A Real-Time Ergonomic Coaching System for Neurosurgeons Using Virtual Reality and Machine Learning-Based Posture Analysis

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Abstract: Background: Musculoskeletal disorders continue to affect neurosurgeons with the prevalence of work-related musculoskeletal disorders exacerbated by long hours of static postures in performing delicate and precise surgeries. Ergonomics training, despite its increasing emphasis, is still not adequately integrated within the structure of neurosurgical education.

Objective: In this paper, we present to you the Automated Ergonomics Coaching System (AECS)- a virtual reality-based training platform with Artificial Intelligence-powered pose estimation that enables real-time feedback in creating ergonomic awareness during neurosurgical simulations.

Methods: Twenty-four neurosurgical residents were randomly divided into two groups, an AECS group and a control group. All participants underwent three sessions of simulation training on spine surgery. The quantification of posture deviations was carried out by the model pose and was supplemented by pre- and post-usability questionnaires to assess usability and ergonomics awareness

Results: Though not proven statistically, there was a difference in the ergonomic error rates between the two groups (p=0.278). AECS members showed steady progress from one trial to the next. They had good posture check, were more confident in their ability to correct ergonomics, and gave the system high marks for usability. A large percentage, 73.91%, said that they now have better knowledge as to the strains that come with postures.

Conclusions: AECS shows potential as a practical, feedback-rich training system that enhances ergonomic posture in surgical education. Real-time pose estimation and interactive guidance support a safer, more sustainable learning pathway for surgeons. Future work will explore long-term retention and cross-institutional validation.

Keywords: Ergonomics, Virtual Reality (VR) , Machine Learning (ML), Neurosurgery, Pose Estimation, Surgical Training.

1. Introduction

The operating room was humming with machinery as the neurosurgeon performed a delicate spinal deformity surgery, battling against time and precision. After hours of the surgery, the human body of the surgeon performing the operation begins to rebel— the muscles of the back become stiff, pain in the neck enhances to an unbearable extent, and concentration begins to waver. The toll was being constantly added to with every trivial repositioning in the chair, every slight awkward angle. While he kept his focus fixed on surviving his patient, who was to guarantee the same for him? In a domain where typically sturdy hands and precise minds stand to rescue lives, who stands to see the surgeon through?

The neurosurgeon takes the patient through the surgery which is required to pay high attention and focus hours together since it is a physical and mental stressful procedure for both the patient and the doctor. Prolonged static postures, which are usually awkward in the Operating Room (OR), creates stress on the body energy leading to musculoskeletal injuries after building up fatigue. The extension on ergonomics into practice contributes a lot towards a safer and more productive surgery context with win-win outcomes for all.[1]

This silent struggle has its roots in ergonomics. Ergonomics is that very science concerned with designing workspaces, tools, and systems to fit human needs and not making people adjust to rigid environments. In high-stakes surgery, physical strain may lead to loss of concentration and focus; thus, ergonomics is vital not only for the well-being of the surgeon but also for the patient's outcome. Left unaddressed, such issues predispose surgeons to burn out, compromise their performance, and even make them quit their occupation.

What if there were a method of training neurosurgeons to address these ergonomic risks from the moment they ever step into the operating room? Enter artificial intelligence and virtual reality convergence of state-of-the-art technologies set to transform surgical training. Immersive VR training with AI-driven pose-estimation models may offer real-time monitoring and correction for ergonomic flaws that are otherwise deemed intractable. Such a system would be able to create a mimicry of an operating room, giving the surgeons actionable feedback on posture and movement to bring down the risk of long-term injuries while ensuring better technical precision.

Among the areas in which VR and AR have the potential to be the most promising are precision, safety, and results at education. Intraoperatively, both VR and AR can provide enhanced visualization through immersive 3D and live overlays to reduce the chances of error in a procedure, therefore increasing accuracy in tumour resection. In return for the potential for error, learning applications have transformed neurosurgical training and allowed students and residents to perform quite rare and complicated procedures in a risk-free environment. Applicability to a patient-centric application shows promising postoperative results with functional preservation and adverse effects reduction. Perfect alignment with the most recent navigation systems including neuronavigational and mixed reality have enhanced surgical workflow as well as preoperative planning to a maximum capacity. However, several obstacles remain in this technology which includes high costs and accessibility along with tactile realism that should be further enhanced as much as possible. The long-term future expects that cost reduction, increased access, and improved user interface will maximize the usability of systems for VR and AR technologies in neurosurgery.[2]

This study introduces an Automated Ergonomics Coaching System by merging AI with VR technology for catering to the physical demands of neurosurgery. If developed by simulating practical surgical environments within an immersive, controlled setting, AECS will help not only train the surgeons to master their skill but also protect them from numerous unseen hazards related to this profession. Equipped with advanced pose tracking and personalized feedback, the system is designed to address ergonomic risks with a view to minimizing them and enhancing surgeon endurance for better patient care.

The work of a neurosurgeon involves high-stakes life-and-death decision-making under a great deal of physical and mental stress. At the AECS, we see this future where technology does not only sharpen their expertise but also builds up their grit—so those saving lives can take care to save their own as well.

2. Literature Review

With both physical and mental dimensions, neurosurgery is ranked among the most intricate, demanding medical branches. Frequently dynamic with plenty of long procedures, surgeons perform their tasks mostly in static postures; these repetitive actions can result in (MSDs). Such ergonomic risks need special attention for maintaining the health and work performance of neurosurgeons. The occupational profile of a neurosurgeon makes him/her highly prone to ergonomic risks. Vural and Sutsunbulogu [3] have defined these risks at three different levels: physical, cognitive, and organizational. Such risks not only compromise the health of the surgeon but also degrade the surgical outcome and safety of the patient.

Ergonomic discomfort has been associated with the absence of focus, reduced attentiveness, and increased likelihood of committing an error in the operating room. They also underscore that musculoskeletal pain distracts the surgeon from the optimal decision and optimal performance for them to do so.[4] These issues also cumulatively work to induce burnout and dissatisfaction with a career among surgeons. Ergonomics, or human factors engineering, intends to set up working conditions in accordance with capabilities. The International Ergonomics Association[5] speaks in tailoring the tools and workspaces for minimum strain and maximum efficiency. The statement is most relevant to neurosurgery because the development of an ergonomically suitable working situation may greatly reduce the associated risks.

2.1 Defining Ergonomic Challenges in Neurosurgery

The mix is static postures, dynamic actions and repetitive actions that neurosurgical procedures comprise might lead to musculoskeletal strain if not conducted with proper posture. Conditions that may arise from such strains are lower back pain, neck stiffness, and wrist injuries. Ergonomic risks were classified into three basic groups by Vural and Sutsunbuloglu [3] :

•Physical factors: Postural stress, prolonged static positions, and repetitive dynamic movements.

• Cognitive factors - fatigue leading to imprecision in surgery

• Organizational factors - workspace layout and workflow inefficiencies

A proper ergonomic training system design rests on an awareness of these risk factors.

2.2 Virtual Reality-Based Ergonomics Training

The most recent development is the VR-RET system by Kim and Lee [6] which builds REBA and RULA-based assessments into VR training with visual and auditory cues, but it does not support real-time AI-driven posture correction. Just as, in 2006, Haque and Srinivasan [7]put more emphasis on the technical training advantages of VR, in their 2023 study, they emphasized retrospective ergonomic analysis.[8] Yu et al. [9] conducted an off-line structured educational intervention in ergonomics, without the benefit of dynamic, in-procedure feedback. In contrast, AECS introduces an innovative integration of Immersive Virtual Reality (IVR) environments with AI-based 3D pose estimation and voice-guided feedback, allowing trainees to correct postures immediately. This makes AECS a strong context-aware system for neurosurgical ergonomics training and advances the state of the art over prior systems that could not monitor dynamically in real-time with systems as demanding as YOLOv11 for high-risk surgical environments. In general, while past studies provided basic knowledge, AECS creates an important gap by adding hands-on learning with active, smart computer-based help that is related to work.

2.3 Simulation for Skills Training in Neurosurgery

Simulation systems in surgical training are one of the most common applications for creating a realistic controlled environment without patients at risk to train technical skills. In this regard Davids and Marcus undertook a global systematic review, meta-analysis, and bibliometric analysis of simulation in neurosurgical training. These researchers had accessed 56 studies with 50 types of simulators from cadaveric and low-fidelity models to advanced VR systems. According to their findings, there is highly compelling evidence that simulation enhances the acquisition of both procedural knowledge and technical skills. Despite an increased tendency, especially in the use of VR-based systems, until now they are not universally accepted in neurosurgical training because of the limitations of validation as well as integration. The previous insights clearly indicate the need for more research regarding the conversion of potential into practical application in VR-based simulations.

VR has been adopted as a great innovation for use in medical education. It creates an immersive environment free of risks, allowing the surgeon to practice and perfect his art. According to the study by [10], the use of VR-based training modules enhanced the technical skills of medical trainees and

reduced cognitive load. Yet, how ergonomic feedback could be integrated into these systems remains a less-studied area.

2.4 Virtual Reality Simulation for Skills Training in Neurosurgery

VR is one of those technologies at the vanguard of surgical training, delivering immersive training for skill acquisition and error minimization. In [11], it performed a systematic review of 33 studies published between 1990 and 2021 on the topic of VR in neurosurgery without reporting human performance. The paper further breaks down APMs employed across these studies, such as distance to goal, force application, kinematics, task completion time, blood loss, and volume of resection. For instance, APMs in terms of kinematics (velocity, acceleration, jerk) and time metrics proved very helpful in the detection of different levels of training as well as for tracking progress. The VR system from NeuroVR came out to be the most implemented, appearing in 15 of the works.[12]

AI-driven pose estimation models like OpenPose [13]allow accurate tracking of human motion. They can be used to monitor body posture in real time, thus appropriate for surgical ergonomics. Bringing in the capability of pose estimation to virtual reality environments proves [14] that it can make the ergonomic training more effective in terms of identifying and eliminating postural deviations.

Furthermore, some studies fused machine learning algorithms with VR systems to predict the expertise of the subject. Of the four studies that use AI, three use NeuroVR, and one uses Sim-Ortho. The developments highlight the capabilities of VR in giving pertinent feedback as well as tracking the trainee's progress through metrics by distance, time, or force. APMs, however, have little relevance for ergonomics training since these metrics do not directly touch on posture or biomechanical factors, which are very important in ergonomic skills.[15]

Table 1 illustrates the VR systems by the number of studies and outlines the APM domains assessed by each VR system. As can be seen from Table 1, the VR system NeuroVR is most employed, in 15 studies. Of the APM domains, those best developed concerned distance and time; these two parameters were found to be strong determinants for the description of surgeon experience. The remainder, less well explored, also indicated their potential in the evaluation of technical performance for different training scenarios.

Table 2 shows the four studies which employed ML or AI algorithms within VR simulations to predict the trainee group participant belonged to. Three of these were based on NeuroVR while the others were conducted on Sim-Ortho. The results seem to underline how much virtual reality environments vouch for and convey substantial improvements on an annual basis. APMs achieved through VR systems—distance, time, force, volume— proved useful tests for separating trainee surgeons from fully trained ones and for monitoring the progress of a trainee through a curriculum.

On the other hand, for ergonomics skill training, APMs have scant relevance since they do not influence or measure ergonomic performance. This poses the gap in the current VR-based surgical training systems to integrate more specific ergonomic metrics for better training outcomes. The next section reviews previous work on simulations developed explicitly for training neurosurgeons in ergonomics.

TABLE 1 DISTRIBUTION 33 STUDIES BY VR[12]

VR System	Description	Procedure (no.)	APM Domain					
			Distance	Time	Kinematics	Force	BL	Volume
NeuroVR*	Benchtop simulator head; haptics-enabled instruments	Brain tumor resection (13); hemi-laminectomy; aneurysm repair	✓	✓	✓	✓	✓	✓
ImmersiveTouch	Benchtop simulator head; haptics-enabled instruments	Ventriculostomy (5); spinal needle placement; pedicle screw place-ment; percutaneous rhizotomy	✓	✓				
Sim-Ortho	Video-based platform; haptic & auditory feedback; operators wear 3D glasses	Anterior cervical discectomy & fusion (2)	✓	✓	✓	✓		✓
Own AR/VR†	Abhari et al., 2015[9]	Brain tumor resection	✓	✓				
	Burström et al., 2019[15]	Pedicle cannulation	✓					
Own VR	Roitberg et al., 2013, 2015[27,28]	Pedicle cannulation (2)	✓	✓		✓		
	Hooten et al., 2014[19]	Ventriculostomy	✓	✓				
	Cagiltay et al., 2017[16]	Brain tumor resection	✓	✓				
	Heredia-Pérez et al., 2019[18]	Brain tumor resection	✓	✓	✓			
	Teodoro-Vite et al., 2020[32]	Aneurysm repair	✓		✓	✓		

BL = blood loss.
Descriptions for each VR system were outlined or referenced. The associated VR procedure with APMs examined was listed.
* Formerly known as NeuroTouch.
† For these studies, computer-generated information overlaid the real world (AR) with the option for a completely VR view or derived APMs from VR.

TABLE 2 SUMMARIZE STUDIES USING VR SYSTEM WITH MACHINE LEARNING TO PREDICATE THE TRAINING LEVEL OF PARTICIPANT[12]

Authors & Year	Assessment	Machine Learning Algorithms	Accuracy	Variables Incorporated	APMs Incorporated*
Mirchi et al., 2020[41]	Training level: A/F vs S vs J	Artificial neural network	83.3%	13	Distance; time; kinematics; force; blood loss; volume resected; contacts made w/ tissue; angle of instrument
Winkler-Schwartz et al., 2019[35]	Training level: A vs F/S vs J vs M	K-nearest neighbor Naïve Bayes Discriminant analysis SVM	90% 84% 78% 76%	6	Distance; kinematics; force
Bissonnette et al., 2019[13]	Training level: A/F/S vs J/M	SVM K-nearest neighbor Linear discriminant analysis Decision tree analysis Naïve Bayes	97.6% 92.7% 87.8% 70.7% 65.9%	12	Distance; time; kinematics; force; contacts made w/ tissue; angle of instrument
Mirchi et al., 2020[25]	Training level: A/F/S vs J/M	SVM	92%	4	Distance; kinematics; force; blood loss

The following key was used for the subdivision of participants under the assessment column: A = attending; F = fellow; J = junior resident; M = medical student; S = senior resident.
* The APMs listed were collected by the most accurate machine learning algorithm for each study.

2.5 Simulation for Ergonomics Training in Neurosurgery

The application of coaching ergonomics has been neglected in the few studies that focus on surgical training use. To some extent, these insights may highlight how principles relating to ergonomics should find a place in training through simulation for better habits and hurt-preventative behaviors. Alsharif et al. identified the ergonomic challenges in neurosurgery and put forward a VR training framework, with an eye for integrating surgical simulation with ergonomic feedback towards addressing an improvement in postural habits among surgeons. This work indeed emanated the very critical need for ergonomic considerations in neurosurgical training and filled a big gap that existed with traditional simulation approaches. [16] Hamilton et al. [17] described a novel approach to ergonomics training, incorporating AI-driven video assessments for actionable feedback. This addressed, albeit in part, better neck and shoulder postures observed in the resident learners while performing laparoscopic skills training—hence pointing to real-time ergonomic monitoring with AI-enhanced systems.

Most studies in this area are of experimental design, testing VR and AI in controlled or quasi-experimental settings. For example, randomized trials done with medical trainees proved VR-based ergonomics training to be effective in improving posture and decreasing strain [18]. These studies usually have an evaluation before and after training to assess the same. Even though they are effective, the application of these methodologies is quite limited. They do not often mimic the real dynamic and unpredictable characteristics of work in operating rooms. Apart from that, long-term benefits of ergonomics through VR training are insufficient due to a lack of longitudinal data.

2.6 Gaps and Opportunities

From the studies reviewed, simulation systems have made excellent progress in neurosurgical training. The gap that results in no dedicated systems for ergonomics skills training underscores it as a critical one. Whereas VR-based simulations are apt for the development of technical skills, ergonomics development is the weaker aspect of their application. Most of the extant systems do not practically implement real-time feedback into posture, motion, and other ergonomic features. Besides, their scalability and accessibility in resource-constrained environments, particularly by the demonstration of these systems, remain challenges.

- It highlights the areas in which VR and pose trends could further shape neurosurgical training beyond addressing ergonomic challenges: Key areas of research are:
- Longitudinal Studies that would consider the long-term effects—both with respect to surgeons' health and performance.
- Real-World Testing for practical applicability in live surgical environments.
- Holistic Frameworks that reflect the physical, cognitive, and organizational aspects of ergonomics.
- Scalable Solutions that would make them more widely available to a broader population of surgical practitioners.

The gaps in existing research define an alternative, creative path to solutions in the proposed research regarding the human factor's aspects within neurosurgery, with well-being and efficiency linked to patient outcomes for improvement.

3. Methodology

The current system will develop an integrated real-time feedback system through VR and ML for enhancing surgeons' ergonomic practices right during simulated training. The proposed work will be developed for identifying and mitigating long-term musculoskeletal disorders by considering short-term risks and improving surgical performance.

3.1 System Architecture

The system architecture as shown in figure 1 is designed using three layers: front end, application layer, and back end. The data flow and functionality of each layer are described below. In the present work, a real-time feedback mechanism for surgical ergonomics is brought into the light. The architecture is three-tiered: front end, application, back end— for assured data flow throughout and good functionality.

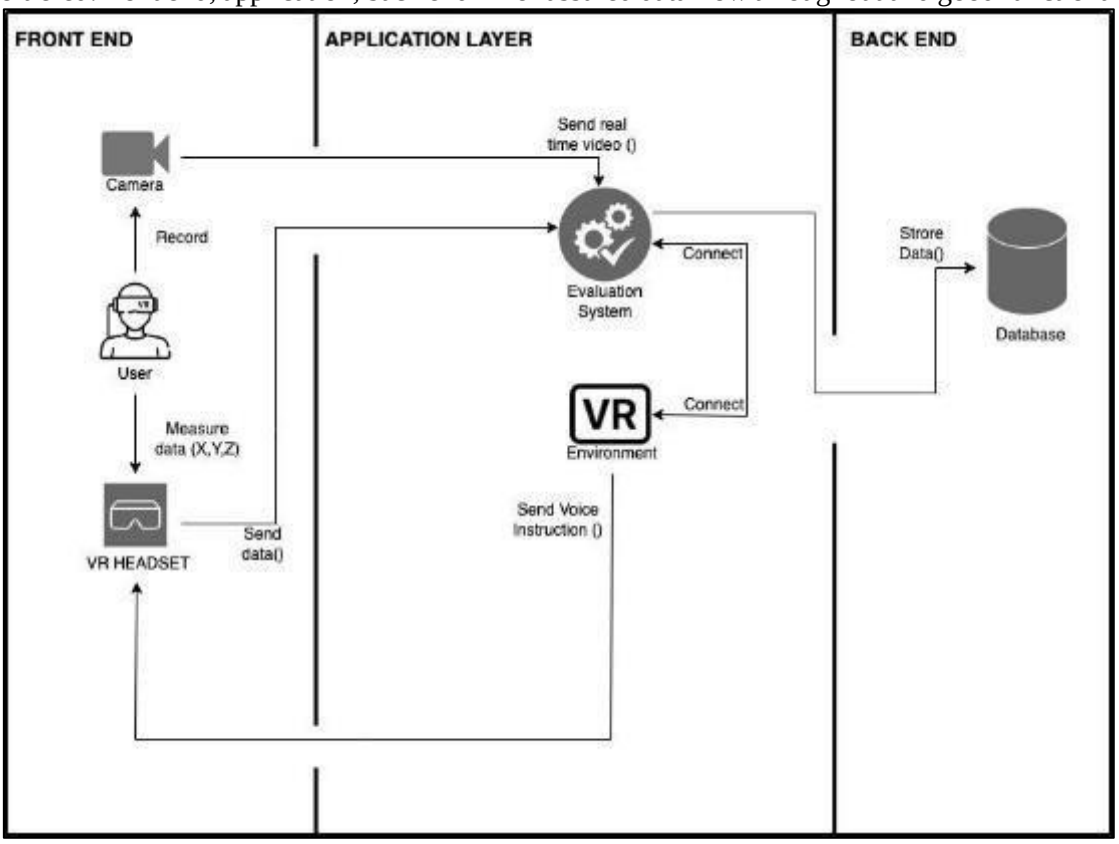


Figure 1 System Structure

The front-end layer captures raw input data from the user, through a VR headset and camera. The VR headset monitors head movements. The camera records real-time posture and movements. These are processed inputs for calculating ergonomics parameters, like the angles of the neck, which are then sent for evaluation to the application layer.

The application layer, which is at the heart of the system, utilizes ML algorithms to analyze ergonomic parameters. Real-time data at this layer is checked against predefined ergonomic standards. If any deviations happen, the same shall be immediately communicated by auditory feedback through the system and by appropriate visual guidelines within the VR to guide the user to set right the posture. Processed data along with the evaluation results will have been saved in the back-end database for future analysis.

It is the back-end layer that is responsible for managing data storage and supporting model improvement. It records user performance metrics as well as ergonomic assessments of users' longitudinal progress. This layer also allows the updating of the ML models so that the system can learn from new user interactions and scenarios.

3.1.1 Machine Learning Methodology

In the figure2 depicts the ML pipeline as a multistage process, comprising four principal modules— Data Collection, Training, Deployment, and Evaluation. Each module plays a critical role in its associated phase of developing, deploying, and maintaining strong ML models to deliver real-time ergonomic feedback in the proposed system.

- Data Collection Module: This module collects raw data from the VR system (head movements and posture metrics) required for the initiation of the ML pipeline. Major stages of it are Data Preparation, Validation, Analysis, Labeling, and Feature Engineering. Processed data, after these processes, is saved in a Central Database Accessible for Execution of the Subsequent Module Training process.
- Training Module: The module trains the ML model using the collected data. This involves training data preparation, model creation, accuracy testing, hyperparameter tuning, and cross-validation. Testing data, after all of this, is akin to proving ground for checking if the model really has learned what the training data says (generalization and robustness of the model) before deploying it.
- Deployment Module: After a model has been trained and validated, it is deployed. The model is exposed to the real operational environment. Equates to testing the model in production conditions and including mechanisms for real-time model adaptation based on feedback and new data.
- Evaluation Module: This is the final stage that tracks whether the system serves security and compliance purposes. It tracks model performance and version control, recording experiment details to make iterative improvements. Continuous validation of such a system would be of great importance to ensure its effectiveness and relevance.

3.1.2 Virtual Reality (VR) Setup

The VR setup bridges user interactions with ML algorithms through hardware and software components:
Hardware Components:

- VR Headset: Captures head movements and delivers immersive feedback as shown in figure 3.
- Controllers: Tracks body movements for detailed analysis.
- Computing Unit: Processes data in real time.

Software Components:

- 3D Virtual Environment: Simulates realistic surgical scenarios.
- Tracking Software: Monitors user movements and interactions.

The combination of VR and ML can, therefore, create a dynamic intelligent system for real-time ergonomic assessment and feedback. The processes involved in the integration of the above two are briefly explained below

- Data Acquisition: During the simulation of surgical scenarios, detailed movement and interaction data of the users in real-time are obtained by the VR hardware, e.g. headsets and controllers.
- Data Preprocessing: It involves normalizing and scaling the raw data obtained from VR devices to make it compatible with ML algorithms, which includes elimination of noise or any disparities.
- Real-Time Ergonomic Analysis: ML algorithms assess posture and movement patterns. With it, it is possible to get actionable recommendations by evaluating ergonomics risks and offering them in the form of real-time feedback.
- Feedback Loop: As such, the system will provide feedback in real-time through the VR interface by using visual indicators (e.g., warnings color-coded red) and text-based suggestions to drive users toward ergonomically sound practices.

That integration shall thus ensure that VR training modules do not just represent real-world environments but intelligently enhance user performance by constantly checking and enhancing ergonomic behaviors.

3.2 Scope of Ergonomic Assessment

AECS covers static and awkward postures often assumed in long neurosurgical procedures. Following the ergonomic principles set by ISO 11226, the posture is evaluated based on clinically significant joint angles and the duration for which the posture is sustained. The validated thresholds against which postural risks are assessed are as follows: Such flexion that is greater than 20° at the neck leads to increased loading on the cervical spine and muscular strain; hence, neck pain and fatigue in the execution of microsurgical tasks[19].Trunk flexion > 30° increases the pressure on the spinal disc and is strongly related to lower back symptoms in surgeons operating for long hours[20][21]. Elevation of shoulders > 25°, especially if sustained for more than 10 seconds, results in the elevation of trapezius

electromyographic activity and is considered high in the risk for shoulder muscle fatigue and possible shoulder injury[22]. Asymmetry in elbow angle > 15° indicates that there is imbalanced and asymmetric loading, which may lead to localized upper limb disorders in the future [23]. The thresholds are from existing ergonomic literature and validated models: RULA [24], REBA[25], and the ISO 11226 [20]posture standards. AECS does not provide procedural guidance or interfere with surgical techniques, but it does help because it raises real-time auditory alerts when and once an ill ergonomic posture is detected and has been maintained for more than 10 seconds, drawing attention to adjust posture proactively without any disruption to surgical workflow.

3.3 Posture Angle Estimation Framework

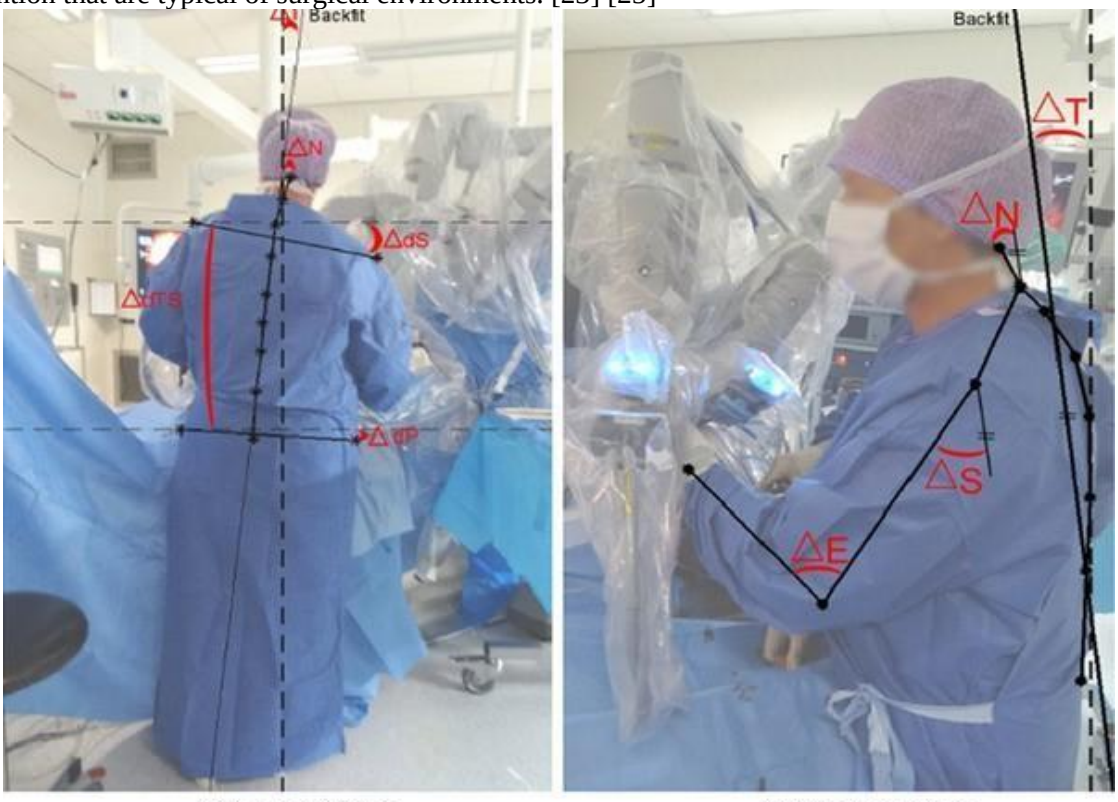
To assess ergonomic risks in real time during surgical procedures, the AECS calculates key joint angles that have links to (MSDs) in prolonged and constrained occupational activities. These angles have been selected based on ergonomic guidelines from ISO 11226:2000 and validated observational tools such as RULA and REBA which are common in surgical ergonomics studies. [19] [20] [21][24].

Biomechanical indicators tracked by the AECS are as follows as shown in figure 2:

- Neck Flexion and Rotation: more than ±20° from the normal axis of the neck
- Trunk (Back) Inclination: forward T de more than 30° from the vertical plane
- Shoulder Elevation and Abduction: arm elevation above 25° with respect to the torso
- Elbow Flexion Asymmetry: flexion is less than 90° or more than 135°, or a left-right difference greater than 15°.

These values result from 2D keypoint detection computed by models for pose estimation such as YOLOv11, YOLO-NAS, and OpenPose applied to RGB video streams; for each body region, joint angles are computed from vector geometry and the law of cosines between three anatomical landmarks (e.g., shoulder–neck–spine for neck tilt; hip–spine–neck for trunk lean).

When there is a high-risk deviation for more than 10 seconds, the voice-guided feedback system is activated. Thus, real-time correction allowing the surgeon to adjust posture without interrupting his workflow enables both immediate correction and long-term ergonomic habit formation. The system is designed to minimize cognitive load with feedback that is aligned with requirements for sustained attention that are typical of surgical environments. [23] [25]



(a) *Dorsal plane* (b) *Sagittal plane*

Figure 2 Ergonomic postural angles evaluated in the dorsal (a) and sagittal (b) planes during a neurosurgical procedure. Key anatomical deviations are marked, including neck tilt (ΔN), shoulder elevation (ΔS), elbow angle (ΔE), and trunk inclination (ΔT).[26]

3.4 Real-Time Feedback Algorithm

The real-time feedback algorithm ensures ergonomic compliance during training. The pseudocode is summarized below:

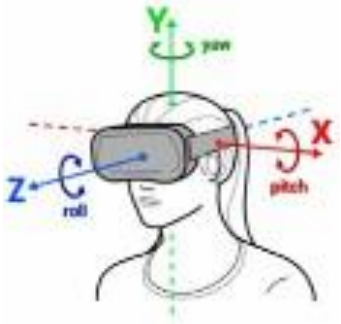


Figure 3 Headset measurements [27]

Algorithm: VR Coaching Ergonomic System

1:	**INPUT**	Video stream from webcam V
2:		Matrix of headset M
3:		Table height h
4:	**OUTPUT**	Voice instructions *VO* for correcting posture
5:		Integer flags: *wFlag* and *rFlag*
6:		Matrix of position *MH* (neck, elbow, back, shoulder) during surgery
7:	**MAIN**	Enter the VR environment.
8:		Start recording the webcam: V = Record(webcam).
9:		**Initialize** headset input: $M\ (x, y, z)$ = Headset Input().
10:		**Initialize** wFlag, *rFlag* = 0
11:		While (game is not ended)
12:		Evaluate the System (M ,V)
14:		Get the height input (h) from the user.
15:		If (h != elbow height)
16:		Do While
17:		1. Play instruction to correct position (VO).
18:		2. wFlag =+ 1.
19:		Else rFlag =+ 1.
20:		If User get surgery tools
21:		Do While
22:		If wrong position != 1
23:		1. Check the neck angle and add to (MH).
24:		2. Check the elbow angle and add to (MH)
25:		3. Check the back angle and add to (MH).
26:		4. Check the shoulder angle and add to (MH). 5. rFlag =+ 1
27:		Else
28:		1. Play instruction (VO) to correct the position.
29:		2. wFlag = + 1.
30:		Get rFlag , wFlag and matrix (MH).

The algorithm focuses on the following:

1. Initialization: Initialize VR environment and inputs. After this, record the movement of the user by webcam and headset.
2. Evaluation and Feedback Loop: The major loop, in this case, carries out the evaluation of posture. It does this using specific pre-fed ML algorithms. Posture identified by the user is, for example, not an ergonomically required position (like the height of the elbow not equal to the required height) real-time feedback will be done by the system through voice instructions for proper guidance of the user into the correct posture.

3. Tool Usage Monitoring: Interacts with surgical tools. Constantly notes any wrong posture by the user.
4. Scoring: Keeps a record concerning how well correct posture and tool use are scored. Adds it into a scoring system based on the practice of ergonomics being correct and uniform.
5. End Game: Issues a final score regarding the whole activity. Gives an in-depth posture analysis.

Finally, the proposed system combines VR and ML to deliver real-time ergonomic feedback, addressing a critical gap in surgical training. By reducing musculoskeletal risks and enhancing surgeon efficiency, the system has the potential to transform training practices. Future work will focus on validating the system in real-world settings and optimizing its scalability for broader adoption.

3.5 Experimental design

Objective: This experiment aims to investigate whether a VR ergonomics coaching system significantly improves the ergonomics skills of surgeons. The study will follow a pretest-post-test design with two groups: one group receiving training via the VR ergonomics coaching system (experimental group) and the other group receiving no such training (control group).

Hypothesis: Null Hypothesis (H_0): The coaching on the VR ergonomics coaching system has no impact on the ergonomics skills of surgeons.

$$H\_0: \mu\_0=\mu\_1$$

Alternative Hypothesis (H_1) The coaching on VR ergonomics coaching system has a positive impact on the ergonomics skills of surgeons.

$$H\_1=\mu\_0<\mu\_1$$

Where:

μ_0represents the mean ergonomics skills of surgeons who are using the VR ergonomics coaching system.

μ_1represents the mean ergonomics skills of surgeons who aren't using the VR ergonomics coaching system.

Participants

The participants will be randomly assigned to one of the following two groups:

Group A (experimental group): In this group, training will be given using VR ergonomics coaching system.

Group B (control group): This group will not receive any coaching, but assessment will be done under normal conditions

Martials tools

The materials required for this experiment include:

VR Ergonomics Coaching System: A virtual reality system designed to coach participants on proper ergonomics during tasks.

Task Simulation: A standardized task performed by both groups to evaluate ergonomics skills.

Assessment Tools: Tools to measure participants' ergonomics performance, such as posture, movement, and efficiency.

3.5.1 Procedure Expected scenario

Pre-test:

All participants will perform the same standardized task without any coaching. Their ergonomics skills will be assessed and recorded using objective measures such as posture and movement efficiency.

These initial assessments will serve as the pre-test scores, establishing a baseline for comparison.

Intervention:

Group A (Experimental Group): Participants will undergo training using the VR ergonomics coaching system. The system will provide real-time feedback on posture and movement, coaching participants on improving their ergonomics.

Group B (Control Group): Participants will continue with their tasks without any VR coaching or intervention.

Post-test:

After the intervention, both groups will perform the same standardized task again.

Their ergonomics skills will be reassessed using the same measures as in the pre-test, and post-test scores will be recorded.

3.5.2 Data Collection and Analysis

The experimental group's performance will be compared with that of the control group through statistical analysis using t-tests. If Group A shows significant betterment than Group B, this will show if the hypothesis of the VR ergonomics coaching system is effective.

3.5.3 Ethical Considerations

Informed consent will be obtained from all participants, and they will be informed of their right to withdraw from the study at any time. All data collected will be anonymized to ensure confidentiality.

3.5.4 Decision Criteria

If the p-value from the t-test is less than (or equal to) α, then reject H_0 in favour of the claim that VR ergonomics coaching positively affects the ergonomics skills of surgeons (H_1).

If the p-value is greater than α, it fails to reject the null hypothesis, indicating no significant evidence to suggest that VR coaching impacts ergonomics skills.

This experiment design should help systematically investigate the effect of VR ergonomics coaching on surgeons' ergonomic skills.

4. Result of proposed system

4.1. ML Phase: Pose Estimation Module Comparison

4.1.1. Pose Estimation Module Evaluation Strategy

We assessed five state-of-the-art pose estimation frameworks to determine an appropriate model for ergonomic analysis in real time within complex surgical settings. Each has varying accuracy under occlusion and the time taken to deploy in real-time settings:

- OpenPose: This is a bottom-up system for multi-person 2D pose estimation which connects keypoints by learning it with Part Affinity Fields. Good in multi-person detection, it performs less than state-of-the-art in heavy occlusion; scenarios.[13]
- MediaPipe BlazePose: A model created by Google for lightweight, real-time pose tracking on mobile/edge platforms. While efficient, it shows sensitivity to occlusions and dynamic motion. [28]
- MoveNet: A very fast model for pose estimation from TensorFlow made for easy applications. It does well under clear visibility but has issues with joint continuity and occlusion.[29]
- YOLOv11-Pose: A deep learning model for high-performance analysis of ergonomics in dynamic and occluded environments. It combines EfficientNet-B5, PAN, and self-attention to increase precision, recall, and robustness in surgical scenes.[30]
- YOLO-NAS-Pose: The newest version, made by Deci.ai, uses Neural Architecture Search and post-training quantization for better speed-accuracy trade-offs. It is made for fast use on embedded systems and VR apps.[31]

4.1.2. Experimental Setup and Evaluation Metrics

All models were trained and tested on a unified, ergonomically labeled dataset comprising 700 annotated images, with labels denoting postural risks for the neck, shoulder, elbow, and back. The data was split into a standard split, as provided below:

70% for training
15% for validation
15% for testing

To ensure comparability, identical preprocessing, augmentation, and evaluation procedures were applied for each model. The following performance metrics were to benchmark:

Mean Average Precision (mAP)
Precision
Recall
F1-Score
Frames per Second (FPS)
Occlusion Handling Rating

The results of our evaluation are summarized in Table 1 below:

Table 3 Performance comparison of five pose estimation models

Model	mAP (%)	Precision (%)	Recall (%)	F1-Score (%)	FPS	Occlusion Handling
OpenPose	65	67	70	68	7	Moderate
MediaPipe	67	66	53	60	25	Low
MoveNet	62	58	44	50	30	Low

YOLOv11	**94.5**	**95**	**84.7**	**89.5**	18	High
YOLO-NAS	91.2	93.4	82.3	87.5	**35**	**High**

The comparative results of the five leading pose estimation models, namely OpenPose, MediaPipe, MoveNet, YOLOv11, and YOLO-NAS, are illustrated in Figure 4 and table 3 based on their mAP, Precision, Recall, and F1-Score. Among them, YOLOv11 turns out to be the best with 94.5% mAP, 95% Precision, 84.7% Recall, and 89.5% F1-Score. A high occlusion-handling ability specifically caters to YOLOv11 for robust environments, such as operating rooms (ORs), where body landmarks are most often occluded. This has been justified by its design, which incorporates EfficientNet-B5 and a self-attention mechanism for improved robustness in dense visual scenes.[32]

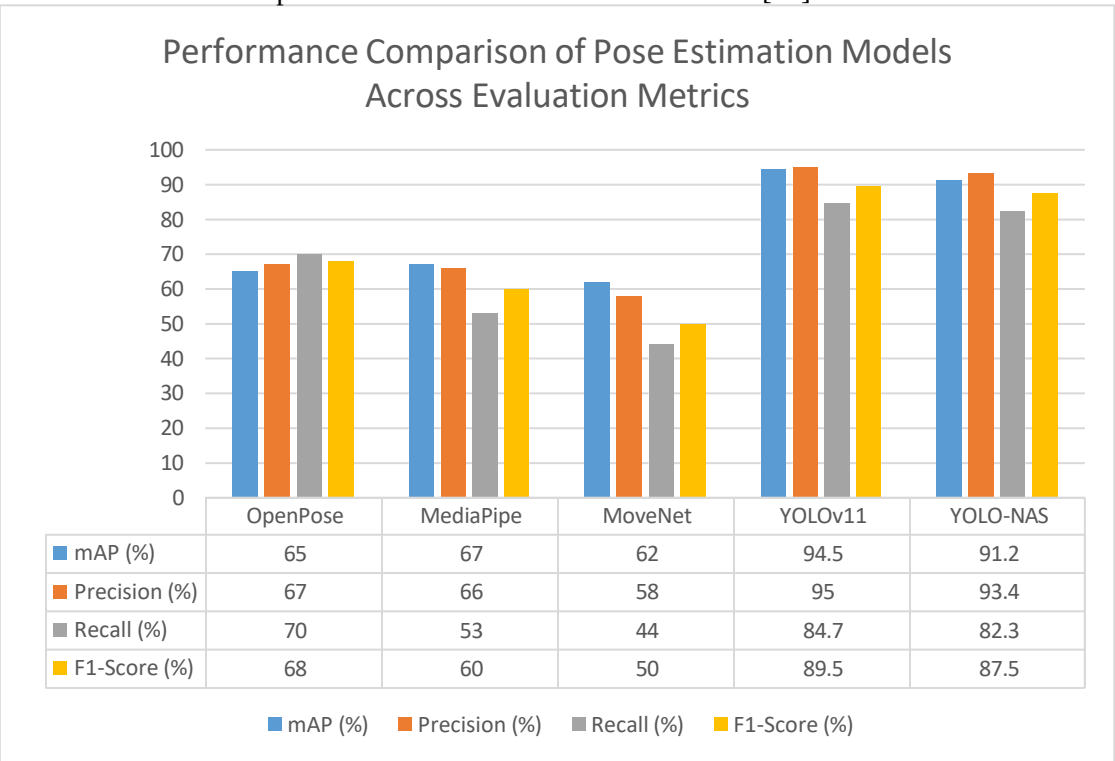


Figure 4 Performance Comparison of Pose Estimation Models Across Evaluation Metrics

The highest Frames Per Second, at 35, is achieved by YOLO-NAS, with impressive acumen: mAP 91.2%, Precision 93.4%, Recall 82.3%, F1-score 87.5%. It combines Neural Architecture Search (NAS) with post-training quantization. The optimization is for both latency and accuracy where the target is the deployment on edge devices and VR systems. OpenPose, is effective in the detection of multiple people and is also known for its computational intensity; moderate handling of occlusion is attained at mAP 65%, F1 68%. Since it's roughly about 7 FPS, its performance when it comes to real-time applications like monitoring surgical ergonomics is quite low due to occlusion. MediaPipe, and MoveNet, deliver high inference speeds but have somewhat lower recall (on the level of 53% and 44%) and F1-score (around 60% and 50%) especially for more complex or occluded postural scenarios; thus, this and that may not be very suitable for the most sensitive environments, for example, operating theatres, where posture should be watched very precisely. These results answer the question of whether YOLOv11 is the most accurate model for high-accuracy, occlusion-resilient pose analysis, while YOLO-NAS gives the best trade-off between detection quality and deployment efficiency. MediaPipe and MoveNet work fast, yet they struggle to keep ergonomic accuracy when dealing with more complicated postures.

4.2 VR phase

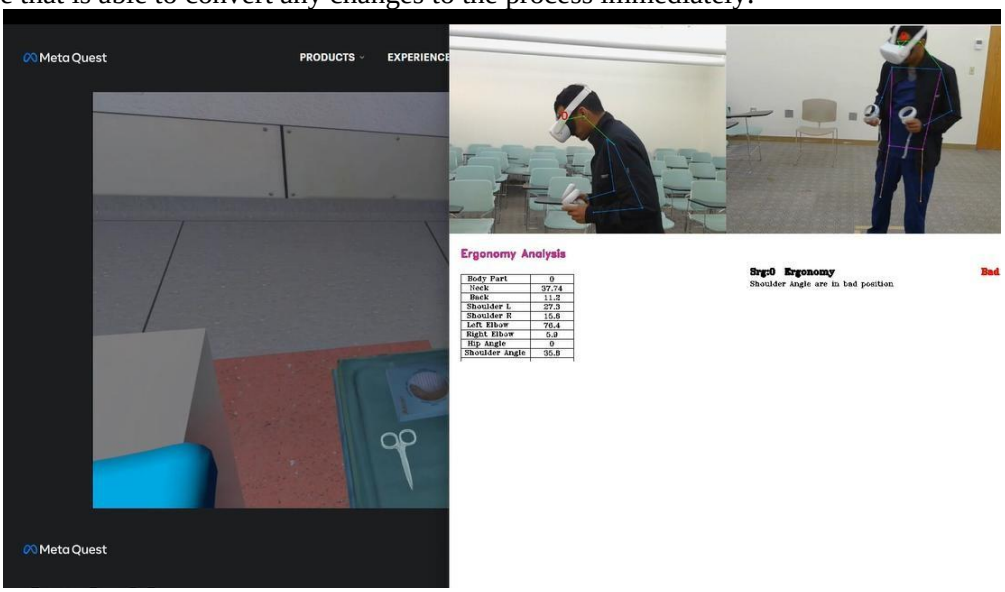
The VR system shown in Figure 4 is an upgrade of the virtual reality simulation created by Dr. Alshrif H in 2021.[27] To make the simulation environment more effective for real-time ergonomic assessment, some major changes have been made to it. The most major change is the integration of real-time auditory feedback that gives voice alerts as soon as it detects improper ergonomic postures.

A special Python-based middle layer was made to help different parts talk to each other smoothly: the Unity-based VR world and the ML. This join made it possible to check how well a person sits using data on key points found by the YOLOv11-pose model, which turned out to be the best in our module.

Figure 5 Virtual Reality of Operating Room of Spine Surgery

Figure 5 shows interface of AECS used in a virtual reality-based training for spine surgery. This system lets them check the surgeon's posture in real time by combining visual pose estimation overlays with measurements of joint angles and ergonomic risk. The most important angles— like how much the neck tilts, or the trunk leans forward, or the shoulder rises, and the elbow bends — are calculated from 2D keypoints using models based on YOLO-v11, then checked with ergonomic rules as shown in section 3.3.

In the upper panel, shoulder angles are found to exceed ergonomic limits and are labeled "bad posture" with alerts marked in red. Whereas in the lower panel, there is actual realignment of joints, the system now validating the posture as "good" in green. The system provides trainees with real-time voice guidance that is able to convert any changes to the process immediately.



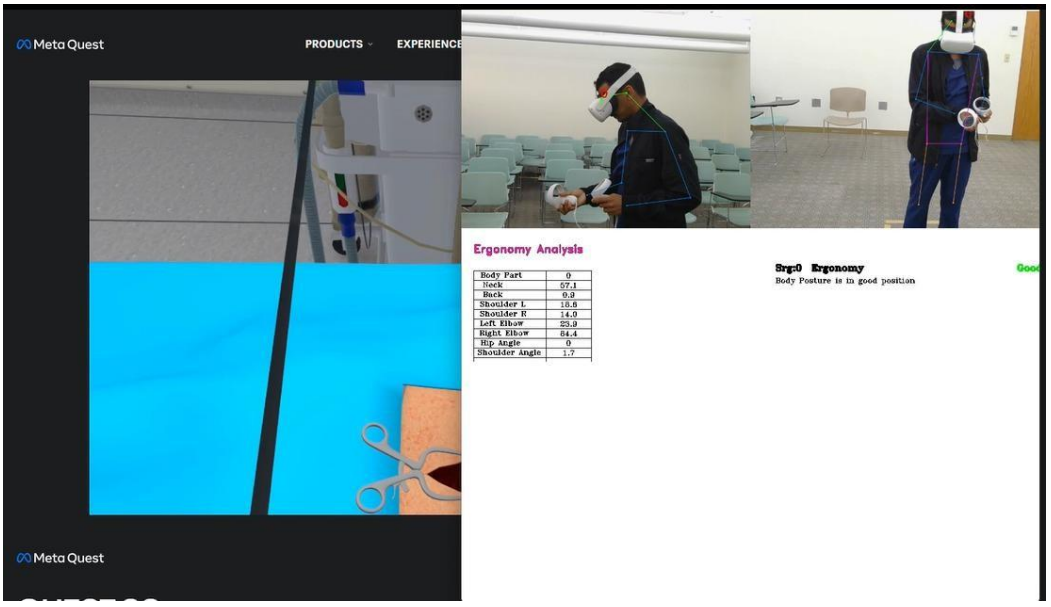


Figure 6 Screenshots from the Automated Ergonomics Coaching System (AECS) deployed in a VR-based surgical simulation

Also, the whole time is recorded and kept, so surgeons can check back and watch how they did the postures after training. This helps think about it more, strengthens proper ergonomics, and supports constant betterment. The varied feedback system—mixing live sight checks, sounds to go with it, and watching the session after¬ward—gives a strong plan for making lasting ergonomic habits and cutting the chances of muscle and bone problems in surgery settings.

5. Results of Experiment: Group-Based Ergonomic Performance Evaluation

5.1 Average Ergonomics Score Analysis

Ergonomics scores were computed as the percentage of postural deviations detected during each trial. The average score per participant across all three trials was used to compare the groups. As shown in Figure 7, Group A achieved a lower average error score (Mean = 42.53%, SD = 17.94) compared to Group B (Mean = 50.82%, SD = 18.56). However, an independent samples t-test revealed no statistically significant difference between the groups ($t = -1.11$, $p = 0.278$), indicating that while Group A performed slightly better, the results were inconclusive given the sample size.

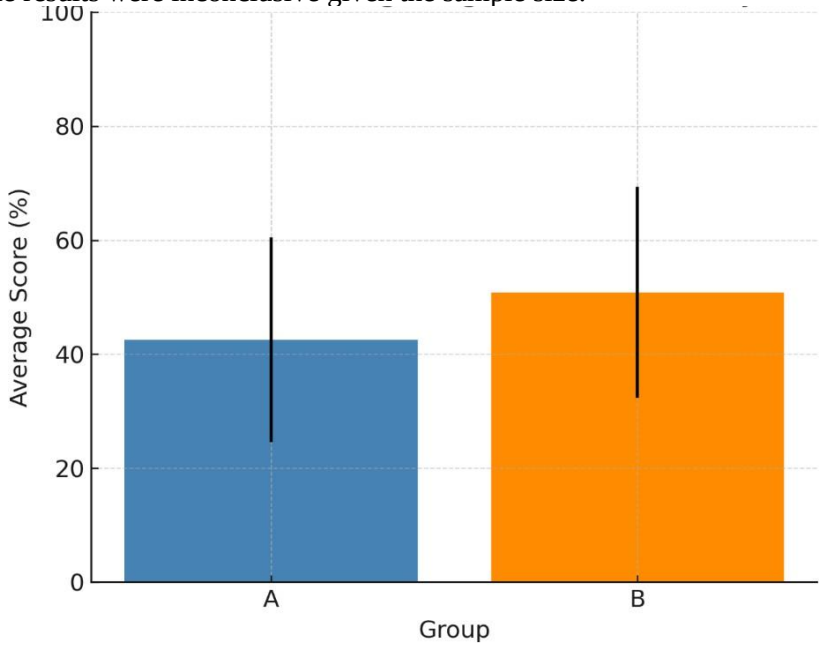


Figure 7 Mean Average Ergonomics Score by Group

5.2 Learning Curve Trends Across Trials

To assess intra-group improvement, trial-by-trial averages were compared. Group A demonstrated a steady reduction in posture error scores across the three trials (Trial 1: 48.6%, Trial 3: 38.6%), while Group B exhibited minor fluctuations with limited improvement. These trends are visualized in Figure 8, which shows both group averages and individual learning trajectories. The individual participant lines show variability in learning outcomes, with Group A participants tending to stabilize at lower scores over time.

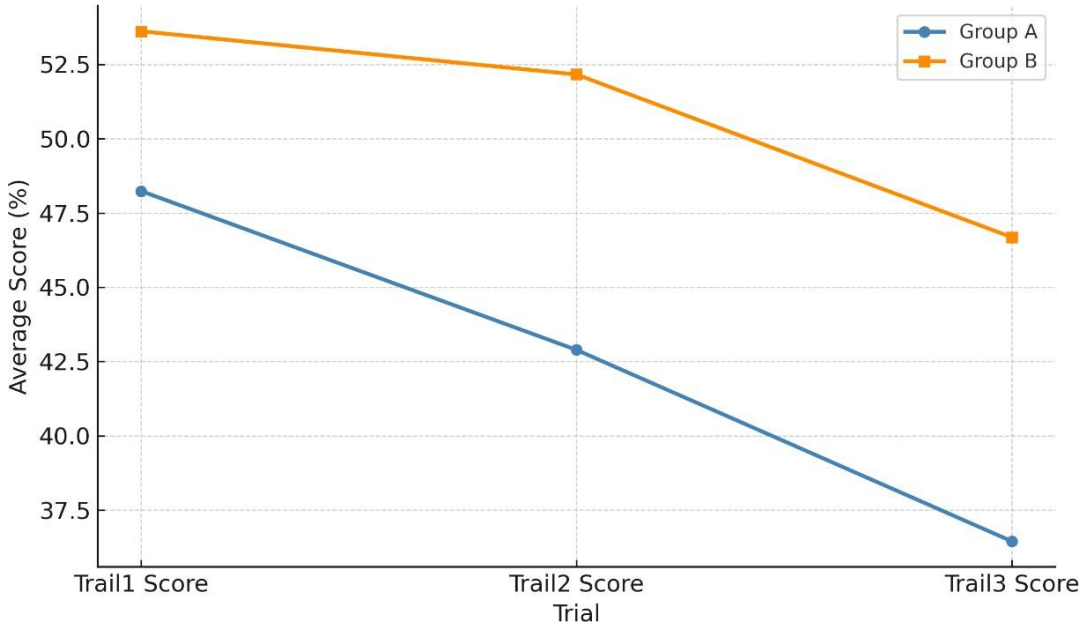


Figure 8 Group Learning Curves Across Trials

5.3 Distribution and Variability

As seen in Figure 9, a boxplot of average ergonomics scores illustrates greater score dispersion in Group A, with several low-scoring outliers suggesting stronger individual performance. Group B showed a more consistent but higher error rate, indicating less effective adaptation despite enhanced feedback features.

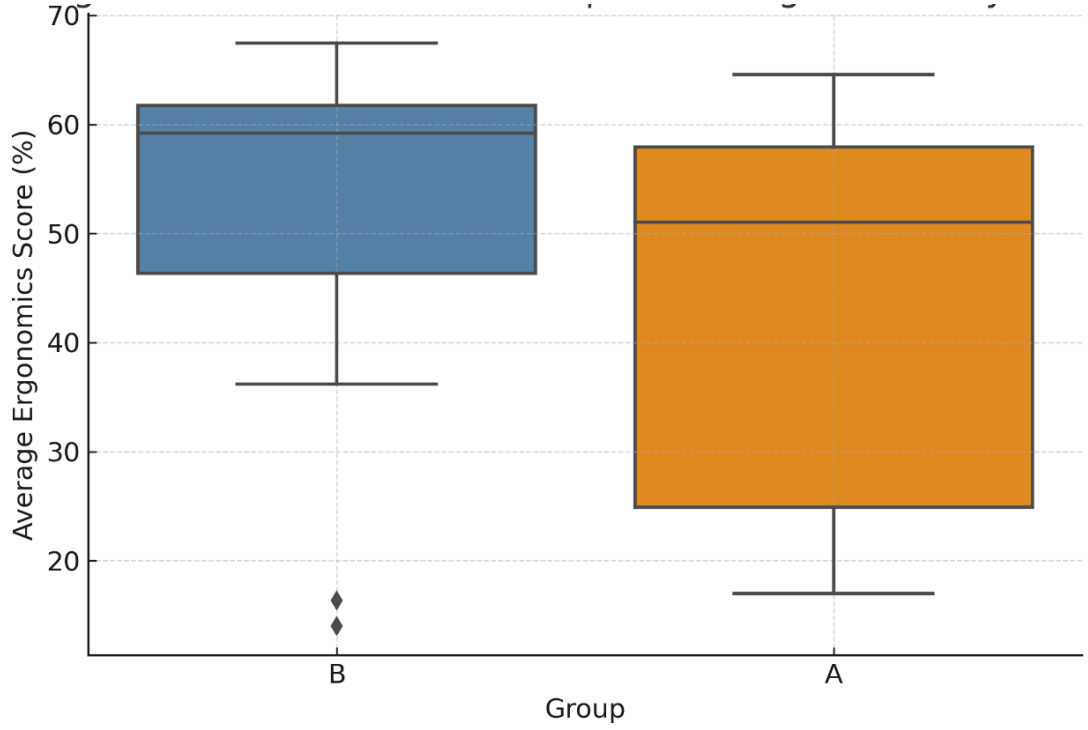


Figure 9 Distribution of Participant Average Scores by Group

From previous figures 7,8, and 9, Although no statistically significant difference was found between groups, the consistent improvement trend in Group A suggests the base VR simulation provided effective ergonomic awareness. Meanwhile, Group B's lack of notable gains despite enhanced feedback raises considerations about feedback design, timing, clarity, or over-reliance on automation. These findings indicate the need for deeper behavioral analysis and iterative improvement in AECS real-time guidance mechanisms.

5.4 Questionnaire-Based Evaluation (Pre and Post Simulation)

To further assess the perceived impact of the system, all participants completed pre- and post-simulation questionnaires covering awareness, attitudes, and confidence in ergonomic posture practices.

5.4.1 Participant Experience and Perception

The post-simulation questionnaire data supports the usability and acceptability of the AECS platform. Specifically:

47.83% of participants rated their confidence in transferring learned postures to real surgeries at the highest level (4 out of 4), with an average score of 3.13.

43.48% believed VR is a highly effective tool for ergonomic training (score 4), and the average effectiveness rating was 3.0.

73.91% reported increased awareness of posture and posture-related pain prevention after using the system.

Participants rated the helpfulness of the system in understanding posture at 3.17, and self-perceived improvement in posture skills at 2.83.

These findings highlight that the AECS system is not only operationally effective but also positively received by its users. Prior studies similarly report that VR simulation increases learner engagement, confidence, and performance [7][33]

5.4.2 Ergonomic Relevance and Prior Experience

Pre-simulation data revealed that 82.61% of participants had already experienced posture-related discomfort during surgeries, underscoring the practical necessity for ergonomic training. Surgeons frequently report (MSDs) due to poor posture, with prevalence rates exceeding 70% [21]. However, only 41.67% had prior exposure to VR simulation tools, confirming that AECS introduces new and needed technology into many trainees' learning environments.

5.4.3 Qualitative Feedback and Areas for Improvement

Free response feedback from participants emphasized several strengths of the AECS platform, including:

Safe and repeatable training environment

Real-time correction support

Opportunities to simulate posture-intensive procedures without clinical pressure

Suggestions for improvement included enhanced instrument realism, better interaction fidelity, inclusion of more advanced procedural scenarios, and pre-session tutorials. These comments provide a critical roadmap for future development iterations and align with broader calls for improving simulation fidelity in surgical education.[34]

6. Discussion

This study introduces and evaluates (AECS), a novel posture-focused solution integrated into (VR) training for surgical ergonomics. The findings provide preliminary but promising evidence that real-time posture feedback can reduce exposure to musculoskeletal risk factors during neurosurgical simulations.

6.1 Comparison with Existing Systems

The investigation of how to utilize virtual reality in the educational field of surgery has primarily concerned the acquisition of procedural skills, rather than the ergonomic awareness that is associated with it. For example, the study by Kim and Lee (2023) [6]introduced the VR-RET system, which combined virtual reality with the risk of ergonomics assessment using REBA and RULA, but the system lacked automatic posturing correction or feedback mechanisms that were AI-based.

Similarly, a meta-study by [7] discussed the effectiveness of VR simulators in improving technical abilities but lacked concern regarding ergonomic optimization during procedures. Their later study in the American Journal of Surgery in 2023 emphasized the value of AI-based video analysis for improving ergonomics, however, the feedback was not real-time or retrospective.[8]

Yu et al. [9]developed a structured training intervention for ergonomics that was part of a surgical simulation-based training regimen. However, the method was purely offline, based on pre- and post-assessment that lacked active participation in the procedure.

Alsharif et al.[27] developed a virtual reality-based trainer dedicated to the ergonomic training of patients during spinal surgery, the primary concern was the degree of neck rotation and the height of the elbow. However, their system lacked integrated feedback that was real-time or based on AI, this limited the ability of the system to dynamically correct the posture of the train during training sessions.

A recent investigation by [35] created an AI-powered tool that evaluated videos in real time and provided residents with instantaneous feedback. While it was effective at raising awareness and improving metrics on posture, it was limited to 2D video analysis and lacked interactive or immersive components in its design.

In contrast, the AECS system that was implemented in this study has unique features that include real-time AI-based pose estimation and voice-activated feedback within virtual reality simulations that are immersive. This facilitates the active correction of posture during the procedure- this is an important advancement for high-risk, posture-bound environments like the neurosurgical profession. AECS incorporates current literature to enable both immediate ergonomic coaching and performance monitoring using models like the YOLOv11-Pose, these limitations are addressed by AECS.

6.2 Practical Implications

AECS aligns with occupational safety guidelines (e.g., ISO 11226, NIOSH) by identifying sustained postural deviations known to contribute to musculoskeletal disorders (MSDs). The reduction in neck and trunk alerts observed in this study underscores the system's targeted impact on high-risk areas. These results support AECS as a viable educational intervention for ergonomic injury prevention in surgical training.

6.3 Limitations

Several limitations should be acknowledged. First, the study was conducted at a single academic site with a limited sample size (n=24), potentially reducing generalizability. Second, posture improvement was observed only in the short term (3 sessions). Long-term behavioral retention and actual MSD prevention were not assessed. Third, the system does not account for anthropometric constraints or physical OR limitations that may restrict posture correction. Additionally, reliance on voice alerts may vary by individual, with some users potentially becoming desensitized over time.

6.4 Future Directions

Future studies should include multi-center trials, larger and more diverse cohorts, and longitudinal tracking of ergonomic behavior retention. Additional feedback modalities (e.g., haptic or visual cues), integration with biometric sensors, and adaptation to specialty-specific ergonomic demands could further increase AECS effectiveness and user personalization.

7. Conclusion:

The study describes the design and first testing of the Automated Ergonomics Coaching System (AECS), a virtual reality platform meant to help people learn ergonomics - proper body movements while doing surgery. AECS helps with a big hole in thinking about and preventing muscle and bone problems - giving quick advice on how to sit and stand straight while in very lifelike surgical practice.

Statistically, there was no significant difference between AECS and the control group in the average posture error rate, but AECS users showed greater improvement over the trials. They also have shown improvement in confidence, awareness, and satisfaction. The survey brought out a high prevalence regarding discomfort due to posture amongst the participants, and there is a strong perceived value of AECS in improving ergonomic awareness and training quality.

These results prove that AECS might help the future with the new ways of learning that focus on getting feedback right away and being fully engaged. The detailed feedback also shows how AECS could help build ergonomic skills in risky, hands-on learning environments.

Limitations of the study were the small sample size and the variability in the participants' prior experience with surgery and virtual reality, which may not have provided enough statistical power. Future research should make a more extensive validation of the system across larger and more diversified cohorts, assess task-specific fidelity, and examine long-term behavioral and clinical outcomes.

Despite these limitations, AECS proves a workable and novel approach to bettering work safety in education on surgery. Putting it into the programs for training may help to lower the risk of MSD and make the performance better, thus supporting the well-being of the surgeon and the excellence of the operation.

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