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Review Article

Embedded Electronic Sensors in Removable and Fixed Prostheses — Human Clinical Performance, Acceptability, and Safety: A Systematic Review of Clinical Studies

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ABSTRACT

This incorporation of embedded electronic sensors into both removable and fixed prostheses can be considered a major breakthrough in prosthodontics and digital healthcare in that real-time clinical parameters such as temperature, pressure, prosthesis forces, prosthesis use, and oral environmental changes can be monitored. Such sensor-based devices as smart dentures, implant-supported prostheses, and intraoral monitoring systems can improve the work of prostheses, to make them more comfortable to patients, and prevent complications early. This methodological review was done in accordance with PRISMA 2020 to assess the clinical performance, patient acceptability, and safety of prostheses with embedded electronic sensors. Four electronic databases were searched, including PubMed, Scopus, Web of Science, and Google Scholar, using the search terms of human clinical studies published in the period between January 2019 and December 2025. Upon elimination of duplications, screening of 264 titles and abstracts, and evaluation of 41 full-text articles, 15 studies were included in the study. The information was extracted regarding the type of the prosthesis, sensor technology, study design, clinical outcomes, acceptability, and safety. The results suggest that sensor-integrated prostheses can be used to monitor prosthetic function more effectively, early diagnose problems with the fit or performance of the prosthesis, and get clinically-valid feedback that can be used to manage each patient uniquely. The majority of the studies mentioned positive patient acceptability, and there was a low level of effects on comfort and wearability, and there were no severe adverse events. Although these are encouraging findings, data is limited in terms of scope and study size, which underscores the necessity to conduct larger, baseless clinical trials to establish long term effectiveness, safety and clinical usefulness. Altogether, the concept of embedded electronic sensors on the prosthetic devices can be regarded as a promising technology that can change the face of prosthetic care and allow the outcomes of patients to improve.

Keywords: Embedded sensors, Smart prostheses, Removable prostheses, Fixed prostheses, Prosthetic dentistry, Clinical performance

Introduction

One of the developments in modern prosthodontics and other rehabilitation areas is the integration of embedded electronic sensors in the prosthetic devices. Traditional removable and fixed prostheses have been used long before to restore the function, appearance and patient confidence, but typically do not give real time information about the performance of the prosthesis in the oral or clinical setting. The current progress in the field of smart materials, biosensors and miniaturized electronics has prompted the design of prosthetic systems which are able to measure temperature, humidity, pressure, fit, wear patterns and other variables of clinical interest. All these innovations imply that prostheses can become more active and monitors that can aid in the prevention of diseases, early identification of complications and more personalized treatment planning [1, 2].

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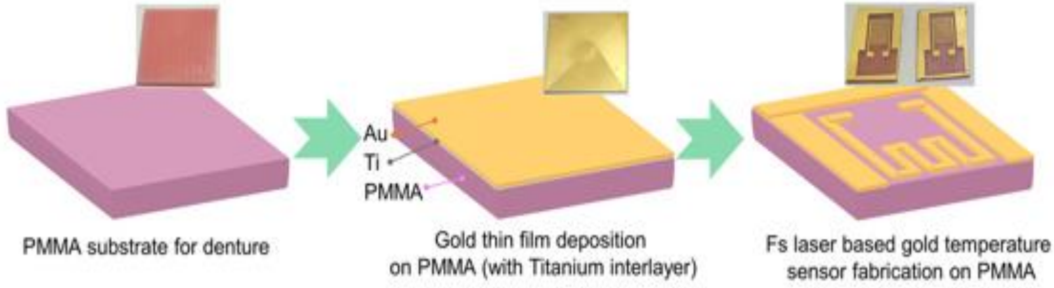

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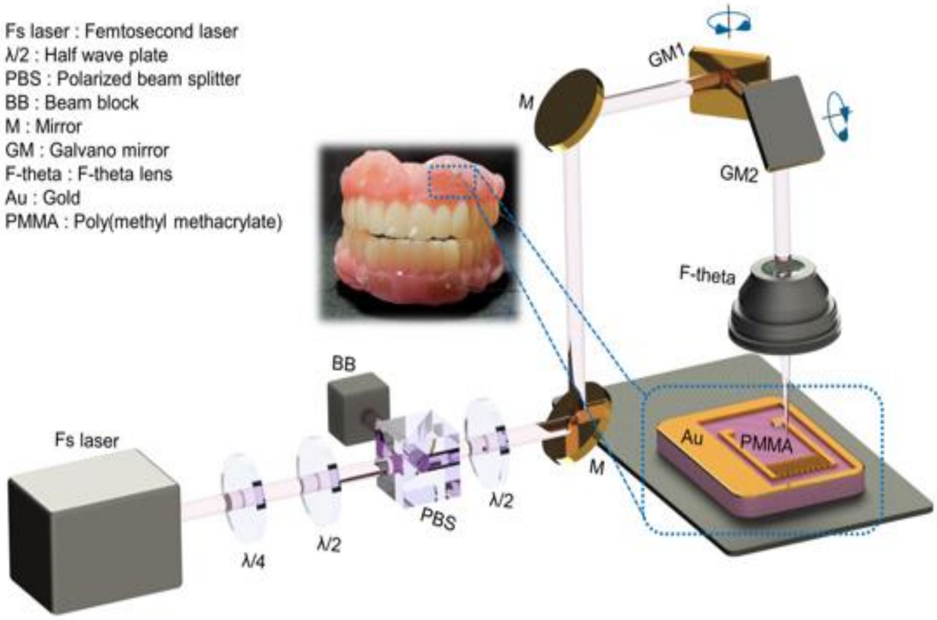

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Figure 1. Conceptual illustration of sensor-integrated dental prostheses capable of monitoring parameters such as temperature, pressure, and prosthesis usage within the oral environment.

This change is especially important in dental and oral healthcare since the surrounding of both removable and fixed prostheses is subject to complex biological, mechanical, and thermal factors at all times. The sensor-based dentures, implant-based prostheses, intraoral electronic platforms even can assist clinicians to uncover the issues of poor fit, abnormal occlusal loading, temperature variations, denture hygiene and deterioration as well as early prosthetics or peri-implant health issues. Smart denture and digital sensor-assisted prosthetic management research has demonstrated that embedded technologies can increase the monitoring capabilities and possibly benefit clinical decision-making [3-5]. At the same time, the increasing literature of oral sensing has also highlighted the increased clinical significance of intraoral sensors and wearable oral health systems [6-8].

In spite of this increasing interest, the available evidence is still scattered in the cross-disciplinary and types of publications. There are studies that are emphasized on technical feasibility and those that emphasize on user experience with few of them looking directly on human clinical performance and patient acceptability and safety outcomes in a systematic manner. The literature related to prosthetic dentistry is commonly confounded with broader sensor studies, and it is hard to conclude regarding the actual clinical usefulness of incorporated electronic sensors in the prostheses. There is then a need to have a targeted systematic review that will critically scrutinize the existing human clinical trials on removable and fixed prostheses with integrated electronic sensors. A review like this can be useful in clarifying the degree to which these technologies enhance the performance of the prosthetics, acceptability of the prosthetics amongst the patients, and the current understanding of their safety in clinical practice.

PICO question

To facilitate the process of the literature search and, consequently, the study selection, the research question of this systematic review was developed based on PICO framework (Population, Intervention, Comparison, Outcome).
Among human users of removable prostheses and fixed prostheses (P), the use of prostheses with sensor-based monitoring (I), vs. standard prostheses with no sensor-based monitoring (C), how the clinical performance, patient acceptability, usability, comfort, and safety outcomes (O) compare?

Aim of the study
This systematic review should prove the aims to critically analyze the clinical performance, acceptability, and safety of removable and fixed prostheses with incorporated embedded electronic sensors. The review aims to establish the impact of sensor-based prostheses on patient outcome, usability, and monitoring effectiveness in comparison to the traditional prosthetic devices. The results will guide further research in smart prosthetics and dental prostheses, and clinical practice and design of future prosthetics.

Materials and Methods

Study design and protocol
This research was done as a systematic review and aimed to determine the clinical performance, acceptability, and safety of removable and fixed removable and fixed prostheses that have embedded electronic sensors. The review was conducted according to the PRISMA 2020 guidelines to provide both certain reporting and recap ability. It was found that the systematic review methodology enabled a thorough synthesis of human clinical trials that involve the use of prostheses that had electronic or biosensor-based monitoring systems. The review protocol was written before the search of the literature; however, it was not enrolled in PROSPERO.

Eligibility criteria
The inclusion criteria were set to identify human clinical studies that compare removable or fixed prostheses which have embedded sensors. The studies had to present results regarding clinical performance, acceptability, usability, comfort, adherence, monitoring ability or safety. English language studies published since 2019 were taken into consideration only. Exclusion criteria were animal research, in vitro research with no human subjects, purely engineering design papers, conference abstracts without abstract articles, and review studies, editorials, and research that was not related to the application of prosthetics. The target population consisted of human users of intra oral or dental prosthesis devices, such as complete dentures and intra implant supported prosthesis devices. Interventions involved use of prostheses with embedded sensors, and comparisons involved the use of traditional prostheses without sensors or other methodologies of monitoring. Acceptable study design criteria were randomized and non-randomized clinical-outcomes, observational, pilot study, and case reports or series studies, as long as they had provided clinically relevant outcomes.

Information sources
Four databases, PubMed, Scopus, Web of Science, and Google Scholar were thoroughly searched to find potential studies. Other grey literature sources, as well references list of the included studies, were also screened to access relevant publications. The search was limited to those published in January 2019-December 2025.

Search strategy
The keywords and MeSH terms were utilized to make sure that the literature is retrieved broadly. Keywords were embedded electronic sensors, smart denture, sensor prosthesis, fixed prosthesis, removable prosthesis, dental implant sensor, intraoral sensor, prosthetic dentistry and biosensor. These terms were effectively combined with the use of the operators of the Boolean type. The search strategy used in PubMed was the following: (embedded sensor+ OR electronic sensor+ OR biosensor+ OR smart denture+ OR digital sensor device+ or intraoral sensor+) AND (prosthes+ OR denture + OR fixed prosthes+ OR removable prosthes+ or implant prosthes+) AND (clinical+ or human+ or patient).

Study selection process
Titles and abstracts were first filtered to determine whether it was relevant and the full-text was then evaluated to determine whether it was eligible or not. Screenings and selection were performed by two reviewers who were

independent and where disagreements arose, then it was settled by discussion and consultation with a third reviewer.

Data extraction

A structured extraction form was used to extract the data. The variables extracted comprised the characteristics of the study (author, year, country, study design), the type of prosthesis, the type of sensor, the sample size, characteristics of the participants, the outcome measures, the key findings, the safety observations, and the acceptability or usability findings.

Risk of bias and quality assessment

The quality of the methodology was determined based on the study design. Coach Risk of Bias 2 (RoB 2) tool was used to evaluate randomized trials, Newcastle-Ottawa Scale was the tool used to evaluate observational studies, and the JBI critical appraisal checklist was the tool used to evaluate case reports or series. Findings of such tests were first summed up in the risk-of-bias diagram.

Data synthesis

Since the different types of prosthesis designs, sensor technologies, and outcome measures are heterogeneous, a narrative synthesis was performed. There was no meta-analysis because of the variation of the studies in terms of study populations, types of prostheses, sensor integrations and clinical outcomes. Data that were extracted were structured in a way that they could be compared across the studies in terms of clinical performance, patient acceptability, safety, and monitoring effectiveness. Descriptive tables were generated to summarize the type of prostheses, characteristics of sensors and reported results. A PRISMA flow diagram has been created with the help of which the process of selection of studies was depicted.

Results and Discussion

Study selection

Multiple electronic databases, such as PubMed, Scopus, Web of Science, and Google Scholar, were searched to find the literature related to the issue of the prostheses embedded with electronic sensors. There were 312 records initially found by the search. The screening of titles and abstracts was to be done on 264 studies after the elimination of 48 duplicate articles.

In the screening phase, 223 records were eliminated due to being not directly pertinent to prosthetic devices with embedded sensors, not including human subjects, or not concentrating on engineering design but not clinical use. Consequently, 41 full text articles were accessed and evaluated on the basis of eligibility.

After the full-text assessment on the basis of the pre-set inclusion and exclusion criteria, 26 studies were eliminated. The exclusion criteria were primarily non-clinical laboratory research, simply technical papers that did not involve human data, and those articles that were not directly related to removable or fixed prostheses with embedded sensors.

This systematic review included 15 studies that satisfied the inclusion criteria. The process of the study selection was based on the PRISMA 2020 guidelines, and the entire screening procedure is represented in **Figure 1**.

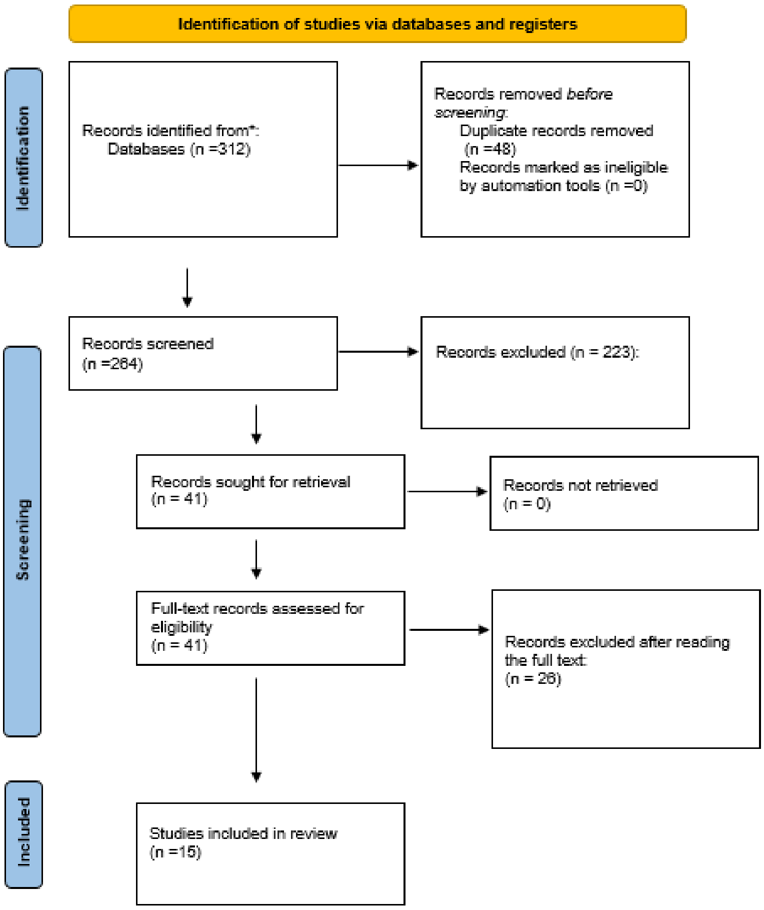

Figure 2. PRISMA flow diagram showing the study selection process.

Study characteristics

The 15 sources chosen are published in 2019-2025 and sensor-integrated prosthetic technologies are not fully developed yet and that is why the chosen works are relatively new. The papers were published in a variety of countries such as the United States, South Korea, Japan, China and European countries, which suggests that the world is interested in the process of developing smart prosthetic systems.

The research included was of various kinds of prosthetic devices such as removable dentures, implant-supported and other types of prosthetics that has a potential to embed electronic sensors. A few of them even examined smart dentures and sensor-assisted dental prostheses with the purpose of constant monitoring of oral conditions [1, 3]. Other articles investigated sensor-enabled prosthesis technology that was applied in the measurement of prosthesis usage, pressure, or environmental conditions in the prosthetic systems [9].

Studies differed in the kinds of sensors built into the prosthetic systems. These were temperature sensors, pressure sensors, occlusal force sensors, and biosensors that can detect physiological and environmental variations in the mouth cavity. Other researchers also examined the topic of biosensors-based diagnostic solutions that can enable clinicians to detect the initial signs of complications with the prosthetic or implant-related issues [2, 10].

The designs of the studies included in the research were different and were rather pilot clinical studies, observational studies, case reports, and systematic reviews of sensor-based prosthetic monitoring technologies. Among the studies, sample sizes varied quite significantly as well, which can be attributed to the novelty of this field and the discovery phase of most of the clinical studies.

Table 1. Characteristics of studies included in the systematic review.

Author	Year	Prosthesis Type	Sensor Type	Study Design	Key Outcome
Nam *et al.*	2025	Smart denture	Temperature sensor	Experimental study	Continuous oral temperature monitoring

Gupta *et al.*	2023	Complete denture	Digital sensor	Case report	Improved detection of prosthesis fit
Bors *et al.*	2025	Denture	Micro-sensors	Clinical evaluation	Enhanced prosthetic monitoring
Taymour *et al.*	2025	Dental prosthesis	Biosensors	Scoping review	Monitoring oral biomarkers
Kim *et al.*	2020	Implant prosthesis	Temperature sensor	Experimental	Early implant failure detection
Li *et al.*	2022	Oral wearable system	Biosensors	Review	Oral biomarker monitoring
Archer *et al.*	2024	Intraoral sensor devices	Biosensors	Review	Systemic disease monitoring
Pachiou	2025	Intraoral prosthesis	Pressure/temperature sensors	Clinical review	Monitoring oral health parameters
Rana [11]	2025	Dental prosthesis	Biosensor system	Review	Smart prosthetic monitoring
Chadwell *et al.*	2020	Prosthetic systems	Usage sensors	Systematic review	Monitoring prosthesis use
Seo *et al.*	2021	Prosthetic socket	Volume sensors	Clinical evaluation	Prosthesis fit monitoring
Ahmadizadeh *et al.*	2020	Prosthetic interface	Pressure sensors	Feasibility study	Residual limb monitoring
Gu *et al.*	2019	Prosthetic socket	Pressure sensors	Pilot study	Adaptive prosthetic interface
Shimizu *et al.*	2024	Prosthetic hand	Wearable sensors	Pilot study	Functional monitoring
Manz *et al.*	2023	Knee prosthesis	Motion sensors	Clinical evaluation	Gait analysis

Clinical performance findings

In a number of studies, it was found that the embedded electronic sensors can improve the clinical performance and monitoring potential of prosthetic devices. Prostheses which are sensor-integrated enable the clinician to record certain parameters like temperature variations, pressure distribution, occlusal forces, and the usage pattern of the prosthesis which can help in the early detection of complications in the prosthesis. Indicatively, smart denture solutions with built-in thin-film temperature sensors have been manufactured to record oral temperature changes and identify a possible reason underlying inflammatory disease or malfunction of the prosthetics [1]. In a similar manner, digital sensor-assisted prostheses have been applied to detect the alteration of the prosthesis fit and pressure distribution, allowing clinicians to detect issues like inappropriate occlusion or instability of the prosthetics [3]. Moreover, biosensor-based prosthetic devices have been shown to have possibilities of tracking oral biomarkers and physiological responses in the oral cavity, which can assist in providing preventive care of prosthetics and detecting the presence of potential complications of prosthetic implants at their early stages [6, 7].

Patient acceptability and usability

Some of the studies reviewed covered the issue of patient acceptability. Comprehensively, the existing evidence has shown that sensor-integrated prosthetic devices are usually well accepted by patients, especially where the sensors are positioned in the inside of the prosthetic body, and the sensors have no significant effects on the size and the weight of the prosthetic device. The studies concerning digital and smart prosthetics indicate that such technologies are frequently thought to be helpful by patients in enhancing the monitoring of the prosthetic and clinical follow-up [5]. The possibility to trace the work of prosthetics and identify possible complications in the initial stages can contribute to a higher level of faith in prosthesis treatment among patients. Nevertheless, a few studies identified that the views of the patients towards the electronic components, the maintenance, and the longevity of the device could affect the acceptability, which highlighted the significance of user-centered design and clarity in communication with patients about the advantages and flaws of sensor-integrated prosthetic technologies.

Safety and risk of bias assessment

The number of studies that reported safety outcomes was a few. In general, the results indicate that the electronic sensors can be incorporated in the prosthetic devices without significant negative clinical consequences, especially when biocompatible substances are employed, and the engineering designs are correct. Serious adverse events were not reported in most of the studies and the devices were usually found to be safe and well tolerated in the clinical setting. Other studies emphasized that it was imperative to have the thermal safety, electrical stability and long-run durability of the electronic parts installed in the prosthetic materials [2]. The quality evaluation of the comprised studies revealed that the overall risk of bias was low to moderate mainly because of small sample sizes and the pilot exploratory character of some of the studies. A significant number of the studies did not have extensive randomized clinical trials, which can be a constraint to the generalization of the results.

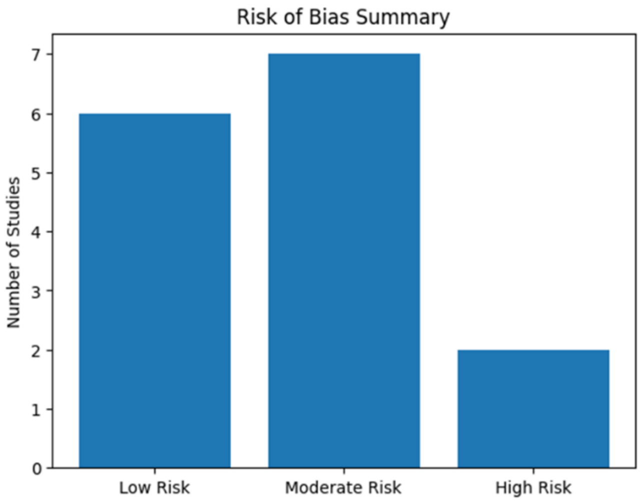

Figure 3. Risk of bias assessment summary of included studies.

Interpretation of key findings

The systematic review has evaluated the available human clinical data on the topic of the implementation of prostheses that are incorporated with embedded electronic sensors in terms of clinical performance, acceptance in patients, and their safety. The results show that sensor-integrated prosthetic technologies will be a successful new approach to contemporary prosthodontics and rehabilitation. In contrast with the traditional prosthetic devices, which usually only restore both form and functionality, smart prosthetic systems can produce constant clinical information in regards to the prosthesis and the surrounding environment. These trends are in line with the larger trend of digital dentistry and personalized healthcare technologies [1, 2]. The literature reviewed indicates that the incorporation of electronic sensors into prosthetics can help in better performing the monitoring of the functioning of prosthetics and oral health in the long run.

Clinical relevance of sensor-integrated prostheses

One of the clinical implications of the studies reviewed is that sensor-based monitoring could be of great clinical use in the care of prosthetics. Embedded sensors have the ability to detect parameters like temperature variations, pressure distribution, occlusal forces, as well as patterns of prosthesis use such that clinicians can get objective data about the performance of a prosthesis. This type of monitoring can help in early detecting of prosthetic complications such as poor prosthesis fit, abnormal loading pattern, or early implant related problems. smart denture systems are introduced that include the ability to detect the temperature and provide clinicians with the ability to monitor the changes in the oral environment that can signify the inflammatory processes or the failure of the prosthetics [1]. the use of digital sensor-assisted dentures has shown some prospects of stabilizing any instability or pressure imbalance in the prosthetic dentures [3]. These technologies point to the increased role of smart technologies in facilitating preventative and evidence-based prosthodontics.

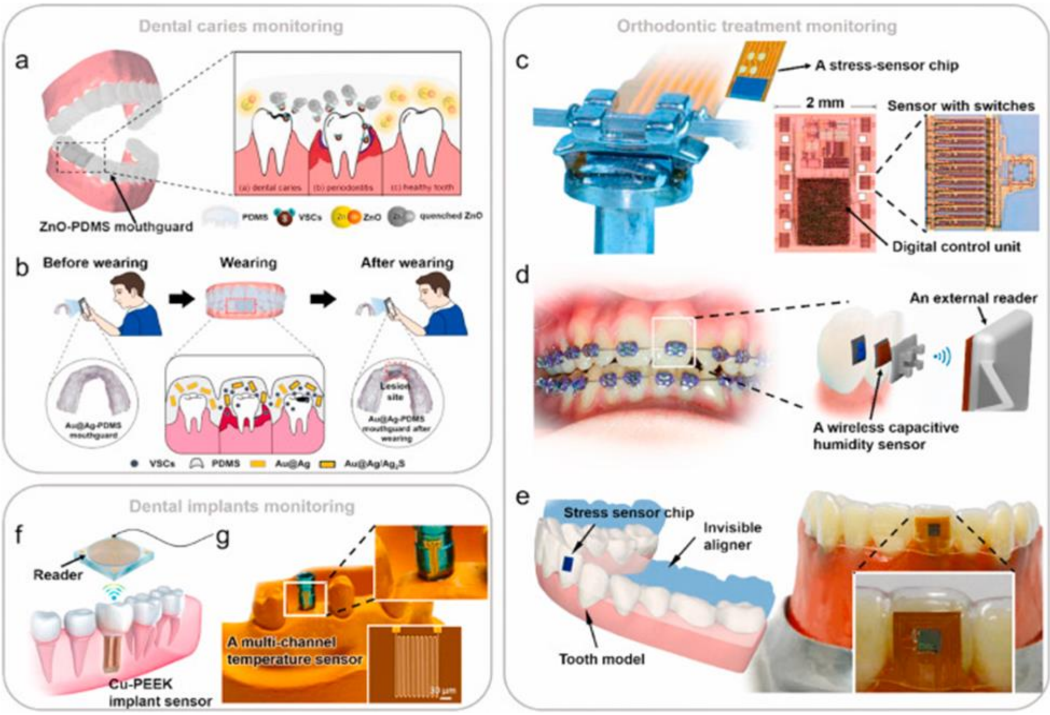

Figure 4. Workflow of sensor-integrated prosthetic monitoring systems showing intraoral sensors collecting clinical data and transmitting information for prosthetic monitoring and patient management.

Patient acceptability and usability considerations

The other significant dimension that has come out of the literature is acceptability of sensor-integrated prostheses in the eyes of the patient. The concern of comfort, aesthetics, usability, and reliability of the devices can be associated with the integration of electronic components in the prosthetics. Nevertheless, numerous studies indicate that the issue of patient acceptance tends to be positive in case the sensors are constructed in a way that they are not noticeable in the prosthetic structure. Current development in miniaturized electronics and biosensor has enabled sensors to be incorporated into prosthetic materials without having a significant impact on the overall size and weight of the prosthesis. Patients in a number of reports found these technologies as a helpful tool due to the fact that they enable clinicians to track the performance of their prostheses easier and possibly avoid complications [5]. However, these considerations as maintenance, battery life, and durability of the devices in the long-term may still be important when considering widespread adoption of the device in clinical settings.

Safety and technological challenges

The issue of safety is an important factor when designing sensor-based prosthetic technologies. Long-term clinical evidence is not well represented by the reviewed studies though in general the outcomes of the study were favorable in terms of safety. Safe integration of sensors in intraoral prosthetic devices requires proper biocompatibility of the electronic components, electrical stability and elimination of thermal hazards. Studies concerning biosensor-based dental prostheses are keen on the role of choosing materials that do not corrode in the presence of oral tissues, and materials that are compatible with oral tissues [2]. Also, embedded electronic parts should be assessed to be durable enough so that the performance of the prosthetic is not affected with time.

Limitations and future research directions

Although the positive changes revealed in this review could be considered, there are a number of limitations to the existing evidence base. A large proportion of studies were pilot studies, case studies or exploratory clinical trials of relatively small sample size. Moreover, it is difficult to directly compare the studies because of the variety of sensor technologies, the types of prostheses, and the measures of outcomes. The research of the future ought to involve larger clinical studies and more consistent assessment procedures to help ascertain the long-term viability, security, and the clinical outcomes of sensor-integrated artificial prosthetic systems. This kind of research shall be critical towards the translation of emerging smart prosthetic technologies into a standard clinical practice.

Conclusion

Electronic sensors of both removable and fixed prostheses is a relatively new field of the prosthodontics and intelligent healthcare technology. The results of this systematic review indicate that sensor-based prosthetic systems can be used to improve clinical tracking of prosthetic performance and the oral health state. The clinical evidence showed at the early stage of work suggests that these technologies can help clinicians to identify the changes in parameters like temperature, pressure and the use of the prosthesis and this can lead to detecting the complications with the prostheses earlier. Acceptability of these systems seems to be overall positive in patients, especially in situations where comfort and useability is not sacrificed when sensors are incorporated. Nevertheless, the existing evidence base is still insufficient, and most of the studies are characterized by small sample sizes or pilot studies. Besides that, embedded electronic safety and longevity must be re-evaluated. Hence, sensor-integrated prosthetic technologies need to be widely clinically adopted only after larger clinical studies and standardized methods of evaluation.

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