Can Coffee Improve Surgical Robot Accuracy?

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INTRODUCTION

Transnasal skull base and sinus surgery is often assisted via image guidance systems (e.g. the Brainlab Kolibri [1] – Fig. 1) which show the real-time locations of surgical instruments with respect to the 3D map provided by preoperative volumetric medical images. Image guidance systems often employ optical tracking to measure in real time the locations of both surgical instruments and the patient's head. The accuracy of these systems relies on the rigid coupling between optical tracking markers and the patient. However, the markers are often attached to the patient using an elastic headband that can shift if bumped during use [2].

In this paper, we propose the use of both layer jamming and granular jamming to improve the accuracy of image guided robotic transnasal sinus and skull base surgery. Granular jamming involves drawing a vacuum on a bag filled with granules (e.g. coffee grounds) [3]. Layer jamming involves drawing a vacuum on a bag filled with thin layers of material, to increase the normal force between them and thus prevent them from sliding over one another [4]. We use these technologies to securely and non-invasively attach optical tracking markers to the patient, which enables accurate registration of preoperative medical images to guide surgical robotic systems, or even manually operated instruments. The prototype described in this paper extends our prior work in which granular jamming alone was used with a plastic frame [2]. Here, we use layer jamming in conjunction with granular jamming to create a headband that conforms to the patient's head, becoming rigid when a vacuum is drawn.

An example of where this would be useful is in robot-assisted drilling. Drilling is often required as a first step in transnasal skull base and sinus surgeries to access the surgical site. It has been previously shown that collaborative human-robot systems (in which both the surgeon and the robot hold the drill simultaneously) can assist the surgeon [5] by enforcing virtual fixtures (see [6] for a review) around sensitive anatomy. Another example where registered images and virtual boundaries can be useful is in pituitary surgery, where they have been proposed as a means to prevent damage to the optic nerves and carotid arteries in manual [7] and robotic [8] surgical approaches.

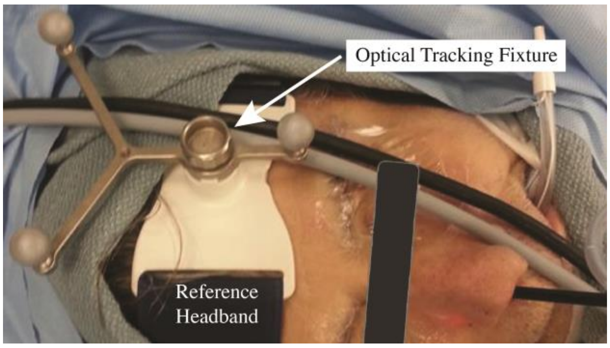

Fig. 1 The Brainlab Kolibri reference headband with an optical tracking fixture attached is shown positioned on a patient during an image-guided transnasal surgery.

MATERIALS AND METHODS

The use of granular jamming and layer jamming in concert enables our headband to both locally and globally conform to the patient's head and then solidify. This enables the headband to non-invasively, yet rigidly, affix optical tracking markers to the patient (see Fig. 2). The granular jamming pads enable local conformation to the contours of the patient's head and layer jamming creates a structure to connect the pads to one another that can similarly stiffen when a vacuum is drawn. The layer jamming band consists of a 0.25 inch stack of 20lb bond paper sealed within an airtight plastic sleeve (Uline, WI, USA), and the granular jamming pad consists of a latex membrane filled with ground coffee. The sleeve was sealed around the paper using a heat sealing machine. To facilitate optical tracking a fixture containing fiducial markers was screwed to the layer jamming band.

To mount the device to a patient, the elastic band surrounding the layer jamming band is first cinched tight, and then a vacuum is drawn on both the granular and layer jamming components to solidify them. A felt tip was used on the ends of the vacuum tubing to ensure that coffee was not suctioned into the tube.

The granular jamming pads are positioned on the temples and at the back of the head as shown in Fig. 2 to position them over areas of the skull with significant variation in

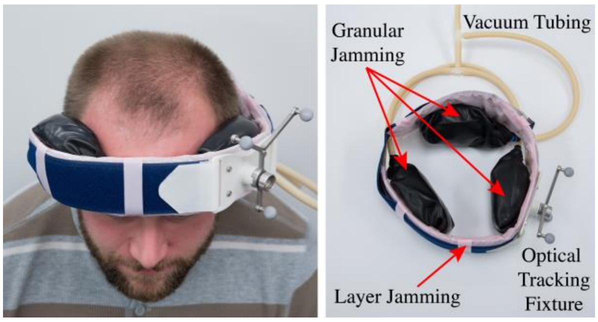

Fig. 2 Our new fixation device features three granular jamming pads, which conform to the patient's skull, and are mounted to a layer jamming band that can solidify to hold them in place relative to one another when a vacuum is drawn.

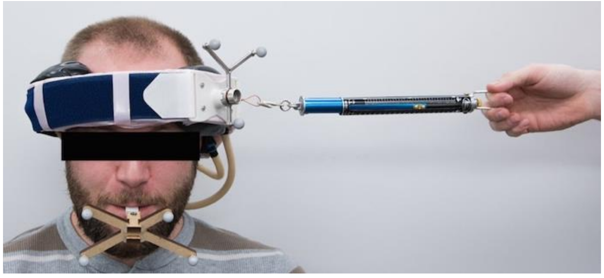

Fig. 3 The test setup for our experiments applying perturbations to the granular/layer jamming headband. A spring scale was used to pull on the headband in four different directions. The movement of the headband markers with respect to bite block markers was measured using an optical tracker as force was applied by hand using the spring scale.

local curvature. After the pads conform to these areas, the layer jamming band holds them in place relative to one another. The elastic band that surrounds the layer jamming band serves to apply an inward force on all components so that the granular jamming pads do not pull away from the patient as they solidify.

In our experiments, we followed the typical clinical positioning of the optical tracking fixture over the patient's left temple – this positioning keeps it out of the surgeon's way and aims it towards the typical tracker mounting location. To test the performance of our device against the standard Brainlab headband, we performed a series of force perturbations (9.81 Newtons) in four directions (up, down, left, and right in the plane tangent to the patient's head under the optical tracking fixture, with "up" being toward the crown of the patient's head). We then optically tracked the position of both the fiducials on the headband, and a second set of fiducials on a bite block in the patient's teeth (see Fig. 3). Note that these forces were applied by hand with a spring scale, and that while every attempt was made to increase the force linearly with respect to time, since the pulls were applied by hand this was not controlled precisely. Tracking was accomplished using the Polaris Spectra (Northern Digital Inc.).

RESULTS

We recorded the movement of the headband markers relative to the bite block markers for both the Brainlab headband and our new granular/layer jamming headband due to the force perturbation, with results shown in Fig. 4. These tests were used to compare the ability of the two headbands to fix the optical tracking markers to the head. Compared to the Brainlab headband, the granular/layer jamming headband reduced the maximum error by 15.1 mm, 7.8 mm, 6.1 mm, and 12.5 mm in the down, up, left, and right directions, respectively.

DISCUSSION AND CONCLUSION

The granular/layer jamming headband presented here provides superior rigidity compared to the standard Brainlab headband. It appears to us that the main source of error with the Brainlab headband is skin mobility over the surface of the skull. The granular jamming pads mitigate this mobility by conforming to areas of

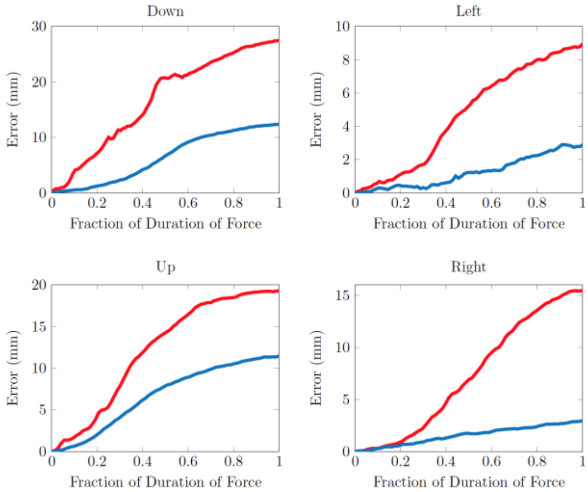

Fig. 4 The error (i.e. movement) of the Brainlab headband (red) vs. the granular/layer jamming headband (blue) as a force of 9.81 N was applied by hand using a spring scale.

curvature variation in the skull. In a real-world operating room we expect a wide variety of perturbation conditions, both constant and intermittent, including those caused by impact, constant loads such as those applied by the wires shown in Fig. 1, etc. We leave it to future work to study the effects of more complex loading conditions, but note that we studied pull and release loads using granular jamming alone in [2]. It is also worth noting that rigidly affixing objects to the patient using our technique has implications beyond image-guidance. It may be useful to attach robots directly to the skull in the future, especially in the context of eye surgery where skull motion relative to the robot can lead to damage to sensitive intraocular structures.

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