The Impact of Operator Experience on the Accuracy of Neuronavigation Systems

O impacto da experiência do operador na precisão dos sistemas de neuronavegação

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Abstract

Introduction Neuronavigation systems have become an essential tool for accurate surgical guidance. However, the influence of operator experience on the accuracy of these systems is still debated.

Objective This study aims to investigate the accuracy and precision of neuronavigation in an environment mimicking the conditions found in a surgical room and the impact of operator experience.

Methods We conducted a series of experiments using a neuronavigation system with operators of varying levels of experience. The accuracy of the system was measured and compared across 3 different operators.

Results Inexperienced operators exhibited significantly lower levels of accuracy compared with their more experienced counterparts. The measured accuracy for an experienced operator was 2.9 ± 1.2mm, with an overall mean of 3.5 ± 1.7 mm when including results from inexperienced individuals. The best scenario appears to be when the point of interest is in the right temporal region, closer to the stereo vision camera of the tracking system.

Conclusion Our results demonstrate different accuracies in the neuronavigation system between operators with varying levels of experience. However, individuals without prior experience or training exhibit an acceptable level of accuracy for its use in surgical applications.

Keywords
- neuronavigation
- classification
- education
- methods
- instrumentation
- statistic and numerical data

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Resumo

Introdução Os sistemas de neuronavegação tornaram-se uma ferramenta essencial para a orientação cirúrgica precisa. No entanto, a influência da experiência do operador na precisão desses sistemas ainda é debatida.

Objetivo Este estudo visa investigar a acurácia e a precisão da neuronavegação em um ambiente que simula as condições encontradas em uma sala cirúrgica e o impacto da experiência do operador.

Métodos Realizamos uma série de experimentos utilizando um sistema de neuronavegação com operadores de diferentes níveis de experiência. A precisão do sistema foi medida e comparada entre 3 operadores diferentes.

Resultados Os operadores inexperientes apresentaram níveis de precisão significativamente menores em comparação com seus colegas mais experientes. A precisão medida para um operador experiente foi de 2,9 ± 1, 2 mm, com uma média geral de 3,5 ± 1,7 mm ao incluir os resultados de indivíduos inexperientes. O melhor cenário parece ser quando o ponto de interesse está na região temporal direita, mais próximo da câmera de visão estereoscópica do sistema de rastreamento.

Conclusão Nossos resultados demonstram diferentes precisões no sistema de neuronavegação entre operadores com diferentes níveis de experiência. No entanto, indivíduos sem experiência ou treinamento prévio demonstram um nível aceitável de precisão para seu uso em aplicações cirúrgicas.

Palavras-chave
- neuronavegação
- classificação
- educação
- métodos
- instrumentação
- estatística e dados numéricos

Introduction

Neuronavigation systems have become integral to neurosurgical procedures, contributing to reduced invasiveness, shorter surgical durations, and improved postoperative outcomes.[1] These devices operate based on a three-coordinate system that correlates preoperative images with the patient's anatomy. This technology facilitates the precise localization of targeted cranial regions and is currently regarded as the gold standard in image-guided neurosurgery.[2]

Accuracy of neuronavigation systems is a critical feature, since the effectiveness of this device lies solely in its ability to identify anatomical structures accurately. Several factors impact accuracy, including the quality of computed tomography (CT) and magnetic resonance imaging (MRI) scans, the registration approach employed, tracking technology, the software employed, and issues that are inherent in the operator. Measurement errors can adversely affect the performance of this technology and may even render its use unfeasible.[3] Furthermore, the impact of operator experience on the accuracy of these systems remains a topic of ongoing debate.[4–6]

The goal of this study is to assess the accuracy and precision of neuronavigation systems in a setup that simulates the conditions typically encountered in an operating room setting, with operators of varying skill levels in the technique.

Material and Methods

Neuronavigation System

The EXIMIUS neuronavigator (Artis, Brasilia, Brazil) is an optical tracking (infrared) neuronavigation system that employs retroreflective spheres and point-to-point registration. It comprises a stereoscopic binocular camera, a navigation probe, a dynamic reference frame, previously calibrated surgical instruments, and a workstation equipped with the Eximius MED neuronavigation platform (Artis, Brasilia, Brazil). The software offers functionalities such as linear and angular measurements, trajectory determination for biopsy procedures, three-dimensional reconstruction of anatomical structures, image fusion, and surgical planning. For this study, version 4 of the software was utilized, employing a paired point registration method based on anatomical landmarks, where registration is achieved through the correspondence between fiducials and target points (►**Fig. 1**).

Phantom and Image Acquisition

The phantom was printed to full scale on a Projet 360 rapid prototyping 3D printer (3D Systems, Inc., Rock Hill, South Carolina, USA) from a previous inspection. Eight electrodes were positioned, one each in the regions allocated: right and left frontal, right and left parietal, right and left occipital, and right and left temporal regions. A computed tomography (CT) scan of the mannequin was subsequently acquired. The CT images were obtained using a volumetric protocol with 1 mm thick slices (Brilliance 64 CT Scanner, Philips, Amsterdam, the Netherlands). The DICOM files were then imported into Eximius version 4 software (Artis, Brasília, Brazil) and three-dimensional reconstruction of the mannequin was performed in virtual space.

Experiment

The phantom was positioned in the same manner as a supine patient with a neutral head in a head holder, thereby

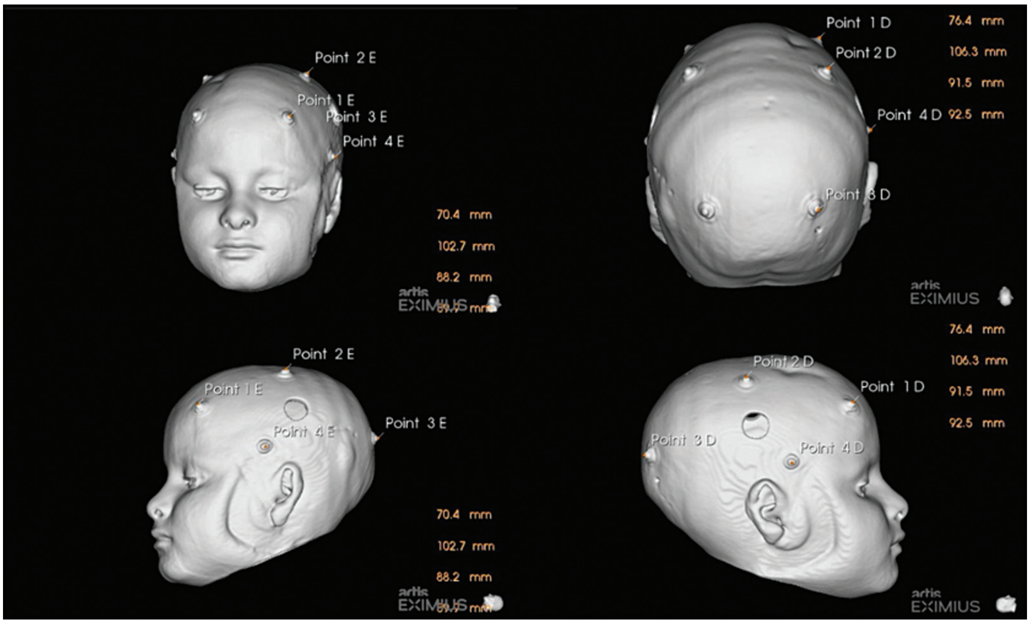

Fig. 1 Three-dimensional reconstruction of the model utilized in the tests, incorporating fiducial points

mimicking the experiment as much as possible with actual surgical conditions. The real coordinates of the eight points of the electrodes on the mannequin were found by direct marking on the volumetric CT. The dynamic reference was placed on the left side, and the stereoscopic camera was placed frontally to record the mannequin, navigation probe, and dynamic reference (►**Fig. 2**). The reference set was maintained in the same position and under the same conditions for all operators. Three examiners participated in the experiment with different levels of experience: two without experience or training and one experienced technician. An experienced operator was defined as one who had received special training and had performed at least 100 surgeries. Facial registration was performed, and the navigation probe was positioned on each of the eight points outlined above (►**Fig. 3**) by all examiners. The coordinates of the position of the probe when in contact with the electrodes were recorded, and the Euclidean distance between these and the coordinates located on the CT was calculated. This figure was established as the target registration error (TRE). The procedure was conducted 30 times by each examiner, with one examiner conducting a further 30 times on another day, one week later. The mean square error (MSE) values of every registration were also recorded, with a maximum of 3 mm being acceptable. Based on the MSE and the position of the neuronavigation probe, the software indicated a predicted TRE value.[7]

Accuracy and Precision

The overall accuracy of the neuronavigator is determined by comparing the coordinates from a previously marked database on the CT with those obtained through neuronavigation. Accuracy is represented by the overall meaning of the target registration error (TRE), while precision is indicated by the standard deviation of this distribution. TRE is calculated using the Euclidean distance formula for two points in three-dimensional space.

Fig. 2 Setup

$$D_{ab} = \sqrt{(Xb - Xa)^2 + (Yb - Ya)^2 + (Zb - Za)^2}$$

Statistical Analysis

Parametric independent or paired sample *t*-test and ANOVA were applied as needed to compare the mean accuracy

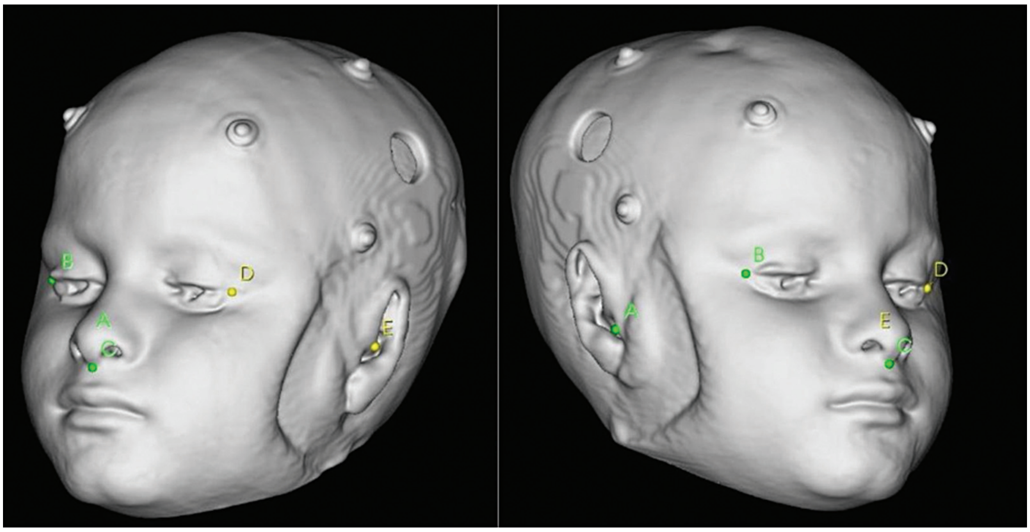

Fig. 3 Cloud of facial registration points

among groups. Factors such as brain region, laterality, and examiner experience were analyzed. Tukey's post hoc test was used to identify discordant subgroups to study the influence of various parameters on the overall neuronavigation system accuracy. For concordance analysis, the intraclass correlation coefficient (ICC) was utilized, with reliability defined as values above 0.75. All tests were conducted at a statistical significance level of 0.05. The analysis was performed using IBM SPSS Statistics for Windows version 20.0 (IBM Corp, Armonk, NY, USA).

Results

The target registration error (TRE) for experienced users was 2.9 ± 1.2 mm, reflecting the overall practical accuracy and precision of the navigation system. This value was calculated based on the means of TRE for each brain region, but it varies significantly according to laterality and examiner experience. None of the records were rejected by the system.

Coordinates in Cartesian Space

►**Table 1** demonstrates the intraclass correlation coefficient between the real (marked) coordinates and those captured by the examiners with the navigation probe. The ICC showed excellent reliability between the coordinates of the predefined points (real X; real Y; real Z) and those captured by the examiners (X neuronavigation; Y neuronavigation; Z neuronavigation); (ICC $X = 0.999$; [95% CI $= 0.999–0.999$]; $F(951) = 1700.1$; $p < 0.001$); (ICC $Y = 0.996$; [95% CI $= 0.996–0.997$]; $F(951) = 569.5$; $p < 0.001$); (ICC $Z = 0.999$; [95% CI $= 0.999–0.999$]; $F(951) = 2671.3$; $p < 0.001$).

Table 1 Intraclass correlation coefficient of real and neuronavigator coordinates

	ICC	CI 95%	p-value
real X – neuronav X	0,999	0,999–0,999	< 0,001
real Y – neuronav Y	0,996	0,996–0,997	< 0,001
real Z – neuronav Z	0,999	0,999–0,999	< 0,001

►**Fig. 4** demonstrates the linear regression between the specified coordinates, indicating a high correlation between

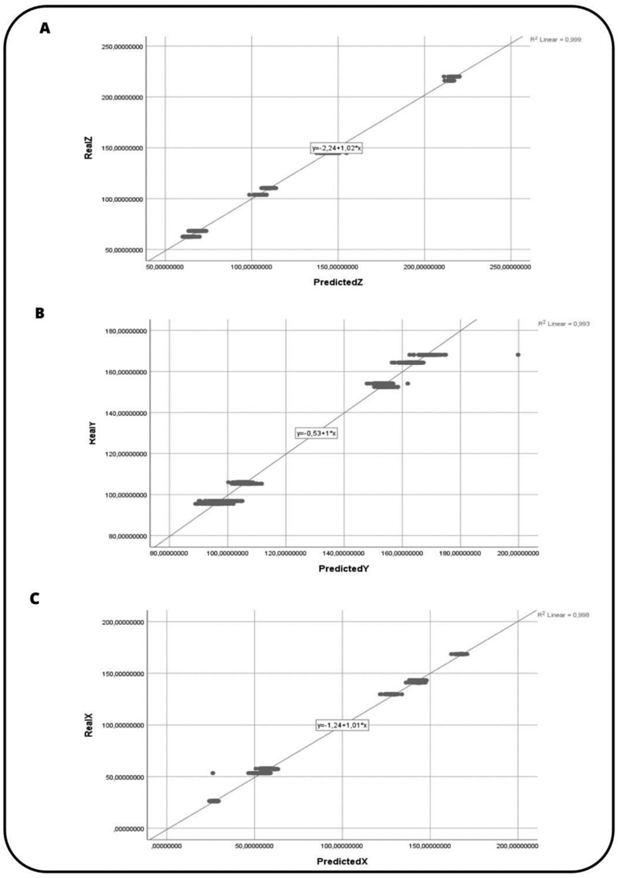

Fig. 4 **Linear regression of real and** neuronavigator coordinates

the marked coordinates and those provided by the neuronavigator. In other words, the neuronavigator effectively presented the intended coordinates.

Previous Experience of the Examiners

The root mean squared error (RMSE) was not statistically significantly different between the experienced examiner and the novice examiners (1.7 ± 0.5 mm versus 1.7 ± 0.4 mm, $p = 0.631$). Variation in the target registration error (TRE) as measured by the examiners was anticipated based on their experience with neuronavigation, and the study validated this expectation. The TRE measured mean was 2.9 ± 1.2 mm for evaluator 1, 3.9 ± 1.2 mm for evaluator 2, and 3.5 ± 1.1 mm for evaluator 3, and that there was a statistically significant difference between the most experienced evaluator (evaluator 1) compared with the rest (F(3,948) = 12.483; $p < 0.001$). ►**Fig. 5** depicts the mean TRE of each of the evaluators and the retest performed. Tukey post-hoc test sorted them into two statistically distinct categories (a and b), making it clear that the most senior examiner (examiner 1) had a greater mean compared with the least experienced ones (examiners 2 and 3). Conversely, paired *t*-test was utilized to verify the test and retest data, indicating that there was no statistically significant difference between the two attempts of the second examiner (3.9 ± 1.2 mm versus 3.9 ± 3.1 mm, $p = 0.611$).

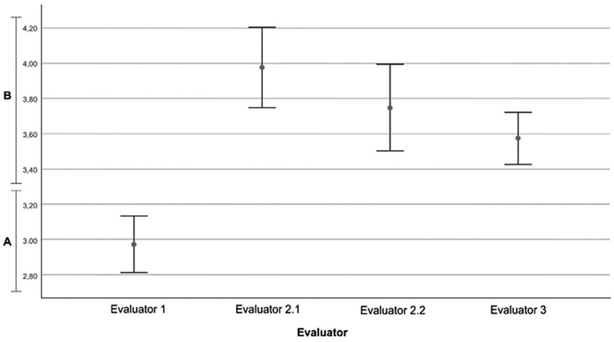

Fig. 5 Tukey's post-hoc test for inter-rater TRE comparison. ^{a,b} Different letters indicate groups with a statistically significant difference between the means in Tukey's post hoc test

Laterality

Laterality refers to the hemisphere in which the lesion is located: right or left. ►**Table 2** illustrates how the means of the root mean square error (RMSE) and the predicted target registration error (TRE) by the neuronavigator vary according to laterality. When evaluated individually, the more experienced evaluator (evaluator 1) did not demonstrate a statistically significant difference in terms of laterality (t (238) = −1.796; $p = 0.074$). In contrast, the less experienced evaluators (evaluators two and three) exhibited statistically different performances between the sides, with results of t (238) = 2.514; $p = 0.013$ and t (238) = −3.476; $p = 0.01$, respectively (►**Table 3**).

Influence of Brain Region

The expected brain region impact on neuronavigator precision was confirmed by ANOVA testing (►**Table 4**), which indicated a significant brain region impact on mean target

Table 2 Averages of root mean squared error, of the real target registration error and predicted by the neuronavigator according to laterality

	MEAN	SD	CI 95%
RIGHT			
RMSE	1.58 mm	0.45 mm	1.54–1.62mm
real TRE	3.44 mm	1.58 mm	3.30–3.58 mm
predicted TRE	3.42 mm	1.41 mm	3.29–3.55 mm
LEFT			
RMSE	1.58 mm	0.45 mm	1.55–1.62 mm
real TRE	3.76 mm	2.41 mm	3.55–3.98 mm
predicted TRE	3.45 mm	1.45 mm	3.32–3.58 mm

Table 3 Student's t test comparing the real TRE according to laterality per examiner

(Right – Left) TRE real	P	Mean difference	SD	CI 95%	N
All raters	0.014*	−0.32 mm	- 0.13mm	- 0.58 a 0.06 mm	950
Evaluator 1	0.074	- 0.29 mm	0.16mm	- 0.61 a 0.02 mm	238
Evaluator 2	0.013 *	0.57 mm	0.22mm	0.12 a 1.02 mm	238
Evaluator 3	0.001 *	- 0.50 mm	0.14mm	−0.79 a 0.21mm	238

$^{*}p < 0.05$.

Table 4 Descriptive statistics by brain region, ANOVA* and Tukey's post hoc test

Brain Region	MEAN TRE	SD	CI 95%
1-left frontal region	4.0 mm[c]	± 1,5mm	3.8–4.3 mm
2-left parietal region	4.2 mm[c]	± 3.9mm	3.4–4.9 mm
3-left occipital region	3.7 mm[b]	± 1.7mm	3.4–4.0 mm
4-left temporal region	3.0 mm[a]	± 1.3mm	3.7–3.2 mm
5-right frontal region	3.6 mm[b]	± 1.4mm	3.3–3.8 mm
6-right parietal region	3.6 mm[b]	± 1.6 mm	3.3–3.9 mm
7-right occipital region	4.1 mm[c]	± 1.4 mm	3.8–4.3 mm
8-left temporal region	2.3 mm[a]	±1.2 mm	2.1–2.6 mm

[a,b,c] Different letters indicate groups with a statistically significant difference between the means in Tukey's post hoc test; $p < 0.001$ ANOVA.

registration error (TRE) (F(7,944) = 12.103; $p < 0.001$), with the temporal regions (points 4 and 8) being the most precise. Tukey post-hoc test categorized the regions into three groups statistically different based on mean TRE: Group A - right and left temporal areas (points 4 and 8); Group B - right frontal, left occipital, and right parietal areas; and Group C - left frontal, left parietal, and right occipital areas. The trend was present even in operator-stratified analysis.

Correlation Between Predicted TRE and Real TRE

Linear regression analyses (►**Figs. 6** and **7**) revealed a low correlation between the predicted target registration error (TRE) by the neuronavigator and the actual TRE ($R^2 = 0.043$, $p = 0.001$), with no statistically significant correlation between the root mean squared error (RMSE) and actual TRE ($R^2 = 0.006$, $p = 0.876$). Furthermore, the intraclass correlation coefficient indicated poor reliability between the actual

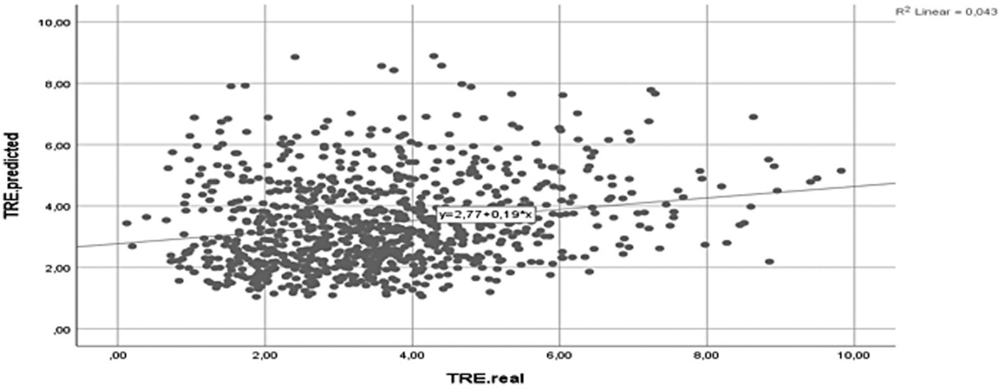

Fig. 6 Linear regression predicted TRE x real TRE

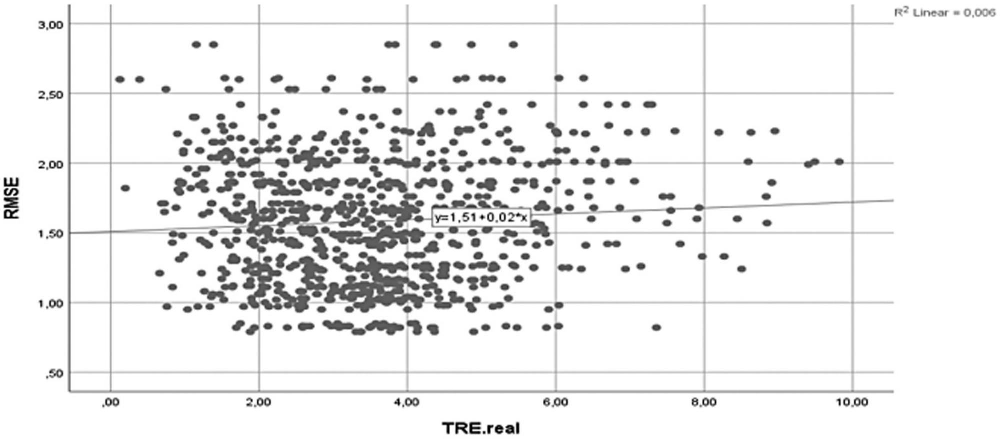

Fig. 7 Linear regression RMSE x real TRE

and predicted TRE by the neuronavigator (ICC = 0.206; [95% CI = 0.145 - 0.266]; F(951) = 1.522; $p = 0.001$).

Discussion

The accuracy and precision of neuronavigation systems are among the most important factors that surgeons must consider when using them, and these factors depend on various inherent variables across different systems. Failures in these variables are defined as application errors (EA) and include those related to discrepancies between the image and the intraoperative anatomical condition at a given moment (brain shift), as well as failures in transferring the point of interest from the image to the patient. This includes errors in fiducial location, fiducial registration error, target registration error (TRE), and surface registration error.[2]

Errors that occur after the registration phase, such as target registration error (TRE), are the main predictors of the accuracy of neuronavigators,[8] and their importance lie in allowing surgeons to account for this margin of inaccuracy during their planning. Previous studies have defined clinically acceptable values of up to 4 mm[9]; however, for surgical applicability, values between 1 and 2 mm should be targeted in the areas of interest.[10]

This study was designed to mimic real-world conditions, aiming to establish target registration error (TRE) values that most accurately reflect real use, rather than values inflated by methodological issues that tend to yield artificially low results.

In the experiment, the neuronavigator correctly detected the eight points corresponding to each cerebral region defined by electrodes with high reliability between the actual coordinates marked on the volumetric image and those measured by the examiners. The intraclass correlation coefficient (ICC) between the coordinates of the predetermined points (actual X, actual Y, actual Z) and those measured by the examiners (X neuronavigation, Y neuronavigation, Z neuronavigation) was nearly 1, indicating perfect agreement.

Although the results obtained by even inexperienced users are still within what would be considered acceptable root mean squared error (RMSE), which speaks to the robustness of the method, users with prior training achieved significantly better average target registration error (TRE) values, as observed in previous studies[4,5] The average accuracy measured in our study for an experienced operator during anatomical registration was 2.9 ± 1.2 mm, with an overall average of 3.5 ± 1.7 mm when including the results from inexperienced individuals. Despite TRE variations, the operators demonstrated similar RMSE. This indicates that the better accuracy of the experienced operator cannot be explained simply by better registration. The operating style of the device appears to influence accuracy, e.g., experienced operators insert the probe in the correct location, but inexperienced operators insert the probe too obliquely. Variations of this type may be accountable for TRE variations. Our findings emphasize the importance of adequate training and experience when using neuronavigation systems. The surgeons should be highly trained and experienced in using the system to ensure its efficacy and utmost precision.

A previous study suggests that visual coordination between the surgical field and the monitor may be distracting for the surgeon [10]. In other words, ergonomic issues may be significant. Consequently, various systems have been developed over the years in addition to conventional infrared neuronavigation, such as electromagnetic tracking neuronavigation and augmented reality neuronavigation.[11] All methods demonstrate comparable accuracies but differ in ergonomic advantages. In a meta-analysis comparing augmented reality systems with conventional optical tracking devices, the former showed a good target registration error (TRE) of 2.5 mm but did not exhibit significant differences compared with the latter.[3]

The present study confirmed a high accuracy of the conventional infrared method, with values close to those found in the literature, ranging from 0.31 mm to 5.9 mm.[12–14] Augmented reality, however, appears to be a valuable ally not only for ergonomic benefits but also as a complement to standard neurosurgical training.[6]

Even though the same facial registration is used, it is noteworthy that target registration error (TRE) varies when marking points in various regions of the brain. Our results indicate that the best situation for a cloud of facial registration points takes place in the temporal regions, where an accuracy of 2.3 ± 1.2 mm is obtained. Conversely, ipsilateral regions to the dynamic reference (i.e., left frontal and parietal) show worse TRE than their contralateral counterpart, possibly due to experimental considerations. Having the camera held in a fixed position throughout the experiment might have placed more interaction between the probe and the dynamic reference, necessitating occasional tilting of the probe. The dynamic reference is most often placed on the opposite side of the surgical approach for ergonomic benefits. Our computation demonstrates that positioning the probe contralateral to the moving reference decreases interaction with the overall system, resulting in higher accuracy.

Another study compared the accuracy of neuronavigation by brain region with various types of registration. It reported that the type of registration has a significant effect on target registration error (TRE) values by anatomical region, with the occipital regions being more difficult. These issues may be addressed by employing hybrid registration methods[10]

There are different types of registration that can be used for neuronavigation, including registration based on fiducial markers positioned in a previous exam, paired anatomical points, surface registration, and automatic registration. Earlier studies analyzed the accuracy of these registration techniques using anatomical and fiducial markers, finding that both provided similar accuracy when correlated to the surgical point of interest.[1] Therefore, anatomical marker-based registration has long been more widely used due to its low cost and greater efficiency in execution time.[15] However, more recent studies have identified fiducial registration as the gold standard among non-invasive methods, demonstrating higher accuracy than the combination of anatomical points[12]. Fiducial registration presents good accuracy ranging from 0.7 mm to 3.1 mm, depending on the tracking method.[11,13,16,17] The present study demonstrated an accuracy similar to that reported in the literature for studies using anatomical marker-based registration, ranging from 2.3 mm to 4.8 mm.[18,19] Although these values are lower compared with fiducial registration studies, they still have acceptable clinical applicability.

Although point-based registration (PBR) is the most used method, newer techniques such as line-based registration (LBR) and surface-based registration (SBR) have been proposed to address the disadvantages of PBR. LBR involves marking one or more lines in physical space using a laser pointer, which, when combined with the cranial surface, facilitates registration. Studies utilizing double or more line-based registration methods have observed a significant reduction in target registration error (TRE) for tumors to 2.0 mm, a value that appears smaller than that obtained in the present study. However, because LBR and SBR require additional, more complex devices, they are still less commonly used in clinical practice.[20]

There is also automatic registration, which serves to facilitate and expedite the paired point method. This technique involves using bands fixed to the patient's head during pre-operative image acquisition and the procedure, aiming to automatically recognize reference points and reduce the time spent positioning markers.[21] Studies using this method reported a target registration error (TRE) of ~1.7 mm, ranging from 0 to 3.19 mm.[22–24] However, there are disadvantages related to inadequate positioning of the bands and the software's inability to add new points during surgery, which represent significant limitations.[21]

Regarding the reference imaging modality method of choice for spatial accuracy, MRI-based research was not shown to differ notably from CT-based research, as was the case according to the current study results. In contrast, studies that employed intraoperative cone beam CT imaging, when combined with the conventional infrared system, demonstrated improved accuracy, with average error values approaching 0 mm.[21]

Regarding the predicted registration error (TRE) provided by the neuronavigator,[7] it does not appear to correspond to the actual accuracy measured. Therefore, these estimates have to be taken with caution. Care should be that the surgeon visually ensures accuracy, always attempting to perform better than in suboptimal performance.

Despite efforts toward matching the experiment to the realities of surgical centers, a firm mannequin was used. Even though it accurately mimicked bone anatomy, it did not mimic surface deformation by the registration probe, which occurs in actual surgery.[12] This may be a figure that overestimates the overall accuracy of the system when employed in this type of study since it makes the registration process more accurate because the surface that is mapped to the patient's skin cannot be distorted. More studies must be conducted to get the experiment closer to actual conditions.

Conclusion

Our findings show considerable differences in the accuracy of the neuronavigation system depending on the experience of the operator. We noted that while untrained or novice operators can provide sufficient levels of accuracy for surgical use, the efficiency of the system is greatly improved by more trained operators. The average target error measured with experienced operators was 2.9 ± 1.2 mm, which shows how training plays a vital role in achieving maximum precision. In addition, the data indicates that despite the lack of special training, the neuronavigation system can be efficient with a clinically acceptable error margin. These results highlight the necessity for continuous training and the value of educational interventions for neurosurgeons to maintain efficacy and safety while performing complicated surgical interventions.

Conflict of Interest
None declared.

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