A Pneumatic Haptic Feedback Actuator Array for Robotic Surgery or Simulation

Chih-Hung KING [a,b,] , Adrienne T. HIGA [a,b], Martin O. CULJAT [a,c],
Soo Hwa HAN [a,c], James W. BISLEY [d], Gregory P. CARMAN [a,b],
Erik DUTSON [a,c], and Warren S. GRUNDFEST [a,b,c,1]
[a]*Center for Advanced Surgical and Interventional Technology (CASIT)*
[b]*UCLA Henry Samueli School of Engineering and Applied Science*
[c]*UCLA Department of Surgery*
[d]*UCLA Department of Neurobiology*

Abstract. Robot-assisted minimally invasive surgery (MIS) offers improved range of motion over standard laparoscopic techniques, but is characterized by a total loss of haptic feedback, requiring surgeons to rely solely on visual cues. Pneumatic tactile displays have many advantages, including low mass, low cost, compact size, and adaptability. A pneumatic haptic feedback actuator array has been developed that is suitable for mounting unto surgical robotic tools. The balloon actuators consist of spin-coated thin-film silicone membranes and molded substrates with cylindrical channels. Human perceptual tests were conducted on balloon diameters ranging from 0.75 to 2.0 mm to determine the optimal size that can be effectively detected. The control system was programmed to sequentially inflate a single balloon to one of the three levels, 100% (full hemispherical deformation), zero, 50% (half deformation), and 0% (no inflation). Blinded subjects (n=5) were asked to determine which of the two inflation levels was higher. Test results suggest that balloon diameters greater than 1.0 mm can deliver high detection accuracy. This indicates that pneumatic balloon-based actuation is a viable solution for generating haptic feedback. In addition to surgical applications, many other fields such as virtual reality-based simulators and neuroprosthetics can benefit from this technology.

Keywords. Tactile display, haptic feedback, robotic surgery, pneumatic actuator

1. Introduction

Minimally invasive surgery (MIS) has revolutionized surgical care by decreasing the need for medication and shortening recovery times through the reduction of trauma to patients during operations [1,2]. Current surgical robots for MIS enable surgeons to operate remotely with improved range of motion, bringing their expertise in-theater to address critical needs such as those encountered in battlefield surgery. While surgical robots offer many benefits, they suffer from a total loss of haptic feedback, requiring surgeons to rely solely on visual cues during operations. This drawback has led to longer learning curves for surgeons, and has increased the chances of inadvertent surgical errors [3,4]. The addition of tactile information will enable surgeons to "feel"

---

[1] Correspondence to: Warren S. Grundfest, MD, warrenbe@seas.ucla.edu

Proceedings of Medicine Meets Virtual Reality 15: in vivo, in vitro, in silico: Designing the Next in Medicine, 6-9 February 2007, Long Beach, CA, 217-222, 2007

tissue characteristics, appropriately tension sutures, identify pathologic conditions, and will enable expansion of MIS to other surgical procedures and simulations. It is proposed that the haptic feedback actuator, when integrated with a tactile sensor array mounted onto the tips of robotic graspers, can effectively translate tactile information to the surgeon's fingertips. The actuator can also provide virtual tactile information when implemented with surgical simulators.

Various haptic feedback actuator and system technologies have previously been explored, including piezoelectric, shape memory alloys, electromagnetic, and servo motors [5-9]. Pneumatically actuated tactile displays have also previously been described [10,11], but have not been implemented on surgical robotic systems. Pneumatic balloon actuation has various advantages, including surface conformation, compact size, and large deflection. In this paper, we present a modular and scalable pneumatically driven balloon-based actuator array suitable for mounting onto surgical robotic tools. This system uses the human sensory apparatus in the skin as a pathway for providing information to the brain. Human perceptual studies, which provide preliminary guidelines for determining the optimal balloon diameter, are also discussed.

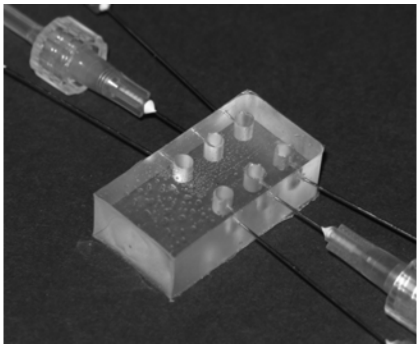

Figure 1. 3 x 2 pneumatic balloon actuator array

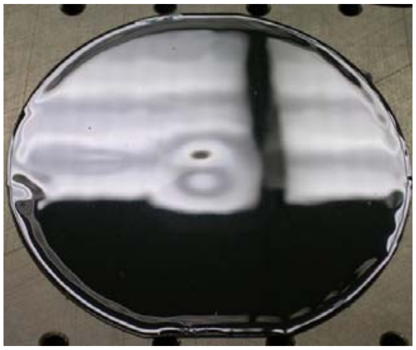

Figure 2. Thin-film silicone membrane on a wafer

2. Design and Methods

The pneumatic balloon actuators are constructed from thin-film silicone membranes and molded polydimethylsiloxane (PDMS) substrates (32 mm x 17 mm x 10 mm) with cylindrical channels (Figure 1). The flexible PDMS material has the advantage that it can conform to the shape of the fingers, and the highly elastic silicone membrane can be bonded to the PDMS substrate while expanding into balloons above each of the channels. The membrane was fabricated by spin coating silicone in liquid form on a silicon wafer. The spin coater (Headway EC101D) was used to control the thickness and uniformity of the membrane. A cured thin-film silicone membrane (~300 µm) is shown attached to a silicon wafer in Figure 2. Using this process, balloon actuators with diameters of 0.75, 1.0, 1.5, and 2.0 mm were fabricated with array sizes up to 3 x 2 elements.

The schematic of the control system to the balloon actuators is illustrated in Figure 3, consisting of a microcontroller and associated electronics, pressure regulators, an air source, and pneumatic tubing and fittings. The microcontroller (PIC16F877A, Microchip, Chandler, AZ) was programmed and controlled by a computer via the serial interface (RS-232) to: (1) receive control instructions from the operator, (2) determine the required inflation level of the balloon actuator, and (3) generate the corresponding analog control signals to the pressure regulators (Marsh Bellofram T3210), which in turn inflated the balloon actuators with proportional pressures.

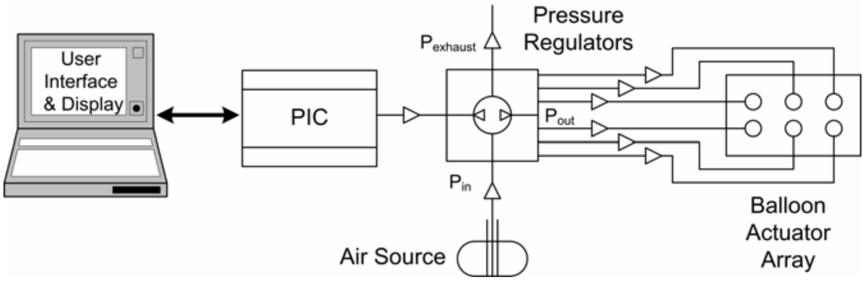

Figure 3. Schematic of the control system

Human perceptual tests were conducted for each of the existing balloon diameters to determine the optimal size that can be effectively detected. The control system was programmed to sequentially actuate a single balloon to one of three actuation levels based on the instruction of the operator. The three inflation levels used in this study were 100% (full hemispherical deformation), 50% (half deformation), and 0% (no inflation). There were six possible combinations of sequential actuation among the three inflation levels: 0-50, 0-100, 50-100, 100-50, 100-0, and 50-0. For instance, 0-50 represents the actuation sequence from 0% inflation to 50% inflation.

Five subjects (three men, two women, age range 23-40 years) participated in the study, and were trained to ensure that they were familiar with the haptic feedback system. Each subject was asked to perform one session for each of the four balloon diameters; for each session, the subject asked to perform 15 two-alternative forced choice trials, comparing two sequentially presented stimuli. The stimuli were presented over a 4 s period, were separated by a 100 ms delay, and had a < 100 ms inflation time. After each trial, the subjects had to inform the operator whether the first or second stimulus had more pressure. The 15 sequential actuation trials were selected pseudo-randomly from all of the possible combinations, with each combination repeated at least once. Subjects placed their index fingers in contact with the balloon actuators, and the same finger was used for the duration of testing. Accuracy was calculated based on the percentage of total correct responses divided by the total number of trials.

3. Results

Table 1 provides the results of the human perceptual tests. The total numbers of trials are different for each combination due to the pseudo-random selection of each trial sequence. Figure 4 shows the detection accuracy for each balloon diameter and each actuation combination. Combination 0-100 achieves the highest average accuracy (100%) of all six combinations. Responses for the 0.75 mm balloon diameters under combination 50-0 were the least accurate (50%) and were significantly worse than any other combination ($p<0.05$, χ^2 test). Combinations 0-50 and 50-0 accounted for 72% of total inaccurate responses. 92.3% of the inaccurate responses from combinations 0-50 and 50-0 were experienced with 0.75 and 1.0 mm diameter balloons. Overall, combination 50-0 had the lowest average accuracy (83%).

Average accuracy as a function of balloon diameter is shown in Figure 5. Average accuracy was directly proportional to balloon diameter, with the lowest average accuracy (86.4%) for the smallest balloon diameter (0.75 mm). This performance was significantly worse than that seen with the 1.5 and 2.0 mm balloons ($p<0.03$, χ^2 test). In the debriefing, subjects indicated that 0.75 and 1.0 mm balloon diameter tests required greater concentration than the 1.5 and 2.0 mm balloons. For balloons with 0.75 mm and 1.0 mm diameters, the average accuracy under combination 0-100 and 100-0 was 96.7%, whereas that of combination 0-50 and 50-0 was only 76.9%. These results indicate that it was significantly more difficult to determine more than two pressure levels in the 0.75 and 1.0 mm balloons ($p=0.001$, χ^2 test).

Table 1. Human Perceptual Test Results

Balloon Diameter	**0.75 mm**		**1.0 mm**	
Combination	**Number of Trials**	**Accuracy (%)**	**Number of Trials**	**Accuracy (%)**
0-50	12	83.3	13	84.6
50-0	14	50	13	92.3
0-100	12	100	11	100
100-0	15	93.3	15	100
50-100	12	91.7	13	100
100-50	10	100	10	90
Balloon Diameter	**1.5 mm**		**2.0 mm**	
Combination	**Number of Trials**	**Accuracy (%)**	**Number of Trials**	**Accuracy (%)**
0-50	13	100	12	100
50-0	14	92.9	14	100
0-100	11	100	11	100
100-0	14	100	16	93.8
50-100	13	92.3	12	100
100-50	10	100	10	100

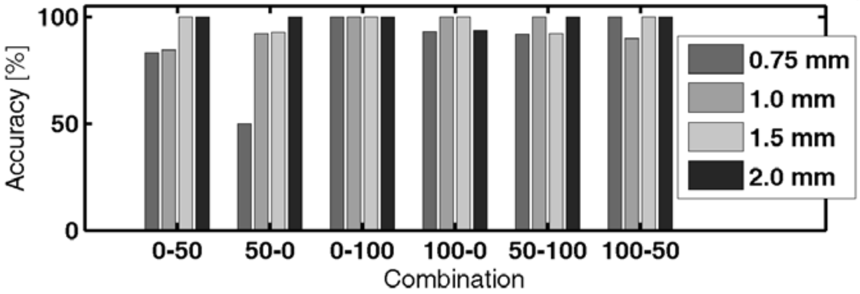

Figure 4. Detection accuracy of each balloon diameter and each combination of the sequential actuation.

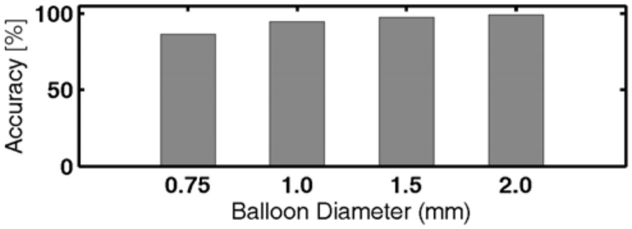

Figure 5. Average detection accuracy of each balloon diameter

4. Discussion

Balloons with diameters larger than 1.0 mm deliver high accuracy (>90%) in all sequential actuation combinations and no significant differences were seen in performance among any of the combinations. This result suggests that balloons with diameters larger than 1.0 mm can effectively deliver three or more levels of reliable tactile sensation, and that the number of detectable inflation levels increases with diameter. This observation is consistent with previous studies, which have demonstrated that a range of forces between 10 and 70 g wt can be estimated in solid spheres with radii as small 1.4 mm [12].

In addition to reduced accuracy of the 0.75 and 1.0 mm balloons, the requirement of increased concentration for sensing multiple inflation levels of these balloons might adversely affect task performance; by dedicating more effort to interpreting the feedback information, a user's concentration on the task may be interrupted.

The relationship between balloon diameters and the number of detectable inflation levels is an important factor in determining the optimal balloon diameter for a haptic feedback actuator. Ideally, an actuator that can generate a higher number of discreet levels will deliver more dynamic haptic feedback, allowing the tactile information to more closely resemble the actual sense of touch. However, larger balloon diameters limit the number of actuator array elements that can be organized in a fixed space, therefore decreasing spatial resolution. Future studies will focus on actuator miniaturization, fabrication techniques, frequency response, and optimization of balloon diameters, element spacing, array sizes, and geometries.

5. Summary

The presented pneumatic balloon actuator array has many advantages, including flexibility, low mass, compact size, scalability, and adaptability. Preliminary human perceptual tests have demonstrated that balloon diameters greater than 1.0 mm provide effective haptic feedback to the human index finger. When combined with a micro-sensor array and closed-loop pneumatic system and integrated onto robotic surgical instrumentation, surgical performance and training can be improved and enhanced. In addition to surgical applications, many other fields such as virtual reality-based simulators and neuroprosthetics may benefit from this technology.

6. Acknowledgements

The authors would like to thank Dr. E. Carmack Holmes for his support of this project, and Mr. Sam Y. Bae and Mr. Victor White of the Jet Propulsion Laboratory for their creativity and their contributions to this work. The authors most gratefully appreciate funding provided for this work by the Telemedicine and Advanced Technology Research Center (TATRC) / Department of Defense under award number W81XWH-05-2-0024.

References

[1] Feussner H, Siewert JR, “Reduction of surgical access trauma: reliable advantages”, *Chirug* 2001 Mar 72(3):236-44.

[2] Jacobs JK, Goldstein RE, “Laparoscopic adrenalectomy: a new standard of care” *Ann of Surg,* 225(5): 495-501, 1997.

[3] Sung GT, Gill IS, “Robotic Laparoscopic Surgery: A Comparison of the *da Vinci* and Zeus Systems,” *Urology*, 58: 893-898, 2001.

[4] Chapman WHH, Albrecht RJ, Kim VB, Young JA, “Computer-Assisted Laparoscopic Splenectomy with the da Vinci™ Surgical Robot.” *J. Laparoendosc. Adv. Surg. Tech*., 12(3): 155-159, 2002.

[5] Hayward, V., Cruz-Hernandez, M, “Tactile Display Device Using Distributed Lateral Skin Stretch,” in *Proc. of 8th Symp. On Haptic Interfaces for Virtual Environment and Teleoperator Systems*, *ASME IMECE2000*, 2000, pp. 1309–1314.

[6] Kontarinis DA, Son JS, Peine W, Howe RD, “A tactile shape sensing and display system for teleoperated manipulation,” in *Proc. IEEE Int. Conf. Rob. Autom.*, 1995, pp. 641–646.

[7] Hannaford B, Trujillo J, Sinanan M, Moreyra M, Rosen J, Brown J, Lueschke R, MacFarlane M, “Computerized endoscopic surgical grasper,” in *MMVR-98*, Jan. 1998, pp. 111-117.

[8] Okamura AM, Webster RJ, Nolin JT, Johnson KW, and Jafry H, ”The Haptic Scissors: Cutting in Virtual Environments,” in *Proc. IEEE Int. Conf. Rob. Autom.*, 2003, pp. 828-833.

[9] Taylor R, Jensen P, Whitcomb L et al, “A steadyhand robotic system for microsurgical augmentation,” *Int. J. Robotic. Res.*, 1999;18:12.

[10] Moy G, Wagner C, Fearing RS. "A compliant tactile display for teletaction," in *ICRA 2000 IEEE Int. Conf. Rob. Automat.*, 2000, pp. 3409 - 3415.

[11] Caldwell,DG Tsagarakis N, Giesler, C, "An Integrated Tactile/Shear Feedback Array for Stimulation of Finger Mechanoreceptor", in *Proc. IEEE Int. Conf. Rob. Autom.*, 1999, pp. 287-292.

[12] Goodwin AW, Wheat WE, “Magnitude estimation of contact force when objects with different shapes are applied passively to the fingerpad,” *Somatosens. Mot. Res*. 9:339-344, 1992.