

Article

In Vitro Biomechanical Simulation Testing of Custom Fabricated Temporomandibular Joint Parts Made of Electron Beam Melted Titanium, Zirconia, and Poly-Methyl Methacrylate

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Abstract: Total alloplastic temporomandibular joint (TMJ) replacement has become common. This in vitro study aimed to evaluate wear response of custom-fabricated electron beam melted titanium (EBM-Ti), zirconia, and acrylic TMJ parts when subjected to biomechanical simulation testing. Eighteen prosthetic TMJ parts (condyle, glenoid fossa) were custom-fabricated using computer aided design and manufacturing (CAD/CAM) techniques based on patient's radiographic images. Biomechanical simulation testing of TMJ parts (in different combinations) were done in a modified chewing simulator (108,000 cycles, 1 Hz frequency, 45–60 N compression, strokes-downward 0.15–0.25 s/horizontal, 0.4–0.5 s/upward, 0.25–0.45 s/displacement, 1.5–2.0 mm). Qualitative analysis using scanning electron microscopy revealed wear facets on leading edges of vertical and horizontal simulation strokes. Measurement of pre-test and post-test weights of TMJ parts revealed non-significant reduction in weights due to wear. EBM-Ti and acrylic TMJ glenoid fossae articulating against zirconia condyles during simulation testing had significantly higher wear, evidenced by greater mean reduction in weights. Based on results of this preliminary study, custom-fabricated alloplastic prosthetic TMJ are a viable alternative to stock alloplastic joints. While EBM-Ti and acrylic are suitable biomaterials for custom-fabrication, use of zirconia results in greater wear and requires further studies to optimize their role in customized alloplastic TMJ.

Keywords: temporomandibular joint replacement; alloplastic joint; cad/cam; electron beam melting; titanium; zirconia; acrylic; biomechanical simulation

1. Introduction

Total temporomandibular joint (TMJ) replacement and reconstruction have become the treatment of choice for irreversibly damaged joints as a result of inflammatory and degenerative processes. In addition TMJ replacement provides a plausible functional treatment choice in the treatment of TMJ ankylosis [1]. Although several materials, both autologous and alloplastic have been reportedly used for TMJ replacement and reconstruction, the goals of achieving a stable joint which supports oral function and facial form remain the same [2]. The TMJ is a unique synovial joint in the body, which includes bilateral synchronous articulation between two bones, the mandibular condyles, and

the glenoid fossae of the temporal bones [3]. In addition to the anatomic features of synovial joints, such as fibrous tissue capsule with synovial lining and fluid, fibrocartilaginous disc, and support ligaments, the TMJ is also characterized by rotational and translational movements during function (ginglymoarthrodial joint) [4]. Although the left and right TMJ are two separate synovial joints, together they physiologically comprise the craniomandibular articulation [4]. Due to the above-mentioned anatomic, functional, and physiological complexities, the choice of TMJ reconstruction or replacement has to be decided based on the clinical condition, pre-existing pathology, and patient needs [2].

While several studies have reported the use of autogenous bone and soft tissue for functional reconstruction of the TMJ [2,5,6], total alloplastic replacement has emerged as the preferred treatment for management of refractory joint disease, including failed autologous joint reconstruction [7–9]. The only contraindications for alloplastic TMJ replacement could be chronic focus of infection at the surgical site and documented hypersensitivity to the material used [8]. Originally conceptualized based on prosthetic hip joints, alloplastic TMJ have come a long way and have been used with considerable clinical success for more than three decades and several systems of prosthetic joints are commercially available [8,10,11]. The predominantly used combinations of alloplastic biomaterials for fabrication of prosthetic TMJ include titanium or cobalt-chrome (Co-Cr) alloy for the condyle and titanium, ultra-high molecular weight poly-ethylene (UHMWPE), or Co-Cr alloy for the glenoid fossa [8,12]. Although biocompatible, most currently available prosthetic TMJ systems avoid metal-on-metal articulations owing to the risk of foreign body giant-cell reactions to metallic particles generated at the contact points [13]. Furthermore, majority of these systems involved the use of a custom-fitted stock prosthetic TMJ, which requires sufficient intra-operative time for fixation [14]. While the idea of custom-made TMJ prostheses are not new, they have gained greater importance owing to advances in craniofacial radiology and patient specific digital design modalities [10,15,16]. Custom fabrication enables better adaptability of the surgical prostheses, reduces surgical time, and restores form and function with greater predictability [16]. Consequently, newer trends in patient specific total alloplastic TMJ replacements has fueled the need for newer biomaterials which are capable of custom fabrication.

Several additive manufacturing technologies such as selective laser melting (SLM) [17], direct metal laser sintering (DMLS) [18], and electron beam melting (EBM) [19], have been employed for custom fabrication of biomedical implants. EBM is approved by the United States Food and Drug Administration (USFDA) for the fabrication of orthopedic and cranio-maxillofacial implants using an alloy of titanium (Ti6Al4V) [20]. In comparison to stock implants milled out of solid titanium, EBM enables precise fabrication of patient specific implants based on three-dimensional (3D) radiographic images of the patients [19]. In addition, EBM is capable of designing customized titanium implants with different pore geometries, which helps in better osseointegration, and also lessens the bulk [14,17,19]. These findings have indeed been reported based on an *in vivo* study by a group of the present authors, which evaluated EBM titanium reconstruction plates for reconstructing mandibular continuity defects [14]. The same computer aided designing (CAD) protocols for EBM can also be used for custom fabrication of biomedical implants utilizing subtractive processes such as computer aided milling (CAM) [16]. Two biomaterials which are routinely used in dentistry and are capable of custom fabrication through CAM are zirconia and acrylic (poly (methyl methacrylate), PMMA). Both of these materials have been used for craniofacial biomedical implants, and zirconia has in fact been used to design the stock condyle and fossa elements in the Groningen total TMJ replacement system [21,22].

It would be alluring to hypothesize that the above-mentioned biomaterials can be used as effective alternatives for custom fabrication of prosthetic TMJ. However, the most important considerations are the biocompatibility of the biomaterial to promote osseointegration or unhindered bone formation around the implant and the biomechanical ability to withstand rotational and translational TMJ movements over a long period of time [8]. While the favorable biological properties of EBM titanium, zirconia, and acrylic have been reported clinically [21–23], their mechanical performance when used in differing combinations of opposing joint parts are not clearly delineated. This is imperative considering the fact that materials with very weak mechanical properties might wear out easily, and a very strong

material might hasten bone resorption through stress shielding [14]. Therefore, the aim of the present in vitro experiment was to evaluate the wear response of custom fabricated EBM titanium, zirconia, and acrylic TMJ parts when subjected to biomechanical simulation testing.

2. Materials and Methods

Following informed consent, computed tomography (CT) scan data was obtained from a 45-year-old male patient who was previously treated by surgical resection for left mandibular tumor involving the TMJ. The CT data acquired as two-dimensional (2D) DICOM (Digital Image and Communications in Medicine) file format were processed into digital three-dimensional (3D) models using Materialise-MIMICS 17.0[®] (Materialise Interactive Medical Image Control System; ©2014 Materialise NV, Leuven, Belgium) software (Figure 1). In the next step, the digital 3D model was subjected to pixel-based image segmentation and region growing technique using MIMICS[®] to achieve the region of interest, which was the entire skull in the present case (Figure 2). The skull model obtained through the region growing technique was exported to Standard Tessellation Language (STL) file format for custom processing and design of prosthetic TMJ condyle and glenoid fossa.

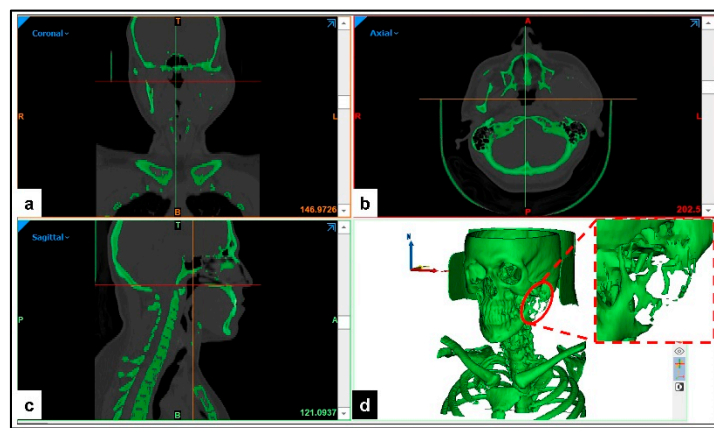


Figure 1. Two-dimensional computed tomography data acquired from the patient (a) coronal section; (b) axial section; (c) sagittal section, converted into digital three-dimensional models, (d) volume rendering with inset image showing the complete destruction of temporomandibular joint (TMJ) anatomy on the left side.

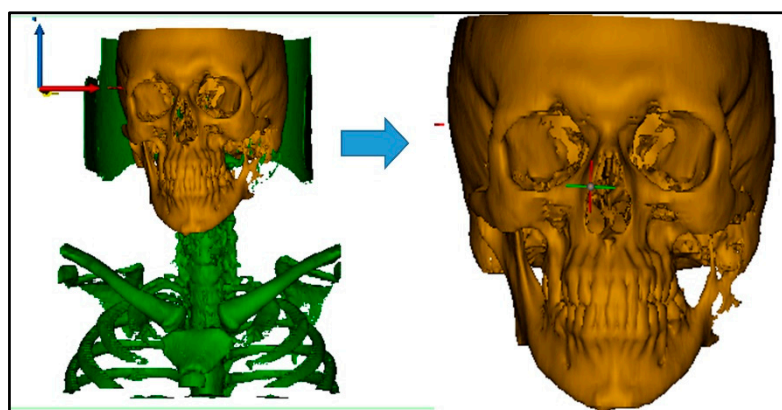


Figure 2. Three-dimensional model of the region of interest (skull) generated using image segmentation and region growing technique in Materialise Interactive Medical Image Control System (MIMICS[®]).

The custom design process utilized a mirror reconstruction technique based on healthy bone in the unaffected side, using 3-Matic 9.0[®] software (©2014 Materialise NV, Leuven, Belgium) [16,19]. The steps involved in mirror reconstruction and designing the custom TMJ parts (condyle and glenoid fossa)

are outlined in Figure 3. In order to biomechanically test the prosthetic TMJ parts under functional simulation of jaw movements, the condyle and fossa regions from the custom fabricated digital 3D models were separated (Figure 4). The separated TMJ condyle and fossa parts were imported into Magics® 18.03 software (©2014 Materialise, NV, Belgium) for STL fixing, support generation and build orientation, and the in-built automatic diagnostic tool was used for fixing STL errors. These error free STL files were finally utilized for custom fabrication of the TMJ parts using different biomaterials, namely EBM titanium alloy (EBM-Ti), zirconia, and poly (methyl methacrylate) (acrylic).

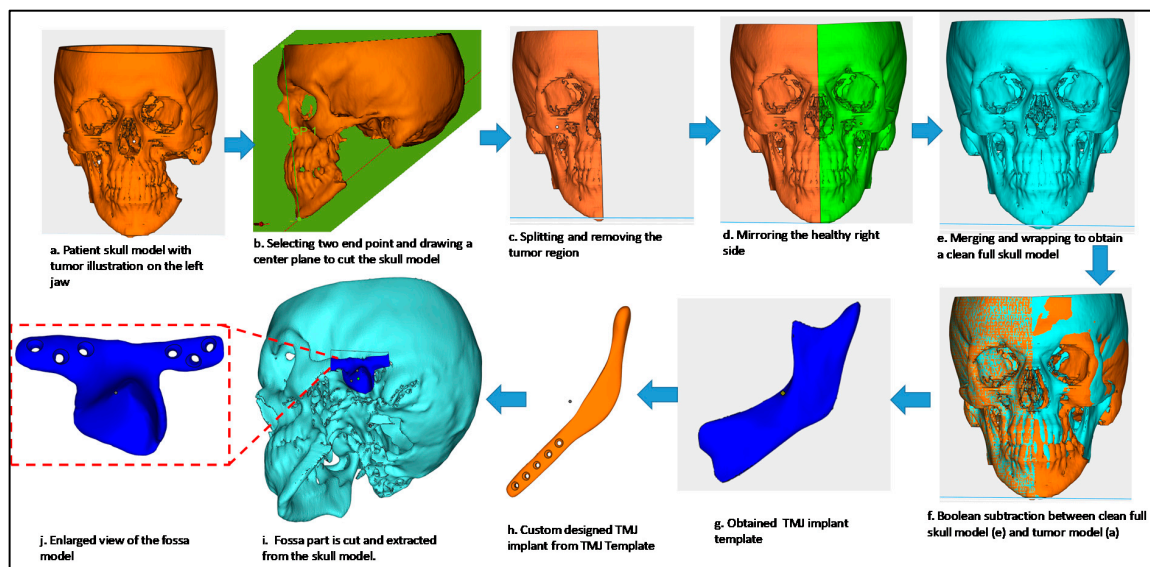


Figure 3. Mirror reconstruction technique and steps in custom designing the prosthetic left TMJ condyle and glenoid fossa parts using 3-Matics 9.0® software; **(a)** three-dimensional (3D) skull model generated using Standard Tessellation Language (STL) files, **(b)** superior and inferior end points of the model marked to assign a central plane dividing the skull into symmetrical halves, **(c)** right side skull with the left half digitally subtracted, **(d)** mirroring of the right half skull on the left side, **(e)** and **(f)** clean skull model obtained after Boolean subtraction operation between the skull model with tumor and mirror reconstructed skull model **(g)** reconstructed model of the left hemi-mandible along with condyle, **(h)** custom design of the prosthetic TMJ condyle along with plate extension for fixation to the ramus of the mandible, **(i)** reconstructed model of the left glenoid fossa (blue), **(j)** custom design of the prosthetic TMJ glenoid fossa along with plate extension for fixation to the temporal bone.

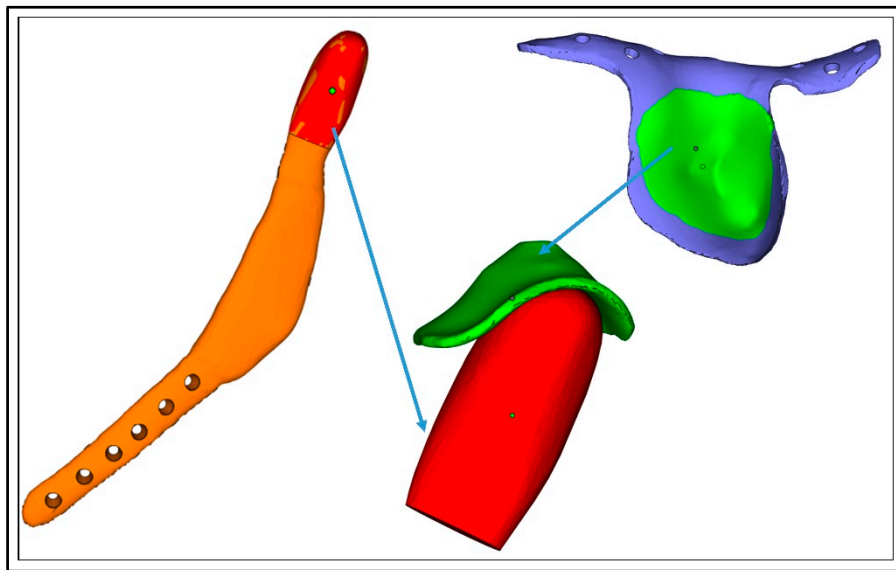


Figure 4. Digital 3D models of the prosthetic TMJ condyle and fossa separated for fabrication and biomechanical jaw function simulation tests.

2.1. Fabrication of the Prosthetic TMJ Condyle and Glenoid Fossa Parts

Custom fabrication of the TMJ parts in titanium alloy was done using an Arcam A2 Electron beam melting (EBM) machine (Arcam AB, Mölnlycke, Sweden) using powdered Titanium alloy (Ti6Al4V). In the present study, Ti6Al4V-ELI (Extra low interstitial) powder with a particle size of 50–100 μm was used. The STL files were imported into the Arcam build assembler software (Arcam AB, Mölnlycke, Sweden), which sliced the 3D part geometry into 2D compressed layers of 50 μm uniform thickness in an “ABF” (Arcam build file) file format. This file format is required to initiate the EBM process in three stages: (a) Preheating the metal powder, (b) scanning and melting the powder, and (c) lowering the build platform and raking of powder. These three phases were repeated cyclically until the final 3D model was built (Figure 5). The final obtained EBM-Ti components were finished and polished using a fine-grit rotary drill.

The TMJ parts in zirconia were fabricated from a multilayer zirconia block (Ceramill® Zolid FX, Amann Girrbach AG, Koblach, Austria) using a computer aided milling machine (Ceramill® Motion 2, Amann Girrbach AG, Koblach, Austria). The error free STL files of the prosthetic condyle and glenoid fossa were imported to the milling software (Ceramill® Mind, Amann Girrbach AG, Koblach, Austria), and were utilized by the five-axis Ceramill® Motion 2 milling machine (Figure 6), to generate TMJ parts. The milled parts were subsequently heat sintered in a zirconia sintering machine (Ceramill® Therm 3, Amann Girrbach AG, Koblach, Austria) to obtain the final prosthetic TMJ components. Similar to the previously mentioned protocol, acrylic TMJ condyle and glenoid fossa were milled from a multilayer PMMA block (Ceramill® A-Temp, Amann Girrbach AG, Koblach, Austria) using STL files. The acrylic TMJ parts were usable immediately after fabrication without the need for post-processing.

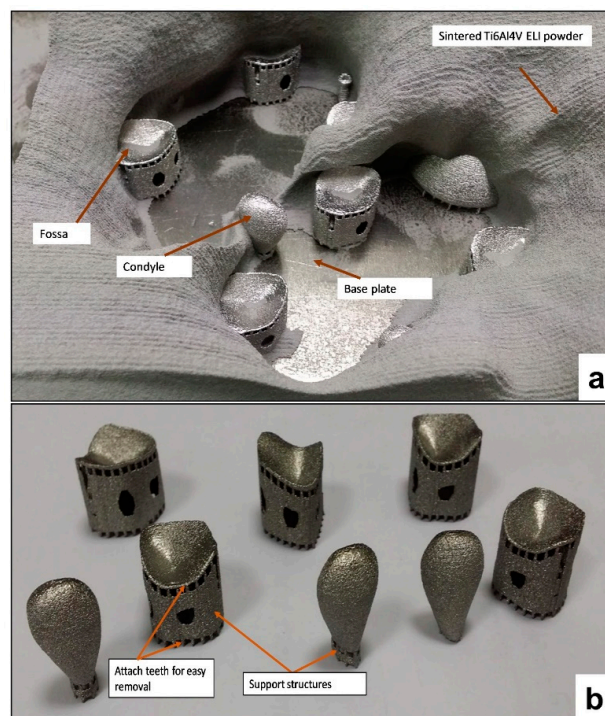


Figure 5. Representative images illustrating (a) the process of electron beam melting (EBM) fabrication of prosthetic TMJ condyle and glenoid fossa parts with support structures, (b) finished TMJ parts with support structures to allow heat transfer and enable easy removal post-fabrication.

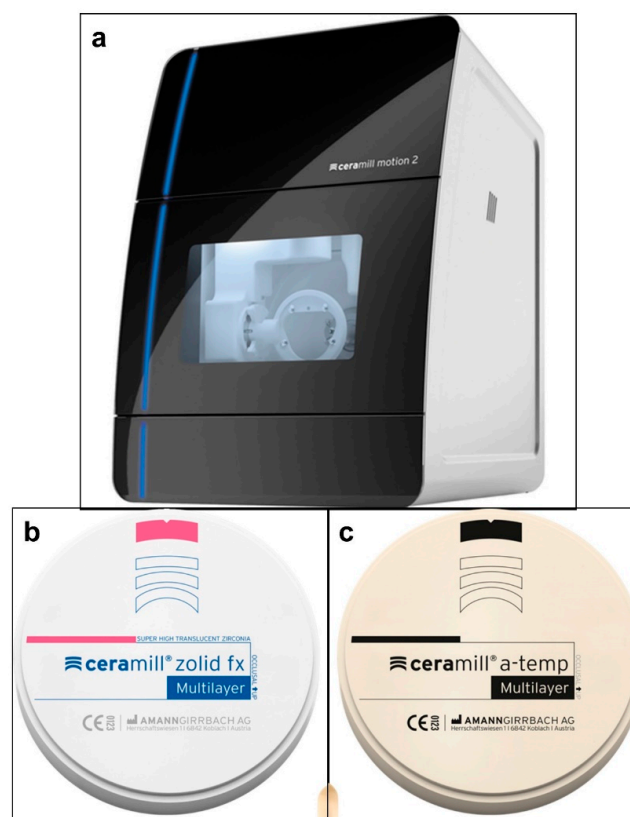


Figure 6. Representative images of (a) Ceramill® Motion-2 five-axis milling machine, (b) multilayer block of zirconia (Ceramill® zolid fx), and (c) multilayer block of acrylic (poly (methyl methacrylate), Ceramill® a-temp).

2.2. Biomechanical Simulation Testing of the TMJ Condyle and Glenoid Fossa

A total of 18 prosthetic TMJ parts (condyle and glenoid fossa) were fabricated in each material to be evaluated. The materials were subjected to biomechanical simulation of TMJ function using a modified chewing simulator (CS-4, SD Mechatronik, Feldkirchen-Westerham, Germany) (Figure 7a). The simulator comprised eight functional simulation units, each with a fixed base and a moving arm, capable of performing downward, translational, and upward movements in a cyclical manner (Figure 7b). The custom fabricated condyle and glenoid fossa parts were embedded in self-polymerizing resin (Figure 8a–f) and fixed to a metallic mold with attachment interfaces to the moving arm and base (Figure 8g,h). In order to simulate biological TMJ function, the glenoid fossa component was attached to the stationary base and the condyle to the moving arm (Figure 7c), and the entire prosthetic TMJ setup was immersed in a distilled water bath.

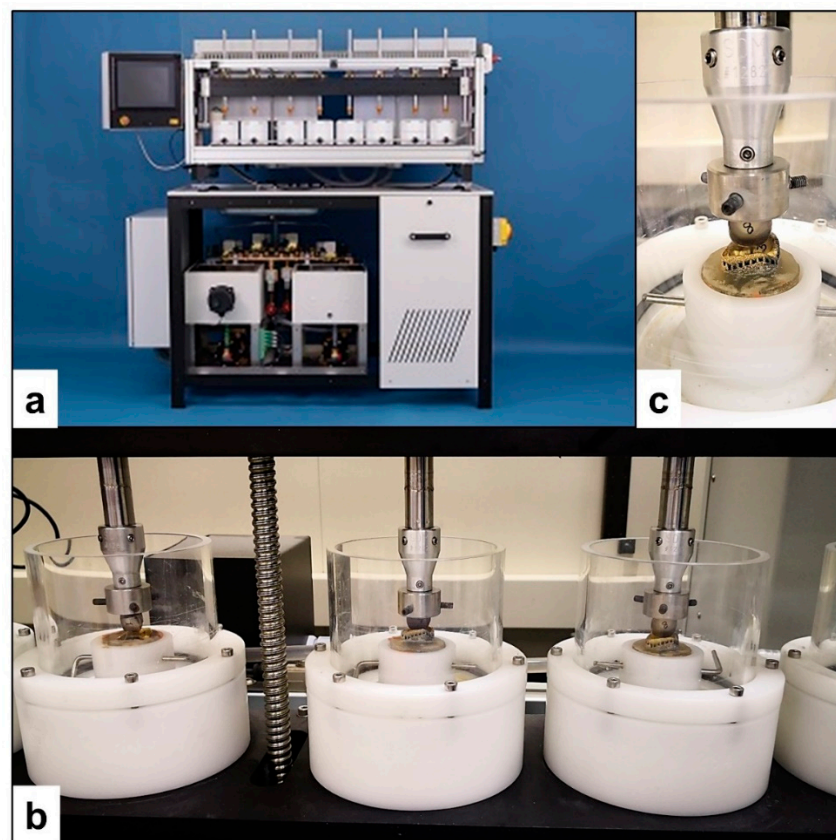


Figure 7. Representative images of (a) SD Mechatronik “CS-4” chewing simulator machine, (b) showing the fixed base and moving vertical arm, (c) with the glenoid fossa component attached to the base and the condylar component attached to the vertical arm, and the setup enclosed in a water bath.

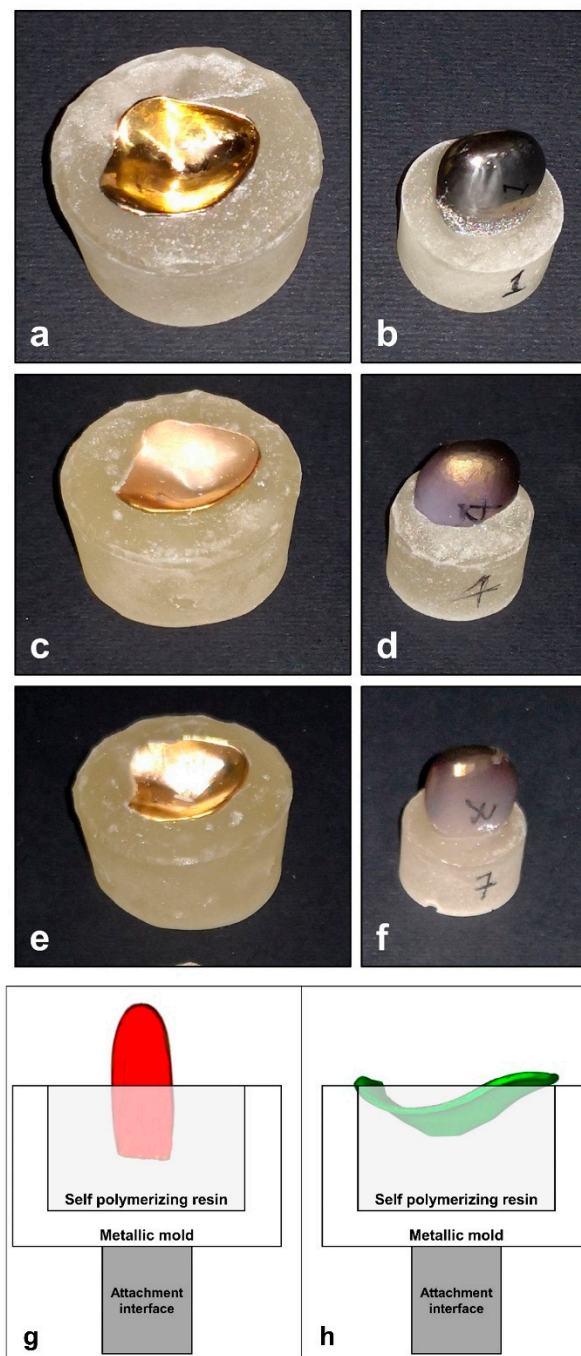


Figure 8. Representative images of the custom fabricated temporomandibular joint parts, (a) titanium glenoid fossa and (b) condyle, (c) zirconia glenoid fossa and (d) condyle, (e) acrylic glenoid fossa and (f) condyle, (g) and (h) schematic diagrams, respectively showing embedding of the condylar and glenoid fossa components within a mold in order to fix it to the simulator.

Simulation testing was done for 108,000 cycles at a frequency of 1 Hz (30 h) and compression force of 45–60 N [3,24]. The simulation cycle started with a vertical downward stroke for 0.15–0.25 s, followed by horizontal translational stroke for 0.4–0.5 s, and ended with a vertical upward stroke for 0.25–0.45 s. The displacement during both vertical and translational strokes ranged from 1.5–2.0 mm. Condyle and glenoid fossa parts fabricated from different biomaterials (EBM-Ti, zirconia, and acrylic) were paired using all possible combinations, for biomechanical simulation testing as shown in Table 1.

Table 1. Combinations for pairing condyle and glenoid fossa parts fabricated from different biomaterials during biomechanical simulation testing. (n = 6 per pair).

Nature of Prosthetic Temporomandibular Joint Parts		Prosthetic Glenoid Fossa Material		
		EBM-Ti	Zirconia	Acrylic
Prosthetic condyle material	EBM-Ti	Pair 1	Pair 2	Pair 3
	Zirconia	Pair 5	Pair 4	Pair 6
	Acrylic	Pair 8	Pair 9	Pair 7

EBM-Ti—Electron beam melted titanium.

2.3. Pre-Test and Post-Test Physical Analysis of the Prosthetic TMJ Parts

In order to ascertain material wear due to compressive loading and friction during simulation testing, each individual part was weighed separately before and after biomechanical testing. Furthermore, the contact surfaces of the prosthetic condyle and glenoid fossa parts were qualitatively characterized using scanning electron microscopy (SEM). Using a calibrated, digital, laboratory micro-balance (Explorer Semi-Micro EX125, OHAUS, Nänikon, Switzerland), all the TMJ parts were weighed in grams, rounded up to five decimal places. Similarly, the specimen surfaces were subjected to pre-test and post-test SEM analysis (JSM 6360 LV, JEOL, Tokyo, Japan), after application of a uniform gold coating of 10–20 nm thickness.

3. Statistical Analysis

Descriptive statistical analysis of the measured pre-test and post-test weights was done for each condyle and glenoid fossa part fabricated out of EBM-Ti, zirconia, and acrylic. The difference in weights for each group of condyle or glenoid fossa specimen was analyzed using paired sample statistics (paired t-test) and the mean difference between different specimen types was analyzed by one-way analysis of variance (ANOVA) along with Tukey-HSD post-hoc test. All statistical tests were performed using the statistical software package (IBM SPSS Statistics, Version 20, IBM, Armonk, NY, USA), with 95% assumed significance level ($p < 0.05$).

4. Results

Following biomechanical simulation testing, there was no physical damage discernible through visual examination or SEM analysis in the TMJ condyle and glenoid fossa parts, except for areas of wear. The wear facets were predominantly observed on the points of contact during vertical stroke and the leading surface facing translation stroke, both in the condyle and glenoid fossa specimens (Figures 9 and 10). Comparing the pre-test and post-test weights of the different TMJ parts, there was an overall reduction in the mean weights of the condyle and glenoid fossa parts under all circumstances. Nevertheless, there were no statistically significant differences observed (Tables 2 and 3). Similarly, comparison of the mean reduction in weights between condylar specimens using one-way ANOVA and post-hoc test revealed no statistically significant differences (Table 4). However, the greatest reduction in weight was observed among titanium condyles tested against zirconia (0.00260) and titanium fossae (0.00178), followed by acrylic condyles tested against zirconia (0.00165) and titanium fossae (0.00153). The lowest reduction in weight was observed among the zirconia condyles (Table 2 and Figure 11).

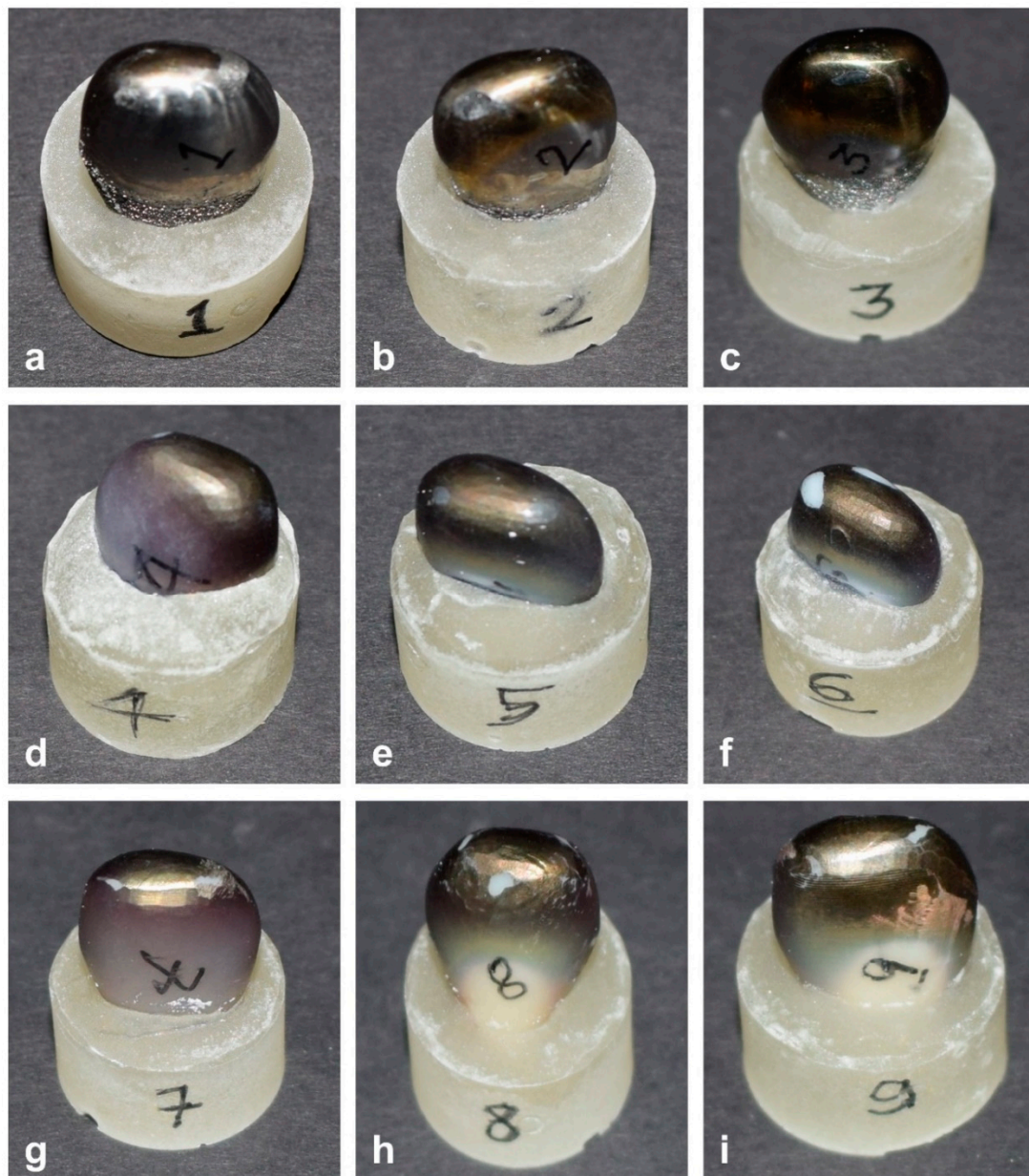


Figure 9. Representative images of condylar parts after completion of biomechanical simulation testing against glenoid fossa parts of different materials, (1st row) titanium condyle against (a) titanium fossa (b) zirconia fossa (c) acrylic fossa; (2nd row) zirconia condyle against (d) zirconia fossa (e) titanium fossa (f) acrylic fossa; (3rd row) acrylic condyle against (g) acrylic fossa (h) titanium fossa (i) zirconia fossa.

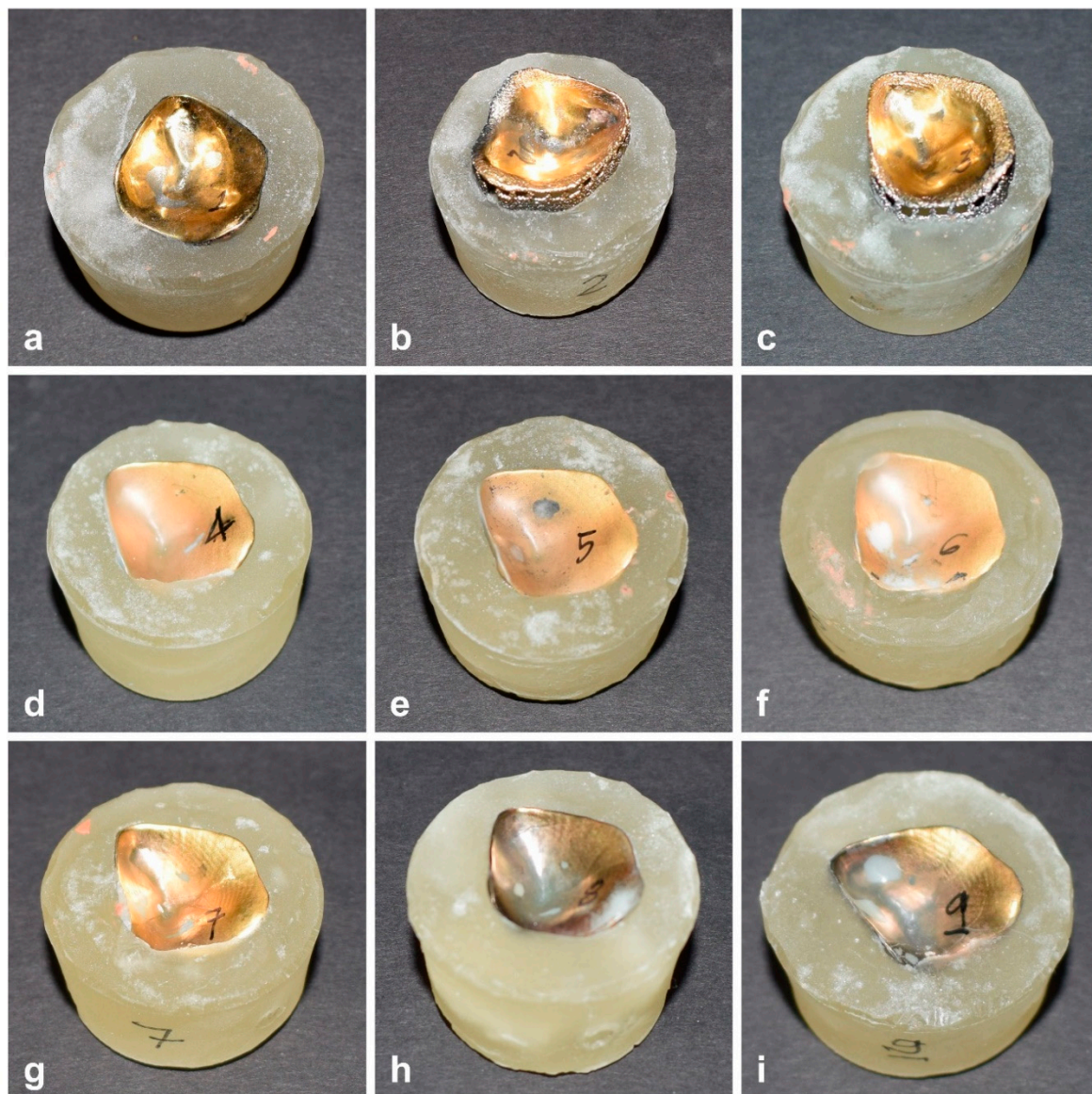


Figure 10. Representative images of glenoid fossa parts after completion of biomechanical simulation testing against condylar parts of different materials, (1st row) titanium fossa against (a) titanium condyle (b) zirconia condyle (c) acrylic condyle; (2nd row) zirconia fossa against (d) zirconia condyle (e) titanium condyle (f) acrylic condyle; (3rd row) acrylic fossa against (g) acrylic condyle (h) titanium condyle (i) zirconia condyle.

Similar to condylar specimens, there was an overall reduction in the mean weights of glenoid fossa specimens too. Additionally, an overall statistically significant difference was also observed based on one-way ANOVA (F-value—6.0337, $p < 0.001$). While the greatest reduction was observed among acrylic fossae (0.00483) and titanium fossae (0.00289), both when tested against zirconia condyles, the lowest reduction was seen among zirconia fossae tested against acrylic condyles (0.00040) (Table 3 and Figure 11). Post-hoc comparison showed statistically significant reduction in the weights of acrylic fossae tested against zirconia condyles in contrast to all other groups, except titanium fossae tested against zirconia condyles (Table 5). There was also a significant difference observed between titanium fossae tested against zirconia condyles and zirconia fossae tested against acrylic condyles (Table 5).

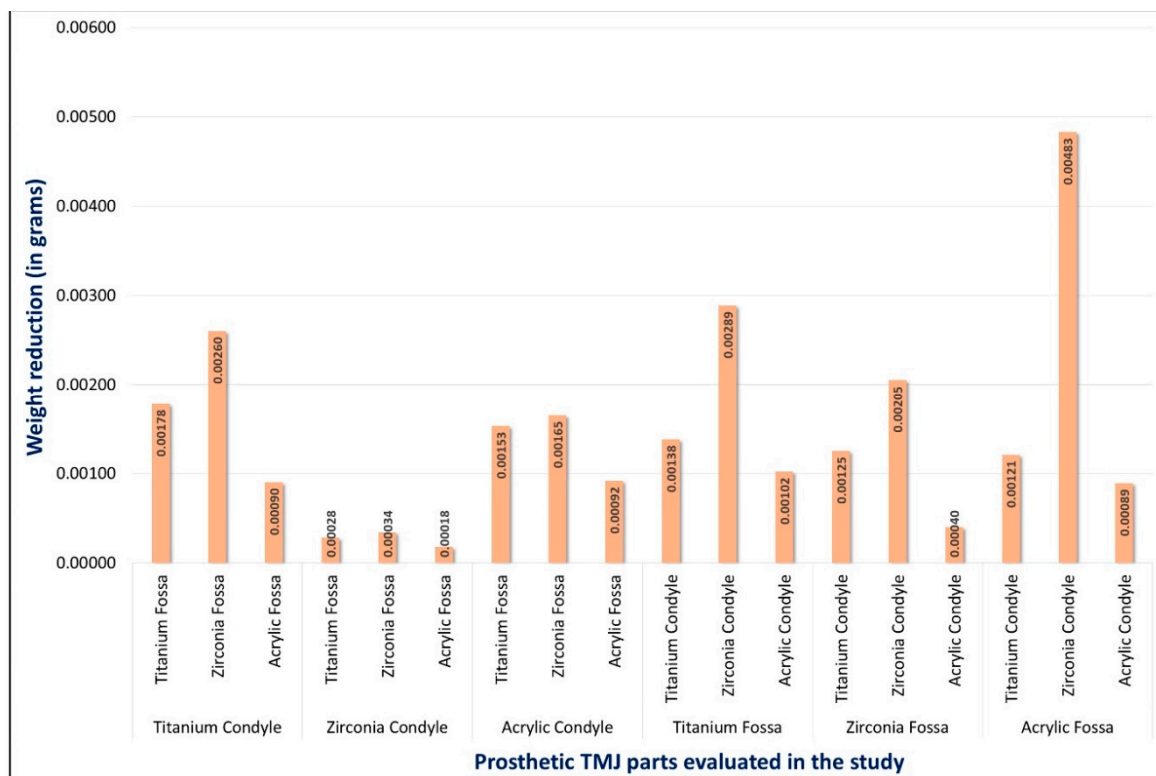


Figure 11. Bar graph showing the mean difference between the pre-test and post-test weights of the different prosthetic TMJ parts after biomechanical simulation testing.

Pre-test qualitative SEM analysis revealed uniform distribution of surface characteristics, depending upon the grain structure, in the condylar and glenoid fossa specimens fabricated from different materials (Figure 12). SEM analysis of the post-test condyle and glenoid fossa specimens revealed a clear demarcation between the areas of the surface which underwent wear and those that were not physically affected (Figures 13 and 14). While this demarcation was marked among acrylic condyle and fossa specimens, irrespective of the opposing material, it was observed to a lesser extent in titanium specimens and almost to a negligible extent (at 500× magnification) among zirconia specimens. Even within titanium specimens, the demarcation of wear facets was less pronounced among condyle and fossae which were tested against acrylic fossae and condyles, respectively.

Table 2. Mean ($\pm$ standard deviation) of the pre-test and post-test weights among the condylar parts of different materials tested against different glenoid fossa materials, along with paired t-test values.

Sample Material (Condyle)	Opposing Material (Glenoid Fossa)	Pre-Test Weight (in Grams)		Post-Test Weight (in Grams)		Paired T-Test Values					
		Mean	S.D.	Mean	S.D.	Mean Diff.	S.E.	p-Value	T-Value	95% C.I.	
EBM-Ti	EBM-Ti	9.91171	0.05663	9.90993	0.05726	0.00178	0.02500	0.94500	0.06990	−0.05172	0.05528
	Zirconia	10.17718	0.05815	10.17458	0.05879	0.00260	0.02600	0.92190	0.09940	−0.05234	0.05753
	Acrylic	10.19273	0.05823	10.19183	0.05889	0.00090	0.02600	0.97300	0.03440	−0.05412	0.05592
Zirconia	Zirconia	11.84253	0.06861	11.84219	0.06868	0.00034	0.03100	0.99130	0.01115	−0.06374	0.06442
	EBM-Ti	11.70935	0.06783	11.70907	0.06790	0.00028	0.03000	0.99278	0.00918	−0.06380	0.06436
	Acrylic	11.75028	0.06807	11.75010	0.06814	0.00018	0.03000	0.99530	0.00590	−0.06381	0.06417
Acrylic	Acrylic	5.29207	0.06205	5.29115	0.07802	0.00092	0.03200	0.97700	0.02920	−0.06531	0.06715
	EBM-Ti	5.30092	0.06215	5.29939	0.07814	0.00153	0.03200	0.96190	0.04850	−0.06480	0.06786
	Zirconia	5.28628	0.06198	5.28463	0.07793	0.00165	0.03100	0.95880	0.05240	−0.06450	0.06780

EBM-Ti—Electron beam melted titanium; SD—Standard deviation.

Table 3. Mean ($\pm$ standard deviation) of the pre-test and post-test weights among the glenoid fossa parts of different materials tested against different condyle materials, along with paired t-test values.

Sample Material (Glenoid Fossa)	Opposing Material (Condyle)	Pre-Test Weight (in Grams)		Post-Test Weight (in Grams)		Paired T-Test Values					
		Mean	S.D.	Mean	S.D.	Mean Diff.	S.E.	p-Value	T-Value	95% C.I.	
EBM-Ti	EBM-Ti	16.62604	0.07611	16.62466	0.07659	0.00138	0.03400	0.96820	0.04040	−0.07036	0.07312
	Zirconia	17.85018	0.08172	17.84729	0.08222	0.00289	0.03700	0.93800	0.07880	−0.07413	0.07991
	Acrylic	18.15195	0.08310	18.15093	0.08362	0.00102	0.03700	0.97850	0.02740	−0.07730	0.07934
Zirconia	Zirconia	16.50227	0.03746	16.50022	0.03753	0.00205	0.01700	0.90410	0.12230	−0.03318	0.03729
	EBM-Ti	17.24061	0.03913	17.23936	0.03922	0.00125	0.01800	0.94390	0.07130	−0.03556	0.03806
	Acrylic	17.06166	0.03873	17.06126	0.03881	0.00040	0.01700	0.98180	0.02310	−0.03603	0.03682
Acrylic	Acrylic	15.43073	0.04929	15.42984	0.05218	0.00089	0.02300	0.96920	0.03920	−0.04680	0.04858
	EBM-Ti	15.31541	0.04892	15.31420	0.05179	0.00121	0.02300	0.95780	0.05370	−0.04612	0.04854
	Zirconia	16.29016	0.05204	16.28533	0.05507	0.00483	0.02400	0.84250	0.20160	−0.04551	0.05517

EBM-Ti—Electron beam melted titanium; SD—Standard deviation.

Table 4. Difference between the mean reduction in weights among the condylar part materials tested against different glenoid fossa part materials.

Sample Material (Condyle)	Opposing Material (Glenoid Fossa)	Sample Material (Condyle)								
		EBM-Ti			Zirconia			Acrylic		
		EBM-Ti	Zirconia	Acrylic	Zirconia	EBM-Ti	Acrylic	Acrylic	EBM-Ti	Zirconia
EBM-Ti	EBM-Ti	-	0.0008	0.0009	0.0014	0.0015	0.0016	0.0009	0.0003	0.0001
	Zirconia	-	-	0.0017	0.0023	0.0023	0.0024	0.0017	0.0011	0.0009
	Acrylic	-	-	-	0.0006	0.0006	0.0007	0.0001	0.0006	0.0008
Zirconia	Zirconia	-	-	-	-	0.0001	0.0002	0.0006	0.0012	0.0013
	EBM-Ti	-	-	-	-	-	0.0001	0.0006	0.0012	0.0014
	Acrylic	-	-	-	-	-	-	0.0007	0.0013	0.0015
Acrylic	Acrylic	-	-	-	-	-	-	-	0.0006	0.0007
	EBM-Ti	-	-	-	-	-	-	-	-	0.0001
	Zirconia	-	-	-	-	-	-	-	-	-

EBM-Ti—Electron beam melted titanium.

Table 5. Difference between the mean reduction in weights among the glenoid fossa part materials tested against different condylar part materials, along with statistical significance (One-way ANOVA with Tukey HSD post-hoc test; * $p < 0.05$ or ** $p < 0.01$).

Sample Material (Glenoid Fossa)	Opposing Material (Condyle)	Sample Material (Glenoid Fossa)								
		EBM-Ti			Zirconia			Acrylic		
		EBM-Ti	Zirconia	Acrylic	Zirconia	EBM-Ti	Acrylic	Acrylic	EBM-Ti	Zirconia
EBM-Ti	EBM-Ti	-	0.0015	0.0004	0.0007	0.0001	0.0013	0.0005	0.0002	0.0035 **
	Zirconia	-	-	0.0019	0.0008	0.0016	0.0029 *	0.0020	0.0017	0.0019
	Acrylic	-	-	-	0.0010	0.0002	0.0010	0.0001	0.0002	0.0038 **
Zirconia	Zirconia	-	-	-	-	0.0008	0.0020	0.0012	0.0008	0.0028 *
	EBM-Ti	-	-	-	-	-	0.0012	0.0004	0.0001	0.0036 **
	Acrylic	-	-	-	-	-	-	0.0009	0.0012	0.0048 **
Acrylic	Acrylic	-	-	-	-	-	-	-	0.0003	0.0039 **
	EBM-Ti	-	-	-	-	-	-	-	-	0.0036 **
	Zirconia	-	-	-	-	-	-	-	-	-

EBM-Ti—Electron beam melted titanium; * $p < 0.05$; ** $p < 0.01$.

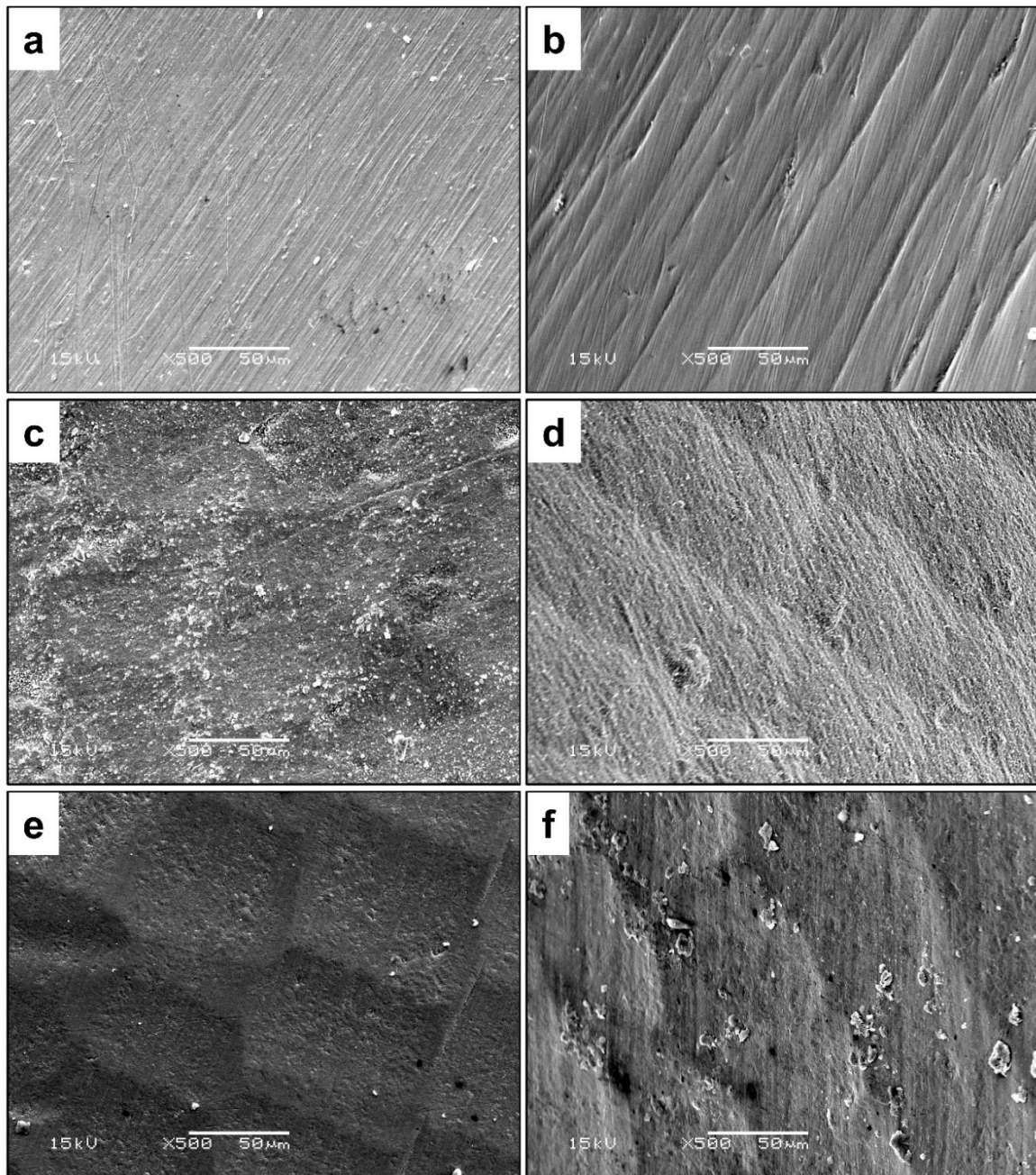


Figure 12. Representative scanning electron microscopic images of the pre-test contact surfaces in (a) titanium condyle, (b) titanium glenoid fossa, (c) zirconia condyle, (d) zirconia glenoid fossa, (e) acrylic condyle, and (f) acrylic glenoid fossa.

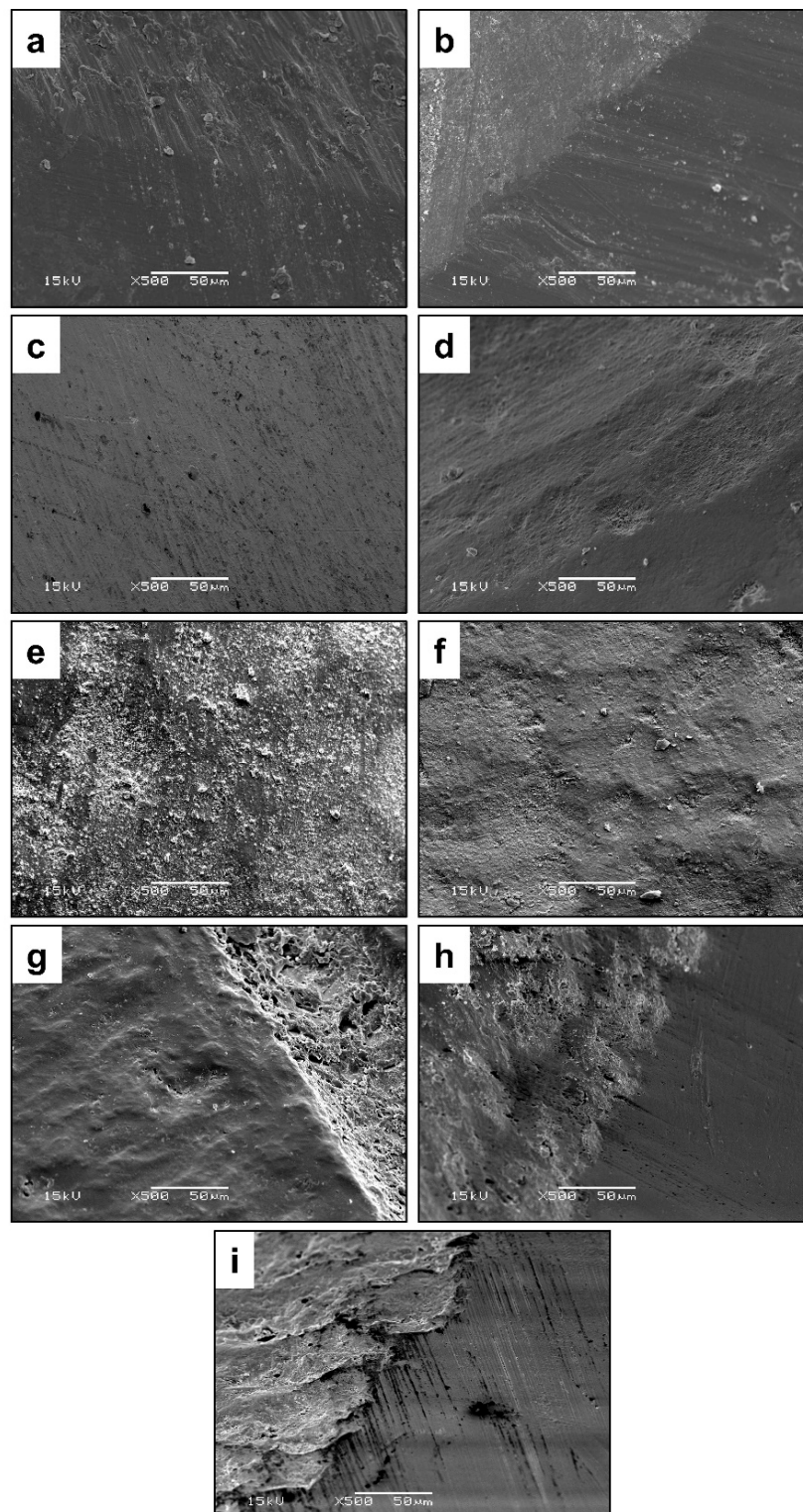


Figure 13. Representative scanning electron microscopic images of the post-test contact surfaces in condylar parts after biomechanical simulation testing against different glenoid fossa parts, titanium condyle against (a) titanium fossa (b) zirconia fossa (c) acrylic fossa; zirconia condyle against (d) zirconia fossa (e) titanium fossa (f) acrylic fossa; acrylic condyle against (g) acrylic fossa (h) titanium fossa (i) zirconia fossa.

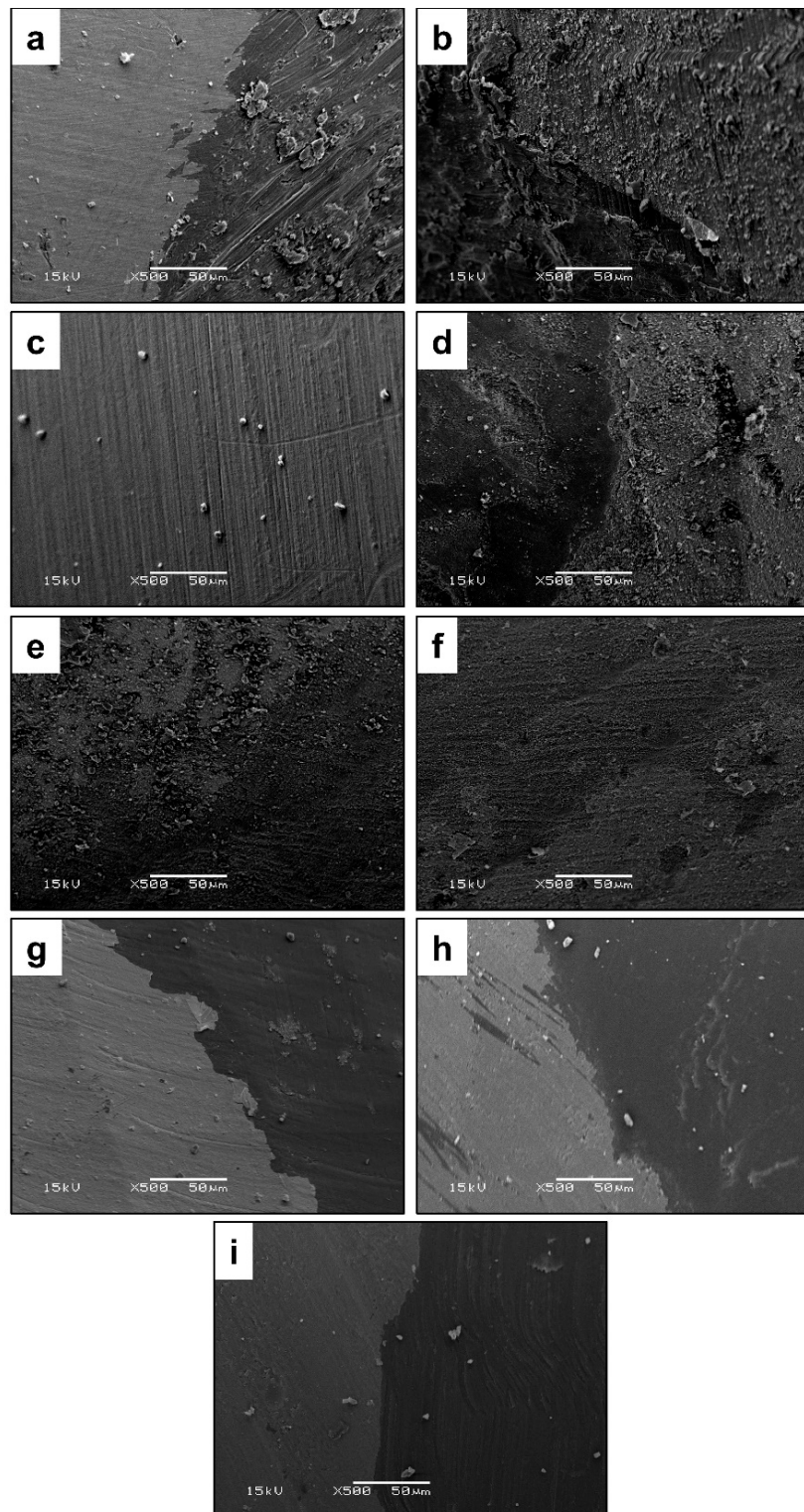


Figure 14. Representative scanning electron microscopic images of the post-test contact surfaces in glenoid fossa parts after biomechanical simulation testing against different condylar parts, titanium fossa against (a) titanium condyle (b) zirconia condyle (c) acrylic condyle; zirconia fossa against (d) zirconia condyle (e) titanium condyle (f) acrylic condyle; acrylic fossa against (g) acrylic condyle (h) titanium condyle (i) zirconia condyle.

5. Discussion

Total alloplastic TMJ replacement systems have become the clinical norm, rather than an exception, for management of refractory end stage TMJ disease and severe functional impairment due to pathological processes [8]. They are reported to improve the post-operative quality of life for patients, through pain alleviation, enhanced range of motion, and better speech and mastication [25]. Irrespective of whether it is a stock or a custom-made prosthesis, alloplastic TMJ replacements have been shown to deliver predictable clinical outcomes in terms of TMJ function [26]. However, custom-made joint replacements were considered suitable only for specific indications such as in TMJ with severe degenerative anatomic changes, failure of stock prosthesis, and concomitant correction of skeletal and dental malocclusion [26]. Interestingly, almost all commercially available custom-made TMJ prosthesis systems, utilize stock condyle and glenoid fossa components designed over a custom fitted fixation plate or implant [15,26,27]. This makes them at best custom-fitted TMJ implants in contrast to the custom fabricated TMJ, condyle and glenoid fossa parts which the present study envisioned.

The idea of total alloplastic TMJ reconstruction is definitely motivated from the clinical success of similar procedures in orthopedic surgery for more than half a century [8,25,26]. As a result of which, the concept of ball (condyle) and socket (glenoid fossa) articulating components have been largely favored in both stock and custom-fitted alloplastic TMJs [8,21]. In addition, eliminating translational joint movement, the ball and socket TMJ design is routinely fabricated with a short condylar component and thick glenoid fossa component, in order to match with the low center of rotation of the natural joint [21,28]. While this may sound practical in clinical scenarios involving bilateral TMJ replacement, unilateral TMJ replacement with currently available alloplastic joint prostheses, could reportedly increase stresses at the condyle and disc articulating surfaces [29]. Based on the above premise, it could be surmised that the custom fabricated alloplastic TMJ design, based on 3D modelling and mirroring of anatomic condyle and glenoid fossa, would simulate clinical rotational and translational joint movements. Therefore, the biomechanical simulation assessment was also designed to that effect.

The three biomaterials evaluated in the present study are not new to the fields of medicine and dentistry, and are being routinely used clinically. Titanium and its alloy (Ti6Al4V) are among the most biocompatible materials used in the fabrication of end osseous orthopedic and dental implants [20,30]. The unique aspect of the titanium alloy used in the present study was only the additive method (EBM) used in its fabrication. Nevertheless, implants of titanium alloys made using advanced manufacturing methodologies such as EBM are equally biocompatible and possess regulatory healthcare approvals [14,19,20]. Based on a clinical case report, Lee et al. [23] have reported successful esthetic and functional reconstruction of the entire mandible printed out of titanium alloy (Ti6Al4V-ELI) using EBM technology. Interestingly, the same titanium alloy and fabrication protocol have been utilized in the present study too. Zirconia or zirconium dioxide is a biocompatible ceramic material used successfully in dentistry for restorative treatment, due to its favorable biomechanical properties and low affinity to dental plaque. In the past decade it has gained popularity as an alternative to titanium for the fabrication of end osseous dental implants, owing to its biocompatibility and the ability to osseointegrate similar to titanium [31,32]. Similarly, poly (methyl methacrylate) (PMMA/acrylic), a low weight polymer with good tensile strength and high modulus of elasticity, is used in clinical dentistry as a denture base material. Fabricated using a combination of liquid monomer activator and powdered polymer particles, it is considered non-toxic and biocompatible when heat polymerized [33]. Heat polymerized PMMA biomedical implants are specifically used for customized bone defect reconstruction of critical non-loading bearing areas, such as following cranioplasty [22]. Similar to the highly popular UHMWPE, PMMA too has orthopedic applications. While UHMWPE is predominantly used as an articulating interface in alloplastic joints, self-polymerizing PMMA is used as a bone cement for fixation [34]. In the present study pre-formed blocks of unsintered zirconia and heat polymerized PMMA were used to custom fabricate TMJ parts based on 3D digital modelling. The justification for selecting these three biomaterials was based on their availability, reported biocompatibility, prospect of CAD/CAM manufacturing, and mechanical properties, which

are either higher than or are comparable to that of cortical bone (Table 6) [35–37]. It must however be noted that the choice of material should be based mainly on the elastic modulus of the biomaterial in comparison to that of natural bone [17–19]. Maietta et al. reported that it is possible to modify the elastic properties of titanium implants manufactured using an additive process, without affecting their mechanical performance, by incorporating advanced porous and lattice structures [17]. In addition to fabrication of implants with Young's modulus closer to that of natural bone, porous structures also help minimize stress shielding effect [17].

Table 6. Mechanical properties of biomaterials used in the study and that of cortical bone [35–37].

Mechanical Properties	Biomaterial			Mature Cortical Bone
	EBM Titanium (Ti6Al4V)	Zirconia (ZrO2)	Acrylic (PMMA)	
Compressive Strength (MPa)	940–970	1200–5200	105–117	100–230
Tensile Strength (MPa)	880–950	115–711	62–75	50–151
Elastic Modulus (GPa)	113.8–334.2	100–250	2.45–3.12	7–30
Hardness (GPa)	1.125–2.18	5.5–15.75	0.66–0.69	0.41–0.89

EBM—Electron beam melted; ZrO2—Zirconium Dioxide; PMMA—Poly (methyl methacrylate).

The biomechanical simulation testing methodology used in the present study was developed indigenously, based on previously reported protocols. The cycling time and compression force applied during vertical and horizontal strokes were designed to simulate anatomic loading of TMJ during an approximate functional life of three years [3,24]. No macroscopic structural damages were observed in the prosthetic condyle and glenoid fossa parts, following biomechanical simulation testing using different combinations (Table 1). Although, wear facets were evident macroscopically and through SEM in both the condyle and glenoid fossa specimens, no microscopic cracks could be appreciated (Figures 13 and 14). The most important findings which were quantified, were the reduction in weight of the prosthetic TMJ parts, when tested using different combinations. This was evaluated based on evidences in the literature which have reported functional wear of alloplastic joints under clinical conditions [38]. Incidentally, while weight reduction in the micro-scale was observed in all specimens evaluated in the study, it was generally greater in the glenoid fossa parts than in the condylar parts (Figure 11). Moreover, the degree of wear significantly differed in the prosthetic glenoid fossa parts, depending upon the type of condylar biomaterial articulated against (Table 5).

The greatest wear in terms of mean reduction in weight of the prosthetic TMJ parts, were seen in acrylic parts, followed by EBM-Ti and zirconia parts. Furthermore, acrylic and EBM-Ti condyle and fossa parts exhibited greater wear in comparison to the zirconia fossa or condyle parts against which they were tested. Schuurhuis et al. [21] based on a clinical series of eight patients treated with Groningen TMJ prosthesis, designed out of zirconia condyle and fossa parts, reported the use of a UHMWPE disc between the articulating surfaces. The purpose of the disc was to optimize the overall biomechanical properties of the joint considering the high compressive strength and hardness, and low tensile strength of zirconia (Table 6). The afore-mentioned factor could also be the reason behind greater wear observed among EBM-Ti and acrylic parts in the present study, when tested against zirconia. The use of a disc fabricated out of biomaterials with low hardness and high tensile strength, such as UHMWPE or PMMA might help prevent wear of the articulating surfaces associated with prosthetic zirconia TMJ parts [21]. Nevertheless, these discs are liable to get displaced during function and might wear out resulting in aseptic joint loosening [21,24]. Although no interposition disc was used during biomechanical testing in this study, it would be an exciting possibility to evaluate, in the future, anatomically designed 3D alloplastic TMJ condyle, glenoid fossa, and articulating disc.

While the novel aspect of the present study was the anatomic precision of alloplastic TMJ parts digitally custom-designed using 3D mirroring techniques, the most critical aspect was the evaluation of mechanical performance of different biomaterials against each other during function. With the help

of digital modelling and CAD, it was possible to generate a 3D model of the TMJ to be replaced and reconstructed, and the same was used for digital manufacturing of condyle and glenoid fossa parts using different EBM-Ti, zirconia, and acrylic. This aspect of the present study is in coherence with several previous studies, which have documented the precision and accuracy achievable through 3D rapid prototyping and CAD/CAM technologies [16,19,20,23,39]. Nevertheless, particulate wear is a major adverse effect associated with alloplastic prosthetic joints irrespective of the biomaterial used or of their mechanical properties [40]. This in-turn contributes to peri-prosthetic foreign body reaction, inflammation, and aseptic loosening of the prosthetic components [21,24,40]. The preliminary results of the present study subscribe to the above-mentioned fact, in spite of the custom fabricated alloplastic TMJ design.

The results of the present study provide evidence favoring the biomechanical stability of custom fabricated alloplastic TMJ, with anatomically mirrored condyle and glenoid fossa parts. This is in coherence with a recent review about the biomechanical properties of different total TMJ replacement systems evaluated through finite-element analysis, and reported lower stress values for customized TMJ components [41]. Furthermore, anatomically mirrored prosthetic condyle and glenoid fossa elements enables their close approximation to the native bone and could facilitate enhanced osseointegration [8]. However, the present outcomes must be considered in light of the following limitations. This study provides information pertaining to preliminary biomechanical evaluation only and the simulation testing while replicating compression and translation movements accurately, could not perfectly replicate rotational movements. Moreover, the 3D CAD/CAM protocol used for fabrication and subsequent biomechanical simulation testing, considered replacement of unilateral alloplastic TMJ parts only.

6. Conclusions

Based on the results of the present study, it could be concluded that custom fabrication of alloplastic TMJ condyle and glenoid fossa parts could be a viable alternative to stock and custom fitted TMJ replacements. Moreover, EBM-Ti and acrylic (PMMA) to a certain extent, had good biomechanical stability during simulation testing and were capable of accurate custom-fabrication of the TMJ parts. The use of custom fabricated zirconia condyle and glenoid fossa resulted in greater wear on the other biomaterials and mandates further evaluation in the context of it being used as a biomaterial for customized alloplastic TMJ replacement.

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