Real-Time 3D Posture Tracking for Surgeons in Pediatric Minimally Invasive Surgery

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Abstract: Minimally invasive pediatric surgery presents ergonomic challenges that significantly increase the risk of musculoskeletal disorders (MSDs) among surgeons due to prolonged periods of suboptimal posture. This study introduces a real-time posture monitoring and correction system designed to address this issue. The system utilizes depth camera technology, interactive feedback mechanisms, advanced skeletal tracking, and ergonomic assessment algorithms to continuously monitor and evaluate surgeons' posture. Through rapid data processing, the system provides real-time feedback, enabling immediate posture adjustments during surgical procedures. It delivers non-intrusive alerts to inform medical staff when incorrect postures are detected, thereby promoting ergonomic well-being and reducing the incidence of MSDs. Designed for seamless integration into the perioperative environment, the system meets strict requirements for privacy, sterility, and operational efficiency. Beyond its application in surgical practice, the system can also enhance surgical education and training by providing real-time feedback, enabling personalized learning pathways, and gamified simulation exercises. It provides detailed analyses of trainee performance, enabling instructors to deliver targeted feedback and develop adaptive training strategies based on detected posture deviations.

1 INTRODUCTION

Minimally invasive pediatric surgery has experienced exponential growth over the past two decades, offering significant benefits in reducing postoperative pain, shorter hospital stays, and less invasive scarring (Marinho et al., 2021). However, new challenges have emerged alongside these evident clinical improvements, mainly related to ergonomics for the surgical team (Rosenblatt et al., 2013; Marinho et al., 2020). Although robotic platforms such as the da Vinci system have enhanced ergonomics through features like tremor filtering and articulated instruments, they do not entirely resolve posture-related challenges (Haidegger et al., 2022). Operating in confined spaces with laparoscopic or robotic instruments initially designed for adult surgery often forces the surgeon to maintain static or suboptimal postures for extended periods. The result is an increased risk of developing musculoskeletal disorders (MSDs) (Alleblas et al., 2017), which can lead to chronic pain and, in the long term, decreased performance or work absences.

Recent studies show that 50-85% of surgeons experience chronic pain and discomfort, mainly in the neck, shoulders, and back (Anwary et al., 2021; Bertram et al., 2023). Lower back and neck pain are among the most common issues surgeons face, affecting their physical well-being and their ability to concentrate and make decisions during surgical procedures (Matern, 2009). Numerous studies have highlighted how the use of ergonomically unsuitable tools, the height of operating tables, and the arrangement of monitors can contribute to incorrect postures (Wong et al., 2022; Schlussel and Maykel, 2019). Furthermore, the anatomical characteristics of pediatric patients require surgeons to perform exact maneuvers

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with minimal margins for error, thereby exacerbating issues related to posture and movement (Walsh, 2023).

To overcome these difficulties, recent non-invasive monitoring solutions using depth cameras, wearables, and machine learning offer real-time posture feedback for reducing musculoskeletal risks and improving surgical efficiency (Romeo et al., 2022; Nadeem et al., 2024; Vermander et al., 2024). Effective ergonomic operating room monitoring requires key features: accurate surgeon tracking, ignoring other personnel (Hu et al., 2022); gesture-based activation for sterile, seamless operation (Gallo et al., 2011; Bigdelou et al., 2012); and privacy via non-RGB video streams (Srivastav et al., 2019; Flouty et al., 2018).

This paper presents the development of an innovative system designed to assist surgeons in pediatric minimally invasive surgery by proactively addressing ergonomic challenges. It aims to reduce the risk of posture-related musculoskeletal issues, enhance the comfort of medical staff during operations, and support sustained concentration throughout surgical procedures. The underlying idea of this research is to combine the acquisition of 3D data through depth sensors with real-time processing techniques to immediately alert the surgeon of any deviations from optimal ergonomic parameters (Romeo et al., 2022; Wang et al., 2024). The feedback interface, designed to be non-invasive and adaptable to the operative workflow, represents a further advancement in making the operating room safer and more comfortable for the entire team (Ayvaz et al., 2023). The anticipated outcome is not only the improvement of individual surgeons' posture but also a broader enhancement of ergonomic standards in minimally invasive pediatric surgery, ultimately reducing the prevalence of posture-related disorders and the associated socio-health costs (Ayvaz et al., 2023). Finally, this paper includes case studies exploring the co-building of posture monitoring in surgical education and training. The study analyzes these technologies to understand how they affect short-term performance improvements and long-term ergonomics awareness among surgical trainees.

2 RELATED WORK

Research on posture monitoring and ergonomic assessment in minimally invasive surgery has steadily increased, reflecting growing concerns about the impact of surgeons' posture on their well-being (Van Det et al., 2008). Traditionally, ergonomic evaluations have relied on post hoc methods, including questionnaires, perceived exertion measures (e.g., the Borg scale), and manual video analysis (Wong et al., 2022; Weitbrecht et al., 2023). One of the most widely used tools for ergonomic assessment is the Rapid Upper Limb Assessment (RULA) method, which enables the static analysis of key postures by evaluating trunk, neck, and upper limb joint angles (McAtamney and Corlett, 1993). RULA has been applied across various healthcare professions, including cleaning staff (Koskas and Vignais, 2024), laparoscopic surgeons, surgical assistants, nurses (Pazouki et al., 2017), and otolaryngologists performing endoscopic sinus surgery (Dabholkar et al., 2020). However, these conventional methods present significant limitations, as their reliability often depends on evaluator subjectivity, and post hoc assessments do not facilitate real-time posture correction (Schlussel and Maykel, 2019; Ayvaz et al., 2023).

In recent years, several studies have explored more objective and automated techniques for posture detection. Notably, there has been increasing interest in the use of wearable inertial sensors, such as Inertial Measurement Units (IMUs), for tracking joint movements (Stefana et al., 2021; Haidegger et al., 2022; Zhou et al., 2006). These devices enable continuous and non-invasive data collection; however, they present challenges related to surgeon comfort and the need for individual sensor calibration (Romeo et al., 2022). Moreover, cables or wearable modules may introduce obstacles in the highly sterile and regulated environment of the operating room (Wang et al., 2024).

Computer vision systems based on RGB-D cameras have gained increasing attention for their ability to non-invasively detect posture and body position in space (Huang et al., 2021; Antico et al., 2021). Originally developed for the gaming industry and later adapted for clinical research, depth cameras enable the extraction of detailed 3D posture information, allowing for precise calculations of joint angles and postural deviations (Vermander et al., 2024). Many approaches leverage computer vision and machine learning algorithms to extract and analyze skeletal data, facilitating real-time applications with high reliability (Romeo et al., 2022; Gallo, 2013; Bertram et al., 2023). Additionally, some methods incorporate dynamic statistical models (Chai and Hodgins, 2007) and data reliability integration techniques (Shum et al., 2013; Zhou et al., 2014) to mitigate noise and inaccuracies typical of RGB-D sensing devices. Advanced data structures, such as the Filtered Pose Graph (Plantard et al., 2017), have also been proposed to ensure continuity even in the presence of occlusions. Recent studies have explored the potential of Microsoft Kinect sensors for automating the RULA assessment method. Research suggests that Kinect sensors can reliably capture joint angle data and compute RULA scores in assembly line operations (Jara et al., 2022; Jiang et al., 2017). Moreover, the accuracy of Kinect-based RULA assessments has been validated through expert evaluations and comparisons with standard motion capture systems.

3 CLINICAL REQUIREMENTS ANALYSIS

A focus group was conducted with the Pediatric Surgery Unit at the Federico II University of Naples to define the system's clinical requirements. During these sessions, surgeons highlighted key ergonomic issues in pediatric minimally invasive surgery, including the prolonged maintenance of static postures and the difficulty of correcting them in real-time without disrupting surgical workflow. The following section outlines the key requirements that guided its design:

1. **Surgeon Recognition and Tracking.** The system must accurately recognize and track the surgeon among the surgical team members. This functionality is essential to ensure that posture monitoring is applied exclusively to the intended subject, preventing interference or data contamination from other personnel present in the room. By isolating relevant parameters, the system enhances the accuracy of postural analysis.
2. **Gesture-Based Identification.** To optimize surgeon identification and eliminate the need for manual interactions, the system must incorporate a gesture-based identification mechanism, performed by the surgeon at the beginning of the procedure. This approach significantly reduces automatic identification errors and ensures swift and reliable control. A predefined, system-recognized gesture allows medical personnel to initiate postural monitoring automatically, eliminating the need for touchscreen interfaces or manual devices. This feature enhances operational efficiency while adhering to the strict hygiene and sterility requirements of the surgical environment.
3. **Privacy Protection.** To safeguard the privacy of both medical personnel and patients, the system must avoid the use of RGB video streams, which could inadvertently capture and reveal sensitive visual information.
4. **Non-Interference with Surgical Equipment.** The system must operate without disrupting existing surgical equipment or restricting the mobility of medical personnel. Its integration should be seamless, ensuring unobstructed workflow and adherence to standard surgical protocols.
5. **Minimal Interaction and Intuitive Interface.** The system must require minimal interaction from the surgeon, thereby reducing distractions and operational downtime. Additionally, posture-related notifications should be designed to be clear, non-invasive, and seamlessly integrated into the surgical workflow, ensuring effective communication without disrupting the procedure.

4 THE PROPOSED SOLUTION

The proposed solution employs a depth camera integrated with advanced skeletal tracking software to automatically identify and monitor human body joints. This system is designed to continuously assess the surgeon's posture during surgical procedures. Upon detecting an incorrect posture, the system generates real-time visual notifications on the operating room display. These alerts enable the surgeon to promptly adjust their position, thereby mitigating the risk of musculoskeletal injuries and promoting ergonomic practices in the operating environment.

4.1 Hardware Configuration

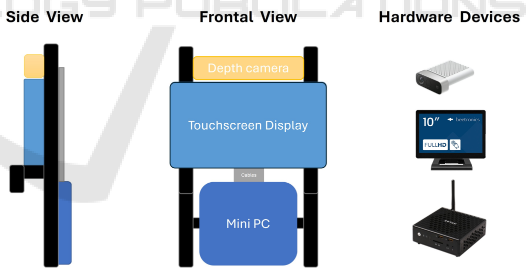

Figure 1: Hardware configuration of the proposed solution.

The hardware configuration is illustrated in Figure 1. To ensure seamless integration without interfering with surgical equipment, the detection device is strategically positioned at an elevated location above the primary operating room display. This placement minimizes obstruction to surgical procedures and avoids hindering the operators' movements. Furthermore, the system is designed to be easily removable or adjustable, facilitating quick modifications as needed. The selected devices have been optimized for miniaturization to reduce physical clutter and maintain an unobtrusive presence in the operating environment.

For surgeon tracking, the system utilizes the Microsoft Azure Kinect DK, a depth camera that employs time-of-flight technology to generate three-dimensional skeletal maps. This approach eliminates the need for processing color images, focusing exclusively on detecting joint positions and tracking the surgeon's movements. This design choice not only safeguards privacy but also reduces computational demands, thereby enhancing system efficiency. Figure 2 depicts the joint mapping capabilities of the sensor.

For notifications, a 10-inch Beetronics Mini Touchscreen Display was selected. This display is equipped with integrated speakers to provide auditory feedback in addition to visual alerts when the surgeon adopts an incorrect posture.

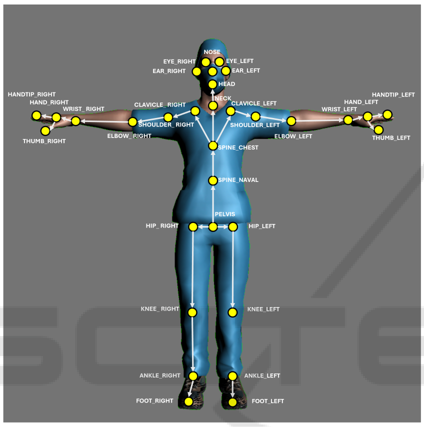

Figure 2: Body joints tracked by the Azure Kinect camera.

Finally, a ZOTAC ZBOX Mini PC equipped with an Intel Core i7 processor and an NVIDIA RTX A4500 graphics card featuring 16 GB of dedicated memory was chosen to handle the graphical processing demands. This hardware configuration ensures efficient three-dimensional skeletal reconstruction and real-time management of visual notifications and enables body tracking at approximately 30 FPS.

4.2 Interface

The interface has been designed to minimize interaction requirements, allowing the surgeon to focus entirely on the procedure without disruptions or complications when using the system. The graphical interface consists of a text-based notification system displayed on a mini-display. Because of the limited screen size, notifications must be brief enough to be read easily during surgery, pointing only to relevant information. The system's workflow is illustrated in figure 3, where the top row shows the perspective from the Azure Kinect sensor, and the bottom row represents the surgeon's viewpoint. Initially, before recognizing the surgeon, the display shows the message "Waiting for identification gesture". To identify themselves, the surgeon must raise their hand for two seconds, after which the display updates to "Surgeon detected. Monitoring on". If the surgeon maintains a correct posture during surgery, the system displays "Posture OK. Monitoring...". However, if a deviation from the optimal posture is detected, a specific alert indicates the nature of the incorrect posture. The visual notification is supplemented by an unobtrusive auditory cue that allows surgeons to receive immediate feedback without looking away from the surgical field. Therefore, surgeons may immediately adjust their positioning, mitigating musculoskeletal strain and reducing the risk of long-term ergonomic issues.

4.3 Postural Tracking

Postural tracking is based on the three-dimensional reconstruction of the surgeon's skeleton, utilizing algorithms that process data from the depth camera. These algorithms analyze joint positions in real time to assess the surgeon's posture during the operation. Among the various techniques for assessing postural risk, we chose to base our approach on the RULA (Rapid Upper Limb Assessment) method, given its extensive documentation in the literature. This method generates a score based on the biomechanical and postural load demands of work activities, with a particular focus on the upper body, including the neck, trunk, and upper limbs. Given our emphasis on analyzing postural discomfort related to the surgeon's upper body, the RULA method was determined to be the most appropriate for this study. This approach is particularly relevant as tracking occurs from the waist upwards, with the operating table obscuring the lower body.

For the calculation of most of the angles required for assessment, we referenced (Manghisi et al., 2017), which uses the Kinect v2 sensor to detect risky postures according to the RULA method. A comparative analysis was then conducted between the joints tracked by the Kinect v2 sensor and those tracked by the Azure Kinect sensor. Unlike (Manghisi et al., 2017), which calculates a comprehensive posture score for the surgeon, our method provides real-time notifications to alert the surgeon whenever an improper posture is detected.

Specifically, the system automatically detects and notifies the surgeon of the following incorrect postures:

- **Trunk Flexion (Forward or Backward)** (see figure 4.a). Occurs when the trunk is excessively in-

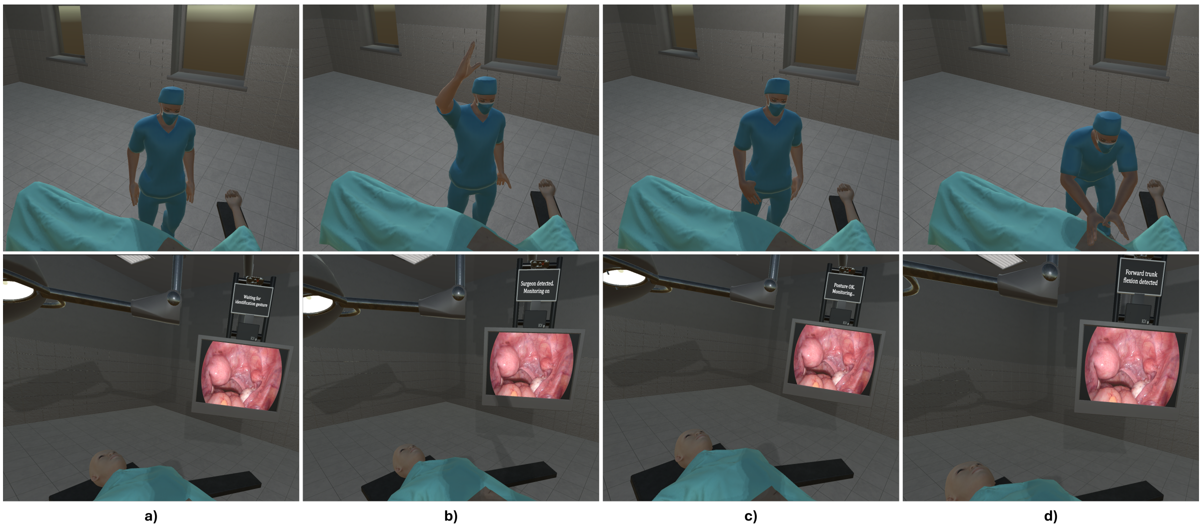

Figure 3: System workflow for surgeon posture monitoring. The top row illustrates the Azure Kinect sensor's perspective, while the bottom represents the surgeon's viewpoint. (a) Initially, the system displays "Waiting for identification gesture." (b) When the surgeon raises their hand for two seconds, the display updates to "Surgeon detected. Monitoring on." (c) If the surgeon maintains a correct posture, the display shows "Posture OK. Monitoring…". (d) When an incorrect posture (e.g., forward trunk flexion) is detected, the system provides real-time feedback through a visual notification, prompting the surgeon to adjust their posture.

clined either forward or backward from the neutral, upright position. The trunk inclination angle is calculated using the positions of the head, pelvis, and spine joints. Positive values correspond to forward flexion, while negative values indicate extension or backward bending.

- **Lateral Trunk Inclination** (see figure 4.b)**.** Occurs when the trunk is excessively tilted to one side relative to the vertical position. The lateral inclination angle is measured based on the positions of the head, pelvis, and spine joints. Higher values indicate a greater degree of lateral tilt.
- **Trunk Rotation Around the Vertical Axis** (see figure 4.c)**.** Occurs when the trunk undergoes excessive rotation around the vertical axis, which is a critical condition leading to asymmetric postures. The trunk torsion angle is measured by comparing the rotation of the torso relative to its initial position, using the relative positions of the torso and shoulder joints.
- **Excessive Arm Extension** (see figure 4.d)**.** Occurs when the elbow is overextended, keeping the arm rigidly straight without sufficient flexion for ergonomic movement. The arm flexion angle is computed by analyzing the positions of the shoulder, elbow, and wrist joints. An angle of 0° represents a fully extended (straight) arm, with insufficient flexion indicating an incorrect posture.
- **Excessive Shoulder Abduction** (see figure 4.e)**.** Occurs when the shoulder is raised laterally beyond ergonomic limits. The shoulder abduction angle is measured by analyzing the three-dimensional positions of the shoulder, elbow, and wrist joints. Positive values indicate outward movement (abduction), while negative values represent extension or adduction.

5 CASE STUDY: POSTURE MONITORING IN SURGICAL EDUCATION AND TRAINING

The real-time posture monitoring system introduced in this paper holds much promise for changing surgical education, particularly in pediatric minimally invasive surgery. The system's introduction into training programs could help novices and veteran surgeons become attuned to proper ergonomic practices, possibly reducing the risk of musculoskeletal disorders in the long term. The primary advantages of utilizing such a system in surgical education and training are as follows:

- **Real-Time Feedback in Simulated Environments.** An important component of efficient surgical training is the ability to recreate safe and reproducible real-life scenarios. The posture monitoring system gives trainees ongoing feedback on

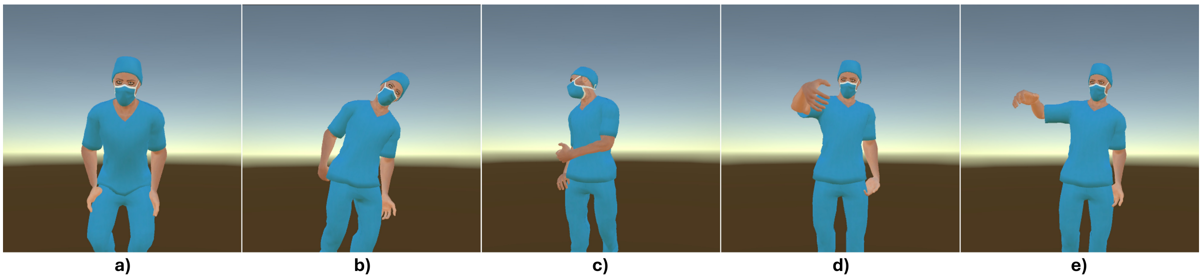

Figure 4: Set of postures tracked by the system: a) Forward trunk flexion; b) Lateral trunk inclination; c) Trunk rotation; d) Arm extension; e) Shoulder abduction.

their posture in a simulation setting. For example, if the trainee strays away from an optimal ergonomic position, immediate visual and auditory signals notify them to correct their stance. Over time, this instant feedback could reinforce healthy posture habits. It adds to the real-time monitoring of surgeries, just like they experience at the simulation center.

- **Personalized Learning through Analytics.** Data processing functions of the system keep detailed records of every candidate's performance through posture tracking during practice sessions. Analyzing these data allows the instructors to perceive recurring faults, customize their interventions, and present individually tailored comments to their trainees through custom-made reports. Trainees can self-navigate individual learning paths that encourage continuous improvement in posture management. Tools like heatmaps—which highlight areas where a candidate frequently deviates from proper posture—offer clear visual feedback that should allow trainees to find and correct their common mistakes.
- **Gamification to Engage in Ergonomics Learning.** Serious games tailored for ergonomic-focused learning could enhance learning with the posterior monitoring system. These can simulate game-like procedures where trainees perform simulated surgeries while maintaining an accurate posture with points or levels gained due to their compliance with ergonomic guidelines. This gamification approach increases motivation and engagement, making learning enjoyable and effective. Challenge scenarios such as maintaining posture during complex maneuvers or under time pressure can closely mimic the demands of actual surgery. Such gaming can replicate the physical and cognitive stressors imposing conflicts on the novice in the operating room, giving an all-around training opportunity. Examples include holding a posture during critical interventions or working with multiple tools. Other benefits are real-time leaderboards that allow friendly competition and encourage continuous practice.
- **Promoting Long-Term Ergonomic Awareness.** Integrating ergonomic education into surgical training is important to prevent long-term health problems. Integrating a posture monitoring system into residency training highlights the importance of proper ergonomics from the beginning of a surgeon's career. Early exposure to these concepts helps protect physical well-being in the long run, which, in turn, has a positive effect on surgical performance. Using theoretical lessons and practical simulations supported by monitoring tools like the one proposed, surgical trainees may better understand ergonomics in practice. Workshops and training modules should integrate theoretical content with practical tutorial sessions using the monitoring system, laying the foundation for fostering an ergonomic culture within surgical teams.
- **Research Opportunities in Educational Settings.** Future investigations should concentrate on how such a monitoring system impacts surgical training in parametric and clinical environments. Researchers could consider establishing measurements of musculoskeletal complaints, RULA scoring improvement, and surgical performance metrics. Moreover, this study could assess how automated alerts about posture influenced participant and instructor stress and focus in a simulated surgical environment. Feedback from participants and instructors' quantitative data related to ICT usage would supplement other measurement methods to give a more holistic view of usability and educational benefits. Ultimately, these studies will contribute to the expanding body of literature supporting the integration of advanced posture monitoring technologies into medical education. This, in turn, will enable future research to demonstrate clear benefits

for both health and learning outcomes, reinforcing the role of ergonomic training as a standard component of surgical education.

6 CONCLUSION AND FUTURE WORK

Minimally invasive pediatric surgery presents significant ergonomic challenges that may increase the risk of MSDs among surgeons. This study introduced a real-time posture monitoring system that leverages depth sensors and 3D skeletal tracking to provide immediate feedback on postural deviations, with the goal of enhancing both surgeon well-being and procedural efficiency. The system ensures privacy protection and offers seamless, unobtrusive integration into the operating room without disrupting workflow. While the system shows promise, further validation in routine surgical environments is necessary. Critical aspects to assess include its stability in tracking the surgeon despite occlusions from medical staff, accuracy under varying lighting conditions, and the potential for false alarms that could interfere with concentration. Beyond surgical practice, this study also explored the integration of posture monitoring into surgical education and training. Real-time feedback, personalized learning pathways, and gamification strategies could enhance trainee engagement and encourage the early adoption of proper ergonomic habits.

Future research will focus on experimental validation and evaluating the system's applicability across different surgical specialties. Additionally, long-term studies will examine the impact of integrating posture monitoring technology into educational programs, assessing its effects on ergonomic awareness, trainee evaluation, and improvements in occupational health outcomes.

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