Advancements in temporomandibular joint total joint replacements (TMJR)

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Abstract

The goal of this paper is to review the advantages and disadvantages of the various treatment options of temporomandibular joint (TMJ) total joint replacement (TJR). TMJ articles published within the last 20 years were reviewed to collect the information on non-invasive and invasive TMD treatment methods. Recent technological advancements helped the evolution of treatment methods and offered significant value to TMD patients and surgeons. Considering the TMD levels, the therapeutic procedures can involve general health examinations, physical therapy, medication, oral rehabilitation or as an end stage clinical invention, temporomandibular joint replacement. In fact when intra-articular TMD is present, the effective treatment method appears to be TJR. However, concern for infection, material hypersensitivity, device longevity and screws loosening issues still exists. Further combined research utilizing the knowledge and expertise of, surgeons, material scientists, and bioengineers is needed for the development of improved TMD therapeutic treatment.

Keywords Temporomandibular joint disorder (TMD) · Total joint replacement (TJR) · Technical advancements of TMJR

1 Overview

TMD (temporomandibular disorders) is a general term that encompasses the intra- and extra-articular disorders affecting the temporomandibular joint (TMJ) [1]. The clinical distinction between these two varieties of TMD is a prerequisite for appropriate diagnosis and patient management [2]. Although much more is understood about TMD today than

decades ago, it is surely helpful to investigate the topic to promote further advancements of diagnostic and management methods.

TMD symptoms arise when there are problems that affect the jaw muscles, the TMJ itself, or both. Allowed to progress, any of these can lead to a chronic disorder, which can result in physiological dysfunction of the jaw [3]. This is detrimental to the patient because the TMJ is essential to the life functions such as mastication, speech, airway support, and deglutition [4]. When these important life functions are compromised by end-stage TMD intra-articular pathology that leads to anatomical distortion of the TMJ itself then the TMJ total joint replacement (TMJR) can be utilized to salvage the joint by an appropriately trained surgical team and restore mandibular function and form.

Research technological advancements have permitted an in-depth investigation of TMJR procedures and their clinical outcomes. The information and well-established investigative techniques from orthopaedic TJR research can be translated to TMJ research. This will assist in understanding the causes of TMJR device failures and the effects of these devices on the surrounding tissue and ultimately result in improved and more effective devices.

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2 Introduction

The TMJ is a sliding-hinge articulation that connects the mandible to the temporal bone of the skull (Fig. 1) [5]. It is a complex joint because of its close association with other structures in the head. Acute or chronic extra-articular TMD is diagnosed when problems or pain associated with the jaw and muscles of mastication that surrounds the TMJ are present. Chronic TMD can develop into end-stage intra-articular pathology, which is the indication that invasive treatment options may be necessary [6]. TMD symptoms include pain in the jaw and masticatory muscles, decreased the mandibular range of motion, and clicking noises when opening and closing the mouth [3]. It is still not known what specifically causes the advancement of the disorder into the various stages.

Medication and physical therapy can be the first approach to manage TMD symptoms in patients. When extra-articular TMD is present, and the symptoms are not severe, these approaches can be effective in relieving the symptoms [7]. Most TMD cases are of muscular (extra-articular) origin, and 85–90% of TMD cases can be improved employing non-invasive management options [3]. When intra-articular end-stage TMD develops, more invasive methods may be necessary to restore mandibular function [8].

Fig. 1 Illustration of the TMJ which is a sliding-hinge articulation that provides the articulation of the mandible with the temporal bone of the skull. The TMJ is a complex joint with both translational and rotational moments

It is helpful to study the causes of intra-articular end-stage TMD to develop more effective treatment and prevention methods. These investigations led to the development of TMJ total joint replacement (TMJR) devices that aim to improve and restore mandibular function and form [9]. Today, about 3000 patients with end-stage TMD undergo TMJR surgery each year [10]. Because of the complexity of TMD, its form and function, and the implant materials presently available, it is still difficult to construct a completely successful joint replacement device with significant longevity.

New technologies, such as bioengineered tissue and 3D printing, are being studied for use in the management of intra-articular TMD [11]. However, TMD cannot be cured, only managed so that TMJ function and form are optimized, and the patient has increased quality of life.

The understanding of TMD, its management, and material science technology has expanded with the advancements made through research into failed devices. This review will discuss the evolution of TMD treatment methods for patients with intra- and extra-articular disease, and measure their effectiveness. Total joint replacement for patients with the intra-articular disease will be the focus. Results of these studies will lead to future technological advancements in joint replacement device design, material composition, and manufacturing techniques.

3 TMJ disorders

TMD occurs when functional and pathologic problems with associated pain arise in the TMJ area of the jaw [3, 12]. Symptoms of this disorder include TMJ sounds such as clicking, limited movement of the mandible, ear pain, neck pain, and headaches [13, 14]. Clicking was found to be the most common symptom with 65% of patients experiencing this symptom [15]. This disorder is most prevalent in patients 20–50 years old [3]. About 40–75% of adults in the United States show at least one sign of the disorder, and of those, 33% show at least one symptom [3]. TMD can be acute or chronic. In the latter case, symptoms are on-going, and pain is persistent and severe. Of those with symptoms, only about 5–10% with TMD require treatment [3].

It is important to understand the clinical distinction between the intra- and extra-articular disorder types, for the proper TMD clinical management. 95% of patients present with signs and symptoms associated with extra-articular TMD [1]. Of that 95%, 50% have problems not associated with the TMJ, leaving 45% with true extra-articular, muscle related TMD, which does not require invasive treatment methods [1]. Only 5% of patients have intra-articular TMD, which is related to developmental, neoplastic, traumatic arthritic, and ankylosis end-stage pathology [1]. These

patients have demonstrable TMJ end-stage disease on imaging, often requiring invasive procedures [1].

3.1 Causes and symptoms

The causes of TMD are multifactorial [16, 17]. Many of these play a significant role in the onset of TMD, including behavioural, physiological, environmental, and even genetic factors [18]. The pain relating to extra-articular TMD is associated with the head, neck, and masticatory muscles [19]. Together, these structures contribute to a common symptom of TMD, which is facial pain [3]. Some other symptoms of TMD include clicking or popping sounds when opening and closing the mouth, reduced mandibular range of motion, difficulty chewing, and swelling and tenderness of the face [20, 21]. Extra-articular TMD signs and symptoms are managed non-surgically with the use of medication, oral appliances, or physical therapy.

One of the causes of intra-articular TMD related problems is disc displacement within the TMJ [5]. The articular disc is located between the fossa and condyle components of the TMJ [22]. It functions to provide cushion for the many stresses placed on the joint, and help with movement of the condyle [5]. Disc displacement occurs when there is uncoordinated movement between the condyle and the articular disc [23]. The disc can be forced out of its normal position, which results in the clicking or popping sound when opening and closing the mouth [24]. It is important to note that clicking or popping sound is one of the TMD symptom and not everyone who clicks requires treatment.

Other causes of intra-articular TMD include trauma to the jaw, mechanical overloading on the TMJ, grinding or clenching of the teeth, developmental anomalies, neoplasia, ankylosis, or arthritic disease [4, 25]. There are several types of surgical treatments that have been found to be successful through research, but only the small portion of patients with intra-articular end-stage TMD dictate the need for invasive surgical procedures such as TMJR.

3.2 Misdiagnosis

In 1934, James Costen believed TMD symptoms resulted from posterior positioning of the condyle putting pressure on the auriculotemporal nerve [3]. He felt this was due to missing teeth, which caused improper jaw alignment [3]. When the missing teeth were replaced, patient's symptoms decreased. Thereafter, the commonly accepted treatment for TMD was to alter the patient's dental occlusion [26]. This theory was anatomically disproven by Sicher in 1947 [27].

Misguided and untested theories have led to misdiagnosis or over-diagnosis of TMD. Since physicians and dentists were not looking at the TMJ as an anatomical and physiologic orthopedic unit, the emphasis was placed on cure

rather than management. This led to erroneous theories that TMD was mainly caused by occlusion or articular disk position.

4 Technological advancements

Technology within the areas of TMJ research has led to the evolution and advancement of management options for patients with TMD. The investigation into different management modalities will be helpful in developing new and more successful TMD management options. If researchers continue to pursue the causes of management failures and propose solutions, more effective and advanced treatment options will result. These advancements will improve TMD management and increase the patient's quality of life.

4.1 Non-invasive technological advancements

Imaging is one of the diagnostic tools that can be used to evaluate TMD patients [28]. The panoramic radiograph is one of the most beneficial screening imaging technique used today [3]. This radiograph is made of the patients' maxillo-facial region to obtain more details about the structure [29]. Computed tomography (CT) and the cone-beam CT (CBCT) provide options for more specific study of any TMJ bony involvement [30]. Magnetic Resonance Imaging (MRI), skeletal scintigraphy, and arthroscopy (minimally invasive) are other screening techniques that can be used, each with their own advantages and limitations [3]. The best type of screening tool is the one tailored to the patient's specific case.

Medication, oral appliances, and physical therapy can be the first steps taken to relieve the patient's symptoms in extra-articular TMD cases [3]. Over-the-counter analgesic medication may be utilized to relieve pain, or the doctor may prescribe muscle relaxant medication. Oral appliances are plastic mouthpieces that cover the mandibular or maxillary teeth and are used to eliminate attrition of the teeth due to bruxism, as well as aid in masticatory muscle relaxation [3, 31]. If the non-invasive methods do not provide improvement and an intra-articular condition is demonstrated on imaging, then more invasive management options may be considered. It is important that non-invasive methods be exhausted before surgery is presented as an option to the patient.

4.2 Invasive technological advancements

Arthrocentesis is the minimally invasive form of intra-articular TMD management [32]. It is performed on patients that cannot completely open their mouth due to acute intra-articular TMJ disc displacement. The purpose of this procedure

is to insufflate and irrigate the joint with a sterile isotonic solution to lyse early fibrous adhesions and remove the inflammatory cytokines from the TMJ [5].

Arthroscopy is another type of minimally invasive intra-articular TMD management option that not only can be used to remove inflammatory cytokines and the more mature fibrous adhesions they promote but also to free up and/or reposition the articular disc [33]. If the attachment ligaments of the articular disc have been stretched and the disc is out of position, and it is healthy, the ligaments can be repaired either arthroscopically or by open surgery [5].

When the articular disc is found to be unhealthy, torn, completely dislocated, or misshapen and when there is a clinical and image evidence, a discectomy may be performed based on clinicians recommendation [34]. This procedure includes the surgical removal of the impaired, dislocated articular disc of the TMJ [5].

4.3 Total joint replacement

If intra-articular disease progresses to the end-stage, autogenous or alloplastic joint replacement may be required. The former involves grafting of autologous bone, typically a rib and associated sternal cartilage (costochondral graft) to replace the condyle ramus component of the TMJ (shown in Fig. 2a); and soft tissue, typically a temporalis muscle fascia flap, to line the temporal glenoid fossa. However, the costochondral graft has been shown to be unpredictable, as 54% have been reported to fail due to overgrowth in children or ankylosis [6, 35].

Transport distraction osteogenesis is another method for reconstructing the TMJ in patients with end-stage intra-articular disease [36]. This procedure, in the absence of a

bone graft, stimulates bone formation by the slow distraction of surgically created bony segments [37]. A posterior mandibular vertical ramus osteotomy is performed first. Then a distraction device is implanted in that segment and attached to the distal mandible. Using a jackscrew opened slowly over days, a vertical vector is developed between the osteotomized posterior mandibular segment and the stable proximal mandible, moving the osteotomized segment of the posterior mandible towards the glenoid fossa in an attempt to form a neo-condyle [6]. This procedure was designed not only to improve mandibular function but also to increase the posterior facial height providing for better facial form [35]. Figure 2b shows the X ray image of a TMJ implant which positions and aligns the facial structure.

Sir John Charnley introduced alloplastic orthopedic joint replacement in the 1960's [6]. This surgery uses prosthetic devices to replace articulating components of the joint. In the TMJ, most patients that require alloplastic reconstruction have end-stage, pathologically generated anatomical distortions of the ramus/condyle and fossa components.

In alloplastic TMJ replacement, osseointegration of an implant fixation into the bone is needed for long-term stability and success [38]. The condyle ramus component is fixated with screws into the lateral ramus of the mandible, while the fossa component is mounted with screws to the zygomatic process of the temporal bone (Fig. 3a). These components articulate with each other to develop improved function and form of the end-stage diseased TMJ. The goal of TMJR is to return the mandible to correct form and improve its function [9]. However, the translational mandibular movement is often lost because the lateral pterygoid muscle is sacrificed when removing the diseased condyle, therefore the mandible only rotates [6]

Fig. 2 Illustration of **a** TMJ reconstruction using an autologous costochondral bone graft (rib) to replace TMJ condyle ramus component; **b** imaging of an implanted TMJR

Fig. 3 **a** TMJR patient-fitted components on a stereolithic model and **b** implanted TMJR device (i) fossa component and (ii) ramus component: The alloplastic custom-fitted components of “UHMWPE fossa with commercially pure titanium mesh backing” and “titanium ramus component with CoCrMo condylar head”

5 TMJ total joint replacement

Intra-articular end-stage TMJ pathology results in degradation of physiologic function and form of the mandible and dictates the need for TMJR. Since the mandible and TMJ play a key role in supporting the essential life functions such as mastication, speech, and airway support, the end-stage disease has serious consequences [39]. This type of pathology causes decreased mouth opening and dental occlusal changes, which can result in mandibular dysfunction and pain [6]. The components of the TMJR

devices is illustrated in Fig. 3b. Since the TMJ undergoes more loading and unloading than any other joint in the human body, the TJR implant must be able to withstand the stresses presented to the joint [40]. Pain alleviation is considered a secondary benefit to TJR, therefore, should not be the major goal of this surgery [41].

Criteria for successful repair devices have been developed to create quality TMJR devices. Biocompatible materials must be employed. Currently, FDA approved three implant materials (titanium, cobalt-chromium-molybdenum (CoCrMo) and ultra-high-molecular weight polyethylene (UHMWPE)) (Table 1). Since the TMJ is complex

Table 1 TMJR device material composition

Device type	Component material		Manufacturer
	Fossa	Condyle	
Stock (off-the-shelf) and Custom (patient-specific) ^a Prostheses	UHMWPE	CoCrMo	Zimmer biomet [64]
Custom (patient-fitted) Prosthesis (Fig. 3)	UHMWPE (Mesh backing = titanium)	Spherical head = CoCrMo Condyle body = titanium	TMJ Concepts [64]
Christensen stock prosthesis Screws	CoCrMo Titanium	CoCrMo	TMJ implants/nexus [64]

UHMWPE ultra high molecular weight polyethylene, CoCrMo cobalt–chromium–molybdenum alloy

^aThe Zimmer Biomet Custom (patient-specific) is available worldwide except in the USA

joint any TJR must be able to withstand the stress placed on the joint over its full range of motion [42]. The device, therefore, must be stable at the site of implantation to have an effective long-term outcome. If it is not, there will be micro-motion leading to degeneration of the bone surrounding the device components; the TJR will become loose and fail.

The amount of load that is applied on TMJ varies with patient gender. Male patient has a higher biting force than female patients. As of today, there is no research information available to indicate the accurate maximum loading values. However, researchers and surgeons estimate these loads are to be 125 N to 300 N (approximately half of the masticator loads of 250 N to 450 N). Initial research studies considered 200 N on each side of the mandible to validate the mechanical stability of the devices [63]. However, most of the recent research studies using the “muscular load actions on the mandible at 15 mm mouth opening” for determining stability [62]. TMJR should be designed to withstand the maximum muscular load actions acting on the mandible.

Finally, the surgery must be performed under the right conditions. The doctor must carefully assess the patient's specific case and decide whether or not it is the right case and the right time for treatment [6] and most importantly whether he/she is the right person to do this surgery.

6 TMJR failure and adverse outcomes

There are some issues related to total joint replacement. Along with the cost of the device, it is also possible for the device to fail due to inappropriate stress bearing resulting in micromotion leading to loosening of screws, or broken components [4, 6]. The TMJR is a complex mechanical articulation, which is under constant motion and pressure, therefore wear particle generation and corrosion can occur. It is important that the material used for implantation is compatible with the patient tissues to reduce the chance for particle generated inflammation, micromotion and device failure.

Problems with the TMJR and the adverse outcomes can result from a variety of issues. Some adverse outcomes include increased pain levels than before the TJR was implanted, worsening of TMD symptoms, infection at the site of implantation, and the formation of bone in places where it may cause detrimental issues [4, 6]. Infection at the site of implantation is rare, but if it does occur, the results can be detrimental [52].

An important problem that results in many failed devices is the corrosion of the material used for the implant. The material must be able to withstand the environment in which it is implanted, and must be compatible with the patient, or otherwise failure is possible.

7 Future of TJR

Even though TMJR is a safe and effective management modality for end-stage TMJ disease, there are many fewer TMJR devices implanted when compared to orthopaedic hips and knees. There must be ways to overcome these limitations in the future to improve patient's quality of life. Ideally, they could be overcome with new or advancements in technology and methods to treat the patient.

7.1 Bioengineered tissue

Since some major limitations stem from the use of synthetic material, there have been efforts to produce a TJR that utilizes bioengineered tissues. Advancements in the tissue engineering field (such as bio mimic surfaces, bone regenerations) have led to the capability of reproducing viable bioengineered TMJ components [53]. Proposals have been made for using bioengineered tissue for the regeneration of biological components surrounding the mandibular condyle [54]. Unlike synthetic devices, the bioengineered tissue is responsive to biological changes within the TMJ [53]. These cells could produce proteins that form new fibrocartilage within the joint, particularly on the articulating condyle [55]. The fibrocartilage not only increases the mechanical load the TMJ can withstand and decreases the stress placed on the joint but also decreases the likelihood for the development of implant-related infection and other associated adverse outcomes [56].

The first disadvantage that accompanies bioengineered tissues includes complications with healing at the site of implantation, and infection may occur [57, 58]. There also is a limited quantity and quality of the bioengineered tissue, which can result in a poor fit of the replacement to the patient [43]. With more research to improve the bioengineered tissue method, the shift in focus from replacement devices to a more biologically focused replacement technology could provide a successful alternative to the TJR implant devices. However, bioengineered devices would be susceptible to systemic and local pathology, just as autogenous bone grafting.

8 Computer aided design (CAD) and computer aided engineering (CAE) methods

Computer Aided Design (CAD) and Computer Aided Engineering (CAE) techniques are presently being used to design and manufacture patient-fitted TMJR devices. The surgery time is drastically reduced with the patient fitted

devices as there is no shimming of bone and/or cementation is needed [47]. This facilitates in reduced surgical cost for the patient. Computer aided design (CAD) generated stereolithographic files are used to design and fabricate the patient fitted devices.

In the future, using CAD/CAE/Simulation and associated analytical techniques, an improved TMJR could be designed, simulated and tested electronically to determine failure modes when subjected to maximum biting forces, and also device longevity is estimated under fatigue conditions (Fig. 4).

This technology may provide data leading to the development of more successful joint replacement devices with improved longevity by designing and validating the devices in the initial design stage rather than analyzing failure data.

The major advantage of the CAD/CAE techniques is the ability to rapidly test the mechanical stability of the implant materials in the initial design phase rather than resorting to manufacturing and testing prototypes.

9 Three-dimensional (3-D) printing

Three-Dimensional printing is an additive manufacturing technology used to design and fabricate complex bio-medical devices at lower costs. In this method, the 3D components are produced by adding material on a layer-by-layer basis rather material removal in any conventional fabrication methods. This material addition method allows producing much complex contours and intricate parts easily.

Different types of Materials such as Polymers (synthetic or natural), Plastics, Ceramics and metals can be

3D-printed. Three-dimensional printing utilizes Computer-Aided-Design (CAD) models that are created from high-resolution images. 3D printer reads the 3D CAD model data and prints patient-specific anatomical structures [59, 60]. These high-resolution images can be acquired through CT scans or surface scanning [59].

There are several benefits of 3D printing, but the most important is its ability to design and fabricate more accurate and complex patient specific prostheses and implants. These custom-made devices match precisely with patient contours and offers very good value to the patient in-terms reduced surgical time and surgical cost. The time of producing 3D printed components is another benefit as only few hours are needed to fabricate a 3D component.

There are still challenges with 3D printing and especially with bio-materials selection as only limited options available. An increased resolution of the 3D printers without sacrificing the shape and strength is another concern. To overcome the limitations development of new bio-materials that can be printed in-conjunction with cells in necessary. Also, there is a need to improve the bio-compatibility and mechanical properties for cell support which facilitates the creation of soft tissues.

When all the challenges are addressed the 3D-printing technology could enable the fabrication of multifunctional scaffolds or implants that meets the structural, mechanical and nutritional requirements. Currently, use of this technology to design and manufacture TMJR devices is not currently FDA approved [49, 61].

Fig. 4 CAD, FEA model of TMJ and displacement and stress analysis plots: The figures represent the mechanical stability (stress contour plot) and micromotion (displacement contour plot) of Christensen TMJR implant when subjected to biting forces using CAD/CAE techniques

10 Future direction TMJR in advanced healthcare

TMJR surgical procedures performed by an experienced TMJ implant surgeon may be helpful to correct severe degenerative changes in the joint and fossa and stabilize the function and comfort of the joint. Customizing the implant (fossa and condyle) allows for adaptation to these discrepant features providing maximum fixation and improved function. In addition, the materials utilized for manufacturing the implants (titanium alloys, cobalt-chromium-molybdenum (CoCrMo) and ultra-high-molecular weight polyethylene (UHMWPE)) have been selected to minimize wear and fragmentation to reduce the potential for foreign body reactions (Table 1).

Some materials used in the construction of TMJR devices were inappropriate and ineffective [43]. Materials and bearing surfaces such as Proplast-Teflon (Vitek, Houston, TX), acrylic-on-metal, and metal-on-metal have been shown to result in the released wear particles and debris into surrounding tissue often resulting in device failure [43, 44]. An important lesson learned from these failed materials is that the difference in an electrochemical gradient within the TMJ can lead to a reaction from the patient's body [43].

A stock device is one of the two categories of devices that are approved by the FDA in the United States [45]. It is composed of an ultrahigh molecular weight polyethylene fossa, paired with a cobalt-chromium alloy condyle ramus component [46]. This device is a “stock” (off-the-shelf) device that is it is not made specifically for the patient. The surgeon must make the implant conform to the patient's bone during the surgery [4]. Most of the failures in the early stock devices were due to the failure of the device itself. This includes fracture of the device, mechanical loosening leading to failure of the components.

Custom-made TMJR devices, or patient-fitted devices, are similar to the stock alloplastic devices, but these are designed to fit the patient's specific anatomy. Patient-fitted devices are designed and manufactured from a protocol CT scan of the patient's clinical condition. Patients with these devices implanted had significantly improved subjective and objective long-term outcomes [47]. Because custom device components fit the specific patient's anatomical situation so well, recovery of mandibular function, important for long-term success, can begin a short time after implantation, through active physical therapy.

Chromium-Cobalt-Molybdenum alloy and ultrahigh molecular weight polyethylene (UHMWPE) were chosen for the bearing surface materials for TMJR because these materials had been the gold standard for orthopedic TJR devices [43]. UHMWPE has a low coefficient of

friction, but just like any other device, can still be susceptible to wear [48]. In long-term follow-up studies of TMJR patients implanted with these materials, results have shown that these materials are reliable and without adverse side effects in surrounding tissues [44].

Tribocorrosion is a relatively new material science field for the study of joint device wear-related problems and their effect on the surrounding tissues [49]. Tribocorrosion can occur when the components of an implant device repeatedly rub against each other, causing mechanical wear and erosion [50]. Metal ions and particles are then released into the surrounding environment, resulting in chemical responses from the body at the implantation site and then the ultimate failure of the implant [45]. It is essential to understand this process to overcome the early failures and complications of TJR devices.

UHMWPE, cobalt-chromium alloys, commercially pure titanium, alloyed titanium are currently the only materials approved by the US FDA for the manufacture of TMJR devices [43]. They are associated with low friction for the TJR implant, therefore reducing implant wear [51]. Less wear and debris within the TMJ environment will reduce the risk for wear related implant failure.

11 Concluding remarks

This review presents some of the clinical options employed in the management of TMD. Based on the literature reviewed, TMJR appears to be a safe and effective management option for patients with intra-articular end-stage pathology. The different aspects covered in the review is in the area of TMJR are described in the Table 2 and Fig. 5. Each TMJR option has its own advantages and limitations, so it is important that the doctor and the patient discuss which method is suitable for their particular case. In addition, translational research within the scientific community has great role to enhance the clinical performance of TMJR as in the case of orthopaedic TJR. Combined efforts of clinicians, material scientists, bioengineers and biochemists will lead to improved management options and patient outcomes.

The concerns for infection, longevity, material hypersensitivity and early failure still exist in TMJR surgery. There is a need for a more in-depth investigation into the causes of failed TJR devices and how these devices can be improved. Also, further research is needed into the design of these implants, including studying the ability of the TMJR device components to withstand the mechanical stresses, as well as the forces they are subjected to during maximum functional loading.

Table 2 Summary of the TMJR review

TMJ disorders TMD	<p>The TMJ is essential for life functions such as:</p> <p>Mastication [4]</p> <p>Speech [4]</p> <p>Airway support [4]</p> <p>Deglutition [4]</p> <p>TMD is the intra or extra-articular disorder effecting the TMJ thus effecting the listed life essential functions [1]</p> <p>Symptoms of TMD are:</p> <p>Pain in the jaw [3, 12]</p> <p>Clicking noises when opening and closing the mouth [15]</p> <p>Decreased mandibular range of motion [3, 13, 14]</p>
TMJR	<p>Extra articular TMD are treated with medication and physical therapy [3, 7]</p> <p>Intra-articular end stage TMD are treated with TMJR to restore mandibular function and form [8, 11]</p> <p>US FDA currently approved two TMJR devices</p> <p>Stock Prosthesis (off-the-shelf) prosthesis (Fig. 4) [45, 46]</p> <p>(Manufacturer: Zimmer Biomet, Jacksonville, FL)</p> <p>Custom (patient fitted) prosthesis (Fig. 3) [47]</p> <p>(Manufacturers: TMJ Concepts Ventura, CA; Zimmer Biomet, Jacksonville, FL^a)</p>
TMJR adverse outcomes and challenges	<p>Components failure and device fracture due to improper stress, loads and micromotion [4, 6]</p> <p>Mechanical screws loosening due to micromotion [4, 6]</p> <p>High cost [4, 6]</p> <p>Infection</p> <p>Tribocorrosion due to release of wear particles [43, 44, 48–50, 52]</p> <p>Material hypersensitivity [43]</p>
Technological advancements	<p>Bioengineered TMJR components using advanced tissue engineering[53, 54, 56]</p> <p>Development of more stable and stronger TMJR components using CAD/CAE techniques [47]</p>
Future TMJR	<p>To develop new bio-compatible materials needed as to minimize or avoid corrosion and infection</p> <p>Using CAD/CAE methods determine the maximum masticatory loads in order to design TMJR to withstand those loads</p> <p>Use 3D printing technology to create a bioengineered tissue with appropriate mechanical properties and FDA approval</p> <p>Decrease cost</p> <p>Collaborative research amongst clinicians, bio-engineers and material scientists to produce an improved TMJR</p>

^aThe Zimmer Biomet Custom (patient-specific) is available worldwide except in the USA

Fig. 5 Summary of the review on TMJR : This paper provide in-detail insights about TMJ dis-orders (TMD), symptoms, causes and effects of TMD, past and current treatment methods, different types of TMJR devices, technological advancements, challenges and future goals

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Compliance with ethical standards

Conflict of interest The authors declares that they have no conflict of interest. Except, Dr. Mercuri is a compensated clinical consultant and shareholder in TMJ Concepts, Ventura, CA.

Ethical approval The article does not contain any studies with human participants or animals performed by the author.

Informed consent Yes all authors agreed and given consent.

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