraints. The dynamic and personalized forces felt in the compliant active mechanism could be a reason for this enhanced performance. The active constraint is also much less invasive than the passive constraint, allowing the user to have an experience closer to that of holding an unmodified instrument. Therefore, when the user returns to using no constraints, there is a less significant transition. Additionally, the users of the active constraint required significantly lower volumes of motion to



(a) Scores (b) Path Length (c) Depth Perception

(d) Volume of Motion (e) Motion Smoothness (f) Velocity

Fig. 8: The results from the simulated tissue intracorporeal knot after the fourth trial. No Constraint: ——- , Active Constraint: ——- , Passive Constraint: ——-

TABLE II: Post-Test Task Statistical ANOVA Summary

Source	Prob > F
Path Length	.8842
Volume of Motion	.9221
Depth Perception	.8864
Motion Smoothness	.4761
Score	.3599
Velocity	.6729

complete the tasks during trials 2, 3, and 4 (P = .0151). Neither of the two constraints demonstrated effects on score, velocity, or depth perception. The post-test task results can be found in Figure8 and Table II and showed no significant differences between any of the tested groups.

In every metric except for motion smoothness, the active constraint group performed the best. Interestingly, all of the groups showed increasingly worse motion smoothness throughout the course of the study. However, the passive constraint group showed more smooth movements than the other groups with the passive constraint showing significantly lower integrated jerk metrics after intervention (P = .0338). This could be a result of the reduction in hand position variation from using an instrument with constraints. Because the constraints act as a fixture on the hand, each location of the finger on the instrument is more stable and is less likely to see significant changes during use. With this improved stability, the hand is less likely to slip resulting in a jerky movement. Given the small sample sizes of each group, it is possible that many of these metrics would show significance in a larger study.

IV. Conclusions

We conducted a longitudinal study with twelve participants to investigate the potential for haptic constraints to improve laparoscopic skills training. The active constraint was a success in preventing over-grip after returning to the tool with no constraint in the fourth trial. Additionally, the active constraint showed reductions in the volume of motion utilized to complete each task. This is an especially crucial metric as laparoscopic surgery requires the surgeon to perform in significantly smaller areas than that available in the box trainer.

Laparoscopic skills training requires many more sessions than the four that were included in this study. A longer study would be required to investigate the long-term effects of the constraint after the initial learning curve associated with using laparoscopic instruments. It would also be useful to have medical students or surgical residents as study subjects given that they have a greater technical background in surgical skills and are also exposed to surgical instruments in the operating room. Future work will also seek experts in laparoscopic surgery as subjects to establish a baseline for determining when surgical proficiency is achieved.

Finally, encouraged by these results, we plan to optimize the active constraint to better fit a variety of instruments. Currently the device is only capable of being mounted onto the Johnson and Johnson Endopath brand of laparoscopic instruments.

REFERENCES

[1] N. J. Soper, L. M. Brunt, and K. Kerbl, "Laparoscopic general surgery," *New England Journal of Medicine*, vol. 330, no. 6, pp. 409–419, 1994.

[2] M. Talamini, C. Stanfield, D. Chang, and A. Wu, "The surgical recovery index," *Surgical Endoscopy And Other Interventional Techniques*, vol. 18, no. 4, pp. 596–600, 2004.

[3] M. Vassiliou, B. J. Dunkin, J. M. Marks, and G. M. Fried, "Fls and fes: Comprehensive models of training and assessment," *Surgical Clinics of North America*, vol. 90, no. 3, pp. 538–558, 2010.

[4] R. Berguer, W. Smith, and Y. Chung, "Performing laparoscopic surgery is significantly more stressful for the surgeon than open surgery," *Surgical endoscopy*, vol. 15, no. 10, pp. 1204–1207, 2001.

[5] K. Doné, A. DiMartino, and S. Judkins, T. Hallbeck, "Evaluation of laparoscopic tools for usability and comfort," *Proceedings of the Human Factors and Ergonomics Society*, vol. 48, no. 12, pp. 1359–1362, 2004.

[6] R. Berguer, D. Forkey, and W. Smith, "Ergonomic problems associated with laparoscopic surgery," *Surgical endoscopy*, vol. 13, no. 5, pp. 466–468, 1999.

[7] R. Berguer and A. Hreljac, "The relationship between hand size and difficulty using surgical instruments: a survey of 726 laparoscopic surgeons," *Surgical Endoscopy and Other Interventional Techniques*, vol. 18, no. 3, pp. 508–512, 2004.

[8] R. Berguer, "Ergonomics in laparoscopic surgery," in *The sages manual*. Springer, 2006, pp. 454–464.

[9] U. Matern, C. Giebmeyer, R. Bergmann, P. Waller, and M. Faist, "Ergonomic aspects of four different types of laparoscopic instrument handles with respect to elbow angle," *Surgical endoscopy*, vol. 16, no. 11, pp. 1528–1532, 2002.

[10] U. Matern, G. Kuttler, C. Giebmeyer, P. Waller, and M. Faist, "Ergonomic aspects of five different types of laparoscopic instrument handles under dynamic conditions with respect to specific laparoscopic tasks: an electromyographic-based study," *Surgical Endoscopy and Other Interventional Techniques*, vol. 18, no. 8, pp. 1231–1241, 2004.

[11] R. Berguer, S. Gerber, G. Kilpatrick, and D. Beckley, "An ergonomic comparison of in-line vs pistol-grip handle configuration in a laparoscopic grasper," *Surgical endoscopy*, vol. 12, no. 6, pp. 805–808, 1998.

[12] K. D. Tung, R. M. Shorti, E. C. Downey, D. S. Bloswick, and A. S. Merryweather, "The effect of ergonomic laparoscopic tool handle design on performance and efficiency," *Surgical endoscopy*, vol. 29, no. 9, pp. 2500–2505, 2015.

[13] M. Uchal, J. Brogger, R. Rukas, B. Karlsen, and R. Bergamaschi, "In-line versus pistol-grip handles in a laparoscopic simulators," *Surgical*

[20] N. Ulhaq, H. Wadi, T. Amlee, D. Diesen, and A. M. Fey, "Design and evaluation of haptic constraints for laparoscopic instrument handling," in *2018 40th Annual International Conference of the IEEE*

Endoscopy And Other Interventional Techniques, vol. 16, no. 12, pp. 1771–1773, 2002.

[14] C. R. Wottawa, J. R. Cohen, R. E. Fan, J. W. Bisley, M. O. Culjat, W. S. Grundfest, and E. P. Dutson, "The role of tactile feedback in grip force during laparoscopic training tasks," *Surgical endoscopy*, vol. 27, no. 4, pp. 1111–1118, 2013.

[15] A. Araki, K. Makiyama, H. Yamanaka, D. Ueno, K. Osaka, M. Nagasaka, T. Yamada, and M. Yao, "Comparison of the performance of experienced and novice surgeons: measurement of gripping force during laparoscopic surgery performed on pigs using forceps with pressure sensors," *Surgical endoscopy*, vol. 31, no. 4, pp. 1999–2005, 2017.

[16] Y. Okuda, A. Nakai, T. Sato, M. Kurata, I. Shimoyama, T. Oda, and N. Ohkohci, "New device with force sensors for laparoscopic liver resection–investigation of grip force and histological damage," *Minimally Invasive Therapy & Allied Technologies*, pp. 1–6, 2020.

[17] E. P. Westebring-van der Putten, J. J. van den Dobbelsteen, R. H. Goossens, J. J. Jakimowicz, and J. Dankelman, "Force feedback requirements for efficient laparoscopic grasp control," *Ergonomics*, vol. 52, no. 9, pp. 1055–1066, 2009.

[18] R. Berguer, S. Gerber, G. Kilpatrick, M. Remler, and D. Beckley, "A comparison of forearm and thumb muscle electromyographic responses to the use of laparoscopic instruments with either a finger grasp or a palm grasp," *Ergonomics*, vol. 42, no. 12, pp. 1634–1645, 1999.

[19] E. Heijnsdijk, H. De Visser, J. Dankelman, and D. Gouma, "Slip and damage properties of jaws of laparoscopic graspers," *Surgical Endoscopy*, vol. 18, no. 6, pp. 974–979, 2004.
Engineering in Medicine and Biology Society (EMBC). IEEE, 2018, pp. 961–964.

[21] S. of American Gastrointestinal and E. Surgeons. (2021) Fundamentals of laparoscopic surgery. https://www.flsprogram.org/. Accessed: 2021-10-18.

[22] M. Chmarra, S. Klein, J. C.F. de Winter, F. Jansen, and J. Dankelman, "Objective classification of residents based on their psychomotor laparoscopic skills," *Surgical Endoscopy*, vol. 24, pp. 1031–1039, 2010.

[23] I. Oropesa, M. K. Chmarra, P. Sanchez-Gonzalez, P. Lamata, S. Rodrigues, S. Enciso, F. M. Sánchez-Margallo, F. Jansen, J. Dankelman, and E. Gomez, "Relevance of motion-related assessment metrics in laparoscopic surgery," *Surgical Innovation*, vol. 20, no. 3, pp. 299–312, 2012.

[24] S. Cotin, N. Stylopoulos, P. Ottensmeyer, M. Neumann, D. Rattner, and S. Dawson, "Metrics for laparoscopic skills trainers: The weakest link!" in *Medical Image Computing and Computer-Assisted Intervention, 2002*. MICCAI, 2002, pp. 35–43.