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HPDSAR (High Precision Dental Surgery Assisting Robot) as an Endeavour to Enhance the Precision of Non-Invasive Surgical Procedures in the Oral Cavity

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Abstract

The integration of robotics and artificial intelligence (AI) into surgery has yet to be widely implemented in the oral cavity, primarily due to the large scale of conventional robotic systems. This manuscript introduces the high precision dental surgery assisting robot (HPDSAR), a novel, miniaturised system designed to revolutionise oral and maxillofacial procedures with paramount precision and minimal invasiveness. HPDSAR operational superiority is established through an integrated system comprising advanced robotic auxiliary instruments and a Digital AI component. The system initiates with high-resolution imaging via CBCT scans and intraoral imaging, which is processed through deep learning mechanisms—specifically convolutional neural networks (CNN)—to generate a single, accurate surgical diagnosis. This intelligence is then translated into precise performance via robotic arms equipped with ergonomic scalpels and end-effectors, all tracked in real-time through an optical/electromagnetic system and governed by advanced motion planning algorithms. Crucially, the system incorporates haptic feedback and force-sensing to enhance the operator's control and prevent tissue damage, thus ensuring adherence to safety standards. By enabling minimally invasive surgery and drastically improving the visual field and procedural efficiency, HPDSAR offers significant medical advantages, leading to faster patient recovery and a reduced risk of complications such as post-operative infection and nerve damage, which are frequently reported in conventional oral surgery. In essence, HPDSAR represents a critical advancement, utilising a human-intelligence-mimicking system to deliver exceptional accuracy and performance in complex dental operative procedures.

Keywords: Dental surgery assisting robot, dental surgery, digital AI, ergonomic scalpel, surgery automatization.

Introduction

Lately, automated surgery technology based on robotics and artificial intelligence has become a widely discussed topic as it can simplify the work of doctors and healthcare practitioners in performing operative surgical procedures on patients. Furthermore, the accuracy and precision offered by surgical robots based on robotics and artificial intelligence are purported to be significantly superior compared to conventional surgery. However, the use of this technology has been largely confined to systemic applications within the body and has yet to be widely applied to the oral cavity. This is primarily because automated surgical robots are typically very large to enable them to perform surgical tasks with substantial, yet accurate, robotic arms and excellent visual presentation, allowing the surgeon to see every detail of the work being performed by the robot. In principle, a miniature version of this robot could be developed without compromising the fundamental function of a surgical robot: to visually represent the structure to be operated on in detail, process this information, and then output it as a robotic performance in carrying out the surgical procedure according to the specific case with accuracy, precision, effectiveness, and minimal invasiveness (1).

The presence of this technology is expected to assist with all surgical cases in the oral and maxillofacial area, including the temporomandibular joint, which is often underestimated but profoundly affects human facial structure, articulation capabilities, and chewing function. This is crucial given that structural abnormalities in the oral cavity and temporomandibular joint can impact chewing function and sound occlusion, alongside periodontal surgical procedures as a supporting tissue for teeth to maintain them in their proper position, as well as sterile, effective, and less-invasive surgery for neoplasm structures (1). This robot is expected to assist dentists in improving patient oral hygiene and oral health due to the robot's inherent ability to operate sterilely and less-invasively. Moreover, operative procedures performed by the robot will be much faster, thereby effectively and efficiently optimising time efficiency and the frequency of patients requiring operative procedures in the oral cavity.

HPDSAR (high precision dental surgery assisting robot) is a tangible application that merges robotics and dentistry to enhance the accuracy, efficiency, and safety of dental procedures. It aims to assist dentists in performing complex surgical tasks with a high degree of precision and control, offering several superior aspects compared to conventional methods. These advantages include robotic auxiliary instruments, image-based planning, surgical planning and simulation, surgical tracking and simulation, safety features, and improved precision and efficiency (2).

Material and Methods

The discussion on the potencies of HPDSAR (high precision dental surgery assisting robot) to achieve the most effective, accurate, and precise oral surgery treatment was conducted through comprehensive literature review of reputable scientific articles. The sources were accessed through established academic databases, including PubMed, ScienceDirect, SCOPUS, and EBSCO. This review focuses on general information about robotic system; automatization of general and oral surgery mechanism; and the expected result of the integrated system effectiveness on producing an accurate and precise oral surgery treatment. The selected articles for this review were published within the past 5 years, specifically from 2019 onwards, to ensure the relevance and currency of the information. Keywords and phrases that facilitated the search included: dental surgery assisting robot; dental surgery; digital AI; ergonomic scalpel; surgery automatization. A total of ten articles were retrieved for the literature review, drawn from a range of sources to provide a well–rounded perspective on the subject.

Result and Discussion

Operational Feature Superiority of HPDSAR

Robotic Auxiliary Instruments

HPDSAR is equipped with a robotic system that features specialised dental instruments designed to mimic the hand movements of a dentist during tasks such as tooth extraction, periodontal structure repair, and alveolar bone and jaw reformation. Crucially, the robot offers precision and stability that can be enhanced through the dentist's control. The robot's specifications and features are complex but well-integrated as a system to support the aforementioned functions. This integrated system comprises several robotic arms that demonstrate dexterity and an effective range of motion for performing oral cavity treatment procedures. The joints in these arms have a perfect range of bend that can be controlled to follow human arm movements. The tip of the robotic arm is equipped with end-effectors for handling and manipulating dental instruments, which include grippers, drills, forceps, and other small instruments efficiently, supporting minimally invasive surgery.

In addition to the well-integrated robotic arms, the robot is equipped with an imaging and tracking system using the CBCT (cone-beam computed tomography scan) method to provide real-time imaging guidance during the procedure. This is further supported by an optical or electromagnetic tracking system to monitor the position and movement of the robotic arm and instruments relative to the patient's oral structures (1,2). Haptic feedback is also incorporated to provide tactile feedback, allowing the operator to feel the touch and resistance during the procedure. This element enhances the dentist's ability to perform precise and controlled movements and does not solely rely on the robot's skill (3). This feature is supported by a **user-friendly control interface** for closer operator interaction, utilising features such as a touchscreen panel, joystick, or other input devices that allow the operator to control the robotic arm and adjust settings and monitor the operative procedure. Through the haptic feedback feature, supported by the control interface, the robot can ensure patient safety during the procedure via existing and enhanced safety features. These include collision detection and avoidance mechanisms to prevent accidental contact with oral structures, as well as force sensing to limit applied force and prevent tissue damage (2). Efficient advanced software algorithms are also required as an additional 'brain' that controls the robotic arms, processes imaging data, and executes the surgical plan. Advanced algorithms, which include image processing and motion planning algorithms, are used to interpret imaging data, guide the movement of the robotic arms, and assist the operator during the procedure (4). These integrated auxiliary instruments are all designed to improve and perfect the dental robotic system, enabling more precise, efficient, and safe oral cavity treatment procedures.

Image-Based Planning

Before the surgical procedure, advanced imaging techniques such as CBCT or an intraoral scanner are used to capture highly detailed three-dimensional images of the patient's oral structures. This serves as the foundation for treatment planning, which is integrated into the robot system's software. Image-based planning involves several systematic processes, beginning with **data** acquisition and imaging results to obtain high-quality imaging data that represent a detailed three-dimensional view of the patient's teeth, jaw, and anatomical structures of the oral cavity.

Subsequently, image processing and segmentation are performed using specialised software for relevant segmentation and isolation of oral cavity structures. This involves identifying and extracting teeth, jaw bones, and other anatomical features from the imaging data using image processing techniques such as filtering, thresholding, and region growing to support the planning function (5). Once segmented, virtual surgical planning is performed by manipulating the digital models of the teeth and jawbone to simulate the desired surgical procedure. This allows the operator to virtually plan the surgical action using specialised software to facilitate the planning process (5,6).

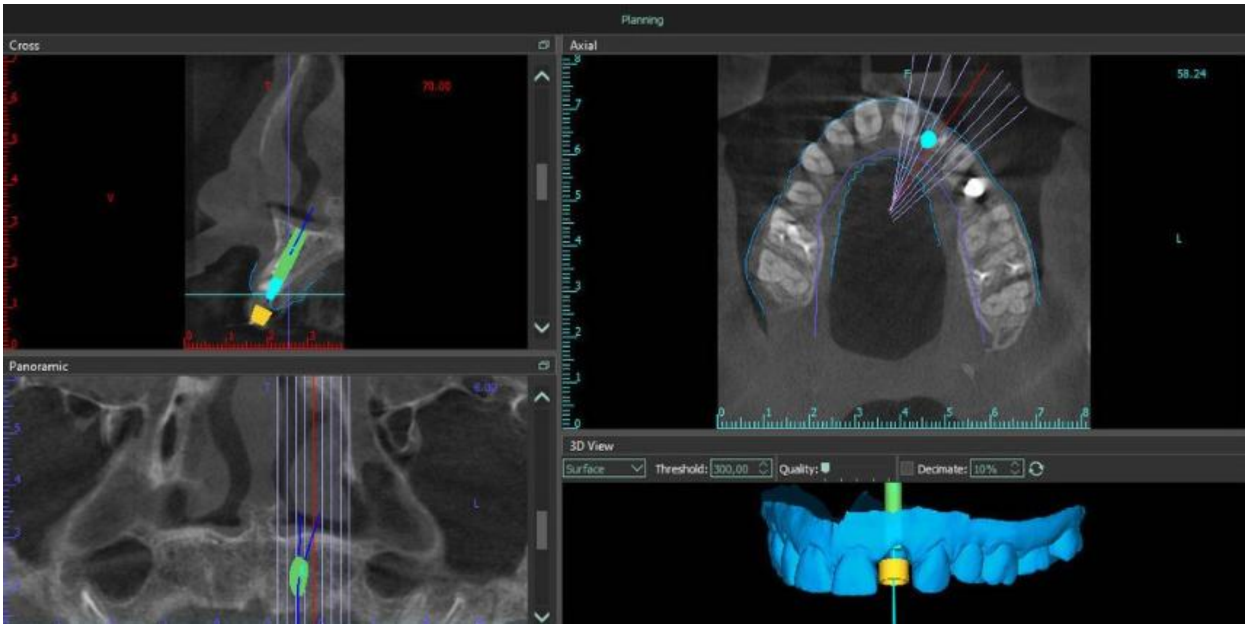

Figure 1. Oral Cavity Imaging via CBCT Technique Performed by the Oral Surgery Robot.

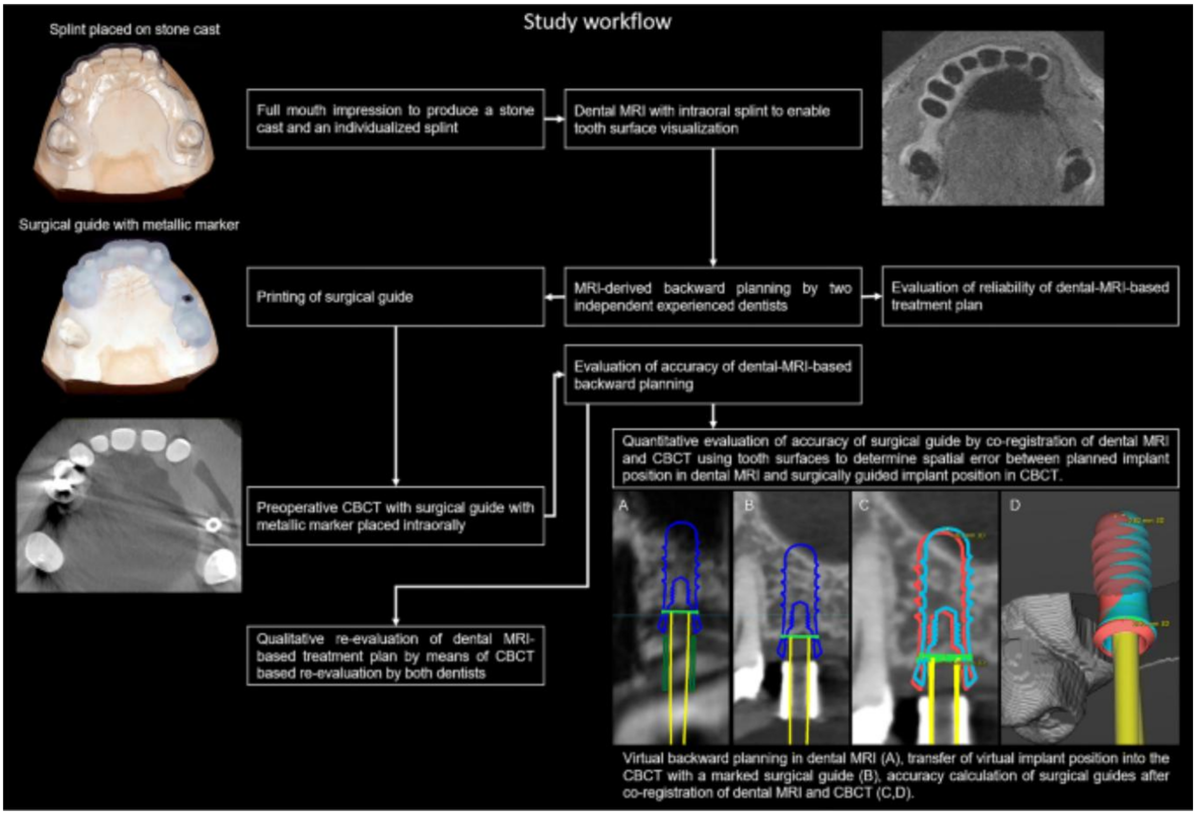

Figure 2. Flowchart Model of Surgical Action Planning based on the Interpretation of Oral Cavity Imaging Results via CBCT Technique by the Oral Surgery Robot.

Alignment of the virtual surgical plan with the actual oral cavity anatomy—the calibration process—is necessary for application in the patient's mouth. This requires registration or alignment with the patient's imaging data through point-based registration or surface-based registration techniques. This alignment must then be supported by a surgical navigation system. This involves integrating the virtual plan with the robotic system and providing real-time guidance during the actual surgical procedure. This system tracks the position and movement of the robotic arm and instruments relative to the patient's oral structures and ensures the precise execution of the planned surgical action. Real-time feedback and visualisation for the operator include a visual overlay of the virtual plan onto the live surgical field, haptic feedback to provide a sense of touch and resistance, and real-time monitoring of instrument position and tissue contact during the procedure. Once the surgical planning and guidance system is established, it undergoes rigorous validation and testing to ensure its accuracy, capability, and safety. This involves testing on phantom models, cadaver specimens, or clinical trials with human subjects (3). These features are also critical for real-time tracking and navigation, which involves tracking the position and movement of the robotic arm and instruments relative to the patient's oral structures during surgery. This is packaged in technology with an optical or electromagnetic-based system consisting of sensors and cameras to track the position and orientation of markers or sensors attached to the robotic arm and instruments (2).

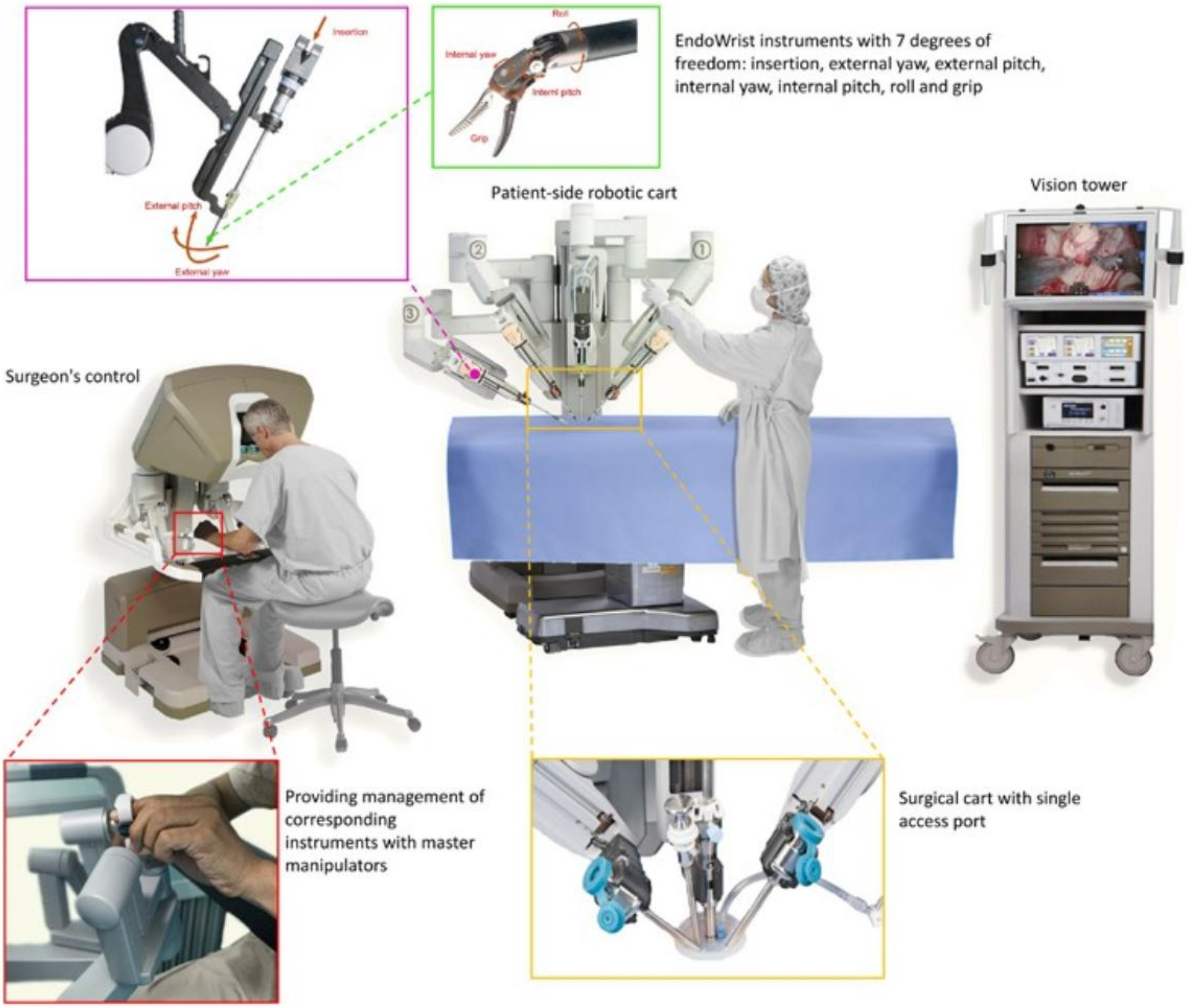

Figure 3. Diagram of Dental Robot Usage and Haptic Feedback Provided by the Robotic Device to the Operator.

System Learning Method for System Optimisation and Task Execution Capability in Dental Operative Procedures

The precision and accuracy of oral cavity surgery can be achieved, enhanced, and developed through a deep learning process in image processing. This is done to establish a single, accurate diagnosis using algorithms such as convolutional neural networks (CNN). CNN can be used in processing imaging results to analyse and interpret dental imaging data like CBCT scans and intraoral images. It then performs automatic segmentation and identification of relevant anatomical structures, thereby enhancing precise surgical planning and accurate representation of the patient's oral cavity anatomy. The CNN algorithm can aid in the systematic surgical planning process by training on a mega dataset of pre-operative images and corresponding surgical plans. This allows it to learn patterns and correlations to generate an automated surgical plan, which can include pathways for tooth extraction, implant removal paths in implant cases, incision and excision paths for oral mucosa surgery, and other operative actions. This automation reduces errors in manual planning and increases precision by leveraging knowledge from abundant existing data.

This algorithm will develop its capability over time to detect and track dental instruments in real-time during surgical procedures. This is achieved by analysing live footage or data from sensors installed on the robotic system, allowing the position and even orientation to be identified and tracked accurately and precisely (7). Automation in executing tasks to control and manipulate robotic arm movements and instrument handling uses deep learning via the reinforcement learning technique. This allows the device to learn appropriate and optimal control to complete dental procedures such as drilling, suturing, or irrigation with precision. This reduces the risk of human error and increases the precision of operative procedures, as is the expectation of this technology (8).

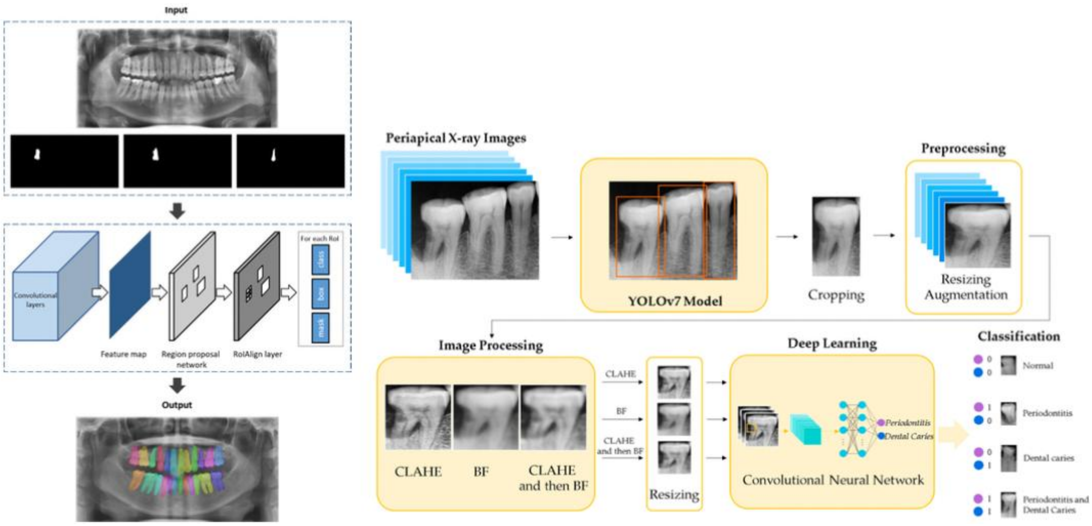

Figure 4. Results of Deep Learning using the Convolutional Neural Networks (CNN) Method on the Maxillary and Mandibular Structures (Left); on Each Tooth for More Accurate Diagnostic Interpretation (Right).

Simultaneously, the device can be trained to provide decision support and risk assessment during dental surgery. This is done by analysing data from sensors, imaging, and instrument tracking to identify risks or uncertainties in a surgical plan, providing warnings or suggestions to the operator to ensure the procedure complies with safety operational standards and minimises the potential for dangerous side effects (9). After being proficient in operating the entire device, manipulating instruments, and determining a well-risk-assessed surgical plan, a process of continuous development is necessary. This is achieved by collecting and analysing data from an even larger dataset with more complex dental cases and procedures. The device can refine its algorithms and adapt to rarer new scenarios over time. Enhancing precision and safety can be achieved by incorporating feedback and outcomes from previous surgeries. Refinement is also supported and driven by the availability of abundant training datasets, the selection of supporting CNN algorithms, and validation through meticulous testing and validation in clinical settings, all of which must be ensured as integrated into a single dental surgical robot technology system (4).

Advantages of HPDSAR over Conventional Oral Cavity Surgery Methods from a Medical Perspective

Surgery with HPDSAR offers significant advantages in terms of **recovery** and the **invasive aspect** compared to conventional oral cavity surgery methods, where both factors are crucial and impact the post-operative period. HPDSAR surgery tends to be minimally invasive because the surgical incision is smaller, thereby reducing trauma to surrounding tissues. The healing process is also faster, and the potential for nosocomial infections, which are prone to occur in post-operative conditions, is reduced (1). The quick and efficient surgical process also plays a vital role in cutting down on patient recovery time and post-operative pain, allowing the patient to return to normal quickly. The risk of bleeding resulting from minimal surgery can be reduced due to the precision of the robot's movements, thereby minimising damage to blood vessels. Furthermore, the improved visual field through imaging with the robot—equipped with robotic arms and end-instruments designed to be highly ergonomic—allows the condition of the oral cavity to be recorded in detail and clearly. This results in more thorough planning for oral cavity surgery based on a more accurate, single diagnosis (9).

Risks of Conventional Oral Cavity Surgery Methods, Making HPDSAR a Superior Preference for Revolutionising Dental Surgery

Beyond complications like bleeding and infection, conventional oral cavity surgery is also reported to cause serious nerve damage in the surrounding area. This can lead to numbness, tingling, or even paralysis in the face, oral cavity, and masticatory components responsible for chewing function and opening the mouth (10). Moreover, the administration of local anaesthesia in the oral cavity can cause allergic reactions or other complications. This is compounded by excessive swelling that occurs as a natural bodily response to invasive surgery, which can also cause difficulty in eating or drinking.

Conclusion

HPDSAR has the capability to effectively and accurately represent operative surgical actions in dentistry. It achieves this through a deep learning mechanism with the CNN algorithm, supported by other algorithms such as detection algorithms and reinforcement learning. This allows it to perform operative actions with precision, accuracy, and outstanding performance based on the diagnostic results interpreted through a long process carried out by this robot. This process involves an integrated system that mimics human intelligence, starting from the imaging of the oral cavity using CBCT scans and intraoral imaging, which is processed through deep learning of a dataset to produce a single accurate diagnosis. This diagnosis is then integrated into the robotic arm and instruments, which are manipulated to create good coordination between the robotic arm and instruments, as well as the system software, enabling the operative action to be performed with minimum invasion.

Declaration of Conflicting Interests

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