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Coffee: The Key to Safer Image-Guided Surgery – A Granular Jamming Cap for Non-Invasive, Rigid Fixation of Fiducial Markers to the Patient

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Abstract

Purpose: Accurate image guidance requires a rigid connection between tracked fiducial markers and the patient, which cannot be guaranteed by current noninvasive attachment techniques. We propose a new granular jamming approach to firmly, yet non-invasively, connect fiducials to the patient.

Methods: Our granular jamming cap surrounds the head and conforms to the contours of the patient's skull. When a vacuum is drawn, the device solidifies in a manner conceptually like a vacuum-packed bag of ground coffee, providing a rigid structure that can firmly hold fiducial markers to the patient's skull. By using the new Polaris Krios optical tracker we can also use more fiducials in advantageous configurations to reduce registration error.

Results: We tested our new approach against a clinically used headband-based fiducial fixation device under perturbations that could reasonably be expected to occur in a real-world operating room. In bump testing we found that the granular jamming cap reduced average TRE at the skull base from 2.29 mm to 0.56 mm and maximum TRE at the same point from 7.65 mm to 1.30 mm. Clinically significant TRE reductions were also observed in head repositioning and static force testing experiments.

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Conflict of interest Patrick Wellborn, Neal Dillon, Paul Russell, and Robert Webster III declare that they have no conflict of interest.

Ethical approva All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This article does not contain any studies with animals performed by any of the authors.

Informed Consent This article does not contain patient data.

Conclusions: The granular jamming cap concept increases the robustness and accuracy of image guided sinus and skull base surgery by more firmly attaching fiducial markers to the patient's skull.

Keywords

Registration; Image-Guided Surgery; Endonasal Surgery; Skull Base Surgery; Granular Jamming

1 Introduction

Image guidance systems are often used to assist in transnasal surgeries including various sinus procedures and endoscopic surgery to remove pituitary tumors. The image guidance system provides the surgeon with a display showing the surgical tool's position with respect to registered pre-operative medical images. Image guidance helps the surgeon navigate to the desired location and avoid delicate critical structures such as the optic nerves and carotid arteries. Thus, accurate registration of the pre-operative image space to the patient in the operating room is critical for safe and effective image guidance [3].

Since the patient's head must be repositioned during surgery to enable the surgeon to obtain advantageous tool angles, the head must be tracked to maintain this registration. Tracking is enabled via fiducial markers that are attached to the patient. These are tracked using an electromagnetic (e.g. the Fusion ENT system by Medtronic, Inc.) or optical (e.g. the Kolibri system by Brainlab, Inc.) tracking system. Fiducials may be attached to the patient in a variety of ways [3,10,11,17]. Of these, stereotactic frames and fiducials that screw directly into the bone are typically avoided in endonasal surgery to reduce invasiveness. Instead, fiducials are attached to the patient non-invasively in the operating room and surface-based registration [3] is used.

For example, the Brainlab Kolibri system uses an elastic headband and double-sided tape to secure a three-prong rigid body to the patient's forehead (see Fig. 1), with each prong supporting a spherical fiducial marker that can be tracked by a stereo camera system. After the headband is placed on the patient in the operating room, the fiducials are registered to patient and image space using a "brow scan" technique. The surgeon uses either a laser pointer to cast infrared rays over the skin of the patient's brow, which are detected by the tracker, or the tip of a tracked pointer to touch multiple surface points on the patient's brow. These points are then registered to the corresponding anatomical surfaces identified in image space. Note that skin-affixed fiducials can also be used with systems of this type, but skin mobility can be very high [12], making this an imperfect solution.

A fundamental assumption with all systems of this type is that the fiducials are rigidly connected to the patient's skull. Since the surface-based registration is performed only once at the start of the procedure, any motion of the fiducials with respect to the skull will result in the patient's anatomy no longer aligning with the preoperative CT scan, and hence the tip of the surgical tool being displayed to the surgeon at an erroneous location. This occurs regularly in surgery. In fact, one study reported that 14% of the time errors are so large that physicians noticed large error and had to re-register the system [9]. Additionally, surgeons report that there is an ongoing loss of neuronavigation accuracy after initial registration due to multiple different factors [14]; therefore, ensuring accurate registration throughout the entire procedure is important. Even in "good" cases, the average TRE observed by the authors was approximately 2 mm, which is larger than one would expect from a theoretical perspective, based on the patient-fiducial geometry and typical brow scan point collection error [18]. However, this level of error is easily explainable when one considers relative motion between the fiducial markers and the patient's skull. The elastic band may shift in response to unmodeled perturbations (e.g. light accidental bumps of the fiducial markers by the operating room staff and/or repositioning of the patient's head which occurs routinely). Experiments later in this paper show that these perturbations can easily explain 2 mm TRE as well as the 14% of cases with very large error. It is worth noting that even if the rigid body containing the fiducials remains perfectly stationary with respect to the skin (double-sided tape is used to secure it), the skin is mobile with respect to the skull. Experiments have shown that human skin can move 5.34 ± 2.65 mm (maximum 13.1 mm) relative to the underlying skull [12]. Others have noted similar problems with errors stemming from inadequate reference frames during image-guided skull base surgery and have explored devices that attempt to reduce TRE [7].

In this paper we propose a novel granular jamming cap as a means to more firmly (yet still non-invasively) attach fiducial markers to the patient. This paper presents an extension to our initial explorations into granular jamming [15,18] in which we positioned several granular jamming pads on the head, which were connected to one another with either a rigid or layer jamming frame. We showed that these can reduce TRE by over 50%. Here, we dispense with the individual pads and the support structure, and instead configure the granular jamming chamber to envelop the head. In this configuration, it forms a helmet-like shell fitted to the contours of the patient's skull when the vacuum is drawn, facilitating higher image guidance accuracy and robustness, and simplifying the device from a mechanical design perspective. Registration is accomplished using the brow scan technique, described above for the Brainlab system.

We compare the performance of this new device experimentally against the standard elastic headband and double sided tape fixation used in the Brainlab Kolibri system. To each we apply both impact and static force perturbations simulating accidental bumping of the fiducials and the structures supporting them. We also explored the effects of the head repositioning movements typically used in endoscopic sinus surgery, as applied by an experienced sinus surgeon.

An added benefit of the cap concept is that many fiducial markers can be placed on its surface so that they surround the head, which is an advantageous configuration for facilitating low TRE within the head [4], since the centriod of the fiducials is much closer to the targets of surgical interest. However, since the locations of the fiducials with respect to one another cannot be known a priori (they are attached to a medium that is deformable until the vacuum is drawn), this fiducial confguration requires a new tracking approach. Fortunately, the Polaris Krios system has just been released on the market and offers exactly the capabilities our system requires. Designed to be a hand-held digitizing scanner for scanning the locations of many EEG probes on the skull simultaneously, it is able to learn the spatial relationships of many fiducials with respect to one another on the fly. It is also robust to occlusion of subsets of fiducials. This enables us to place many fiducial markers distributed over the exterior surface of the cap and track them in real time. The positions of these fiducials relative to one another need only be fixed during tracking (which they will be after the vacuum is drawn), but need not be specified a priori.

Prior to our initial conference papers that served as preliminary studies for the current paper [15,18], granular jamming had not been applied to image-guided surgery. It has been used in the past as a robot gripper for industrial applications [1]. It is based on the ability of particles to flow over one another when loose, and lock together when compressed under vacuum pressure [8,5] just as vacuum packed co ee is solid until the vacuum seal is broken. In addition to robotic grip-pers, granular jamming has been used in robotics to enable locomotion [13] and create variable sti ness robots [2,6].

2 Design of Granular Jamming Cap

The design of the Granular Jamming Cap (GJC) holds two inherent advantages towards higher accuracy, namely the method of fixation and the optical marker placement. Designed to encapsulate the head, the cap is comprised of two silicone caps with one nested inside of the other. Filling the void between the caps is a granular substance, ground coffee, that is able to flow freely and conform around the contours of the patient's skull. On top of the cap is a port for attaching a tube that is used to pull a vacuum on the void between the caps (see Fig. 2). In doing so, the granules jam together as they go from freely flowing to extremely rigid under vacuum (see Fig. 3). Due to the elasticity of the silicone, the granules are pulled towards the skull as they jam together, which ensures a shape that tightly encompasses the contours of the skull for increased fixation. Adding to the rigidity and combating the shift of the cap against the skin is the fact that the silicone has a large coefficient of friction. The result is a granular jammed cap that is rigidly and non-invasively fixed to the skull. The granular jamming cap locks onto the skull, minimizing skin mobility while retaining a truly non-invasive fixation of the fiducials.

In addition to improved fixation to reduce TRE, the GJC reduces TRE further through its unique design of fiducials surrounding the head. It has been shown by West et al. [16] that adding more tracked markers that ensure that the centroid of the fiducials is as close to the target region as possible effectively lowers the TRE. With the ability to simply stick adhesive retro-reflective markers anywhere on the cap, the GJC design ensures proper surrounding of any target point within the skull. The GJC contains 85 fiducials that surround the skull. The Polaris Krios handheld scanner enables this fiducial configuration, since this tracker can learn the geometric relationships between fiduicals on the fly and is robust to fiducial occlusions. After the vacuum is applied and the GJC is hardened, the Krios is used to scan the markers and generate the map of fiducial markers that is subsequently tracked during surgery.

3 Experiments

To compare the Granular Jamming Cap (GJC) to the Brainlab Reference Head-band (BRH), we performed three tests to simulate potential perturbations to the fixation device that may occur during surgery: an impact test, an applied static force test, and a patient repositioning test. The repositioning test offers the most realistic operating room scenario, since the patient's head is routinely moved by the surgeon to obtain optimal tool operating angles. The impact and applied static force tests represent a conservative worst-case scenario for how the fixture may be accidentally perturbed in the operating room by nurses or doctors. The experiments offer a repeatable way to compare the fixation of each device, since the testing parameters (i.e. the impact force and applied static force) can be controlled.

For each test, a bite block with four optical tracking markers served as a ground truth to measure the relative movement between the fixation device and the skull due to the perturbations. Both the bite block and the fixation device were tracked simultaneously (see Fig. 5) to capture any relative movement between the fixation device and the skull. A clinically relevant point at the pituitary gland was used as the target point for error calculations (see Fig. 6). This point was chosen since it is a point where the surgeon must reach with his/her surgical device for multiple endonasal skull base surgical interventions. Registration of the patient to the CT scan was not necessary for these experiments, since we were comparing shifts of the fixation devices after registration that add to the overall TRE. We used a real patient CT scan to estimate the position of the pituitary gland with respect to the bite block; the exact target position is not crucial, as long as the point is in the surgical area. The TRE was calculated by taking the change in relative transform between the fixation device and bite block, applied at the pituitary target point.

To track the BRH, we used the Polaris Spectra (Northern Digital Inc., Waterloo, Ontario, Canada), as it is the same hardware as that is used in the Brainlab surgical systems for optical tracking. For the GJC, we used the Polaris Krios to both create the rigid body (see Fig. 4) from the fiducial array surrounding the cap and to track its movement. It is important to note that the use of two different trackers does not unfairly impact the comparison between the two fixation devices since the FLE of the Spectra is lower than that of the Krios (0.30 mm RMS error vs. <0.5 mm RMS error per the product specifications). Before tracking for the GJC experiments, we placed the cap with pre-affixed fiducial markers (85 adhesive sticker markers) on the patient's head, hooked up a vacuum hose to the port on the top of the cap, and pulled a vacuum to solidify the cap. The markers were then localized to build the rigid body of the GJC. The rigid bodies for the BRH and both bite blocks were calibrated prior to the experiments.

3.1 Impact Testing

The first set of tests looked at the response of the two fixation devices to impacts. The motivation of this test is to evaluate the fixation device's resistance to accidental bumps that occur during surgery. A tennis ball filled with plastic media (m=0.119 kg) was attached to a string (l=63.5 cm) that was tied to a frame above the fixation device and used as a pendulum. It was was dropped from an angle of approximately 75° from the vertical and impacted the fixation device at approximately 3 m/s. The direction of impact was varied and the resulting relative motion between the bite block coordinate frame and the fixation device was recorded after each impact.

Two sets of ten impacts were performed for each device. The mean TRE for the GJC after impact was 0.56 mm, compared to 2.29 mm for the BRH. The maximum TRE after impact was 1.30 mm and 7.65 mm for the GJC and BRH, respectively.

3.2 Applied Force Testing

The next test consisted of applying a known force to the fixation device from different directions. This test represented situations in the operating room when other equipment may be accidentally pushed against the device (e.g. endoscope cables draped over the patient). This test was performed by pushing on the fixation device with a probe connected to a force gauge. Two iterations of this test were performed on the BRH: forces applied to the elastic band of the BRH and forces applied to the fiducial markers of the BRH.

Ten push forces were applied for each test, and the applied forces ranged from 10–15 N. The mean TRE for the GJC was 0.63 mm. The mean TRE for the BRH was 7.77 mm when the force was applied directly to the markers and 2.54 mm when the force was applied to the elastic headband. The maximum TRE for the GJC, BRH (force applied to markers), and BRH (force applied to headband) was1.25 mm, 14.23, and 5.60 mm, respectively.

3.3 Head Repositioning Testing

Finally, a test of relative motion as a result of routine patient repositioning was performed. In sinus surgery, the patient’s head is repositioned several times to enable better access to different regions of the skull base. For this test, an experienced surgeon moved the test subject’s head to the 6–7 positions that are typical in endonasal skull base surgery and the resulting motion of the fixation device was recorded. The test was repeated twice for each fixation device. Unlike the prior two tests, which represent accidental displacements, this test represents expected displacements in routine surgery.

The mean TRE during the repositioning test was 1.40 mm for the GJC and4.09 mm for the BRH. The maximum TRE was 1.96 and 6.64. Regardless of the test, the GJC substantially reduced the TRE compared to the BRH. Figure 10 provides a comparison of the mean, standard deviation, and maximum errors for all three tests for both fixation devices.

While the results clearly show the advantages of the GJC compared to the BRH, the testing methods were not without limitations. The “ground truth” measurements provided by the bite block likely contributed to the error measurements and it was impossible to isolate this error source from the displacement of the fixation device in this experimental setup. The subject reported slight motion in the bite block throughout the experiments and, given the position of the target point at the skull base relative to the fiducial markers on the bite block, small motions could lead to non-negligible errors at the target. However, given that the evaluation of both fixation devices was subject to this measurement error, we suspect that the actual error for both devices is slightly lower than what is reported here.

4 Conclusion

In this paper we have described the design and experimental testing of a new granular jamming cap concept that can secure tracking fiducials firmly and noninvasively to the patient. We have shown that it can substantially reduce both average and worst case errors in comparison to the Brainlab Kolibri system's headband-mounted fiducials. Specifically, our new design reduces worst case TRE at the skull base from 7.65 mm to 1.30 mm in impact testing, 6.64 mm to 1.96 mm when repositioning the head, and 14.23 mm to 1.25 mm under static loading.

We note that the current design which envelopes the head is suitable for sinus surgery but not applicable to neurosurgeries approached via craniotomy. It may be possible to adapt the basic granular jamming technique to an alternate form factor (see e.g. [15,18]), but further research will be required to assess the feasibility of doing so. Additionally, we note that the device is compatible with any patient, including those with long hair. Since the granular jamming cap conforms to the contours of the skull, long hair is compressed by the device, as it is in a swim cap. Further testing of the device with patients with long hair is necessary to determine if there is any difference in targeting error; however, qualitative assessment revealed no noticeable difference between those with short and long hair. Finally, no harm is inflicted on the patient when applying the vacuum. The design of the granular jamming cap prevents this, and no additional pressure beyond the pressure from the elasticity of the silicone cap will be felt by the patient. Since the vacuum is applied to the void between the inner and outer silicone caps, the forces push towards the middle of the void and not onto the patient's skull. Little to no difference was felt by the mock patient when the vacuum was applied, and the patient reported no discomfort due to the cap during testing.

Future work remains to make the granular jamming cap a robust clinical product. One objective is to replace the coffee grounds with a non-organic particle that does not biodegrade over time. The device must also be converted from a lab prototype to a commercial product suitable for operating room use. After these relatively minor changes, however, we believe this device can be immediately useful in increasing the accuracy and robustness of image guidance systems. If we are successful in accomplishing this, surgeons will benefit from increased confidence about their tool locations in sinus surgery, and patients will benefit from increasingly accurate, rapid, and safe surgeries.

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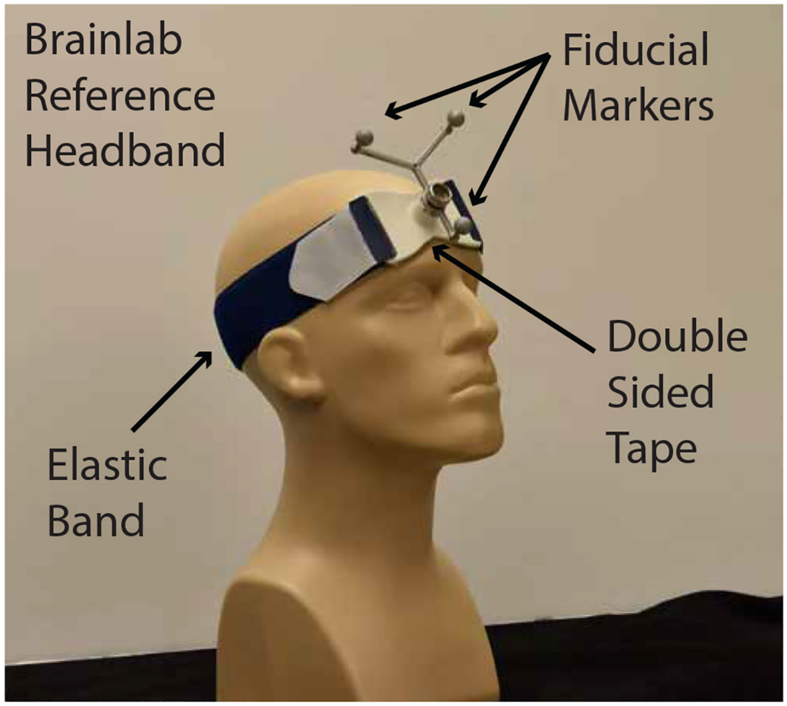

Fig. 1.

The Brainlab reference headband is shown with its features highlighted. The fixation device holds the fiducial markers to the head using double sided tape to stick to the forehead and then an elastic band to secure around the head.

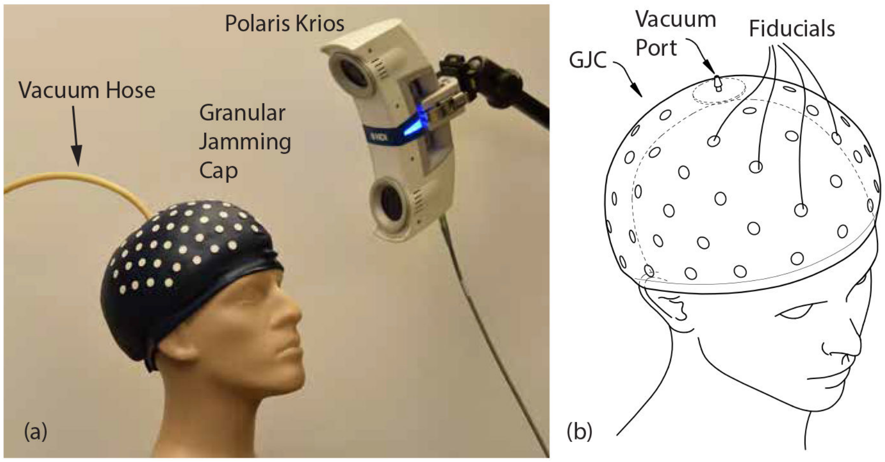

Fig. 2.
The design of the Granular Jamming Cap is highlighted here. In (a), the connected vacuum hose pulls a vacuum on the GJC to make the cap rigid. The Polaris Krios hand-held digitizing scanner is shown next the GJC, as it plays an important role in creating the rigid body from the array of fiducials. The schematic in (b) highlights the fiducial array that surrounds the cap and vacuum port located at the crown of the head.

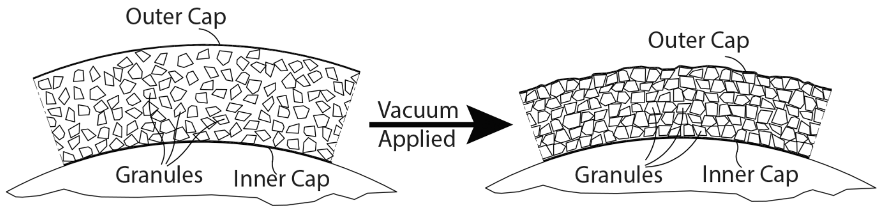

Fig. 3.

When a vacuum is applied on the void between the outer cap and the inner cap, the granules are jammed together to create a rigid fixture. This schematic gives a representation of the jamming process as the vacuum is applied. On the left, the granules are free to move and conform to any structure, but after a vacuum is applied, the granules jam together, just as shown on the right.

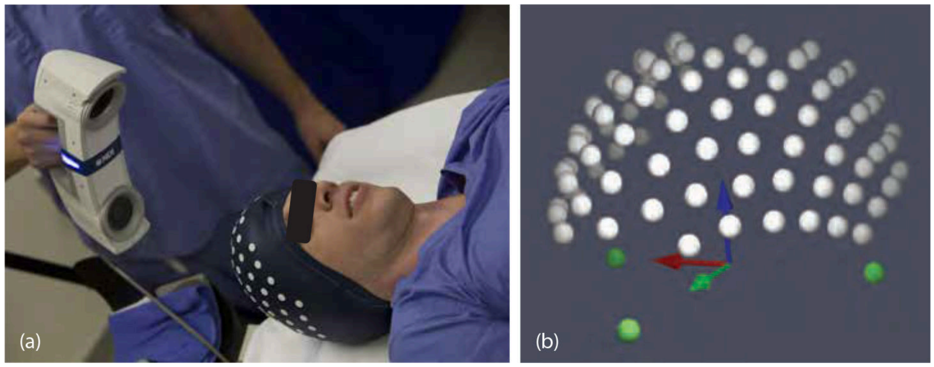

Fig. 4.

The Polaris Krios is used to create a rigid body from the array of fiducial markers attached to the outside of the Granular Jamming Cap, as seen in (a). In (b), the software of the Polaris Krios displays the locations of the fiducial markers and adds a coordinate frame to the rigid body. This scanning procedure was done before every experiment after the GJC was in the hardened state.

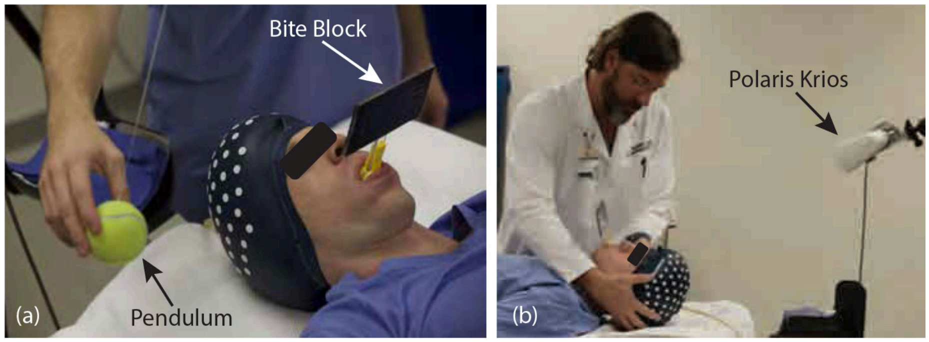

Fig. 5.

Two of the test setups: (a) Impacts were applied using a tennis ball as a pendulum suspended by a string. (b) Head repositioning by an experienced surgeon (co-author Russell) in ways that mimicked the head manipulation typically applied in surgery. In both cases, the Polaris Krios tracks both the GJC and a bite block to capture any movement of the GJC relative to the skull.

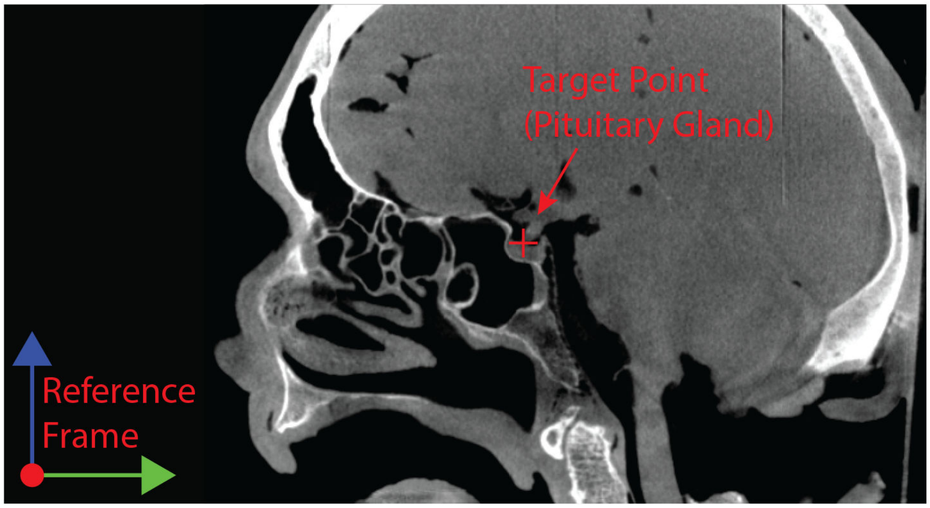

Fig. 6.

Target point located at the pituitary gland used in error calculations. This point was selected in a CT scan and its position relative to the bite block coordinate frame ("Reference Frame" shown in figure) was determined to enable calculation of TRE from the experimental data.

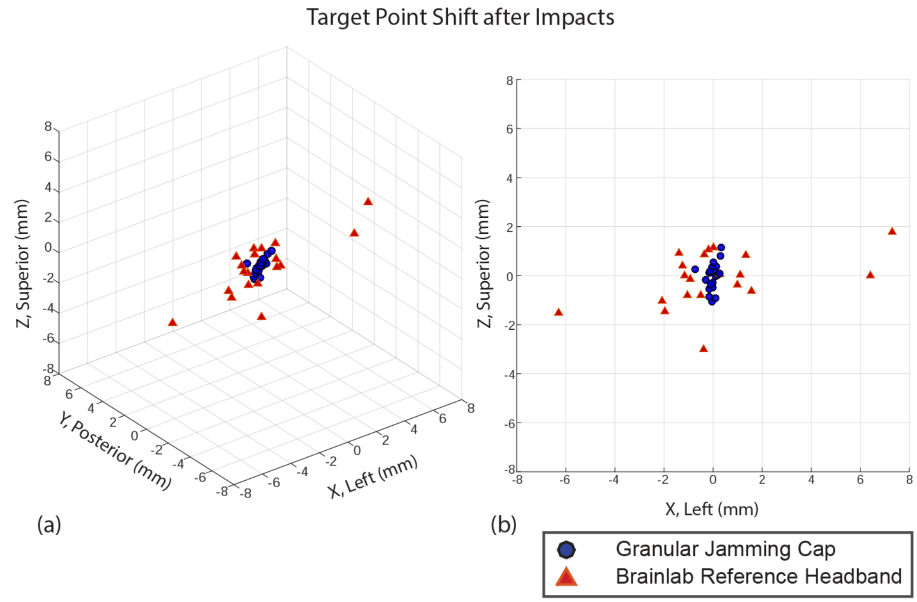

Fig. 7.
The shift in the target point after random impacts with a tennis ball pendulum is shown for both devices in the anatomical coordinate frame. The isometric 3D view is shown in (a) on the left. Since the majority of shift occurs in the coronal plane due to device constraints, this frontal view (b) is included on the right. In both views, it can be seen that on average the BRH shifts more than the GJC due to impacts.

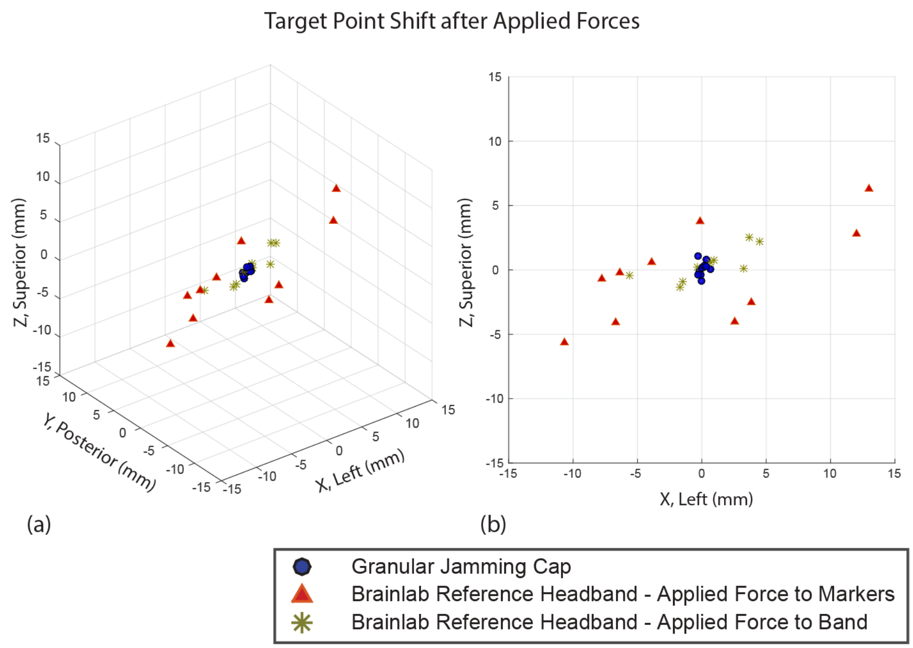

Fig. 8.

The shift in the target point after applied static forces with a compression force gauge is shown for both devices in the anatomical coordinate frame. For the BRH, the force was applied to markers in one experiment and the elastic band in the other. The isometric 3D view is shown in (a) on the left. Since the majority of shift occurs in the coronal plane due to device constraints, this frontal view (b) is included on the right. In both views, it can be seen that on average the BRH, regardless of location of force, shifts more than the GJC due to the applied forces.

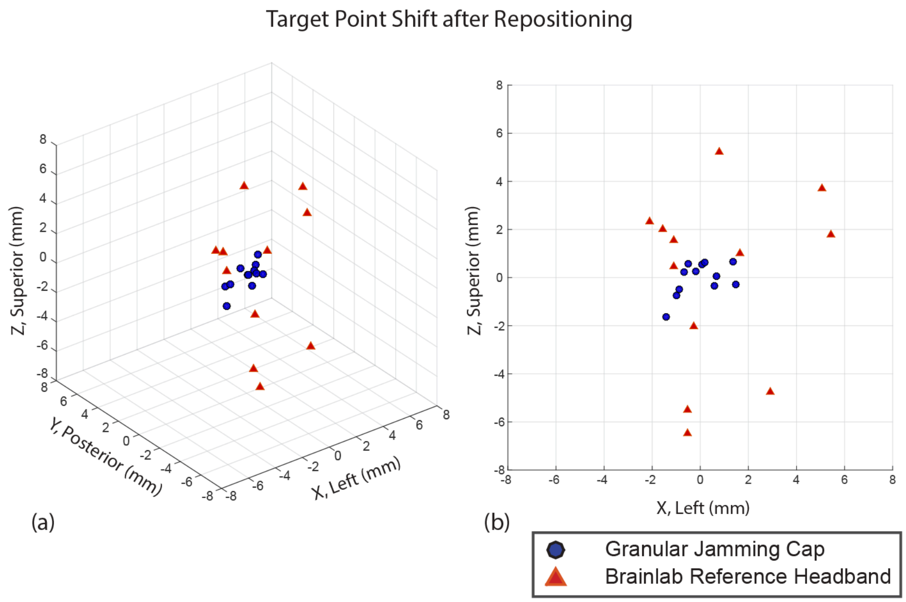

Fig. 9.
The shift in the target point after head repositioning is shown for both devices in the anatomical coordinate frame. The isometric 3D view is shown in (a) on the left. Since the majority of shift occurs in the coronal plane due to device constraints, this frontal view (b) is included on the right. In both views, it can be seen that on average the BRH shifts more than the GJC due to repositioning the head.

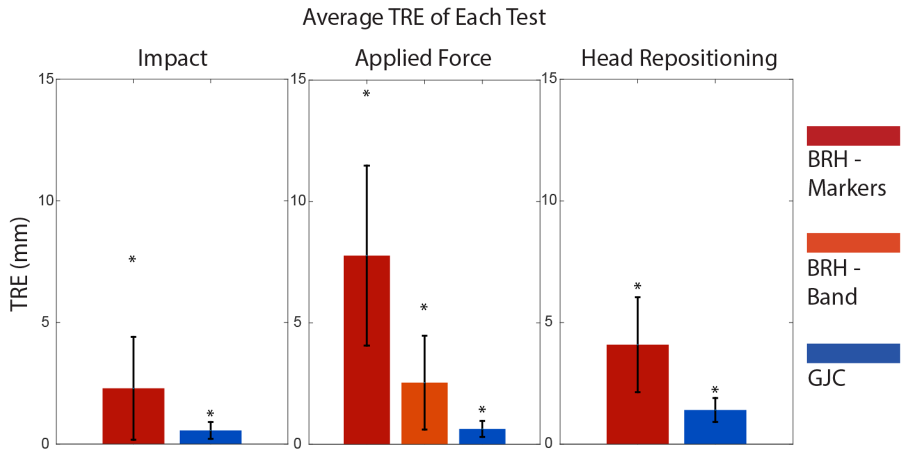

Fig. 10.

The three graphs above represent the average TRE of each of the three tests. The red bar in each represents the results of the BRH as each test is applied, while the blue bar designates the results of the GJC. Looking at the middle graph, since forces were applied to two different positions on the BRH, the red bar represents forces that were applied directly to the markers and orange bar represents forces that were applied to the elastic band. The star above each bar shows the maximum TRE value for each fixture for a given test.