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Head-mounting Surgical Robots for Passive Motion Compensation

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INTRODUCTION

Many up-and-coming therapeutic protocols in ophthalmology are technically difficult, near/beyond the limits of human ability, and are being attempted by only a few surgeons. For example, subretinal injection of stem cells or gene therapies requires placement of a fine cannula in the subretinal space, holding that position steady for ~90 s to inject a bleb of fluid. Surgeon hand tremor places a limit on achievable precision. A wide variety of robot-assisted surgical systems have been proposed to improve the precision of eye surgery [1]. However, there has not been much consideration of patient head motion, which is common among patients undergoing eye surgery under monitored anesthesia, a.k.a. conscious sedation, which makes a patient calm and somewhat sleepy during a surgery, but the patient may still be awake. Head motion in this state is due to breathing, talking, snoring, and other (in)voluntary motions of the patient. Of the 16% of patients who snore under monitored anesthesia, half have sudden head movement during surgery [2]. Movement must be compensated by the surgeon, to the best of their ability, to avoid complications. Benchtop experiments with artificial or enucleated (i.e., *ex vivo*) eyes, which are typical in the development of robotic systems, do not capture the effect of patient motion. Limited *in vivo* studies in humans have placed the patient under general anesthesia [3], [4], which is not typical of eye surgery and results in reduced patient movement (the patient is still breathing, of course). Any clinical robotic system must deal with patient motion. Active compensation (i.e., closed-loop control) can involve sensing the force between the surgical instrument and the eye, or using visual-servoing techniques, or some combination of both [1].

Two groups (including ours) have developed compact telerobotic systems motivated by the prospect of mounting the robot directly to the patient's head to passively compensate for patient motion [5], [6]. However, to date, neither has actually mounted their robot on a living human, let alone quantify the benefits of head mounting. Mounting a robot to a patient's head is not a trivial task. The only way to rigidly mount a robot to a patient's head would be to drill into the skull, which is very invasive compared to current eye surgery. With alternative methods, the soft tissue surrounding the skull makes a truly rigid connection essentially impossible. In [5], the authors proposed a mechanism that would allow their manipulator to be pressed against the patient's face to form a semi-rigid connection. In a more recent work, they proposed a mechanism that would semi-rigidly fix the patient's head with respect to the surgical bed, using granular jamming, and then the robot would be mounted on that head-fixation system [7]. An alternate strategy is to mount directly to the patient's eye, but thus far this has been limited to one-degree-of-freedom robots [8].

In this paper, we introduce a noninvasive head-mounting concept, based on a modified radiotherapy immobilization system, which enables one or more robots to be mounted semi-rigidly to a patient's head (Fig. 1), and we perform an experiment that highlights the potential benefits of this form of head mounting.

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Fig. 1 Radiotherapy immobilization system modified to enable surgical robots to be quick-connected magnetically through a standard surgical draping (not shown). System shown fitted with one robot and counterweights for balance. (Inset) In this study, tracking markers placed on the robot and goggles are used to quantify the displacement of the robot relative to the goggles (i.e., the eye) due to breathing/snoring motion of the wearer.

MATERIALS AND METHODS

We modified a CIVCO Solstat Immobilization System with a U-shaped 8-mm-thick aluminum mounting plate to enable one or more surgical robots to be mounted with high stiffness at the connection (Fig. 1). We modified the

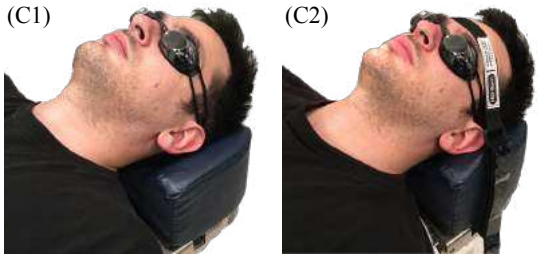

Fig. 2 Control conditions: (C1) Head resting on pillow; (C2) Strap holding head tightly on pillow.

Solstat's quick-release clips, which attach the custom-fit thermoplastic face mask, to accommodate the additional thickness of the plate. The Solstat's masks are already compatible with the standard surgical draping. On/off magnets in the aluminum plate enable the robot(s) to be attached after the draping is applied. We removed the Solstat's component used to rigidly attach it to a table (during radiotherapy), enabling it to fit on a Stryker stretcher pillow. The weight of the robot(s) is carried by the Solstat, not felt by the wearer. Since we only used one robot (which is a modification of [6]), counter-weights were used to eliminate an applied moment.

We performed an experiment to quantify eye movement relative to a static world frame (i.e., the Leica ophthalmic microscope) in three conditions—the head resting on the pillow (C1), the head strapped down to the pillow (C2), and wearing our head-mounting device on the pillow (C3)—and in the final condition, to quantify the movement of the head-mounted robot relative to the eye (C4). C1 and C2 (Fig. 2) represent cases where a surgical robot would be mounted to the bed or bedside table. The position of the eye was tracked using a Sony PMW-10MD camera recording video through the lens of the microscope, using a colored marker attached to swim goggles that are effectively rigidly connected to the skull due to their tight fit in the eye sockets (Fig. 1); the robot was similarly tracked in C4. For each condition, video was recorded for 11 inhale-exhale cycles (i.e., trials), each starting fully exhaled, for gentle (but not shallow) breathing and for deep snoring-like rapid inhalations. The wearer kept his body otherwise still and relaxed. The markers were localized in the images during post-processing. Scale bars of known length on the markers were used to determine the conversion from pixels to millimeters, with the assumption that the markers primarily moved in a horizontal plane. The 2D vector displacement relative to the initial condition was recorded, and converted to a scalar magnitude.

RESULTS

Figure 3 shows peak movement of the goggles relative to the world frame (and thus the eye relative to a hypothetical bed/table mounted robot) was as high as 2.2 mm for gentle breathing and 5.2 mm during snoring-like movements with the control conditions; the head strap was ineffective at mitigating these relatively small motions. The largest movement of our head-mounted robot relative to the goggles (and thus to the eye) was 0.2 mm for gentle breathing and 0.9 mm for snoring-like movements. Analysis of variance, using a Bonferroni correction, indicates that these differences are significant ($p < 0.001$) for both types of movement. Our head-mounting device itself did not reduce patient motion.

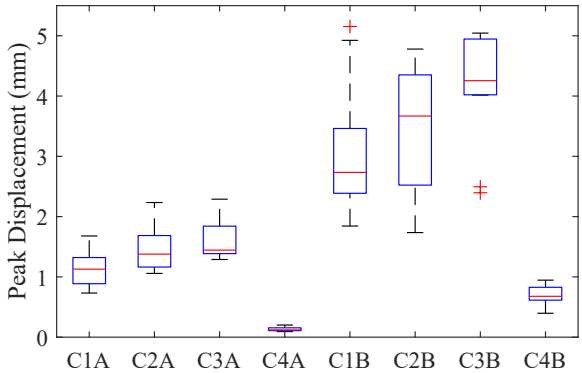

Fig. 3 Box-whisker plots (N = 11) of peak displacement of goggles with head resting on pillow (C1), head strapped to pillow (C2), and when using the head-mounting system (C3), as well as the head-mounted robot relative to the goggles (C4), for gentle breathing (A) and deep snoring-like rapid inhalation (B).

DISCUSSION

These results highlight the potential for head-mounting teleoperated surgical robots to provide substantial passive motion compensation for improved precision and patient safety. In our experiments, no instruments were inserted in the eye, which would further stabilize the eye and reduce relative motion. Also, we rested the head-mounting device on the pillow, which may not be optimal. Finally, passive compensation should be viewed as complementary to active compensation.

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