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Precision and accuracy of consumer-grade motion tracking system for pedicle screw placement in pediatric spinal fusion surgery

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RMS, Root-Mean-Square

ABSTRACT

Adolescent idiopathic scoliosis (AIS) is a 3-dimensional spinal deformity involving lateral curvature and axial rotation. Surgical intervention involves insertion of pedicle screws into the spine, requiring accuracies of 1 mm and 5° in translation and rotation to prevent neural and vascular complications. While commercial CT-navigation is available, the significant cost, bulk and radiation dose hinders their use in AIS surgery. The objective of this study was to evaluate a commercial-grade Optitrack Prime 13W motion capture cameras to determine if they can achieve adequate accuracy for screw insertion guidance in AIS. Static precision, camera and tracked rigid body configurations, translational and rotational accuracy were investigated. A 1-h camera warm-up time was required to achieve precisions of 0.13 mm and 0.10°. A three-camera system configuration with cameras at equal height but staggered depth achieved the best accuracy. A triangular rigid body with 7.9 mm markers had superior accuracy. The translational accuracy for motions up to 150 mm was 0.25 mm while rotational accuracy was 4.9° for rotations in two directions from 0° to 70°. Required translational and rotational accuracies were achieved using this motion capture system as well as being comparable to surgical-grade navigators.

1. Introduction

Adolescent idiopathic scoliosis (AIS) is a spinal deformity characterized by lateral curvature, often combined with vertebral rotation. It has an overall prevalence of 0.47%–5.2%, with a higher prevalence and severity in girls than in boys [1]. Surgery is recommended for patients with curvatures greater than 50° who have not yet reached skeletal maturity or have rapid curve progression and functional impairment [2]. Posterior fusion surgery utilizing instrumentation has become the gold standard of surgical treatment. Segmental pedicle screws are often used to attach the rods to the vertebral body [3].

Accuracy in insertion pedicle screws is critical to prevent complications including injury to nerve roots, spinal cord or vascular structures, pedicle fracture, and instrumentation failure [4,5]. Prior studies have found pedicle dimensions to be 4–18 mm in the transverse direction and 4–14 mm in the sagittal direction, with T4–T8 having the smallest pedicles [6]. Given the narrow width of the pedicles in thoracic levels, a 1 mm error could easily result in a breach of the pedicle.

To maximize accuracy, standardized free hand insertion techniques as well as fluoroscopic-based guidance and computed tomography (CT) navigation have been developed [7,8].

The free-hand method involves insertion of pedicle screws based on visible anatomical landmarks and the tactile feedback, relying heavily on surgeon experience and correct identification of the anatomical landmarks. Fluoroscopy is often used to confirm screw placement when free-hand methods are used and can also be used to guide screw placement. CT navigation uses mobile intraoperative CT systems, to allow for 3D reconstruction of bony anatomy, alongside motion capture cameras to localize surgical tools relative to the bony anatomy [7,9].

CT navigation has been used extensively in spinal fusion for pediatric spinal deformities to good success with breach rates of less than 10% [10–12]. Specifically, for adolescent idiopathic scoliosis, breach rates for free-hand methods have been reported to range from 0.1% to 66.8% [13–16] while for fluoroscopy and CT range

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from 0–50.7% and 7.5–7.9%, respectively [17–21]. In addition to individual studies, four head-to-head studies have shown superiority of CT image guidance over free-hand methods in reducing breach rates [22–25].

However, free-hand methods are still often preferred to usage of navigation systems in adolescent idiopathic scoliosis procedures. Radiation exposure remains a concern for both image guidance methods in the pediatric population [26–29]. Past studies suggest an increased lifetime risk of fatal cancer of 1 in 1000 from abdominal CT scans [30]. Furthermore, in the case of intraoperative CT scans, screw insertional time is increased to allow for registration between image and vertebral landmarks [31]. Lastly, the additional cost and bulk in using intraoperative CT scans remains a barrier to usage of current navigation technologies though this may be mitigated from fewer reoperations or complications [8]. Usage of handheld ultrasound-CT registration for spinal fusion appears to be a promising method of providing image guidance without the bulk, radiation exposure and cost of conventional systems [32]. Further study into the adaptability of commercial-grade mid-range motion capture cameras could broaden the usability of ultrasound-CT registration in the operating room, particularly for adolescent idiopathic patients.

Motion capture systems have been used extensively in gait analysis, providing accuracy of within 1% error for 120 mm translations [33]. Motion capture cameras have light emitting diodes that emit light into a capture area. Markers in the capture area reflect the light back to the camera which then determines the size and location of the marker [34]. Using multiple markers and cameras, the motion capture system is then able to triangulate the actual position of markers in 3D space. However, the accuracy of motion capture depends heavily on both quality of cameras and range of space in which cameras are used [35,36]. The required theoretical accuracy of navigation systems was found to be less than 1 mm and 5° by Rampersaud et al. when considering screw trajectories in 3D space [37]. While good accuracy has been achieved by commercially available navigation systems, the question remains whether more inexpensive and flexible motion capture camera systems can be used in navigation with equivalent accuracy.

The goal of this study is to determine the usability of off-the-shelf motion capture equipment for usage in the operating room and eventual integration with ultrasound-CT navigation system for spinal fusion in adolescent idiopathic scoliosis. The objectives of this study are to evaluate Optitrack Prime 13W motion capture cameras for three attributes: (1) to investigate the static precision of the motion capture system, (2) to determine the optimal camera and marker configuration for highest tracking accuracy and (3) to evaluate the translational and rotational accuracy of the system for varying movement magnitudes.

2. Methods

2.1. Camera specifications and software configuration

Optitrack Prime 13W motion capture cameras (Prime 13W, NaturalPoint, United States) were selected specifically due to their wide 82° x 70° field of view and small size at $69 \times 69 \times 22$ mm. The capture rate was 120 frames per second and used 850 nm infrared light to minimize interference from overhead lights. A schematic of camera positions relative to the capture volume is shown in Fig. 1. Cameras were mounted on tripods and placed on one side of the required capture volume with dimensions of 0.8 m deep, 0.6 m wide and 0.6 m high. Cameras were then placed 0.8–1.2 m vertically from the floor of the capture volume and a horizontal distance of 1.0–1.2 m from the closest face of the capture volume. This setup was based on measurements in an operating room where cameras would be placed at the head of the patient above the operating space. The positions of cameras for evaluating camera configuration are described under Camera and Rigid Body Configuration Testing.

The tracking software, Motive from the manufacturer (Tracker v. 1.10.0, NaturalPoint, United States), was used to obtain motion tracking data. The cameras can record data over a period of time to exported for further processing, but can also continuously output live positional and orientation data for active tracking in separate software. Calibration of the Optitrack system was completed with the Optitrack CW-250 Calibration wand and the Optitrack CS-200 Calibration square for setting the origin. The built-in calibration wanding process was used to calibrate the system which involved moving the calibration wand throughout the entire capture volume for 30 s. At the end of calibration, the software displays the accuracy of the current calibration ranging with six ranks ‘Poor’ to ‘Exceptional’. All calibrations that were used met the ‘Exceptional’ ranking, resulting in software-estimated errors of less than 0.15 mm. Cameras were recalibrated either every day prior to testing, or after camera placement was changed.

Optitrack 7.9 mm markers were placed on Optitrack M3 9 mm bases. The study evaluated the accuracy and precision of the built-in rigid body recognition system, which is able to create a rigid body from three or more markers that are mounted on a single object. Position and rotation values of the center of the rigid body were exported as XYZ translational coordinates and Pitch, Yaw and Roll rotational angles using the XYZ Euler rotation sequence.

2.2. Static testing

The precision of the cameras was determined using two experiments: ten-minute trials and six-hour trial. Precision was defined as the 95% confidence interval of the standard deviation of positional or rotational data. A right triangle with dimensions of 90 mm x 120 mm x 150 mm was created with a 3D printer (Makerbot Replicator 2X, United States) to hold the markers in a stationary position (Fig. 2).

The ten-minute trials involved continuous recording of the position and orientation at 120 FPS for 10 min. To determine if cameras required a heat-up time, two sets of trials were completed: the first with cameras recording data within five minutes of turning on from ambient room temperature (20 °C) and the second with cameras being pre-heated for an hour prior to recording with the mean difference from origin to compare the two trials. Each cold-start test was started on a different day with the pre-heat test completed on the same day, to ensure full cool-down of the cameras. The six-hour trial involved obtaining positional and rotational data every five minutes, acquiring data at 120 frames per second over two seconds to mimic the duration of a long spinal surgery. Cameras and markers were not moved between each of the three six hour trials over three days.

2.3. Camera and rigid body configuration testing

To determine the optimal camera configuration, multiple camera positions were evaluated with combinations of three or four cameras. Cameras at aligned or staggered at heights to a range of ±150 mm, and cameras aligned or at staggered depths to a range of ±200 mm as shown in Fig. 1 were tested. An object with known dimensions, a rigid body with three adjustable arms to mount markers, was created with a 3D printer (Objet30 Pro, Stratasys, United States) and then attached onto a digital caliper (Mitutoyo, Japan) (Fig. 3a) was used to assess accuracy. The accuracy of the caliper was within 0.01 mm. The rigid body was translated ten times by 40 mm for each of the eight camera configurations, with the most accurate camera positions being selected for further evaluating rigid body configurations.

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