Available online at www.sciencedirect.com

ScienceDirect

British Journal of Oral and Maxillofacial Surgery 57 (2019) 722–728

BRITISH Journal of Oral and Maxillofacial Surgery

www.bjoms.com

Review

Review of emerging temporomandibular joint total joint replacement systems

R. Elledge [a,*], L.G. Mercuri [b], A. Attard [a], J. Green [a], B. Speculand [c]

[a] *University Hospitals Birmingham NHS Foundation Trust*
[b] *Department of Orthopaedic Surgery, Rush University Medical Center, Chicago, IL*
[c] *Great Ormond Street Hospital for Children NHS Foundation Trust*

Accepted 14 August 2019
Available online 25 August 2019

Abstract

Total temporomandibular joint (TMJ) replacement has been documented as a viable option for the management of end-stage TMJ disease, but data on long-term outcomes have been reported for only two established systems: TMJ Concepts, and Zimmer Biomet. Other devices are now emerging globally, but reports of preclinical laboratory and clinical outcomes are limited. We retrieved information on the design, material composition, preclinical laboratory tests, regulatory status, and clinical outcomes of new TMJ replacement systems from PubMed and Google, and from personal correspondence with surgeons worldwide. Fifteen countries have developed, or are developing, 27 TMJ replacement systems, of which 21 are custom-designed, but to date, only four have been given regulatory approval. All the devices are designed to have both a skull-based glenoid fossa component and a mandibular ramus or condyle, and 22/27 are similar to the designs of the two established systems. Twenty-one devices use an ultra-high-molecular-weight polyethylene (UHMWPE) fossa-bearing surface, and 10 have a titanium alloy condyle. Nineteen manufacturers report that a titanium alloy is used for the ramus portion of the condyle/ramus component. Preclinical laboratory tests on 12 of the systems have been reported but, to our knowledge, no outcomes have yet been reported on nine of the 27 reviewed. Not all systems are equal in terms of design, material composition, preclinical laboratory testing, manufacturing methods, regulatory status, and reports of clinical outcomes.

Keywords: Temporomandibular joint; total joint replacement

Introduction

The two established temporomandibular joint (TMJ) replacement systems that have been approved by the United States Food and Drug Administration (FDA) are TMJ Concepts (Fig. 1), and Zimmer Biomet. For both, a body of evidence-based publications has shown significant, long-term improvements in mandibular function and form, and quality of life.[1–11]

De Meurechy and Mommaerts have recently published a historical review of the major reconstructive systems,[12] but a global overview of other lesser-known or emerging systems seems to be justified, as they potentially offer more options to the surgeon.

However, not all the systems are equal in terms of design, material composition, preclinical laboratory testing, manufacturing methods, regulatory status, and reports of clinical outcomes. A review of those that are emerging at present shows that these elements vary, and it is important that both surgeons and patients understand this when deciding on the

* Corresponding author. Tel.: +44 78 758 28359/+44 121 249 3719.
E-mail addresses: rosselledge@doctors.net.uk (R. Elledge), lgm@tmjconcepts.com (L.G. Mercuri), Alan.Attard@uhb.nhs.uk (A. Attard), jasongreen@nhs.net (J. Green), speculand@googlemail.com (B. Speculand).

https://doi.org/10.1016/j.bjoms.2019.08.009

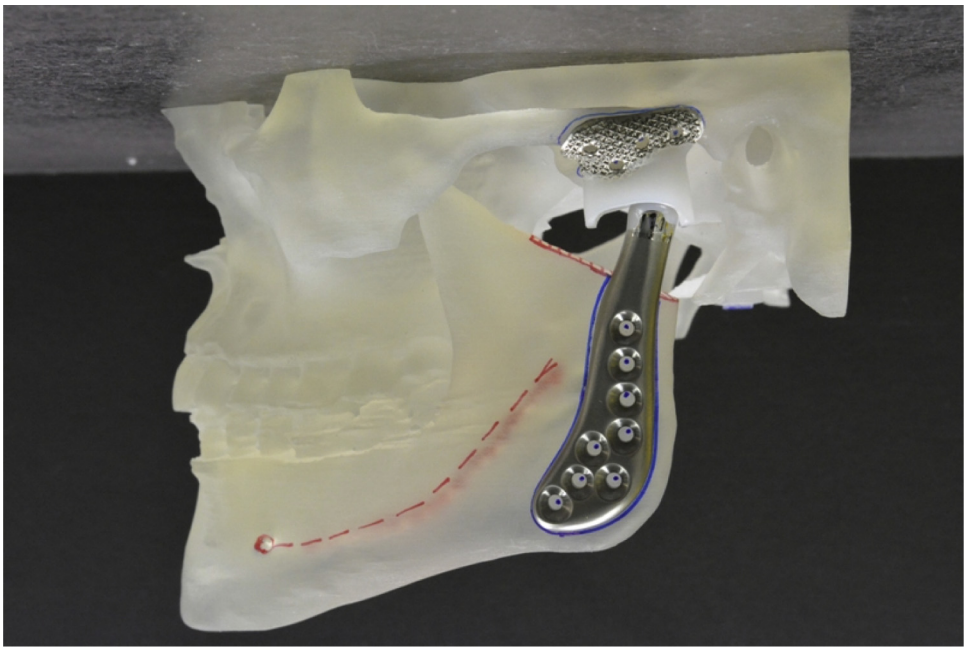

Fig. 1. Custom-made US FDA-approved TMJ Concepts device on stereolithographic model.[1–6,11]

best system to use. The goal of this review therefore was to catalogue these important elements for the emerging devices as they currently exist.

Material and methods

We retrieved information on the design, material composition, preclinical laboratory tests, regulatory status, and clinical outcomes for new TMJ replacement systems from PubMed and Google, and from personal correspondence from surgeons worldwide.

Results

We found out that 15 countries have developed, or are developing, 27 TMJ replacement systems, of which 21 are custom-made and the remainder stock (although it is worth noting that while Biomet produces both custom-made and stock devices, it is the latter version that is universally available) (Table 1).[1–11,13–43] Only four devices have been approved by regulatory bodies, two by the FDA (Table 1: U2 and U3) and two by the Australian Register of Therapeutic Goods (Table 1: A1 and A2). We know of no reports of the regulatory status of the other 23 systems included in this review.

All the emerging and currently available replacement systems are composed of both a skull-based glenoid fossa and a mandibular ramus/condyle. All but five of them – four custom-made (Fig. 3, Table 1: B6; Fig. 4, Table 1: I1; Fig. 5, Table 1: N and U1) and one stock device (Table 1: F1), are similar to the two established systems approved by the FDA (Table 1: U2 and U3) in which the glenoid fossa component is fixed to the zygomatic arch with screws and the condyle/ramus component is fixed behind the mandibular foramen along the posterior mandibular ramus.

In 21 systems (17 custom-made, 4 stock) the fossa component-bearing surface is made of ultra-high-molecular-weight polyethylene (UHMWPE). The fossa component in 11 devices (10 custom-made and 1 stock) is made of metal-backed UHMWPE, and in 10 completely of UHMWPE (7 custom-made and 3 stock). Five systems use metal-on-metal-bearing surfaces (Table 1: F1, I1, I4, S, and U1); and one uses polymer (Table 1: B6).

The condyle of the condyle/ramus component is made of titanium (Ti) alloy in 10 systems (Table 1: A1, A2, B1, C, F2, I3, I5, L, P1-2); cobalt chrome in three (Table 1: G, U1 and U2); cobalt chrome molybdenum in seven (Table 1: B2–B5, B7, B8, U3); and stainless steel in three (Table 1: F1, I1, I2). Other variations include zirconium (Table 1: N), zirconium alloy (Table 1: I4), titanium nitride (Table 1: S), and polyether ether ketone (PEEK) (Table 1: B6).

The ramus of the condyle/ramus component is made of titanium alloy in 19 systems (Table 1: A1, A2, B1, B2–5, B7, B8, C, F2 (Fig. 2), I3, I4, L, N, P1–2, U2–3); stainless steel in three (Table 1: Fi, I1–2); cobalt chrome in two (Table 1: G, U1); titanium nitride in one (Table 1: S), and PEEK in one (Table 1: B6).

The results of preclinical laboratory tests have been reported for 12 systems (Table 1: A1–2, C, F1, I4, L, N, P1-2, U1–3), but only the two established FDA-approved systems have reported large enough numbers with long-term outcomes. The others have reported single cases with short-

Table 1
Total replacement temporomandibular joints currently being produced or developed.

	Country	System	Stock	Custom	Fossa	Ramus/condyle	Start
A1	Australia	OMX Solutions[13,14]		X	All UHMWPE	3D printed Ti alloy (DMLS)	2012
A2		OrthoTiN[15]		X	Metal- backed UHMWPE	Forged Ti alloy	2017
B1	Belgium[16]	CADskills		X	Ti alloy - UHMWPE	3D printed Ti alloy - DLC coated condyle	2017
B2	Brazil	Bioconect[17]		X	Metal-backed UHMWPE	3D printed CoCrMo condyle Ti alloy ramus (DMLS)	2016
B3		PROMM[18,19]		X	All UHMWPE	3D printed CoCrMo condyle Ti alloy ramus (DMLS)	2015
B4		Engimplan[20,21]		X	Metal-backed UHMWPE	3D printed CoCrMo condyle Ti alloy ramus (DMLS)	2016
B5		CPMH[22]		X	Metal-backed UHMWPE	3D printed CoCrMo condyle Ti alloy ramus (DMLS)	2018
B6		Genovesi[23]		X	PEEK LT1 20% Ba	PEEK LT1 20% Ba	2018
B7		Enterprises Artfix[24]		X	All UHMWPE	CoCrMo condyle Ti alloy ramus	2018
B8		Osteomed[25]		X	Ti-backed UHMWPE	CoCrMo condyle Ti alloy ramus	2018
C	China[26]	Yang System		X	All UHMWPE	3D printed all Ti alloy (SLM)	2017
F1	France[27]			X	Stainless steel and zirconium	Stainless steel and zirconium	2014
F2	France[28]		X		UHMWPE	Ti alloy (stem inlay)	2016
G	Germany	Rotec[29,30]	X		All UHMWPE	CoCr condyle and ramus	2008
I1	India[31]			X	Stainless steel	Stainless steel	2009
I2	India[32]		X		Stainless-steel-backed UHMWPE	Stainless steel	2013
I3		G Surgiware Ltd*		X	All UHMWPE	3D printed all Ti alloy (SLM)	2017
I4	Iraq[33]		X		Zr-Nb alloy	Zr-Nb alloy	2014
I5	Italy	Sintac[34]		X	Ti-backed UHMWPE	3D printed Ti alloy ramus (DMLS)	2018
L	Lithuania	OrthoBaltic[35]		X	All UHMWPE	3D printed Ti alloy ramus (DMLS)	2018
N	Netherlands	Groningen[36–39]		X	Ti alloy-backed UHMWPE	Zr condyle 3D printed Ti alloy ramus (DMLS)	2018
P1	Poland[40]			X	All UHMWPE	3D printed Ti alloy (DMLS)	2017
P2	Poland[40]			X	All UHMWPE	Ti alloy (CNC milling)	2017
S	South Africa	Butow[41]	X		Ti nitride alloy	Ti nitride alloy	1994
U1	UK	Dundee[42,43]		X	None	CoCr	2014
U2	USA	Zimmer Biomet[1–3,5–11]	X	X	All UHMWPE	CoCr condyle and ramus	2000
U3		TMJ Concepts[1–6,11]		X	cpTi mesh-backed UHMWPE	CoCrMo condyle Ti alloy ramus	1999

UHMWPE: ultra-high-molecular-weight polyethylene; Ti: titanium; Zr-Nb: zirconium niobium; cpTi: commercially-pure titanium; ELI: extra low interstitial; CoCrMo: cobalt chrome molybdenum; PEEK: polyether ether ketone.

* Mehotra D. Outcome analysis of mandibular patient specific joint replacements in TMJ ankylosis and tumour: a prospective analysis. Paper presented at TMJ Bioengineering Conference, Redondo Beach, CA, June 2018.

term follow up, and nine have yet to report any clinical outcomes.

Discussion

Oral and maxillofacial surgeons have accepted that a replacement joint is a viable option for the treatment of end-stage TMJ disease. The disasters in the US in the 1980s, which were caused by the use of Proplast-Teflon/silicone rubber, have cast long, dark shadows worldwide over the use of any implantable alloplastic material in TMJ surgery.[44] These results have been reversed because the specialty has acknowledged the validity of the data on clinical outcomes that have been reported since 1995 by the two systems approved by the FDA in peer-reviewed journals and textbooks.[1–11]

We found that at least 15 countries have developed, or are developing, 27 different TMJ replacement systems (6 stock, 21 custom-made). The main impetus for this, besides the acceptance of total replacements by OMF surgeons, seems to be cost. Until recently, the two FDA-approved systems maintained the major share of the market worldwide. However, tariffs and the cost of business with foreign countries, as well as the lack of, or restrictions to, healthcare in many countries, have contributed to their high cost. Production of

Fig. 2. Artist's reproduction of novel French design with titanium alloy stem inlay featured in patent application by Dubois and Zwetyenga.[28]

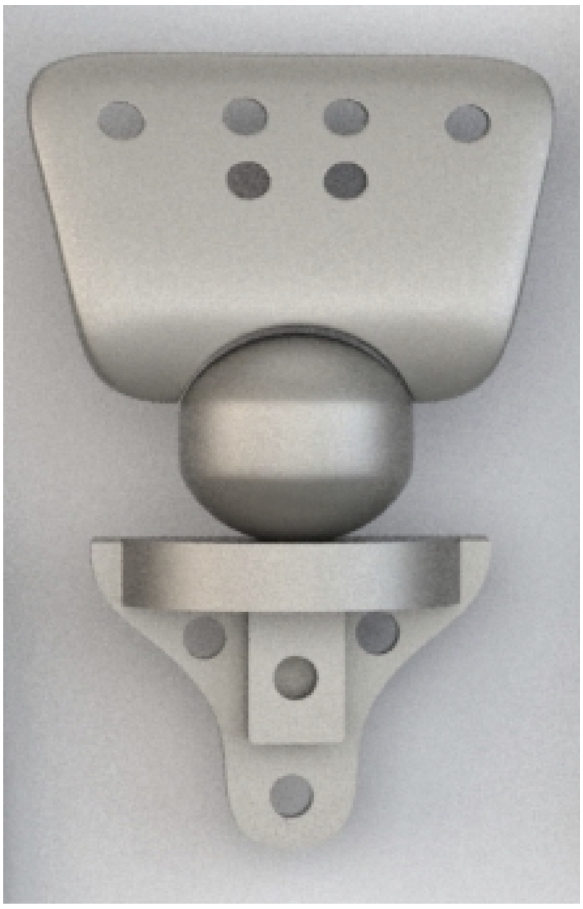

Fig. 4. Artist's reproduction of an Indian device manufactured from stainless steel, as published by Chaware et al.[31]

an "in-country" system therefore has become an attractive alternative.

Manufacturers are working hard to convince surgeons, hospitals, and healthcare managers that computer-assisted

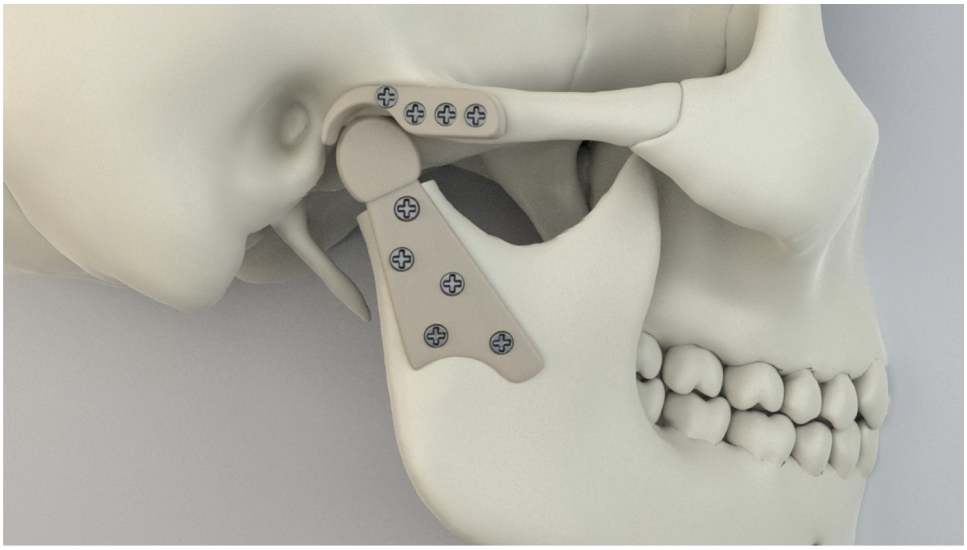

Fig. 3. Artist's reproduction of Brazilian custom-made PEEK device as published by Genovesi.[23]

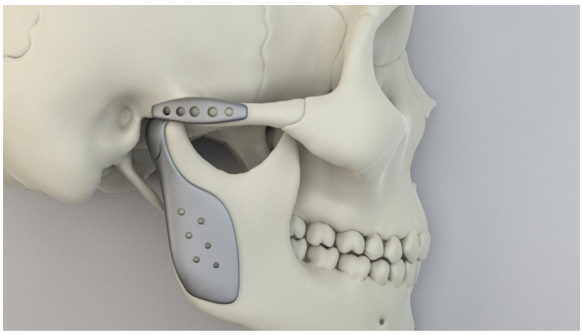

Fig. 5. Artist's reproduction of the Dundee prosthesis featuring cobalt chromium alloy.[42,43]

design (CAD), computer-assisted manufacturing (CAM), and 3D printing will not only result in lower costs, but also reduce delays. This pressure, together with the aforementioned regulations and tariffs, may account for the current proliferation of these systems.

An important fact that is rarely considered is that the supply of replacement systems will surpass the demand. The need for TMJ replacements will never approach the numbers anticipated for replacement hips and knees. Kurtz et al suggested that the number of hips and knees that would need revision or replacement in 2030 would increase by 174% and 673%, respectively.[45] Onoriobe et al used similar statistical methods to show that the probable need for TMJ replacements by 2030 is likely to be much lower (an increase of less than 50%).[46]

Any implanted device must be biocompatible and based on solid biological, biomechanical, and physiological principles. Research workers, surgeons, and patients must understand that no joint replacement will reproduce exactly the function of one that is healthy and disease-free, and that reproduction of all the movements of the native mandible is unlikely. The loss of lateral pterygoid function with condylar resection eliminates protrusive and lateral mandibular excursions, so attempts to design a system that might provide these movements seems to be fruitless and potentially fraught with undeliverable expectations.

The process involves design, materials, and manufacturing. The bony anatomy of the pelvis, femur, and tibia afford the use of modular stock components that can be stabilised initially with screws, press-fitting, or cementing of the components. The bony anatomy of the mandibular ramus and the temporal glenoid fossa does not provide these options, and all TMJ replacement joints must initially be fixed with screws to stabilise both the fossa and ramus/condyle components.

Kashi et al used finite element analysis to show that the maximum stress on a replacement condyle/ramus component during function is concentrated at the most superior screw hole in the ramus.[47] Hsu et al[48] and Ramos et al[49] reported the importance of screw fixation along the lateral aspect of the mandibular ramus to maintain stable fixation. Any system therefore that uses only a short condyle/ramus component and not the full length of the vertical mandibular ramus for screw fixation, may have problems with stability that lead to micromotion, osteolysis, and failure.

For this surface coupling to be successful, metal-on-metal hip replacements require tight geometric congruencies (less than 200 μm) between the metallic femoral head and the metallic acetabular cup.[50] Because the TMJ is not a constrained ball-in-socket joint like the hip, any theoretical advantage that such a bearing surface coupling might provide, cannot be achieved and should not be expected.[51] A stock or custom-made metal-on-metal coupling is therefore theoretically, biomechanically, physiologically, and biologically, unsuitable for a TMJ replacement.[52] Two recent studies have examined the wear and particulates associated with metal-on-metal TMJ replacements.[53,54] As in orthopaedic total joint replacements, the results of these studies have shown that the forces of functional loading at the interface with the bearing surface are the crucial factors in wear. Material wear places these surfaces at risk of degradation, formation of particulate debris, and corrosion in vivo. Therefore, the use of highly-corrosive materials such as stainless steel, and designs that fail to understand the importance of mechanical stability of the ramus component, or of the forces delivered to the articular surfaces of any component, will lead to failure.

Critics cite many concerns about the use of PEEK in joint replacement systems; not least of which is the absence of long-term data regarding the use of carbon fibre-reinforced PEEK (CFR-PEEK) as a bearing surface in orthopaedics.[55] Of particular note, Brockett et al examined its role in total knee replacements and found that wear rates were almost twice those of UHMWPE under comparable conditions.[56] Such evidence should cause concern about the possibility of CFR-PEEK being used for TMJ replacements without further in vitro studies. Concerns have also been raised about the use of all-UHMWPE fossa components.[57]

The introduction of virtual planning, together with the advent and supposed ease of selective laser melting (SLM) and direct metal laser sintering (DMSL) 3D printing, have provided further momentum to this growing phenomenon. Eleven of the 27 systems presented will be, or are being, manufactured using this technology. SLM and DMSL 3D printing may have a number of inherent problems including high porosity, residual stress, cracking, warping, and surface roughness.[58] The use of 3D printed patient-matched or custom-made replacement components may encourage warping of the baseplate of the ramus, and provide inherent problems that will increase the likelihood of mechanical failure and screws becoming loose.[57]

The approximation of fit that is inherent in stock systems and the resultant instability and micromotion that can precipitate mechanical failure of the device is one example of the limitation of technology.[57,59] Many of the devices from less-established manufacturers can easily have one or more of these characteristics, and in the absence of long-term data, they should be used with caution.[60]

The good primary stability afforded by a custom-made system (the "gold standard" biocompatibility of high-grade

titanium alloy and UHMWPE), manufacturing methods that minimise roughness and porosity on the surface, and designs that are tailored to the individual patient, are all elements that contribute to the longevity of any device.[57] Many of those discussed arguably trade one or more of these principles to contain cost.

Conclusion

This review shows that systems are not equal in terms of design, material composition, preclinical laboratory testing, manufacturing methods, regulatory status, and reporting of clinical outcomes. These elements vary widely among the systems that are currently emerging, and it is important that surgeons' and patients' understand this when deciding on the best one to use.

Ethics statement/confirmation of patients' permission

Ethics approval was not required. Patients' permission was not required

Conflict of interests

Dr Mercuri is a clinical consultant and shareholder for TMJ Concepts, Ventura, CA.

Acknowledgement

We gratefully acknowledge the contribution of Mustafa El Muiz who kindly provided the medical illustrations for this publication.

References

1. Speculand B, Hensher R, Powell D. Total prosthetic replacement of the TMJ: experience with two systems 1988-1997. *Br J Oral Maxillofac Surg* 2000;**38**:360–9.
2. Sidebottom AJ, Gruber E. One-year prospective outcome analysis and complications following total replacement of the temporomandibular joint with the TMJ Concepts system. *Br J Oral Maxillofac Surg* 2013;**51**:620–4.
3. Elledge R, Attard A, Green J, et al. UK temporomandibular joint replacement database: a report on one-year outcomes. *Br J Oral Maxillofac Surg* 2017;**55**:927–31.
4. Wolford LM, Mercuri LG, Schneiderman ED, et al. Twenty-year follow-up study on a patient-fitted temporomandibular joint prosthesis: the Techmedica/TMJ Concepts device. *J Oral Maxillofac Surg* 2015;**73**:952–60.
5. Gruber EA, McCullough J, Sidebottom AJ. Medium-term outcomes and complications after total replacement of the temporomandibular joint. Prospective outcome analysis after 3 and 5 years. *Br J Oral Maxillofac Surg* 2015;**53**:412–5.
6. Gonzalez-Perez LM, Gonzalez-Perez-Somarriba B, Centeno G, et al. Evaluation of total alloplastic temporo-mandibular joint replacement with two different types of prostheses: a three-year prospective study. *Med Oral Patol Oral Cir Bucal* 2016;**21**:e766–75.
7. Aagaard E, Thygesen T. A prospective single-centre study on patient outcomes following temporomandibular joint replacement using a custom-made Biomet TMJ prosthesis. *Int J Oral Maxillofac Surg* 2014;**43**:1229–35.
8. Sanovich R, Mehta U, Abramowicz S, et al. Total alloplastic temporomandibular joint reconstruction using Biomet stock prostheses: the University of Florida experience. *Int J Oral Maxillofac Surg* 2014;**43**:1091–5.
9. Leandro LF, Ono HY, Loureiro CC, et al. A ten-year experience and follow-up of three hundred patients fitted with the Biomet/Lorenz Microfixation TMJ replacement system. *Int J Oral Maxillofac Surg* 2013;**42**:1007–13.
10. Westermark A. Total reconstruction of the temporomandibular joint. Up to 8 years of follow-up of patients treated with Biomet® total joint prostheses. *Int J Oral Maxillofac Surg* 2010;**39**:951–5.
11. Speculand B. Current status of replacement of the temporomandibular joint in the United Kingdom. *Br J Oral Maxillofac Surg* 2009;**47**:37–41.
12. De Meurechy N, Mommaerts MY. Alloplastic temporomandibular joint replacement systems: a systematic review of their history. *Int J Oral Maxillofac Surg* 2018;**47**:743–54.
13. Ackland DC, Robinson D, Redhead M, et al. A personalized 3D-printed prosthetic joint replacement for the human temporomandibular joint: from implant design to implantation. *J Mech Behav Biomed Mater* 2017;**69**:404–11.
14. Dimitroulis G, Austin S, Sin Lee PV, et al. A new three-dimensional, print-on-demand temporomandibular prosthetic total joint replacement system: preliminary outcomes. *J Craniomaxillofac Surg* 2018;**46**:1192–8.
15. OrthoTiN TMJ system. Available from URL: https://www.orthotin.com/product-description (last accessed 6 August 2019).
16. Mommaerts MY. When is an artificial jaw joint on the agenda today? *Tijdschrift voor Geneeskunde* 2007;**73**:769–79 (Article in Dutch).
17. JMC Medical. Available from URL: http://www.jmcmedical.com.br/customizacoes.php (last accessed 6 August 2019).
18. de Souza NT, Cavalcante RC, de Albuquerque Cavalcante MA, et al. An unusual osteoma in the mandibular condyle and the successful replacement of the temporomandibular joint with a custom-made prosthesis: a case report. *BMC Res Notes* 2017;**10**:727.
19. Enigmaplan. Available from URL: http://www.engimplan.com.br (last accessed 6 August 2019).
20. de Oliveira-Neto PJ, Marchiori EC, de Almeida Lopes MC, et al. Bilateral alloplastic prostheses for temporomandibular joint reconstruction in a patient with ankylosing spondylitis. *Craniomaxillofac Trauma Reconstr* 2014;**7**:149–53.
21. Moreira CV, Serra AV, Silva LO, et al. Total bilateral TMJ reconstruction for pain and dysfunction: case report. *Int J Surg Case Rep* 2018;**42**:138–44.
22. CPMH. Available from URL: https://www.cpmhdigital.com.br/ (last accessed 7 August 2019).
23. Genovesi W. A new concept and design for an alloplastic total TMJ prosthesis using PEEK LT1 20% BA. Available from URL: https://aaoms.confex.com/aaoms/am1810/meetingapp.cgi/Paper/13584 (last accessed 7 August 2019).
24. Enterprises Importação e Comércio de Produtos Médico e Hospitalares Ltda. Available from URL: http://www.enterprises1.com.br/repairs (last accessed 7 August 2019).
25. Osteomed. Sistema de osteossíntese crânio-facial (CMF). Available from URL: http://osteomedimplantes.com/produto/sistema-de-osteossintese-cranio-maxilo-facial-cmf/ (last accessed 7 August 2019).

26. Xu X, Luo D, Guo C, et al. A custom-made temporomandibular joint prosthesis for fabrication by selective laser melting: finite element analysis. *Med Eng Phys* 2017;**46**:1–11.
27. Ramos A, Mesnard M. A new condyle implant design concept for alloplastic temporomandibular joint in bone resorption cases. *J Craniomaxillofac Surg* 2016;**44**:1670–7.
28. Dubois G, Zwetyenga N (Applications: OBL/Centre Hospitalier Universitaire de Dijon). Patent application for temporo-mandibular joint prosthesis. European Patent Application EP 2 810 621 A1, 2014 (application number13305770.3).
29. Sader R, Leiggener C, Saldamli B, et al. A new innovative solution for total TMJ replacement. *J Cranio Maxillofac Surg* 2008;**36**:S159.
30. Landes C, Korzinskas T, Dehner JF, et al. One-stage microvascular mandible reconstruction and alloplastic TMJ prosthesis. *J Craniomaxillofac Surg* 2014;**42**:28–34.
31. Chaware SM, Bagaria V, Kuthe A. Application of rapid prototyping technique to design a customized temporomandibular joint used to treat temporomandibular ankylosis. *Indian J Plast Surg* 2009;**42**:85–93.
32. Neelakandan RS, Raja AV, Krishnan AM. Total alloplastic temporomandibular joint reconstruction for management of TMJ ankylosis. *J Maxillofac Oral Surg* 2014;**13**:575–82.
33. Aftan K. Total TMJ replacement with zirconium oxide ceramic prosthesis. *Int J Oral Maxillofac Surg* 2013;**42**:1356.
34. Sintac Biomedical Engineering. Available from URL: http://www.sintac.it/ (last accessed 6 August 2019).
35. Ortho Baltic Implants. Available from URL: http://balticimplants.eu/patient-specific-medical-devices/tmj-endoprosthesis/ (last accessed 6 August 2019).
36. Falkenstrom CH. *Biomechanical design of a total temporomandibular joint replacement. PhD thesis*. University of Twente; 1993.
37. van Loon JP, Falkenström CH, de Bont LG, et al. The theoretical optimal center of rotation for a temporomandibular joint prosthesis: a three-dimensional kinematic study. *J Dent Res* 1999;**78**:43–8.
38. Schuurhuis JM, Dijkstra PU, Stegenga B, et al. Groningen temporomandibular total joint prosthesis: an 8-year longitudinal follow-up on function and pain. *J Craniomaxillofac Surg* 2012;**40**:815–20.
39. Kraeima J, Merema BJ, Witjes MJ, et al. Development of a patient-specific temporomandibular joint prosthesis according to the Groningen principle through a cadaver test series. *J Craniomaxillofac Surg* 2018;**46**:779–84.
40. Kozakiewicz M, Wach T, Szymor P, et al. Two different techniques of manufacturing TMJ replacements – a technical report. *J Craniomaxillofac Surg* 2017;**45**:1432–7.
41. Bütow KW, Blackbeard GA, van der Merwe AE. Titanium/titanium nitride temporomandibular joint prosthesis: historical background and a six-year clinical review. *SADJ* 2001;**56**:370–6.
42. Al-Qamachi LH, McLoughlin P, Abel E. The Dundee prosthesis, a novel total TMJ replacement. *Br J Oral Maxillofac Surg* 2011;**49S**:S66. Available from URL: https://www.bjoms.com/article/S0266-4356(11)00193-8/abstract (last accessed 7 August 2019).
43. Abel EW, Hilgers A, McLoughlin PM. Finite element analysis of a condylar support prosthesis to replace the temporomandibular joint. *Br J Oral Maxillofac Surg* 2015;**53**:352–7.
44. Mercuri LG. History of TMJ TJR. In: Mercuri LG, editor. *Temporomandibular joint total joint replacement – TMJ TJR: a comprehensive reference for researchers, materials scientists, and surgeons*. Springer; 2016. p. 44–52.
45. Kurtz S, Ong K, Lau E, et al. Projections of primary and revision hip and knee arthroplasty in the United States from 2005 to 2030. *J Bone Joint Surg Am* 2007;**89**:780–5.
46. Onoriobe U, Miloro M, Sukotjo C, et al. How many temporomandibular joint total joint alloplastic implants will be placed in the United States in 2030? *J Oral Maxillofac Surg* 2016;**74**:1531–8.
47. Kashi A, Chowdhury AR, Saha S. Finite element analysis of a TMJ implant. *J Dent Res* 2010;**89**:241–5.
48. Hsu JT, Huang HL, Tsai MT, et al. Effect of screw fixation on temporomandibular joint condylar prosthesis. *J Oral Maxillofac Surg* 2011;**69**:1320–8.
49. Ramos A, Duarte RJ, Mesnard M. Prediction at long-term condyle screw fixation of temporomandibular joint implant: a numerical study. *J Craniomaxillofac Surg* 2015;**43**:469–74.
50. Lombardi Jr AV, Barrack RL, Berend KR, et al. The Hip Society: algorithmic approach to diagnosis and management of metal-on-metal arthroplasty. *J Bone Joint Surg Br* 2012;**94**(11 Suppl A):14–8.
51. Lundberg HJ. TMJ biomechanics. In: Mercuri LG, editor. *Temporomandibular joint total joint replacement – TMJ TJR – a comprehensive reference for researchers, materials scientists, and surgeons*. Springer; 2015.
52. Mercuri LG, Urban RM, Hall DJ, et al. Adverse local tissue responses to failed temporomandibular joint implants. *J Oral Maxillofac Surg* 2017;**75**:2076–84.
53. Kerwell S, Alfaro M, Pourzal R, et al. Examination of failed retrieved temporomandibular joint (TMJ) implants. *Acta Biomater* 2016;**32**:324–35.
54. Royhman D, Radhakrishnan R, Yuan JC, et al. An electrochemical investigation of TMJ implant metal alloys in an artificial joint fluid environment: the influence of pH variation. *J Craniomaxillofac Surg* 2014;**42**:1052–61.
55. Li CS, Vannabouathong C, Sprague S, et al. The use of carbon-fiber-reinforced (CFR) PEEK material in orthopedic implants: a systematic review. *Clin Med Insights Arthritis Musculoskelet Disord* 2015;**8**:33–45.
56. Brockett CL, Carbone S, Fisher J, et al. PEEK and CFR-PEEK as alternative bearing materials to UHMWPE in a fixed bearing total knee replacement: an experimental wear study. *Wear* 2017;**374–375**:86–91.
57. Mercuri LG. Alloplastic temporomandibular joint replacement: rationale for the use of custom devices. *Int J Oral Maxillofac Surg* 2012;**41**:1033–40.
58. Megahed M, Mindt HW, N'Dri N, et al. Metal additive-manufacturing process and residual stress modeling. *Integr Mater Manuf Innov* 2016;**5**:61–93.
59. Mercuri LG, Anspach III WE. Principles for the revision of total alloplastic TMJ prostheses. *Int J Oral Maxillofac Surg* 2003;**32**:353–9.
60. De Meurechy N, Braem A, Mommaerts MY. Biomaterials in temporomandibular joint replacement: current status and future perspectives – a narrative review. *Int J Oral Maxillofac Surg* 2018;**47**:518–33.