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Patient-Specific 3D Modeling for Improved Understanding of Complex Fractures and Treatment Outcomes

Modelado 3D Específico para Cada Paciente para una Mejor Comprensión de las Fracturas Complejas y los Resultados del Tratamiento

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SUMMARY: Effective medical communication is essential in patient-centered care, particularly for explaining complex conditions such as comminuted fractures. However, traditional 2D imaging methods have limitations in conveying the spatial complexity of injuries and treatment plans. This study aimed to develop patient-specific 3D visualizations to enhance communication between healthcare providers and patients, improving understanding of fracture states, treatment processes, and recovery stages. CT data from a patient with a comminuted fracture of the middle phalanx in the second toe was used to create 3D models. These models visualized the fracture state, treatment process, and recovery stages. Fracture fragments were color-coded for clarity, and a pin insertion process was animated in 3D to illustrate stabilization during surgery. Recovery was visualized using both CT images and unified color models to depict healed bone. Feedback from patients and healthcare providers was collected to evaluate the communication efficacy of the 3D visualizations. The 3D visualizations improved patient understanding of their condition and treatment process. Patients reported increased trust and satisfaction with the explanation provided, and healthcare providers highlighted the models' utility in explaining complex fracture states and treatment plans. The visual tools also facilitated better collaboration among medical teams during surgical planning. Patient-specific 3D modeling significantly enhances medical communication, fostering improved patient understanding and trust while aiding healthcare providers in diagnosis and treatment planning. This approach has potential applications in broader clinical contexts, including other traumatic injuries and chronic conditions.

KEY WORDS: 3D visualization; Comminuted fracture; Medical communication; Patient-specific modeling; CT data analysis.

INTRODUCTION

The modern medical landscape is increasingly shifting toward patient-centered care. This shift is inevitable, as the interaction between patients and healthcare providers has a direct impact on treatment outcomes. In particular, a patient's clear understanding of their condition and treatment plan plays a crucial role in maximizing treatment effectiveness and enhancing patient satisfaction. However, traumatic injuries such as complex fractures often present significant challenges due to their intricate anatomical structures, making it difficult even for healthcare professionals to accurately diagnose and formulate treatment plans. Traditional diagnostic and treatment processes primarily rely on two-dimensional (2D) imaging, such as X-rays or CT scans, which are inherently limited in conveying the spatial complexity of injuries.

As the importance of patient-centered care continues to grow, effective communication between patients and healthcare providers is becoming increasingly critical. Particularly when explaining complex fracture conditions or surgical procedures, medical professionals often rely on 2D imaging. However, this approach is limited in helping patients visually comprehend the injury and treatment process. Such limitations not only reduce patient engagement in their treatment but also negatively affect the establishment of trust throughout the care process. Thus, there is a pressing need for new visual tools that go beyond the constraints of 2D imaging.

Recent studies highlight the limitations of 2D imaging in patient education and surgical planning, emphasizing the

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need for advanced visualization techniques. 3D imaging and virtual reality (VR) have shown significant benefits in improving patient understanding of complex medical conditions and procedures. These technologies enhance communication between healthcare providers and patients, leading to better comprehension of diagnoses, treatments, and discharge instructions (Schooley *et al*., 2015). While challenges such as cost and integration into clinical workflows exist, the growing body of evidence suggests that 3D visualization technologies have the potential to revolutionize patient care and medical education (Ballantyne, 2011).

CT data provides critical information for diagnosing fractures and other traumatic injuries, as well as for developing treatment plans. However, as this data is presented in a two-dimensional (2D) format, it is often challenging to fully comprehend complex structures or effectively use it as a tool to explain such details to patients. While medical professionals interpret CT images to create treatment plans, they face limitations in conveying this information to patients in an intuitive manner. As a result, patients may struggle to clearly understand their condition and treatment plans, potentially hindering their ability to build trust in the treatment process.

Three-dimensional (3D) CT imaging has emerged as a valuable tool in medical diagnosis and patient communication, offering significant advantages over traditional 2D CT scans. Studies have shown that 3D CT provides additional useful information for patient management across various clinical problems (Alder *et al*., 1995). It enhances the accuracy of diagnostic decisions and treatment planning, particularly in complex cases such as acetabular fractures (Potok *et al*., 1995; Garrett *et al*., 2012). 3D CT imaging has proven beneficial in surgical education, improving medical students' understanding of volumetric anatomy (Mastrangelo *et al*., 2003). Furthermore, immersive virtual reality technologies have been developed to create high-fidelity 3D visualizations of CT data, allowing for interactive exploration of anatomical structures at true scale (Lin *et al*., 2013). These advancements not only aid in diagnosis and surgical planning but also facilitate better communication with patients, potentially improving their understanding of their condition and treatment options (Gillespie & Isherwood, 1986).

3D visualization enables the intuitive and immersive representation of complex injuries, such as fractures, allowing patients to actively engage in their treatment process. By utilizing patient-specific CT data to create 3D models, it becomes possible to tailor the visualization of injury states and treatment procedures. This customization fosters effective communication between healthcare providers and patients, enhancing mutual understanding and trust in the medical decision-making process.

This study aims to reconstruct complex fracture states into three-dimensional (3D) models using patient CT data, enhancing communication between patients and healthcare providers. Specifically, it seeks to represent fracture states, treatment processes, and recovery phases through step-by-step 3D visualizations, enabling patients to easily understand their conditions and trust the proposed treatment plans and outcomes. Additionally, the study aims to systematize the 3D reconstruction process to propose a medical communication workflow that can be applied to other clinical cases.

This study explores the potential of three-dimensional (3D) visualization to revolutionize medical communication. By moving beyond the traditional reliance on two-dimensional (2D) imaging, 3D reconstruction enables more intuitive and accurate communication of patient conditions and treatment processes. This approach aims to enhance patient understanding and satisfaction while also providing healthcare providers with clearer insights into injury states, facilitating more effective collaboration during treatment planning.

The study focuses on a case of comminuted fracture, incorporating the creation of patient-specific 3D visualizations of the injury state, simulations of the treatment process, and outcomes of recovery. This tailored approach not only strengthens communication between patients and healthcare providers but also opens new possibilities for engaging patients as active participants in their treatment journey. Furthermore, the 3D visualization process developed in this research holds potential for application beyond complex fractures, extending to various traumatic injuries and chronic disease treatments, demonstrating its broad utility in improving patient-centered care.

MATERIAL AND METHOD

This study focuses on a comminuted fracture of the middle phalanx in the second toe of the left foot. Using CT data, 3D models were created and employed to visualize the treatment process. The methodology consisted of data preparation, 3D model generation and refinement, animation creation, and data integration.

Subject and Data Preparation. CT data from a patient with a comminuted fracture were provided by the hospital and served as the primary source for this study. The CT scans were taken at three key stages: immediately after the fracture, during the treatment phase (after pin insertion), and during the recovery phase (after pin removal) (Fig. 1F, G, H). These datasets were used to visually analyze and describe the patient's condition at each stage.

3D Model Generation. The CT data were converted into 3D models using Mimics software. The entire skeleton was reconstructed simultaneously using automated functions to provide a general visualization of the skeletal structure. For the middle phalanx, where the comminuted fracture occurred, the fragments were segmented and reconstructed manually to enhance accuracy. This step ensured detailed representation of the fracture site, compensating for the limitations of the automated model. The finalized 3D models were saved in STL format and imported into MAYA software for further processing (Fig. 1A-E).

3D Model Refinement. In MAYA, unnecessary elements from the automated reconstruction were removed, retaining

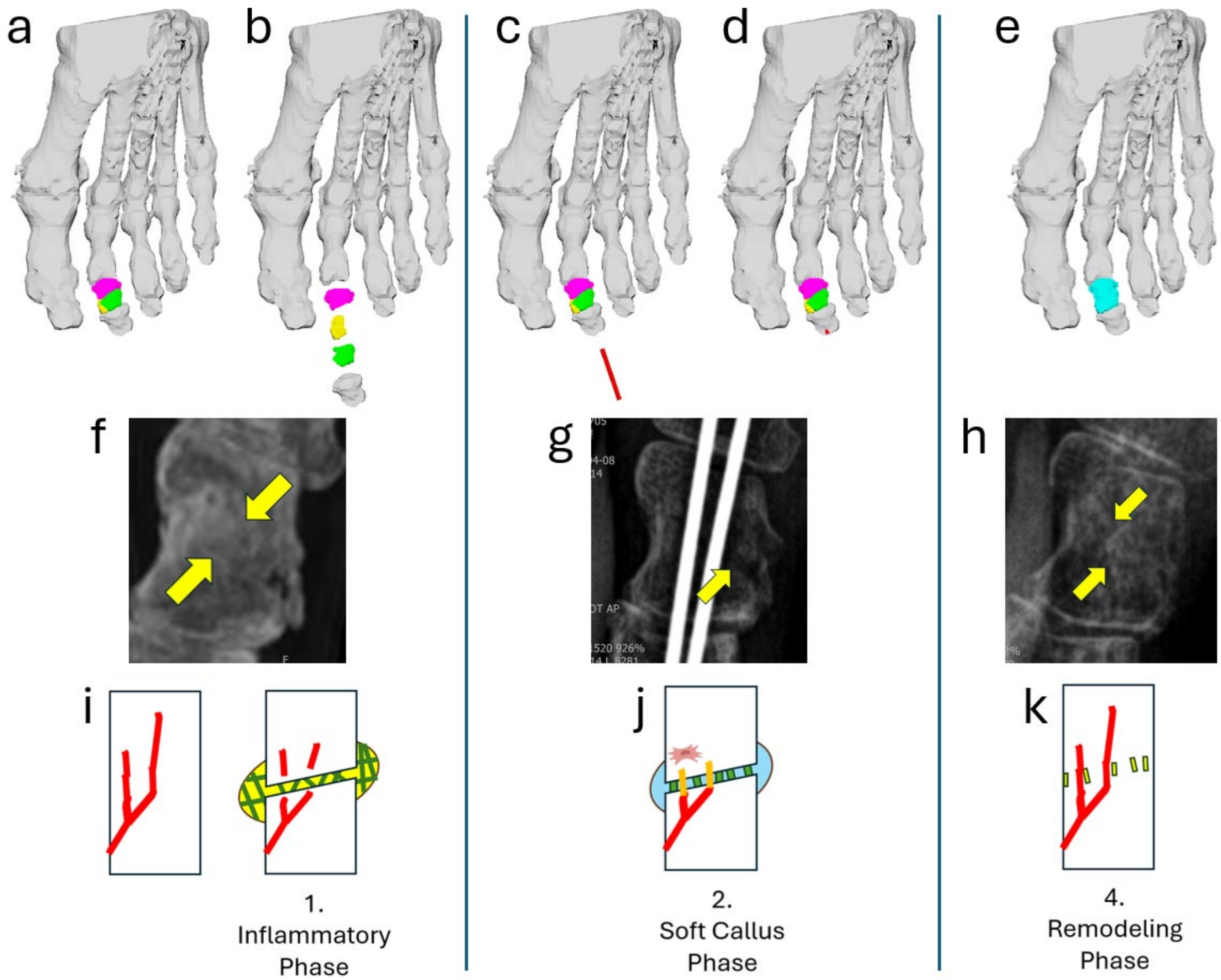

Fig. 1. Visualization of the Fracture Occurrence, Treatment, and Recovery Stages: (a, b) 3D models of the initial comminuted fracture in the middle phalanx of the second toe. In a, the fracture fragments are color-coded (pink, green, and yellow) to highlight their separation and the complexity of the injury. In b, further isolates the fragments, removing surrounding skeletal structures for a more detailed visualization of the fracture morphology; (c, d) The treatment process using 3D models. In (c) a stabilization pin is visualized as it is inserted into the fractured region to align the fragments, (d) demonstrates the fragments being secured in their correct positions, depicting the alignment achieved during the treatment phase; (e) It shows the recovery state, where the fractured fragments have fully healed and are unified into a single structure. The use of a uniform cyan color emphasizes the complete remodeling and restoration of the middle phalanx; (f) It features a CT scan taken during the inflammatory phase, highlighting the comminuted fracture fragments with yellow arrows. The disrupted continuity of the bone is clearly visible in this imaging; (g) It shows CT data from the treatment phase, with yellow arrows indicating the placement and function of stabilization pins in maintaining the alignment of the fragments; (h) It illustrates the recovery phase through a CT scan, where yellow arrows highlight the fully remodeled and healed bone, demonstrating the structural restoration; (i, j, k) It provide simplified schematic representations of the three phases.

only the essential bone structures. The Separate function in MAYA was utilized to efficiently discard irrelevant parts of the model. The manually reconstructed fracture site was then integrated into the whole model to precisely depict the fracture condition, enabling clear visualization of the comminuted fracture within the entire skeletal context (Fig. 1A-E).

3D Animation Creation. To visually explain the fracture occurrence, treatment, and recovery stages, 3D animations were created using MAYA's animation tools.

Fracture State Visualization: An animation was developed to depict the separation of the comminuted fracture fragments based on CT data taken immediately after the fracture. Each fragment was assigned a distinct color to clearly represent its condition (Fig. 1A, B). CT data from the fracture phase were integrated (Fig. 1F). Additionally, a simple schematic illustration was created to complement the visualization and explain the injury mechanism (Fig. 1I).

Treatment Process Visualization: A pin was modeled and animated to demonstrate the stabilization of the fracture during treatment. The animation visualized the insertion and fixation process, incorporating CT data from the treatment phase to enhance reliability (Fig. 1C, D, G). A corresponding schematic diagram was also created to simplify the explanation of the treatment process (Fig. 1J).

Recovery State Visualization: The recovery phase was visualized by unifying the fractured bone fragments into a single color, indicating full healing (Fig. 1E). CT data from the recovery phase were integrated into the model to provide an accurate representation of the healed condition (Fig. 1H). Additional schematic illustrations were created to explain the recovery process (Fig. 1K).

Data Integration and Application. The 3D models, animations, CT data, and schematic diagrams were integrated to visually depict the fracture occurrence, treatment process, and recovery stages step-by-step. These materials were utilized as educational and communication tools to enhance inter-action between patients and healthcare providers. By combining CT data and 3D models at each stage, the reliability of the visual materials was reinforced. Furthermore, the schematics enabled patients without medical expertise to easily understand the treatment process.

RESULTS

This study proposed a method for creating three-dimensional (3D) models to visually represent the complex fracture state, treatment process, and recovery stages using patient CT data, and suggested their application as tools for improving medical communication. The findings are summarized into three key aspects: 3D modeling, evaluations by patients and healthcare providers, and the utility of visualization tools.

Using CT data from a patient with a comminuted fracture in the middle phalanx of the second toe on the left foot, a highly detailed 3D model was reconstructed (Fig. 1A-E). Fractured bone fragments were visualized with distinct colors to clearly depict their positions and conditions, while integrating CT data captured immediately after the fracture to enhance the model’s reliability (Fig. 1A-F). During the treatment process, a pin was modeled and incorporated into a 3D animation to illustrate the stabilization of the fracture, with postoperative CT data used to ensure accurate visualization of the surgical state (Fig. 1C, D, G). For the recovery stage, the condition after pin removal was represented in a single color, providing an intuitive depiction of the healed state (Fig. 1E, H). This was further supported by recovery-phase CT data to facilitate clear understanding of the healing process for both patients and healthcare providers.

The use of 3D visualization materials received positive feedback from both patients and healthcare providers. Patients reported that they gained a clearer understanding of their condition and treatment process by visually confirming the complex fracture and step-by-step animations of the treatment. The visualized data also helped build trust in the treatment outcomes, with increased satisfaction regarding the explanation provided. Healthcare providers, on the other hand, noted that 3D models and animations enabled more effective communication with patients and improved their ability to explain complex fracture states, enhancing the efficiency of diagnosis and treatment planning.

The 3D models and animations developed in this study demonstrated their value as tools for personalized medical communication by clearly visualizing diagnosis and treatment processes. These resources were also shown to have potential applications in medical education for healthcare providers, serving as effective tools for conveying complex injury states and treatment plans intuitively.

These findings highlight the transformative potential of 3D visualization technology in improving medical communication. They provide a foundation for expanding the application of this technology to diverse clinical cases in the future, further enhancing its role in patient-centered care.

DISCUSSION

This study proposed a method for reconstructing the states of complex fractures, treatment processes, and recovery stages into three-dimensional (3D) models using patient CT data, employing these models as tools for medical communication. The findings demonstrate that 3D visualization technology significantly enhances communication between healthcare providers and patients, proving to be an effective tool for improving patient understanding and engagement in their treatment journey. Based on the results of this study, the following discussions are possible.

Firstly, the study confirmed that 3D models are an effective alternative for overcoming the limitations of 2D imaging. While traditional 2D CT scans are valuable for healthcare providers, they have proven insufficient for explaining complex fracture conditions to patients. In contrast, 3D visualization intuitively represented the position and state of fractured bones, enabling patients to clearly understand their condition. Notably, the use of color differentiation to depict comminuted fractures significantly enhanced patients' visual comprehension. This type of visualization not only benefitted patients but also facilitated collaboration among healthcare providers. During the surgical planning process, 3D models served as a reliable tool for clearly communicating fracture states and fixation methods. 3D models are especially useful for visualizing complex fractures, such as those of the tibial plateau, acetabulum, and radial head (Guitton *et al*., 2014; Foo & Kwek, 2019). Studies have shown that 3D models can be superior to 2D CT scans in terms of spatial awareness and assessment of intra-articular fracture patterns (Schooley *et al*., 2015). While 3D models may not always improve postoperative function compared to routine treatment, they consistently enhance understanding of fracture anatomy for both medical professionals and patients (Bizzotto *et al*., 2015).

Research demonstrates that 3D animations and personalized 3D printed models significantly enhance patient education in various medical fields. These visual aids improve patients' understanding of their conditions, treatment processes, and recovery stages (Cleeren *et al*., 2014; Sander *et al*., 2017; Zhuang *et al*., 2019). Patients educated with 3D models show higher satisfaction levels, increased trust in treatments, and better knowledge retention (Williams *et al*., 2017; Zhao & Yam, 2024). Multimedia platforms, including animated videos, have been found to boost patient satisfaction and engagement in surgical procedures (Turkdogan *et al*., 2022). Computer-based visualizations also lead to improved patient satisfaction and knowledge acquisition compared to standard conversations (Enzenhofer *et al*., 2004). Site-specific educational videos are particularly effective in enhancing patients' understanding and confidence in radiation therapy, with notable benefits for those with poor reading ability (Almerdhemah *et al*., 2021). These visual tools prove valuable across different age groups and education levels.

This study also suggests that 3D visualization technology can play a pivotal role in medical education. Healthcare professionals can utilize 3D models to more easily analyze complex fracture conditions and develop treatment plans more effectively. Such visual materials can be employed not only for surgical planning but also as educational tools in medical training, contributing to improved collaboration and communication among medical teams. Three-dimensional (3D) visualization technologies have shown significant potential in enhancing medical education. Studies have demonstrated that 3D printed models and other 3D visualization tools can improve students' understanding of com-plex anatomical structures and fracture patterns compared to traditional 2D imaging methods (Li *et al*., 2015). These technologies have been successfully applied in various medical fields, including orthopedics, ophthalmology, and cleft lip and palate education (Lim *et al*., 2018; Rama *et al*., 2023). 3D models have been found to enhance spatial knowledge acquisition, increase learner satisfaction, and improve confidence in surgical planning (Rama *et al*., 2023). Furthermore, 3D visualization tools can facilitate student-centered learning and help address misconceptions about physiological phenomena (Silén *et al*., 2008). The integration of 3D models into existing medical curricula has shown promise in improving learning outcomes and could potentially address the growing concern of inadequate anatomy education in modern medical schools (Bui *et al*., 2021; Neijhoft *et al*., 2022).

However, this study has several limitations. First, creating 3D models and animations requires considerable time, which can hinder their real-time application in clinical settings. This issue is particularly pronounced in the case of complex comminuted fractures, where precise reconstruction often necessitates manual intervention, potentially increasing the time required for completion. To address this, future research should explore automated 3D model generation techniques integrated with artificial intelligence (AI) to streamline the process. Second, this study was conducted based on a limited case involving a single patient dataset, which restricts the generalizability of the findings. Further studies including diverse fracture types and patient cases are necessary to validate and expand upon the results. Finally, the effectiveness of 3D visualization tools needs to be assessed with a larger population of patients and healthcare providers to confirm their utility in actual clinical environments. Broader evaluations will help establish the practical applications and benefits of these tools in improving medical communication and care.

Future research should aim to validate the processes outlined in this study by utilizing a larger dataset of patient cases, thereby strengthening the reliability and applicability of the findings. Additionally, efforts should focus on improving the efficiency of 3D visualization technologies through automation, reducing the time and resources required for their implementation. It is also essential to evaluate the scalability of the proposed methods to determine their applicability in communicating treatment plans for other types of traumatic injuries or chronic diseases, further broadening the scope and impact of this approach.

CONCLUSION

In conclusion, this study demonstrates the significant potential of patient-specific 3D modeling in improving the quality of medical communication. Beyond merely conveying information, this approach actively engages patients in their treatment process, fostering trust and collaboration between healthcare providers and patients. Moving forward, it is essential to continue validating the effectiveness of this technology across diverse clinical settings and to develop practical strategies for its widespread implementation. This will further enhance its utility in transforming patient-centered care.

Ethics statement. This study was approved by the Institutional Review Board (IRB) of Sehan University, Republic of Korea (Approval No.: SH-IRB 2025-002; Approval Date: 2025-07-02).

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RESUMEN: Una comunicación médica eficaz es esencial en la atención centrada en el paciente, en particular para explicar afecciones complejas como las fracturas conminutas. Sin embargo, los métodos tradicionales de imagenología 2D presentan limitaciones para transmitir la complejidad espacial de las lesiones y los planes de tratamiento. Este estudio tuvo como objetivo desarrollar visualizaciones 3D específicas para cada paciente para mejorar la comunicación entre profesionales de la salud y los pacientes, mejorando así la comprensión del estado de las fracturas, los procesos de tratamiento y las etapas de recuperación. Se utilizaron datos de TC de un paciente con una fractura conminuta de la falange media del segundo dedo del pie para crear modelos 3D. Estos modelos visualizaron el estado de la fractura, el proceso de tratamiento y las etapas de recuperación. Los fragmentos de la fractura se codificaron por colores para mayor claridad, y se animó en 3D el proceso de inserción de clavos para ilustrar la estabilización durante la cirugía. La recuperación se visualizó utilizando imágenes de TC y modelos de color unificados para representar el hueso consolidado. Se recopilaron comentarios de pacientes y profesionales médicos para evaluar la eficacia de la comunicación de las visualizaciones 3D. Las visualizaciones 3D mejoraron la comprensión del paciente sobre su afección y el proceso de tratamiento. Los pacientes informaron de una mayor confianza y satisfacción con la explicación proporcionada, y los profesionales de la salud destacaron la utilidad de los modelos para explicar fracturas complejas y planes de tratamiento. Las herramientas visuales también facilitaron una mejor colaboración entre los equipos médicos durante la planificación quirúrgica. En conclusión, el modelado 3D específico para cada paciente mejora significativamente la comunicación médica, fomentando una mejor comprensión y confianza del paciente, a la vez que ayuda a los profesionales de la salud en el diagnóstico y la planificación del tratamiento. Este enfoque tiene posibles aplicaciones en contextos clínicos más amplios, incluyendo otras lesiones traumáticas y enfermedades crónicas.

PALABRAS CLAVE: Visualización 3D; Fractura conminuta; Comunicación médica; Modelado específico para cada paciente; Análisis de datos de TC.

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