Can a Hand-Held Navigation Device Reduce Cognitive Load? A User-Centered Approach Evaluated by 18 Surgeons

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Abstract. During spinal fusion surgery, the orientation of the pedicle screw in the right angle plays a crucial role for the outcome of the operation. Local separation of navigation information and the surgical situs, in combination with intricate visualizations, can limit the benefits of surgical navigation systems. The present study addresses these problems by proposing a hand-held navigation device (HND) for pedicle screw placement. The in-situ visualization of graphically reduced interfaces, and the simple integration of the device into the surgical work flow, allow the surgeon to position the tool while keeping sight of the anatomical target. 18 surgeons participated in a study comparing the HND to the state-of-the-art visualization on an external screen. Our approach revealed significant improvements in mental demand and overall cognitive load, measured using NASA-TLX ($p < 0.05$). Moreover, surgical time (One-Way ANOVA $p < 0.001$) and system usability (Kruskal-Wallis test $p < 0.05$) were significantly improved.

Keywords: Hand-held navigation device · Surgical navigation · Spinal fusion · Pedicle screw placement · Augmented reality · Cognitive load · Surgical visualization

1 Introduction

Disc degeneration, spondylolisthesis or scoliosis are exemplary indications leading to spine instability, which, in turn, can cause bone deformation or nerve

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damage [16]. In severe cases, an artificial reconstruction of the spine's stability, is performed by introducing a transpedicular screw-rod system into the spine. This treatment fixes the operated segment(s) and restores the spine's stability [5]. Screw placement in the correct angular trajectory, indicated by the pedicle and the vertebral body, is one of the most intricate tasks due to complex anatomic variants [4]. As misplacements of pedicle screws can be a source of bone breaches and neurological complications [5], precise placement and alignment of the pedicle screw instruments presents a crucial step during spinal fusion surgery.

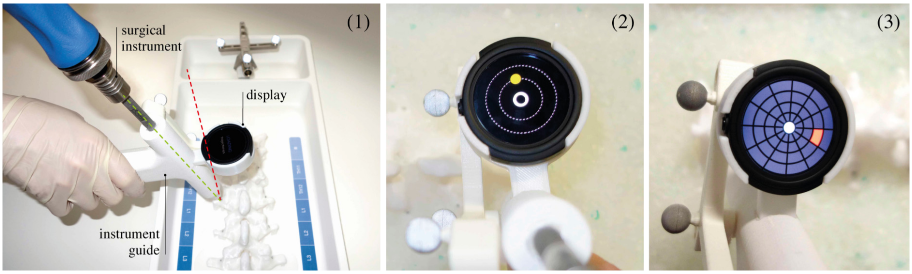

Fig. 1. (1) Hand-held navigation device, green line: instrument trajectory, red line: target trajectory, (2) Close view of Circle Display, (3) Close view of Grid Display (Color figure online)

Navigation systems assist the surgeon during placement and alignment, helping to maximize the precision of pedicle screw insertion [7]. Improved outcome and reduced radiation exposure are reasons to use these systems [15]. However, the complexity of use, and the disruption of the surgical work flow are predominant factors for the conservative percentage of navigated spine surgeries [10]. When using navigation, the operator must split attention between the navigation information, displayed on an external screen, and the situs [11], adding to the complexity of use.

We present a user-centered navigation system for spinal fusion surgery. The solution consists of a hand-held navigation device (HND) which comprises a display for navigation information and a shaft for surgical tool guidance (Figure 1). This way, the HND enables the display of meaningful information in the surgeon's field of view. The primary focus of this study is the evaluation of the HND for the task of angle alignment within the pedicle screw placement procedure. Two different visualizations for angle orientation of the surgical tool were tested with 18 physicians against the visualizations used in clinical routine. The proposed visualizations were also tested against the same visualizations implemented on an external screen. Our results show that this integration of the visualization unit into the HND, combined with a user-friendly visualization, reduces cognitive load when compared to the traditional approach. Furthermore, statistical analysis of the data showed that the proposed system presents a more time-efficient alternative to the state-of-the-art solutions.

1.1 Related Work

Moving the surgeons' attention back from an external screen to the patient is a well-researched topic in the scientific community. Carmigniani et al. [2] utilized augmented (AR) and mixed reality (MR) as well as mobile devices to overlay additional information on top of the patient, enabling the examination of the situs and organs. Likewise, several works have discussed solutions using not only head-mounted displays [1,14], but also half-silvered mirrors [18] to superimpose pre-operative images onto the patient for anatomical navigation. Léger et al. [17] compared in situ AR, desktop AR and traditional navigation with regard to attention shifts and time to completion for craniotomy planning. Their research showed that the use of AR systems resulted in less time and less attention shifts. Liebmann et al. [19] demonstrated the benefits of real-time visualizations using AR without additional intra-operative imaging for pedicle screw placement achieving the same accuracy for screw placement as state-of-the-art navigation systems. Their study examined 3D augmented views using Microsoft HoloLenses, whereas we propose visualizations on a 2D display. Navab et al. [21] developed a surgical AR technology enabling video-augmented x-ray images by extending a mobile C-arm with a video camera. As in our study, instrument axis alignment was evaluated. However, AR images are displayed using a mirror attached to the C-arm, while we propose localization of the visualization unit on the surgical instrument.

Similar approaches, utilizing mobile devices to enable in situ navigation, can be found. Kassil et al. [13] demonstrated that using a tool-mounted display can achieve better positional and angular accuracy for a drilling task. The system augments the image of a camera installed on the tool, whereas our system is a user-centered, graphic navigation interface. Experiments looked at drilling precision and completion time but did not include any evaluation of cognitive load and usability. Weber et al. [22] integrated a Navigated Image Viewer into the surgical process, and proved that this dynamic visualization helps to understand the spatial context. Gael et al. [6] investigated the potential of adding a smartphone as an interaction device. Mullaji et al. [20] presented a hand-held, iPod-based navigation approach for total knee arthroplasty. Both the smartphone and the iPod approach are displaying the traditional visualization in small size on a mobile screen. In contrast to both studies our work presents visually reduced information independent of the external monitor. An exemplary work introducing an approach for measuring cognitive load, user preference, and general usability is presented by Herrlich et al. [11]. The use of an external monitor is compared to an instrument-mounted display for the task of needle guidance. Their display reduced cognitive load while achieving the same performance in terms of time and accuracy. As opposed to their work, clinical experts were used to evaluate cognitive load and system usability during our study. Outside of the medical context, Echtler et al. [3] presented the design and implementation of a welding gun, which displays three-dimensional stud locations on the car frame relative to the current gun position. Their specific visualizations such as concentric rings and compass enabled a correct positioning of the gun tip on the surface of the frame, whereas our work is concerned with angle orientation.

2 Methods

To avoid physical de-coupling of the navigation and the surgical situs, we propose the use of a hand-held navigation device (HND). This HND is a custom-made device, developed as a result of user-centered design [12]. It consists of a handle, a shaft for tool guidance, a tracking array and a visualization unit holder. The HND is designed to hold a surgical instrument while attaching a visualization to it. This idea introduces a paradigm shift, contrasting the solutions used in clinical routine. With this approach the attention of the user is not drawn from the patient to an external screen, but kept on the surgical area.

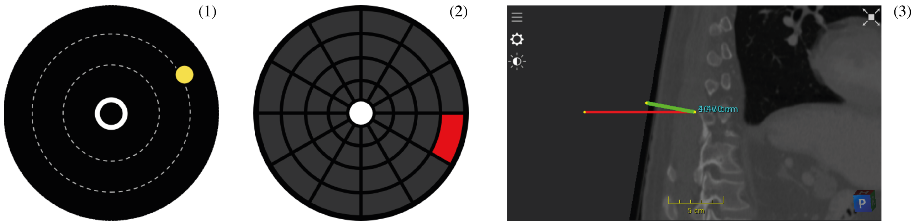

Fig. 2. (1) Circle Display, (2) Grid Display, (3) Transversal view of Traditional External

2.1 Hardware and Software Setup

The system comprises a workstation, a Polaris Vicra (NDI, Ontario, Canada), the HND, and a Ticwatch E (Mobvoi. Beijing, China). The Ticwatch is attached to the visualization unit holder to show the instrument-integrated visualization. A Polaris Vicra infrared tracking system tracks the arrays attached to both the phantoms and the instrument. The calibration between the marker and the tool is known by construction, and checked using a pivot calibration. The software uses a client-server architecture between the Ticwatch E and the workstation. The server is run as a plugin on ImFusionSuite[1], which processes the tracking information and sends it to the Ticwatch to create the visualization.

2.2 Visualizations

We propose two visually reduced interfaces (Fig. 2), displaying abstract 2D guidance for angle alignment, aiming to reduce the complexity of navigation during pedicle screw placement. Both minimalist visualizations map the real-time 3D Cartesian orientation of the HND to a polar coordinate system centered at the pre-planned insertion trajectory. This way, the relative angle distance between the planned and current trajectories is intuitively shown on the 2D screen.

[1] ImFusion GmbH, Munich, Germany (https://www.imfusion.de).

Circle Display - This interface consists of a circular element moving dynamically across the underlying background according to the HND's position calculated as described in the previous section. By orienting the HND in such a way that the circular element enters the central ring of the interface, the user achieves the target trajectory. The correct alignment is communicated to the user by additional visual feedback: change of color of the circular element from yellow to blue and the superimposition of a highlight around the inner ring.

Grid Display - The design is a grid pattern dividing the interface into 12 pie sections and four concentric circles of different radii. According to the relative orientation of the HND towards the planned trajectory, the respective grid field is highlighted in red. By moving the HND into the indicated direction of the red-marked field, the system guides the user towards the right angle. When the user reaches the target orientation, the central circle lights up in green.

Traditional External - The state-of-art visualization uses 3 slices with normal directions $tool_{X,Y,Z}$, and application point $tool_{tip}$. The target trajectory is projected on each of the planes as a red line. The HND's pose is shown as a green line. The right orientation is achieved by aligning each of the different axes individually until both lines intersect.

3 User Study

Our study used two controlled experiments to evaluate the potential benefits of the proposed approach. Eighteen experienced surgeons participated in the first experiment. It investigated the performance and usability of the HND compared to the state-of-the-art navigation system on a realistic spine phantom. A second experiment was employed to isolate and evaluate the two main factors of the solution, the in-situ visualization offered by the HND, and the developed interface itself. For this, the user was presented with an orientation task using the same pair of visualizations, both on the HND and the external screen. The distribution of the participants in both experiments followed a block randomization.

– In comparison with the state-of-the-art navigation system:

  H1. Participants using the HND for angle alignment experience reduced cognitive load and improved usability.
  H2. Participants using the HND for angle alignment achieve the planned trajectory faster and with a shorter euclidean path (Fig. 3).

– In comparison to the same visualization presented on an external screen:

  H3. Participants using the HND for angle alignment experience reduced cognitive load and improved usability.
  H4. Participants using the HND for angle alignment achieve the planned trajectory faster and with a shorter euclidean path.

Fig. 3. (1) Setup experiment 1, neurosurgeon using the external screen, (2) Senior neurosurgeon using the visualization on the HND, (3) Setup experiment 2

3.1 Experiment 1

Participants. 18 volunteers [10 m/8 f] participated in the study. All were practicing surgeons with experience in using navigation systems and traditional techniques for visualization of 3D data (i.e., CT, MR). The mean age was 30 ± 3.7 *std.* None of them had previous experience using the proposed navigation system. 15 participants reported to have executed pedicle screw placement before.

Experiment Setup. A model of the lower lumbar spine, [levels Th11 to L5], was 3D-printed and calibrated to the tracking system. To ensure anatomical coherence, realistic pedicle screw trajectories were selected by a senior neurosurgeon on the CT of the phantom. The trajectories corresponded to the real insertion path for each right and left pedicle screw on levels Th11 to L5 of the spine, summing up to 14 different trajectories evenly distributed on both sides of the spine. The entry point of each trajectory was physically marked on the phantom. First, the user was instructed to place the HND onto one of the predefined entry points on the spine phantom. Then, the physician was asked to align it in the right anatomical, pre-planned trajectory using one of the visualization techniques. This alignment was repeated four times on two randomized trajectories for each side of the spine. The same task was repeated for all three visualizations (Circle and Grid on Display, and Traditional External).

3.2 Experiment 2

Participants. The set of participants consisted of 15 females and 27 males [age 26.8 ± 3.3]. None of them had clinical experience or previous experience using the HND system. However, 31 had experience using AR/VR.

Experiment Setup. We performed a second experiment to isolate the two main factors of our solution: the visualization techniques, and the in-situ visualization. Four different setups were evaluated as a combination of the two interface designs (Circle and Grid Display), and the two displays (integrated and external). An abstract scenario, comprising a conical 3D model with a single entry point, was built. In contrast to experiment 1, where the trajectories are anatomically right, here, random realistic trajectories were created with a fixed insertion point on top of the pyramidal model. After positioning the tip of the instrument on top of the 3D model, the user was asked to align the HND using the visualization. This alignment was repeated five times per visualization, and with the four mentioned setups.

3.3 Experimental Variables

For both experiments, time-stamped poses of the HND handler were recorded. Additionally, users had to fill out a NASA-TLX and System Usability Scale (SUS) questionnaire for measuring the cognitive load and overall usability. Cognitive load refers to the overall task load calculated using the NASA-TLX questionnaire, for six defined variables (Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, Frustration) [9]. Usability was calculated using the System Usability Scale (SUS) questionnaire [8]. Further questions gathered subjective assessments of the interfaces' visual appeal, ease of use and interaction design.

4 Results

4.1 Experiment 1

Cognitive Load and Usability. The recorded data of the NASA-TLX and SUS showed a Chi-squared distribution for all the different variables ($p < 0.001$). A Kruskal Wallis test was run pairwise between visualizations, for each of the NASA-TLX variables and the SUS score. The analysis showed that the usage of both Circle Display and Grid Display resulted in a significantly lower mental demand ($p < 0.05$) and cognitive load ($p < 0.05$) when compared with the Traditional External . The usability (SUS score) for Circle Display ($79.4 \pm 14.1 std$) was significantly better ($p < 0.05$) compared to Traditional External ($68.7 \pm 14.7\, std$). The pairwise comparison of the two proposed designs Circle Display and Grid Display showed no significant difference ($p > 0.05$) (Fig. 4).

Experiment 1	Cognitive load	Mental demand	Usability
Circle	23.7 ± 15.4	23.6 ± 20.1	79.4 ± 14.1
Grid	25.0 ± 14.4	25.8 ± 19.0	76.7 ± 18.1
Traditional	35.3 ± 12.7	42.8 ± 18.3	68.7 ± 14.7

Experiment 2	Cognitive load	Mental demand	Usability
HND	32.2 ± 17.3	33.7 ± 25.3	80.8 ± 13.1
External Screen	33.3 ± 17.1	36.9 ± 26.9	80.2 ± 18.1

Fig. 4. Means and stds for cognitive load and mental demand (NASA-TLX, [0, 100] lower is better), and usability (SUS [0,100], higher is better) for experiment 1 and 2)

Statistical Analysis. The tool's total euclidean path was analyzed. For this, 3D time-stamped poses of the tool's shaft were saved during the experiments.

The euclidean path is calculated as the total sum of the euclidean distances between each consecutive pair of poses. This value expresses the accumulated travel distance of the tool's shaft until the alignment is successful. Intuitively, this measure provides insights into how directly the user moved the tool towards the final pose. (Fig. 5 [Chi-squared distributed ($p < 0.001$)]). Time values showed a normal distribution ($p < 0.05$). Outliers with values outside of $mean \pm 2 * std$ were excluded. A one-way ANOVA test was used to measure significance for time and Kruskal-Wallis for distance. Our approach reached significantly better results in comparison to the traditional approach regarding time ($p < 0.001$). Circle Display performed better against the traditional method, both on distance ($p = 0.0107$) and time ($p < 0.001$).

4.2 Experiment 2

Cognitive Load and Usability. The results of the NASA-TLX and SUS questionnaire showed a Chi-squared distribution of the different variables ($p < 0.001$). A Kruskal Wallis test was employed to compare the group of external visualizations (Circle External and Grid External) with the group of instrument-integrated visualizations (Circle Display and Grid Display) for all variables of NASA-TLX and the SUS score. The analysis showed no significant difference between the two groups ($p > 0.05$), neither for cognitive load, nor for usability, and consequently, pairwise comparisons were not conducted.

Statistical Analysis. To compare the different visualizations, the euclidean distances and total time of each individual task were grouped according to the visualization used (Circle Display, Grid Display, Circle External, Grid External) as shown on Fig. 5. Outliers with values outside of $mean \pm 2 * std$ were excluded from the sample. Normality was tested within the 4 groups (both for time and distance) using D'Agostino's K-squared test ($p < 0.001$). The sample has a 2.004 ratio between the larger and smaller variances. One-Way ANOVA was used to compare the results in terms of euclidean distance and time. Overall,

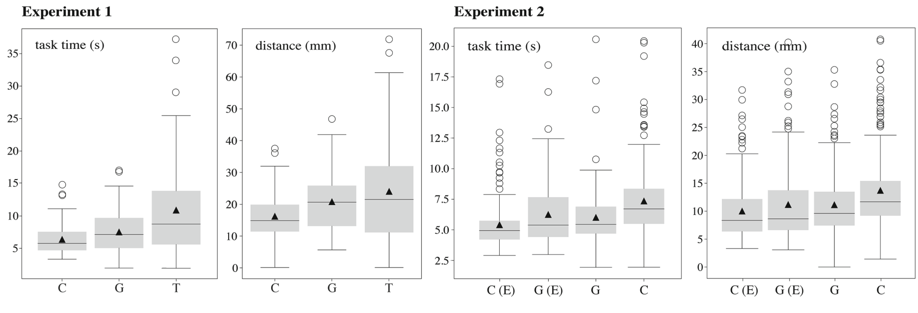

Fig. 5. Time and euclidean distance for Circle Display (C), Grid Display (G), Traditional External (T), Circle External (C(E)), Grid External (G(E))

Circle External performed best, both in terms of time and distance, followed by Circle Display and Grid Display. According to the data, the visualizations on the external screen performed significantly better than the visualizations on the device ($p < 0.001$).

5 Discussion and Conclusion

A hand-held navigation device for spinal fusion surgery was introduced. Preliminary tests revealed significant differences in favor of our approach regarding cognitive load, mental demand and usability (H1). This improvement of user ergonomics leads to a significant increase in performance, measured as total euclidean path and time (H2). Experiment 2 showed no significant results for H3. H4 has proven to be false, as the results on the external display were significantly better.

Possible factors affecting this result are the latency added to the drill visualizations, the lower resolution, and the relative small size of the screen. However, the HND still offers the advantage of in-situ navigation information, keeping the surgeon's attention on the patient. To answer the introductory question: our user-centered approach to spinal navigation enabled a significant reduction of cognitive load for the surgeon. Thus, the solution shows potential benefits for clinical application if properly integrated within the medical workflow.

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