3D Printing Smart Eyeglasses Frames: A Review

Filmon Tsegay [a]*, *Rami Ghannam*[b], *Nardos Daniel*[c], *Haider Butt* [a]*

[a] Department of Mechanical Engineering, Khalifa University, Abu Dhabi 127788, UAE.

[b] James Watt School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK.

[c] Department of Electrical Engineering, Wayne State University, Michigan (313) 577-2376, US.

*Correspondence: filimonwmichael@gmail.com (F.T), haider.butt@ku.ac.ae (H.B)

Abstract

Eyeglasses are typical correctors for refractive error eye disorders. They are commonly placed on frames that are expected to be both stylish and durable. However, current consumer demand for sustainable and eco-friendly frames is gaining interest, especially since conventional frame manufacturing methods follow a subtraction of large blocks of wasted scrap material. Alternatively, additive manufacturing (AM) promises better economic feasibility due to reduced tooling, storage and material costs, as well as enhanced mechanical properties by inducing nanomaterials and composites. Moreover, this synergism between AM and digital design has led to a rising interest in smart or electronic eye glass frames. Consequently, this systematic review assesses commercial eyeglass frames that use standard materials with long-lasting resistance, durability, comfort, and versatility with various materials from metals and polymers. Design aspects and their correlation with Artificial Intelligence (AI) with the use of machine learning Computer Aided Design (CAD) software are also reviewed. Beyond the appealing eyeglass frames technology, there is a subtle frame design in which electronic sensors and chips are embedded. The review also comprises various applications for 3D printing of frames including commercial and biomedical applications. Further topics that are reviewed include the side effects, health risks, shortcomings of AM techniques and materials such as aggregation effect of nanomaterials, void formation inside the matrix that propagate fatigue and shrinkage or density change during the solidification.

Keywords: Smart eyeglass frame; 3D printing; Generative design; Contact lens.

1. Introduction

Eye related diseases are on the rise globally and according to the U.S. Department of Health & Human Services report, more than 4.2 million Americans aged 40 years and older are registered as legally blind (having best-corrected visual acuity, which means the best possible vision an eye can see with corrective lenses is 6 out of 60) [1]. The main causes behind all these eye disorders could be attributed to gadget use habits, diet and natural occurrence. Table 1. summarizes the characteristics of common eye disorders and their treatments.

***Table 1**: Common eye disorder characteristics*

Common eye disorder	**Characteristics**	**Number of affected people**	**Recommended treatment**	**Ref**
Macular degeneration	Loss of the central vision you need to see details straight ahead, blurry or wavy areas in your central vision.	2.95 million	Dietary supplements (vitamins and minerals), injections, photodynamic therapy (injections and laser treatment). Prescribed eyeglass frame.	[1] [2][3] [4][5][6][7]
Cataract	Blurry vision, colors that seem faded, sensitivity to light, trouble seeing at night, double vision.	30.1 million	Surgery, prescribed eyeglass	[8][9][10] [11][12][13]
Diabetic retinopathy	Impairment of the blood vessels of the retina, Blurry vision, floating spots in your vision, blindness.	4.1 million	laser treatment, surgery	[14][15][16] [17][18]
Glaucoma	Damage to the eye's optic nerve could cause loss of side (peripheral) vision, blind spots, blindness.	3 million	Medicine (usually eye drops), laser treatment, surgery	[15][19] [20][21]
amblyopia/lazy eye	When the eye and the brain are not working together correctly	2%–3% of world's population	Eye drops or wearing an eye patch	[22][23] [24][25]
strabismus	Lack of coordination between eyes due to failure of eye muscles working together.		Eyeglasses, medications, and surgery	[22][23] [26][27]
Refractive errors	Blurred vision	150 million	eyeglasses, contact lenses and surgery	[28][29] [30][31]

From the above listed eyeglass problems, refractive errors are the most common type of eye disorder, which affects approximately one sixth of Americans [31][32]. Refractive error disorders in school children include myopia (near sightedness), hyperopia(farsightedness), astigmatism (distorted vision at all distances) and presbyopia (losing the ability to focus up close and inability of reading letter) [28][29][30][33].The recommended solutions to tackle vision loss due to refractive errors include wearing eyeglasses and contact lenses as well as surgery [32][34][35]. Currently, there is a growing market demand for sustainably manufactured firm frames that are durable.

Research on eyeglass frame production has a long history. Several production approaches have been influential in the field because of the dependency of different industries on optimized fabrication methodology. Conventional eyeglass frames were fabricated using traditional die-cutting plastic sheet frames. The process proceeded with the automated machine lifting the die and moving it to successive plastic sheets. The blanks were produced quickly while the plastic was soft [36]. The blanks were removed from the sheet, and the lens portions were extracted from the frames for the separate lens fitting. The process was then followed by a smoothing procedure to remove rough edges by abrasive apparatuses, shaped to smooth the edges of the frame that rests on the cheek and area around the nose.

Another primary theoretical and conceptual framework for the eminent production of eyeglass frames is the patented fabrication process of injection molding, which uses polyetherimide resins. The injection mould process starts with molten plastic, which is fed into a mould that has the shape of a sheet clamped on both sides. Cooling the mould filled with molten plastic is necessary to solidify the sheet structure, which is finally ejected from the machine and is ready for performed sheet process. Next, machining operations are applied to metal sheets and the preformed sheet is trimmed into the glasses frame structure according to the intake design using laser cutting or CNC cutting. Moreover, lens grooves and hinge grooves are introduced in the cut glasses frame. Subsequently, the rough surface of the glass frame is subjected to surface treatment through tumbling or polishing. Traditional eyeglass frame fabrication is often subjected to offsets in accuracy and standard of the eyeglass frames [37]. For instance, the common inaccuracy range of injection molding is typically 0.005, however in 3D printing techniques commonly less than ±0.0035 or ±0.0015 [38][39]. The main reason behind the inaccuracy of the conventional manufacturing process could be an attributed to a significant difference between the size of the mold and the molding materials. Conventional manufacturing methods were limited to a restricted choice of materials (such as metals) and were incapable of producing complex designs until alternative manufacturing techniques emerged.

In fact, traditional and conventional manufacturing involves a subtractive technique that begins with a block of material, which is continuously subtracted or removed until the final desired product is obtained. Tools used for traditional manufacturing often include CNC machining, casting, injection molding, plastic forming, and plastic joining. These processes leave much of the initial material as a waste scrap.

One of the manufacturing standard procedures, called additive manufacturing (AM) technology [40][41], has been popularized over the years to replace conventional fabrication techniques [42][43]. Additive manufacturing (AM) or 3D printing overcomes the various limitations of conventional eye-frame fabrication techniques. Frames can now be fabricated from a wider choice of materials and complex design patterns [44]. In fact, interest in 3D printing technology has been growing since the 1960s when the rapid prototyping were invented [45][46][47][48][49]. Therefore, the purpose of this manuscript is to review the literature on 3D-printed eyeglass frames.

AM has played a substantial role in eyeglasses frame production for various fields such as medical prescription eyeglasses frames, sports, film industries, augmented reality in engineering and medical school, video games, and fashion industries. The frames are produced using different AM methodologies that made a significant impact in tolerance and accuracy of the miniature eyeglass frames that can fit perfectly into the lenses [50]. Moreover, 3D printing technology can be considered environmentally friendly.

The advent of 3D printing in the manufacturing of stiff and flexible eyeglass frames has presented a lot of potential for mass customization of eyeglass frames on a large scale [51]. 3D printing enables the fabrication of unconventional multicoloured intricate eyeglass frames consisting of a variety of shapes, angles, curves and intricate details in layered structures [51].

Thanks to the flexibility of AM, smart eyeglass frames, which are equipped with sensing functions that enhance the daily lives of users, can now be fabricated. These sensors monitor user behavior and can track the user’s vital signs, such as their body temperature, pulse rate, respiration rate, and blood pressure [52]. The advantage of AM is not limited to the production of exotic designs of eyeglasses frames, but it also enhances the frame’s mechanical properties by including nanomaterials and composites. Nanomaterials, including carbon nanotubes (CNTs) and graphene oxide (GO) with high aspect ratio, optimize the mechanical strength and endurance of the frames [53][54].

Fabrication of 3D printed eyeglass frames is a mature field and requires well-defined CAD designs that can be optimized using AI-trained software. One of the world's largest eyewear manufacturing company, Luxottica Group PIVA, has reportedly reduced the material usage by optimizing the topography of the frame morphology using AI and machine learning algorithms. The optimization tools were installed in CAD software platforms as generative design and topography optimization. This field is growing, with a wealth of well-understood methods and design algorithms. AI and machine learning are reshaping how many popular eyeglass frames are designed and processed by providing optimization tools in the software platform. Several commercial companies use machine learning optimized tools in CAD software, such as PTC creo®, Siemens NX®, and Fusion 360 Autodesk® [55]. The main reason behind the utilization of the AI-implemented CAD software is the hand-in-hand relationship between collecting user data and designing it using AM production techniques.

2. Research Methodology

We have searched recent data on 3D-printed fabricated eyeglass frames in scientific journals in Design journals, Manufacturing, science direct, google scholar, and Web of Science. The typical inclusion criteria we have included in this paper are smart eyeglass frames, 3D printing techniques, AI-bucked Generative design, Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AI EDAM) of eyeglass frames application, type of material commonly used, mechanical properties, medically prescribed 3D-printed eyeglass frames, sensor integrated frames, generative design, nanocomposite, cost performance and allergic contact dermatitis (CD) due to the eyeglass frames. The exclusion criteria are characteristics of the eyeglass lens, contact lens, conventional fabrication techniques, and commercial cost analysis. The analysis methods were only concentrated on the additive manufacturing of the eyeglass frames. The most frequent keywords we have used on the search engine to collect data are summarized in table 2. We specifically used the ophthalmology journal to analyze refractive errors and their leading causes since it details some sources for different eyeglass frame designs, particularly for the prescribed lenses. It should be noted that some of the keywords listed in table 2 generated many related peer-review topics; nonetheless, the authors were very selective in filtering the highest outcomes.

***Table 2:** Key words used in searching data*

Most keywords used in search engines	**Number of papers highly matched to the criteria**
Smart additive manufacturing fabricated eye glass frames	91
Additive manufacturing fabricated eye glass frames	290
3D printing smart eye glass frames	135
Generative design toward 3D printed eyeglass frame	14
Material for 3D printed eye glass frames	37
Dermatological aspects of contact dermatitis from 3D printed eyeglass frames.	7

The graph below in figure1 shows the number of papers published on smart AM fabricated eyeglass frames each year since 1999. The graph is generated in reference to Science Direct with the trends depicting the search results corresponding to the indicated keywords.

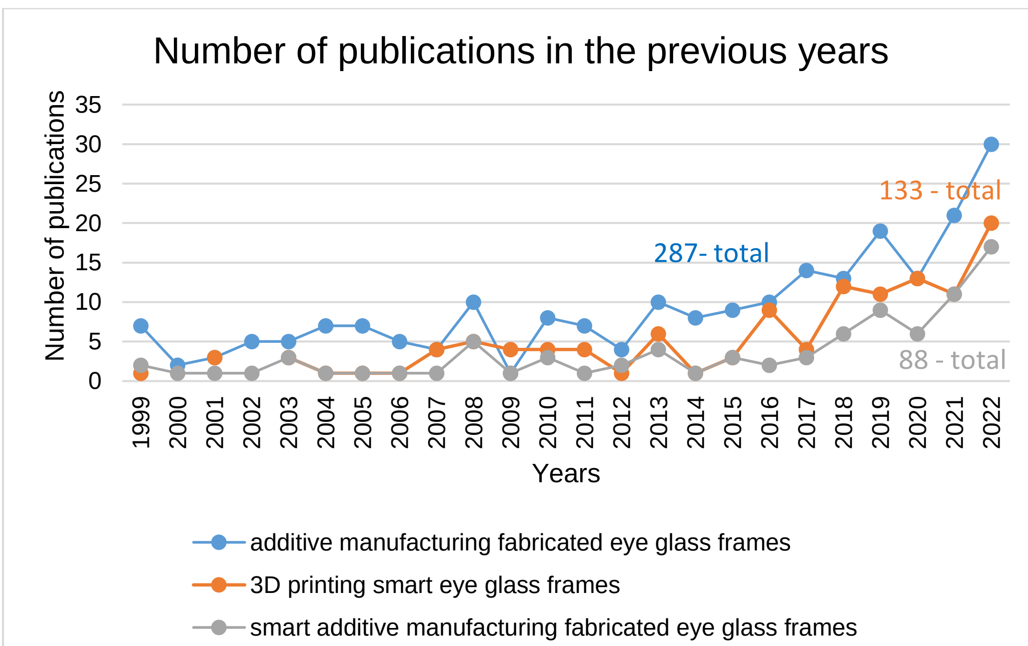


Figure 1: Number of publications in the previous years

3. Additive Manufacturing Techniques

Additive manufacturing (AM) is a process whereby 3D objects are fabricated via layer-by-layer deposition of material. AM substantially balanced the production of prototyping in many industries through quick customization, fabrication of complex geometries, and redistribution of supply chains [44][56]. Also, the AM process is more economically viable than traditional fabrication methods due to the reduced tooling and storage costs.

3D printing can now be used with a wider variety of materials, including biocompatible polymers. It is also being used in healthcare applications for the customized printing of medical apparatuses [57]. AM technologies include fused deposition modeling (FDM), stereolithography (SLA), polyjet process, selective laser sintering (SLS), 3D inkjet printing, and digital light processing (DLP). Each of them has different features (as shown in **Figure 2**) [56]. The features are based on the type of prototypes, time taken to print, the ability to utilize various raw materials, repeatability, prototype resolution, and surface accuracy (shown in **Table 4**) [58][59].

Moreover, there are tradeoffs between the 3D printing features regarding feed stock materials, resolution, repeatability, accuracy, and applications. If one technology excelled in one of the features, the accuracy can be top notch, but it might limit the material usage. Therefore, whenever the application is chosen, there should be a way to select the candidate 3D printer accordingly. Specific 3D printing manufacturing strategies, including the powder bed fusion process, photo-polymerization, lamination, binder jetting, and material extrusion, shorten the time taken to print a sample due to the easy operating principle and quick fabrication of complex 3D models [60][61]. On the other hand, DLP and SLA 3D printers meet the high resolution and accuracy requirement.

Some of the paramount benefits of 3D printing techniques lie in their uncomplicated fabrication process, quick production of prototypes, less manual work, less waste generation, and risk mitigation of releasing particulates and other poisonous chemicals into the air [61]. Table 3 compares the features of the conventional and AM processes from manufacturing chain of economic aspect of the fabrication. As a result, the benefits of 3D printing are only applicable to a specific desired result, which is based on printer technology. For instance, inkjet printing and DLP are capable of providing prototypes with higher repeatability than the previously mentioned traditional fabrication process [59]. Besides, the DLP and SLA have many benefits such as high accuracy, repeatability, resolution, good surface finish and is suitable for complex built, and uncured leftover materials [48] [59]. However, DLP and SLA suffer from challenges such as being unable to print large structures, boxy surface finishes due to rectangular voxels created during the layer depositions, less mechanical properties due to unreacted photopolymers, moisture heat, and chemicals that can reduce their durability [59]. These approaches have been influential in the production of eyeglass frames due to the features that require repeatability, resolution, precision, printing time, processing of various raw metals, and incorporating nanomaterials [62]. Table 4 summarizes different features of the 3D printing methodologies along with their operation principles, working techniques, types of material use, accuracy, and resolution.

Table 3: *Comparison between the traditional fabrication techniques and additive manufacturing.*

Manufacturing process	**Advantage**	**Disadvantage**	**Ref**
AM (3D printing)	A higher level of design freedom. Extensive range of technologies Low cost machines, increased material variability, and high complexity. Customization, complexity advantage. High economic viable and low societal impact.	Low Production Volume manufacturing. The size, orientation, sharpness and location (within joints, exterior surfaces or critical sections of the structure) of defects within an AM part can impact the mechanical properties negatively.	[38][39][45] [63][64][65] [43][66][67] [68][69][70] [71][72] [73][74]
Traditional Manufacturing	Produces machined components with high precision. Less geometric complexity for poor tolerance and relative quality. High Production Volume Based Manufacturing. Traditional manufacturing system has less dependent variables than AM. Repeatability or reliability required for precision manufacturing.	Mass Complexity and Mass Customization. High cost machines. Less material variability.	[45][63] [65][44] [65][75] [76][74]

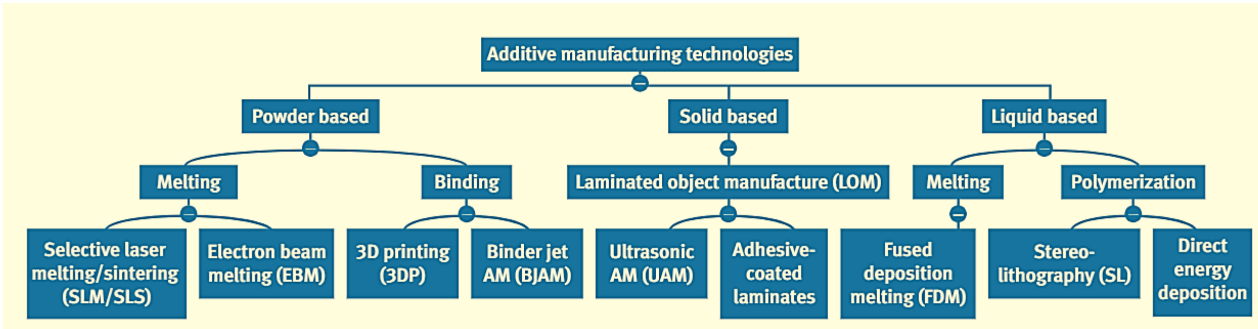


Figure 2: Overview of Additive Manufacturing (AM) [77]. *Reproduced with permission, Copyright @2021 Google.*

***Table 4:** AM features and fabrications techniques*

3D Printing Methods	Type of process	Operation principle	Materials	Accuracy (μm)	Resolution (μm)	Ref
Digital light processing (DLP)	Polymerization(liquid based)	Photo-curing by a digital projector	Photopolymer and photo-resin	10–25	x: 25 y: 25 z: 20	[78][79][80]
Fused deposition modelling (FDM)	Melting (Liquid based)	Extrusion of constant filament	ABS, PLA, Wax blend, Nylon	350	x: 100 y: 100 z: 250	[81][82][83][84]
Polyjet	Binding (Powder based)	Deposition of the droplets of the photo-curable liquid material and cured.	Polymer	10–20	x: 30 y: 30 z: 20	[58][59][43]
Stereo lithography (SLA)	Polymerization (Liquid based)	UV initiated polymerization cross section by cross section	Resin (Acrylate or Epoxy based with proprietary photoinitiator)	25–150	x: 10 y: 10 z: 15	[85][60][61]
Selective laser sintering (SLS)	Melting (Powder based)	Laser-induced sintering of powder particles	Metallic powder, polyamide, PVC	300	x: 50 y: 50 z: 200	[42]
3D Inkjet printing		Extrusion of ink and powder liquid binding	Photo-resin or hydrogel	100	x: 10 y: 10 z: 50	[40][41]

4. Common Materials for 3D Printed Eyeglasses Frames

Most eyewear glasses are made of plastic, stainless steel, nylon, magnesium, and titanium. They are known for their top-notch quality in terms of mechanical strength and durability. While being used extensively by the optical industry, each of these materials, specifically metals, has a drawback in their physical properties in 3D manufacturing. For example, plastic-based eyeglass frames suffer from poor durability, while stainless steel frames are relatively heavy and stiff during 3D printing. The most commonly used material for 3D printing of eyeglass frames is titanium. Commercial companies such as EyeBuyDirect® use titanium for 3D printing due to its toughness, durability, and strength. Moreover, due to its low density, eyeglass frames are surprisingly lightweight, making them suitable for all kinds of lenses. Besides, good corrosion resistance, and biocompatibility [86].

Titanium eyeglass frames are commonly 3D printed using the DMLS (Direct Metal Laser Sintering) or SLM process [86]. The process uses a fine titanium metal powder that is melted with a laser to produce the design layer by layer using powder support. The powder support can be removed without leaving any scar on the sample. Further post-processing using the heat treatments improve the mechanical properties of the eyeglass frames. However, titanium and magnesium based eyeglass frames are very costly compared to steel or plastic-based frames (shown in Table 4) [87].

On the other hand, polymers have gained some attention in 3D printing of eyeglass frames [88][89][90]. The polymers can be prepared in different forms such as powder, cross-linked resins and filaments. They can be coloured or uncoloured for various types of 3D printing techniques. Polyamide, commonly so-called nylon polymer, is a typically used plastic in 3D printing. One of the polyamide family groups called polyamide 11 has strong resistance to different chemicals, fuels, and salt solutions [91]. It also offers excellent abrasion resistance and prevails superior longevity. However, DLP and SLA3D printing process lowered its resistance due to exposure changing UV energy source [91]. Plus, they have weaker resistance to acetic acid and phenols solutions, which hinders them from being employed in the photo-polymerization 3D printing techniques [91]. Since in DLP and SLA printing methods, the post-processing is often done using alcohols. On the other hand, F.Alam *et al.* used a DLP printed polymer resin consisting of methacrylate and diphenylphosphine oxide mixtures to produce smart thermochromatic eyeglass frames for Color vision deficiency (CVD) people [92]. The findings show that change in crosslinking can alter the physical characteristics of the resin. The mechanical testing shows that the frame's tensile strength using the three bending tests 21.9 MPa at the finest ratio of the resin components (i.e. monomers, crosslinkers and photoinitiators). The frames of the lenses were printed in a Masked SLA 3D printer (As shown in **Figure 3a**). The Findings show that the smart thermochromics eyeglass frames can be used for continuous monitoring of the human body's temperature and readout will be colorimetric signal that can be analyzed with smartphone.

The addition of the nanomaterial such as graphene oxide and carbon nanotube (CNT) into polymers enhance the mechanical strength of the polymer-based eyeglass frames. In this regard, graphene-based polymer eyeglasses or sunglasses can avoid the heavyweight, cost and durability issues occurred by conventional eyeglass frames and lens materials. It is well known that graphene oxide has inherently exceptional mechanical properties (Young's Modulus 1 TPa, Tensile Strength: 125 GPa, and Breaking Strength: 42 N/m) which makes it the strongest and lightest material [93]. Luxottica and Ray-Ban commercial eyeglass frame producer companies developed the first graphene-based eyewear glasses in 2017 and have reported their outstanding ultra-lightweight and wear-resistant properties [94]. Likewise, Rudy Project, a leading company in research and development of eyeglass frames launched graphene photochromic sunglasses, which were called "Defender Graphene" due to their ultra-resistant and anti-scratch properties [95]. Besides, the 3D printing process reduces the wasted by-products of graphene and polymer resins that can be produced via conventional manufacturing techniques [96][97].

In experimental studies, the incorporation of graphene oxide into multiple polymers has shown a considerable enhancement in the mechanical properties of nanocomposite. For instance, Yang *et al.* fabricated a strong polyurethane composite reinforced with polydopamine and coated with graphene oxide sheets using solution blending [98]. They demonstrated an elastic modulus of the sample with the highest filler loading was about 6 times more than that of original matrix [98]. Zhang *et al*. also showed that by adding only 1.8 vol% of graphene to poly(vinyl alcohol) (PVA), Young's modulus can be increased by almost 10 times while the tensile strength can be improved by 150% [99].

Furthermore, since most eyeglass frames and lenses suffer from poor scratch-resistance properties, they can be coated with a graphene or graphene oxide layer to reduce any scratches on the frame surface. In addition to the above, Sahoo *et al.* introduced a layer of graphene oxide tribofilm on silicone glasses and found that the resulting friction and wear on the glass substrate reduced by 80% [100]. Evidently, graphene in the eyewear industry is yet to be thoroughly explored as the only graphene based glasses, currently available in the market are Ray-ban and Defender Graphene [94][95]. Nonetheless, AM/3D printing can confer advantages to the created new material using the nanomaterials in which conventional manufacturing techniques are not yet to achieve.

Most of the waste produced in manufacturing eyeglass frames is due to disposed surplus graphene materials left over after the frames are fabricated. This disposed graphene is a catalyst that can contribute to oxidizing the environment. EOS, a supplier company of 3D printers, estimated that a 58% of reduction in carbon footprint can be achieved by only switching the manufacturing technique of eyeglass frames to 3D printing instead of conventional techniques [101]. This shows that the AM helps intensively in reducing the global carbon footprint that can occur from eyeglass frame production. Furthermore, employing 3D printing to fabricate graphene glasses can not only enhance the waste management of the developed eyewear but also pave the way for the customization and functionalization of smart glasses, which will be a game-changer for the ophthalmic industry. Customization of the spectacles' frames can yield aesthetically pleasing designs that are much lighter and durable than their predecessors owing to graphene's addition (**Figure 3b**). Moreover, contemporary fabrication methods of frames inhibit the variation of lenses as they are fixed in their traditional slots within the frame. Very recently, few companies have rolled out clip-on lenses that can magnetically attach to original eyeglasses.

Furthermore, nanofiller cross-linked polymers such as Cellulose Nanocrystal Composite (CNC) can improve the mechanical properties of eyeglass frames. For example, Palaganas *et al.* reported significant improvements in mechanical strength of 3D printed poly(ethylene glycol) diacrylate (PEGDA) brought by CNC [102]. Cellulose such as Methyl cellulose (MC), Ethyl cellulose (EC),Hydroxyethyl cellulose (HEC),Hydroxypropyl cellulose (HPC),Hydroxypropyl methyl cellulose (HPMC) and Carboxymethyl cellulose (CMC) are commonly used for eyeglass frames by adjusting the crosslinking [103]. The mentioned cross-linked resins can be printed in DLP and SLA printers. Coupled with the above researchers Wang *et al*. found that BAPOs (Bis(acyl)phosphane oxides)- attached CNC could convert a conventional mono-functional monomer into a polymeric network without any additional cross-linkers. This was subsequently used in 3D printing to obtain free-standing 3D structured objects [104]. However, there is no explicit discussion about preparing of the nanocomposite materials and integrating them into polymers. Many studies show that the nanomaterial shields the UV light during printing for instance, Titanium dioxide (TiO2) nanoparticles have distinctive ultraviolet (UV) protection and are remarkably resilient to UV radiation [105]. As a result, in the case of DLP, the unreacted monomers will cause diminished mechanical properties. Moreover, agglomeration of nanoparticles can occur in FDM printers due to the adhesion of particles to each other by weak forces leading to (sub) micron-sized entities at the nozzle of FDM printer [106].

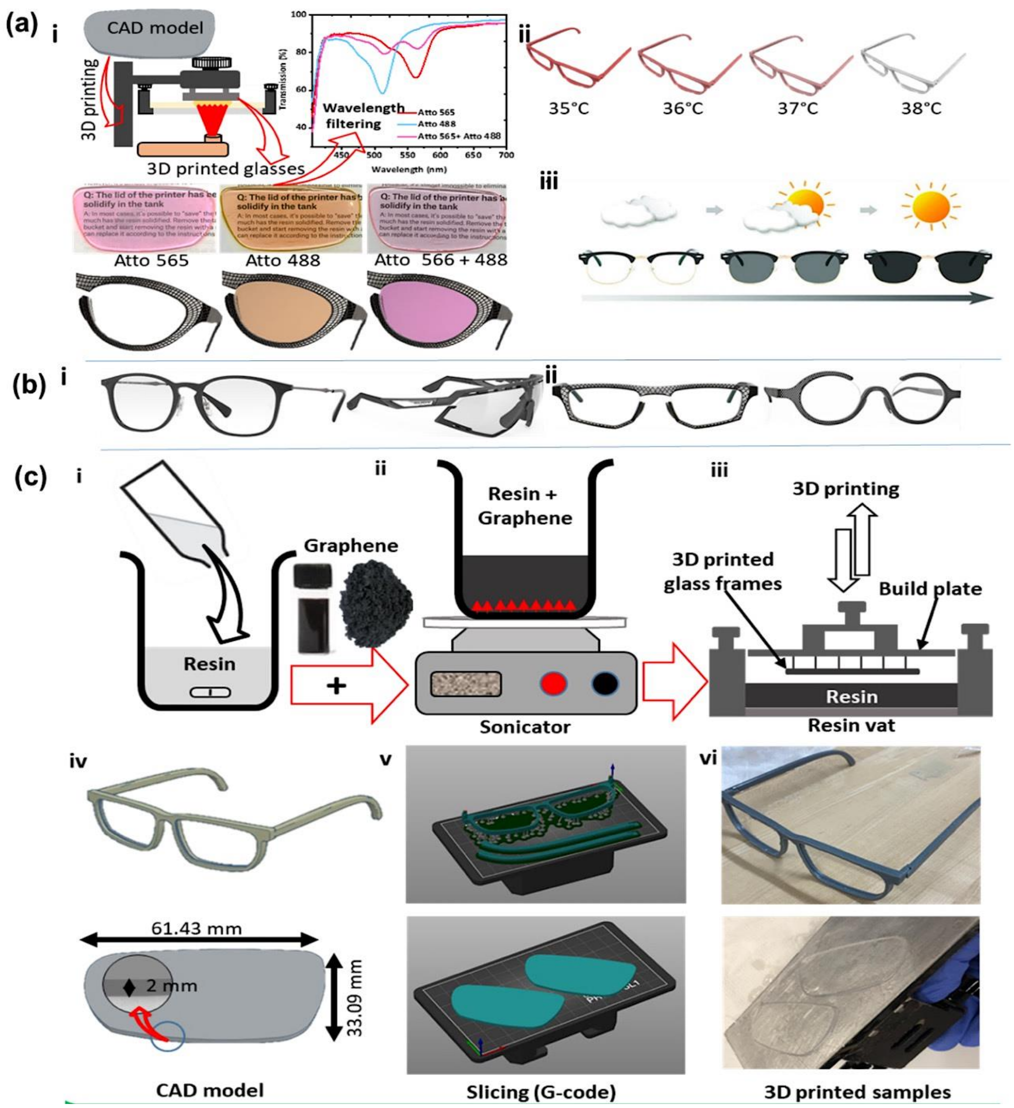


Figure 3:(a)Functionalization and customization ideas for the 3D printed glasses. (i) Our recent work on developing 3D printed wavelength filtering glasses for colour blind patients [92]. (ii) Thermochromics frames for continuous monitoring of the human body's temperature; readout will be colorimetric signal that can be analyzed with smartphone. **(iii)** Adaptive/photochromic lenses to absorb low and high energy UV light, thus reducing eye strain and eye damage. **(b)** Commercial Graphene glasses: **(i)** Ray-ban-Luxottica (Left). **(ii)** Rudy Project (Right). **(c)** Few of our potential customized designs for the 3D printed graphene. Our current methodology for 3D printing frames (with graphene) and glass lenses. **(i)** Resin is initially mixed with graphene and **(ii)** sonicated to inhibit agglomerates formation, followed by **(iii)** SLA 3d printing of the frames. Similar procedure will be utilized for the lenses (without graphene) except we plan to use a two-photon 3D printer to obtain lenses with different dioptric powers and commercial grade optical properties. **(iv)** CAD model, **(v)** models on slicing software, and **(vi)** the 3D printed samples [92]. *Reproduced with permission, Copyright @2021 Advanced Engineering Material.*

Table 5: *Common metals used in the 3D printing of eyeglass frames.*

Types of material	Characteristics	Types of 3D printer	Advantage	Disadvantage	Ref
Magnesium	Lighter than titanium and aluminum. Magnesium is extracted from the ocean or recovered from minerals such as dolomite or magnetite.	Powder Bed Fusion	Super-lightweight material is strong, durable, and hypoallergenic.	Expensive; costs almost 50 percent more than aluminum or steel.	[107][108][109]
Beryllium	More robust than steel and more than 30 percent lighter than aluminum. It resists corrosion and degrades, making it an excellent choice for wearers with high skin acidity or who spend time in or around salt water.	DMLS, SLM, SLS	Lightweight, durable, flexible, and available in various colors.	A minimal number of people are allergic to beryllium.	[110][64][111]
Pure Aluminum	Acquired from bauxite is moderately costly to produce. It is also soft and weak to act as a structural material. Soft enough to carve	SLM, DMLS	Aesthetically pleasing, strong, lightweight, and recyclable.	Aluminum can get rigid, especially in lower temperatures. Thus, integrating elements like flex hinges into an aluminum frame can be challenging.	[112][113] [114]
Titanium Glasses	High-strength, lightweight material, and it is easily accessible.	DMLS, SLM	Strong as steel, lightweight, hypoallergenic, and corrosion-resistant.	This material is more expensive than other materials.	[115][116][117]
Ticral Eyeglass	An alloy of titanium. It is nickel-free and thus hypoallergenic.	DMLS, SLM	Extremely lightweight, Strong, durable, and available in various colors.	Thicker than titanium	[87]
Stainless Steel	An alloy of iron and carbon steel with chromium and other elements.	Metal Jet 3D printer, Binder Jetting 3D printing (BJ3DP)	Non-corrosive, durable, strong, lightweight, and hypoallergenic.	Not as lightweight, heat-resistant, or flexible compared to titanium.	[118][119]

Nickel-Titanium	The metal alloy of nickel and titanium.	Laser powder deposition powder bed fusion (PBF) or directed energy deposition (DED)	More elastic than steel and 25 percent lighter than traditional metals. Also provides increased comfort and durability for patients who are hard on their eyewear.	Ni-Ti is nickel-based; allergies and pitting may be an issue.	[120][121]
Monel™	A nickel alloy containing 68 percent nickel, 30 percent copper, and two percent iron.	Powder bed fusion	Sturdiness and rigidity	A surface discoloration can occur from exposure to atmospheric conditions. Further pitting can occur if exposed to salt water.	[87]
Polymers such as Cellulose acetate & zylonite Nylon	A cost-effective and innovative opportunity for eyewear and is exceptionally lightweight; particularly popular laminating Zyl frames with layered colors.	FDM, DLP, SLS	Hypo-allergenic Light Weight Strong Flexible Corrosion-Resistant Variety of Colors, Patterns, Textures for aesthetic purpose	Luck of mechanical properties	[122][123]

5. Commercial 3D Printed smart eyeglasses frame

Augmented reality in the form of Google Glass, Sony's SmartEyeglass®, and Microsoft HoloLens- has been used recently [124].Behind the appealing eyeglass frames technology, there is a subtle frame design that is embedded with electronic sensors and chips.

Commonly self-sense smart materials are used in smart eyeglass frames, since they respond to stimuli by shape-changing and self-actuating, automated actuation [125]. Furthermore, self-sensing mechanisms allow the smart eyeglasses frames to perform automatic detection and sometimes quantification of external stimuli [125]. Commonly, the sensing mechanism can be achieved using Shape Memory Alloys (SMAs). They have self-sensing approaches that are included in commercial frame brands such as *Flexon* and *TITANflex*, companies that include SMA in titanium glasses [126]. SMAs have properties that set transition temperature below the expected room temperature, which allows the frames to undergo considerable deformation when stress is applied and regain their original shape once unloaded [127]. The main advantage of the SMAs is that they can withstand to a significant stress without permanent damage. Some SMAs recuperate to a preset shape of the eyeglass frame on heating above the transformation temperatures and return to an alternative form on cooling, known as the two-way shape-memory effect [128]. With the substantial role of 3D printing process, the glass frames can be customized to fit each user's face perfectly, allowing for a lighter, more comfortable fit [129].

There are many commercial brands that use the AM to fabricate the eyeglass frames. Some of the commercial eyeglass brands include *BRAGi®, Fritz Frames®, Hoet®, Klenze & Baum®, Materialise's®,* etc. listed in Table 6 along with their crossponding 3D printing technology with a variety of materials for different applications from medical prescription to fashion industries.

Figure 4: (a) and (d): 3D Printed Smart Glasses to Help Dyslexic Children. (e): Sunglasses Developed by Adidas [55] (b): 3D printed eyeglass frame developed by BRAGi® [130](c) Fritz Frames® [131] (d): Hoet® [132](f): Klenze & Baum® [133] (g): Materialise's® [134]. Reproduced with permission, Copyright @2021 Google.

Table 6: Commercial eyeglasses brands summary

Commercial eyeglass frame brands	**Characteristics**	**Types of 3D printer**	**Ref**
Abeye®	Relieve people suffering from dyslexia. Concretely, the wearer can activate a filter by a simple pressure, thus removing all the mirror images seen by the dyslexic person. A rechargeable battery embedded inside the strong frame.	HP Multi Jet Fusion	[135]
Adidas®	Light weight of merely 20 grams, features a special spiral structure Adidas enhanced the glasses with non-slip contact points on the nose pad to improve the stability and make them as comfortable as possible.	Digital Light Synthesis (DLS)	[55]
BRAGi®	72 key points on the face to serve as the basis for the glasses' subsequent frame design.	SLS	[130]
Fritz Frames®	prescription, blue light filtering and sunglasses for both adults and children.	SLS	[131]
Hoet®	The frames are Light weight and rust-free and anti-allergic, light, yet durable and well-fitting. They are available in various lens and bridge sizes.	3D laser-printed	[132]
Klenze & Baum®	Unique function: if the temple is overloaded or overstretched, it can give way and even pop off. Lightweight. To adjust its strength, metal inserts into the frame temple.	DMLS, SLM	[133]
Luxexcel®	They produce augmented reality & virtual reality with a distinctive frame structure.	Inkjet	[136]
Materialise's®	Frames for the fashion industry exhibut different shapes, styles, functionality, and customization.	SLA	[134]
Monoqool®	The frames consist of up to 600 super-fine layers and undergo more than 30 post-processing steps including glass blasting, coloring, coating and polishing, before reaching the final product.	Industrial SLS printer	[137]
MYKITA's Mylon®	Lightweight frame that still has outstanding comfort.	SLS	[138]
NETLOOKS®	It uses PA12 to create frames adjusted to the wearer's morphology – length of the temples, face width, etc. – and the color of the glasses. The wearer can also choose the color of the	Powder sintering	[139]

	frame and thus obtain a result totally adapted to his needs.		
Odette Lunettes ®	Fashion style with high strength	HP Multi Jet Fusion	[140]
Rolf Spectacles®	Flexible, natural and skin-friendly. Lightweight, extremely high quality, and noble material and therefore ideal for the production of spectacles.	SLS	[141]
WiresGlasses®	frames are printed from bio-plastic made from castor beans, a single stainless-steel wire	DMLS	[142]
YOU MAWO®	Scan via cell phone or tablet, YOU MAWO can then use this data to design, adapt and, of course, 3D print the spectacle frames.	Selective laser sintering	[143]

6. Literature review on 3D printed smart eyeglass frames

Smart eyeglass frames integrated with sensors and actuators could serve in many assistive applications, ranging from physiological monitoring to interactive daily lifestyle activities [144]. Smart eyeglass frames respond to external triggered stimuli. For an eyeglass frame to be smart, several sensors such as smart materials, fibers and electronic sensors must be added to the eyeglass frame or can be made using stimuli responsive polymers (i.e., as shown in **Figure 5**, the polymer responds to the change in temperature by changing colors). An essential wearer acceptance criterion for smart eyeglasses is that they are not stigmatizing, i.e., sensing, interaction, and processing functions must remain invisible to bystanders or users. For instance, earlier works have shown that personalized eyeglass frames fitting to match sensor positions with head landmarks is a prerequisite-site to retrieve accurate physiological measurements [144]. The smartness of the eyeglass frames is not restrained to regular eyeglasses but also applied in different commercial eyeglasses by intelligent mega-techs companies such as Google Glass, which substantially affect a person's physiology. Often Google glasses use silicon that can hardly be 3D printed using any 3D printer due to thermal changes. As a result, they use casting silicone into a 3D printed eyeglass frame shape mould, a cost-effective and quick manufacturing method.

A group of researchers managed to use the Google Glass for different physiological applications. J.Hernandez *et al*. have studied the effect of the sensors embedded in Google Glass frames, a head-mounted wearable device, to measure the physiological signs of the wearer such as blood volume pulse (BVP), heart rate and respiration rate. These head-mounted wearable devices often include a gyroscope, accelerometer, camera and other daily life monitoring sensors [145][146]. In particular, they have designed new approaches to use Glass's accelerometer, gyroscope, and camera embedded in Glass to capture subtle head motions of the wearer that are associated with to extract the pulse and respiratory rates of 12 participants during a controlled experiment. The findings indicate that it is feasible to achieve a mean absolute error of 0.83 beats per minute (STD: 2.02) for a heart rate and 1.18 breaths per minute (STD: 2.04) for respiration rate when considering different combinations of sensors [145]. These results comprised testing across sitting, supine, and standing still postures before and after physical exercise. In the end, the researchers recommended that with the continuous technological improvements in AM, they expect their results to be enhanced with the location of the sensors to facilitate non-intrusive access to meaningful physiological information during daily activity.

Likewise, F.Wahl *et al*. have also developed an eyeglass frame that is embedded with sensors and rechargeable batteries inside the eyeglass temple to study the influence of eyeglasses on developing and processing context information according to the wearer's needs [147]. The prototype's primary goal is to integrate a color light sensor that can detect screen use. The result infers the influence of the circadian phase on eye strain. The eyeglasses deliver inertial motion, environmental light, pulse sensors, data processing, and wireless functionality with sensors that are embedded into the bridge of smart eyeglasses frames [147]. To couple with the above, some of the smart eyeglass designs include Micro-electromechanical systems (MEMS), which are small integrated devices that incorporate mechanical and electrical components. The MEMS is intended for monitoring concentration and energy expenditure during physical activity [148].

The AM process plays a vital role in making smart eyeglass frames. For example, R. Zhang *et al.* produced an eyeglass frame that investigates 3D printing of conductive paste to create lines and electrodes on custom-shaped eyeglasses for feasible wearable chewing monitoring applications [144]. They have manufactured the eyeglasses temples that included printed conductive lines and electrodes using the FDM printer. The main reason for using for the FDM printer is they have used polymer filaments that could embed the electrodes and to make the topography of the frames appealing. In **Figure 5a**, the prototype has two electrodes of 20×3 mm, and below prototype has larger electrodes of 20×4.5 mm. Each electrode connects to a line of 300μm width. They evaluated the resistivity of Electrodes 1, 2 as well as Lines 1, 2 for both prototypes and tested the EMG (monopolar Electromyography) as shown in the **Figure 5a**. In the findings, they have observed that the electrode placement and line routing applied on 3D-printed temples with two different electrode dimensions can be used as a home for sensors that can measure Temporalis EMG signals [144].

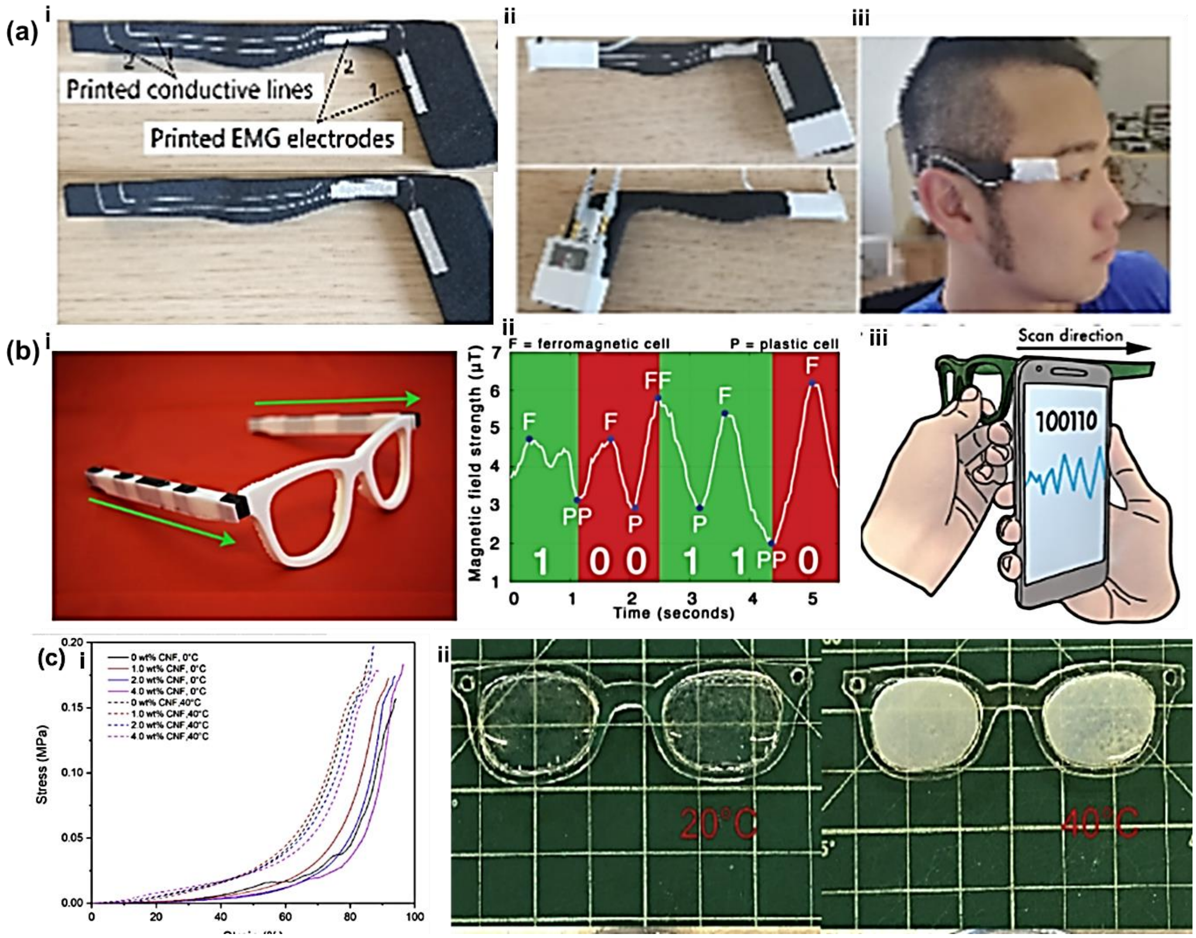


Figure 5: (a). (i) Eyeglasses temples with printed conductive lines and electrodes [102]. (ii): Encoding and decoding magnetic information on various objects. Evaluation setup to analyses EMG signals. (iii): EMG recorder attachment [102]: Participant wearing the setup [102]. **(b)**. (i) Eye glass frames [103] (ii) Eye glass signal [103]. **(c)**. (i) Mechanical strength of CNF at different temperature (ii): The response of the eyeglass at 20 and 40°C. *Reproduced with permission, Copyright @2017 Advanced Material Technology.*

Besides, encoding information inside eyeglasses frames that can be fed to smartphones by scanning QR codes. V.Iyer *et al*. modeled and fabricated a pair of eyeglass frames with embedded magnetic fields that stored piles of data with a symbol length of 1 cm [149]. They have used desktop 3D printers and commercially available plastic filament materials to print the frames. Fundamentally, the application allows users to 3D print eyeglass frames, armbands, and artistic models with embedded magnetic data. The process was achieved by implanting the 3D printed wireless sensors and input widgets into the 3D printed Maglink eyeglass frames that can store data within objects using magnetic fields and decode them using smartphone magnetometers. The primary function of the 3D printed eyeglasses frames was to ingrain wireless sensors, input widgets, and objects that can intercommunicate with smartphones and other Wi-Fi devices without requiring batteries or electronics. **Figure 5(b)** demonstrates the glasses with data inserted inside both arms of the frames, where the black region corresponds to the ferromagnetic material. The frame structure was 12 cm long, with an encode of 6 bits data along the length of each frame arm [149]. The encoded piles of data can be EMG, ECG and any essential data that can be stored inside frame to be read with smartphone by scanning the arm's exterior or internal face. The interpreted signal at the smartphone from the left arm is shown in **Figure 5(b) ii.** Scanning of the frame shows a significant transformation in the magnetic field and thriving bit decoding.

On the other hand, researchers have also noted that the magnetic field information can be embedded discreetly into the frames structure by spray/painting it on the surface [149]. Another group of researchers (X. Sun *et al*.) fabricated a polymer eyeglass frame using a hybrid poly(N-isopropyl acrylamide) (PNIPAm)/cellulose nanofibrils (CNFs) hydrogel composite [150]. It was fabricated by inverted stereolithography (SLA) 3D printing that aims to enhance the mechanical properties and temperature sensing to provide a new platform for regulating lower critical solution temperature (LCST) properties. The hybrid composite has a tune optical and bioadhesive properties. The findings reveaedl that after 2.0 wt% CNF was integrated into the poly (N-isopropyl acrylamide) (PNIPAm)a remarkable 8°C reduction of the LCST was achieved compared to PNIPAm hydrogel crosslinked by TEGDMA without CNF(Shown in **Figure 5(c) i)** [150]. The effect of nanocomposite on the mechanical properties has shown a distinctive improvement as the mechanical strength of PNIPAm hydrogels exhibit different behaviors above and below the LCST. The Young's modulus (E) was calculated as the slope of the stress–strain curves, in the range of strain from 0 to 10 %. The result revealed that the endurance of the hydrogel properties at high temperature are enhanced when the CNF increases accordingly (As shown in the **Figure 5(c**). Besides the prepared PNIPAm/CNF hydrogels possessed highly reversible optical and thermal performance, making them qualified to be employed as durable temperature-sensitive sensors and functional biomedical apparatuses. Furthermore E.Smith *et al*. also have briefly discussed a research on the comfort of head-mounted displays such as smart glasses commonly used as small displays or projection technology integrated into eyeglasses or mounted on a helmet or hat to pick objects [151]. The research aimed at how to increase their product lifecycle using the manufacturing techniques and users comfy by surveying the users (shown in **Figure 6a**) [151]. The study highlights how weight modifications to smart glasses were investigated to determine the impact on the execution of picking/putting tasks. The study was done using augmented reality in warehouse operations by including the participants to respond various survey questions. Some of the top primary responses from the participants are hardware limitations and expensive eyeglass frame cost in case of fragility. According to their answer to the survey questionnaires, the front weighted, side weighted, and back weighted of the frame significantly affect the emotion, attachment, harm, perceived change, movement, and anxiety of the users while they are working [151]. Therefore, the results of the study urge an improvement of the eyeglass frame on the subject matter by inducing the AM techniques to imitate the users need specifically the cost matter.

Biological pulse indicator oximetry is often used to estimate the oxygen saturation level in blood. Recently, they have been integrated with smart sensing that intelligent devices can detect. F. Braun *et al*. invented a novel ear pulse oximeter that automated oxygen titration in eyeglass frames [152]. The ear pulse oximeter works by attaching the sensor to eyeglass frames via a short cable or wireless data and power transmission via a second system connected to the eyeglass frames (shown in **Figure 6(b), (d) and (e)**). The main aim of the invention is to overcome the lack of oxygen delivery mode monitoring challenge, which can be cumbersome for patients with chronic respiratory diseases. Therefore, integrating a pulse oximeter and nasal oxygen cannulas into the eyeglasses frame would reduce the burden of current problem. However, the device was produced using the traditional fabrication methodology and the researchers suggested that the manufacturing can be improved using AM with enhanced topology. Also, they predicted that AM can ease the fabrication techniques and make affordable cost.

In addition to the above, J. Hoon Lee *et al*. produced a 3D printed electronic eyeglasses (E-glasses) to monitor various biological phenomena such as heart rates, and to propose a strategy to coordinate the recorded data for active commands with game operations for human-machine interaction (HMI) applications [153]. In the experiment, they used a UV-responsive, color-tunable electrochromic ionic gel printed in SLA, and accelerometers deliver the capability of tracking precise human postures and behaviors. The sensors, including the soft, highly conductive composite electrodes inserted inside the E-glasses frames, enable them to achieve reliable, continuous recordings of physiological activities [153]. The findings shade light in the usage of smart eyeglass for the psychological and physiological fields, for instance extracting helpful data from the human body specified as exercise-related parameters or simple heart rates (as shown in **Figure 6c).**

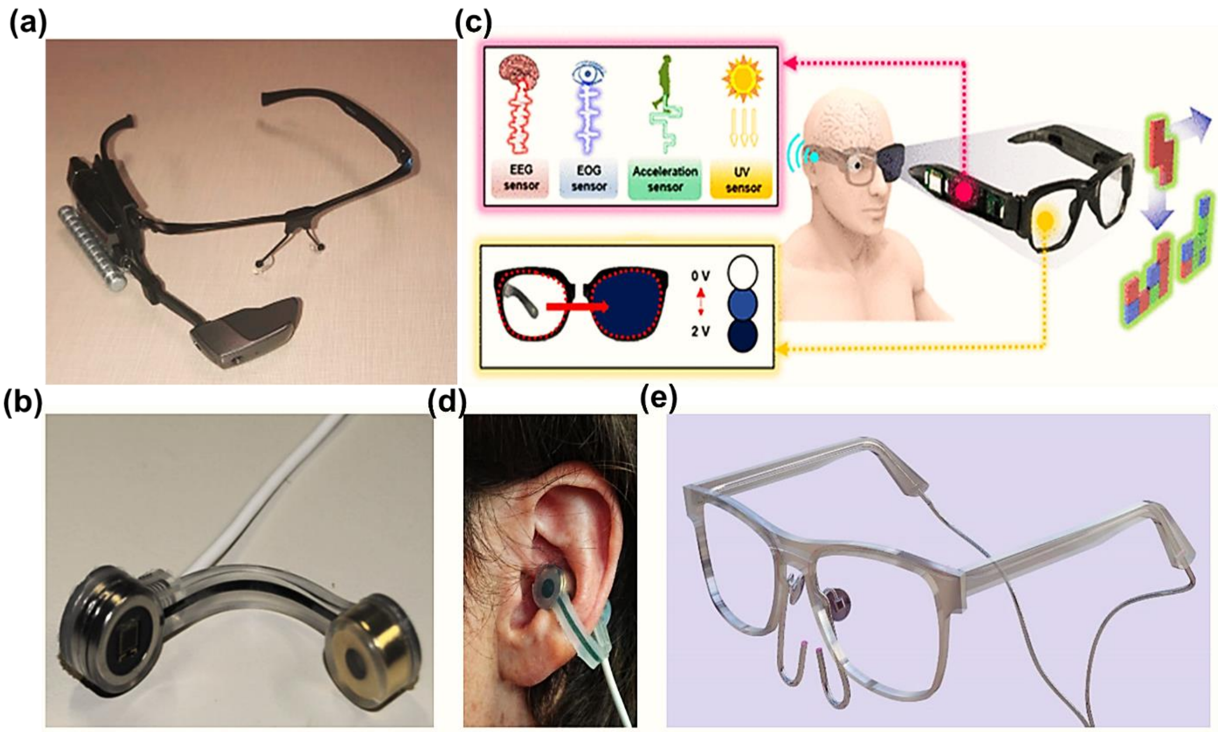


Figure 6: *(a):* Head-mounted displays [151]. *Reproduced with permission, Copyright @2021 Int.J.Ind.Ergon* .Prototype oxygen titration eyeglasses with integrated nasal oxygen cannulas (only for illustration of the future application). **(b):** Attached at the cavum conchae of a volunteer's ear holding together with static magnets embedded in the sensor [152]**.** *Reproduced with permission, Copyright @2020 Sensors.* **(c):** 3D Printed, customizable, and multifunctional smart electronic eyeglasses for wearable healthcare systems and Human–Machine Interfaces [153]. *Reproduced with permission, Copyright @2020 ACS.* **(d):** The magnets attached each other [152]. *Reproduced with permission, Copyright @2020 Sensors.* **(e):** Prototype oxygen titration eyeglasses with integrated nasal oxygen cannulas [152]. *Reproduced with permission, Copyright @2020 Sensors.*

Anjali Das C G *et al*. produced antibacterial eyeglass frames with silver nanoparticles, an antibacterial material, which were synthesized in green through a biological synthesis method [154]. The antibacterial properties were coated on the eyeglass frame materials. The findings demonstrate that the synthesized sample exhibited antibacterial activity against three types of bacteria and two types of fungi. They confirmed the possibility of using an antibacterial material in the process of frame fabrication [154]. However, a detailed manufacturing process and material preparation information was not given in the paper.

Most of the commercial mega-tech companies use Nylon material for the production of 3D printed eyeglass frames. Nylon powders in SLS 3D printer bestow lightweight, durable properties due to their flexibility and they can also collaborate with the new generative design features [51]. Furthermore, Nylon material provides resistance, durability, comfort, and versatility for eyeglass frames. As a result, it is more appealing to use in commercial and academic research.

A team of researchers from the Responsive Environments MIT Media Lab developed a smart eyeglass platform for a cross-context physiological measurement. P.Chwalek *et al*. developed an eyeglass frame for long-term monitoring of the psychophysiological scales (shown in **Figure 7**) [155]. Many underutilized physiological sensors were integrated into a streamlined 3D printed eyeglass frame, to measure nose temperature, blink detection, head motion tracking, activity classification, 3D localization, and head pose estimation [155]. The designed device has a vital role in the field of psychology for trait and anxiety measurement. They opted to manufacture plastics using Nylon PA12 through selective laser sintering (SLS) 3D printing. Since the researchers were using the Nylon PA12, a fine polyamide plastic powder, SLS can print strong and complicated geometries with better accuracy, though not as high as SLA. Also, SLS accomplishes the printing of the eyeglass frames without support. It also saves printing and post-processing time. The psychophysiological monitoring eyeglass frames are equipped with several sensors embedded inside the structure that can be read and interpreted based on their location. The design mainly focused on an aesthetic of the prototype that would minimize social anxiety and stress. It also optimizes users' comfort, weight, sensor selection, and long life battery to let the user put them on for long period [155]. Researchers at MIT concluded that it is meaningful progress in the psychophysiological modelling field, and they asserted that extra modification of the eyeglass frame could promise additional integrated sensors.

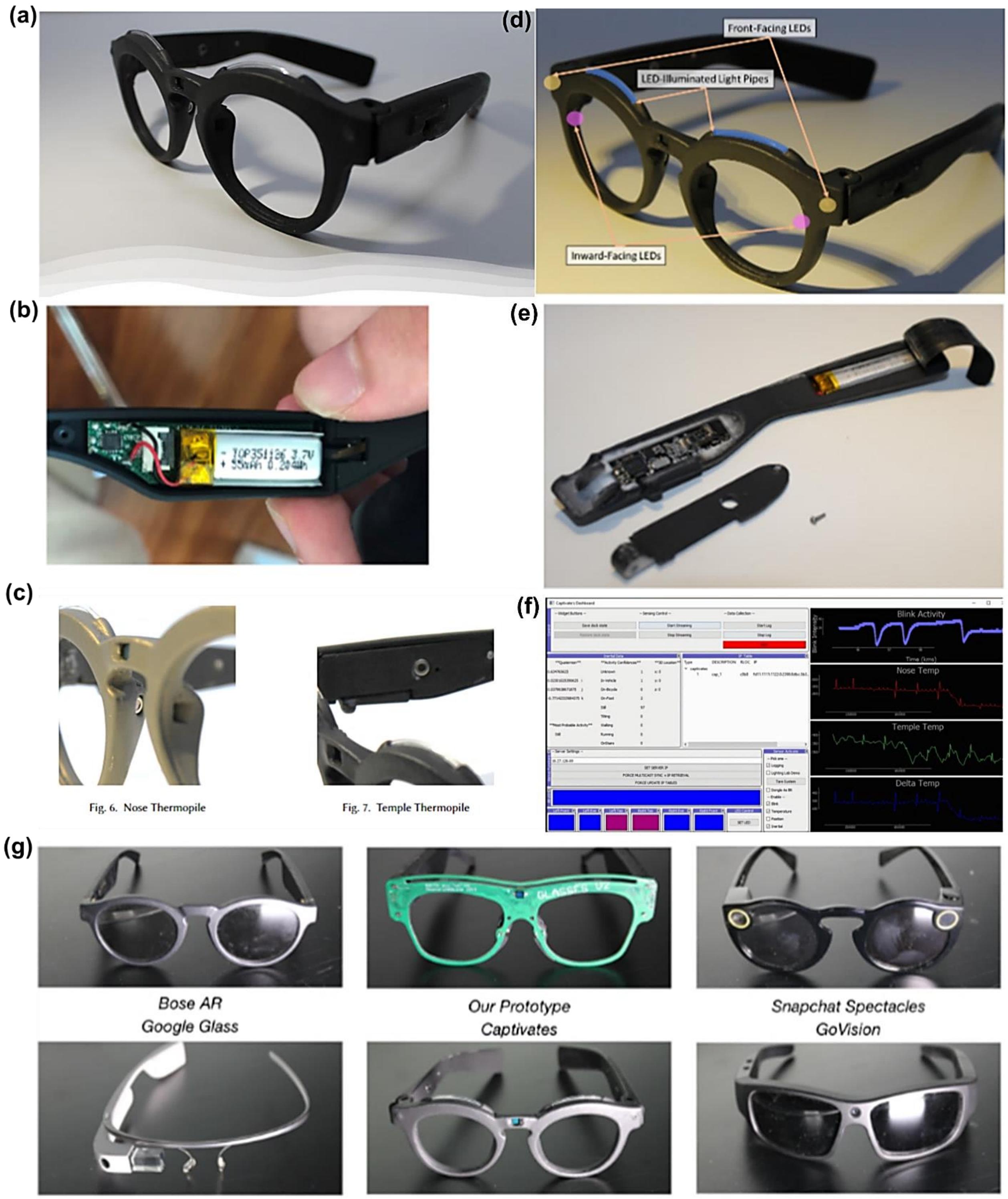


Figure 7:(a): Captivates System (b) One Sided Commercial Battery Design of Smart Eye-Wear (c): Nose Thermopile and Temple Thermopile (d): LED Locations (e): Battery Placement in Captivate's Arm. (f): Graphical User Interface for our Open Thread Border Router. (g): Smart eyeglasses frames Compared in Survey [155]. *Reproduced with permission, Copyright @2021 Google.*

Furthermore , J.Gwamuri *et al.* developed, fabricated, and tested 3D printable designs to confound limitations identified with mass-manufactured self-correcting eyeglasses demand in the 3rd world developing countries [156]. The designed eyeglass frames aimed to make it affordable in areas with alleviated poverty in isolated areas, manufacturing sustainably with minimal waste. The produced 3D printable eyeglass frames have self-adjustable glasses that can profoundly benefit communities with far more diversity in product design since the glasses can be customized for the individual based on their preference. 3D printing can also offer the potential for significant cost reductions since it is open-source 3-D printing that can empower developing world communities via affordable cost and customized products. The fabricated innovation offers the potential to substitute both centrally conventional fabrication systems and self-adjusting glasses. It also minimizes the high cost of conventional optics correction experience, including those provided by the highly-trained optometrists and ophthalmologists and their associated equipment. The authors also asserted that varying the lens shape and size would make it less challenging to meet the temporary, geographical, and clique-shifting socially acceptable provisions specified by the world's teenagers [156].

7. The essence of AM fabricated eyeglass frames with the growing technology trends in the electronic industry

Smart glasses being the future of wearable technology, it is inevitable that their utilization and makeup is required to encompass the latest technologies in its production components[153]. With that, interest in the production of AM fabricated eyeglass frames has also been growing with an expectation to match growing trends in the electronics industry. The technologies used in the development of smart eyeglasses to create the future platform for human-machine interaction (HMI) are some to mention. The personalization of 3D printed smart eyeglasses to overcome the limitations of smart eyeglasses that only monitor various biological phenomena and to enable them to coordinate the recorded data for active commands [153]. And game operations for HMI interaction applications have been one of the growing attentions in the field. Embedding soft, highly conductive composite electrodes in the smart eyeglasses enables us to achieve reliable, continuous recordings of physical activities which can further be custom developed to track precise human postures and behaviors.

Moreover, the semiconductor industry is not only observed to end the international roadmap of semiconductors (ITRS) and embark on quick advancements with the complementary metal oxide semiconductor (CMOS) but also stretch to the Beyond CMOS technology[157]. The production of the current nano-scale transistors with 3D structure and advanced strain engineering has very scaled down gate and source/drain regions according to Moore's law[157]. However, the international roadmap for devices and systems (IRDS) recognizes that the traditional scaling limits are coming to an end although CMOS scaling and Moore's Law are anticipated to continue in the coming years[157]. The extremely heightened prices and fundamental physical effects, such as critical dimensions and statistical distributions in reducing the size of traditional CMOS gate length, are expected to put a roadblock to scaling. Beyond CMOS is the future of digital logic technologies that expand beyond the present CMOS scaling limits. IRDS places a heavy focus on the research and advancement in this technology in producing high performance and low-power consumption semiconductors [157]. Companies such as Intel have also been key players in driving this Beyond CMOS technology forward. The future Beyond CMOS is expected to bring novel computing paradigms, functionalities, and applications at a nanoscale level. Given that, it is assured that its implementation into smart glasses would highly benefit and depend on 3D printed or AM fabricated smart glass frames.

Display technology has been one of the most challenging parts of developing smart glasses. The two main types of displays in smart glasses are the curved mirror displays and wave guide displays [158]. Yet, since the device must be bulkier and the image is less sharp with the curved mirror approach, the waveguides is newer set of technologies which are still being developed for efficient use. It works bending projected light in from of your eyes to display a visual field that includes 3D augmented reality (AR) objects. The challenges with these technologies however are the limited field of view (FOV) and resolution that is lower than desired. Increasing FOV would mean increasing the size of the waveguides and the bulkiness of the glasses[158]. Whereas the complex optical system in smart glasses added with other complications such as colour accuracy and real-world distortions, degrade resolution and increase the challenge in creating a high-quality display. The Clear-vu reflective waveguide technology is one of the technologies designed to combat these challenges. It uses a surface structure made up of several reflecting structures which enables it to have a thinner light guide while maintaining a large eye motion box as well as large FOV[158]. This technology has lower cost, uses traditional coatings and moulded plastic substrate, has better efficiency, large eye box and FOV, and has no colour issues. The main challenge of this technology is to precisely mould the light guide and its surface structure while keeping the right compromise for performance and cost[158]. Luckily, these challenges seem to be easily avoided if the eyeglass is AM fabricated. The precision in the design to encompass these features can be specified in the AM process as discusses in the rest of this paper.

8. Optimizing the Eyeglasses Frames Topography using Generative Design

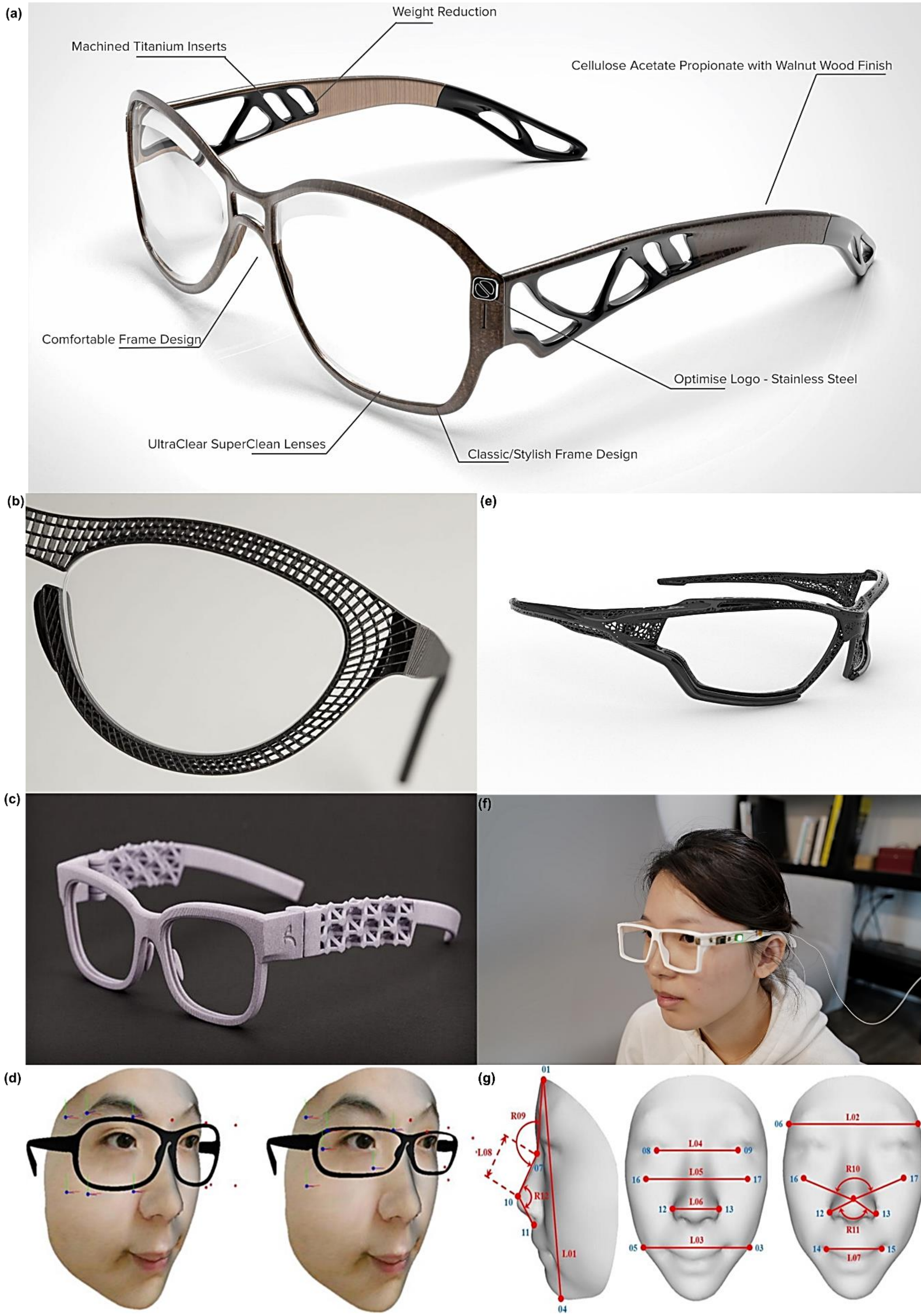
As previously mentioned, in 3D printing, eyeglass frames are fabricated in successive layers. Thus, in some complex frame manufacturing, such as intricate design for the fashion industry, the maximum slope of the overhanging geometry becomes a significant limitation in 3D printing [159]. The most common method to overcome this issue is using an additional support structure composed of the same or different material, then removed after the 3D printing completed. These support materials often result in undesired problems such as waste of material in case of DLP, SLA and FDM. Moreover, they leave scars on the frame structure, which limits the mechanical properties of the frames and initiates crack propagation. Besides, the tolerance of the frame design for the lenses can be diminished. Moreover, the post-processing is time-consuming and frustrating, mainly when the support structures are printed in difficult-to-access regions, or extra surface treatment operations (such as sanding or acetone vapor smoothing) are needed [160]. Therefore, to solve the challenge of manufacturing in terms of support material waste and production time, engineers developed CAD software backed by Artificial Intelligence (AI) algorithms. The CAD software is being trained using piles of design data and can boost the possible future solution of the design based on the comparison of several design possibilities. Most importantly, the AI-supported software mitigates the risk of breaking delicate parts of the printed frames by optimizing the morphology of the eyeglass frame feature. One of the top software that has been commonly used in improving the topography of eyeglass frames is Topology optimization. However, topology optimization is subjected to manufacturability constraints [161].

Due to the complexity of the organic-looking shapes of topology, the process mainly attracts academic researchers rather than commercial entities. However, most commercial eyeglass frame producing companies use generative design software, which is more viable in academic research and real-world production. The fundamental advantage of the generative design process in optimizing the 3D printed eyeglass frames begins by specifying the mechanical properties of the eyeglass frames. This process is performed by providing the software the numerical values such as desired force the sample that can resist at most, and the applied pressure and the type of material intended to use specific sections of the frame section [162]. Also, generative design is used to produce more efficient designs that are lighter, stronger, and in some cases, more artistic design. Nowadays, industrial manufacturing companies are embracing generative design to redesign old products or generate new ideas [163]. As a result, CAD entails designers and engineers exceeding the performance of conventional 3D printing of the eyeglass frames. Autodesk's generative design software implement experiments in simulations for the investigation of fundamental mechanical properties analysis such as buckling, fatigue, and failure points before the sample is being printed [162]. Engineers further refine the design parameters, setting load prerequisites, deflection, rigidity, material selections, cost of production, weight conditions, and even manufacturing techniques without much effort and less time [162]. The fascinating outcome of the generative design accounts for the solution of wear and tear of distinctive manufacturing strategies, such as warpage and deformation occurring in 3D printed samples, saving manufacturers time and capital on dead-end plans (shown in **Figure 8a, b and c**) [162].

R. Ashima *et al.* reported the effect of developing eyeglass frames using the fast-developing automation and manufacturing of smart materials in additive manufacturing technologies using the Internet of Things (IoT) principles [164]. They exclusively discussed the frames that can be manufactured using 3D printing and the functions of embedding integrated electronics inside the frame to store information. Once the structure is equipped with lenses, the 3D-printed smart eyeglasses are ready to track the user's activity using data retrieved from the electronics inside the frame [52].

A group of researchers from MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL) developed a novel 3D printed eyeglass frame, which shows a 3D design environment that allows users to digitally model an object's physical form and electronic function simultaneously [165]. These researchers embedded the *MorphSensor* inside the eyeglass frame with an integrated blue light sensor and microcontroller. The frame structure was well developed to sustain the electronics sufficiently (shown in **Figure 8f**). Its application is aimed at correcting light intensity, where the glasses detect when the user is being exposed to too much blue light and sends alert signals via an LED or noise [165]. All these parameters use the AM generative design to ease the manufacturing system of a lightweight mechanism. Since the generative design initiative optimizes the materials, agility, strength, and cost performance of the eyeglass frames. Besides, *SmarTech* analysis reported that AI and machine learning trained generative design provide greater design possibilities from multiple data stored in the system [166]. Designers have more freedom in creating new looks for future development (as shown in **Figure 8c**). Researchers can test new forms and textures that would be economically challenging and unviable with conventional manufacturing techniques [167]. Therefore, the single most significant segment in eyewear AM is final parts production, which is anticipated to expand to a $1.9 billion opportunity in a market worth $3.4 billion by 2028 [166]. This is why companies are embracing generative design and are using additive manufacturing in various business entities.

Equally important in the design approach, Li *et al.* developed a machine learning-based affective design dynamic mapping approach (MLADM) to optimize the CAD design [168]. Fundamentally, the techniques enabled a faster turn-around time of products. Since the algorithm trains the CAD software with collected social face data that are changing unconsciously, it results in an alteration in consumers' affective reactions. Therefore, the approach to collecting consumers' affective responses extensively, dynamically, and automatically is necessary. In another similar fashion, researchers W. Lu *et al.* presented the methodological framework used to develop the connections between users' emotional responses and the geometrical features of an eyeglass frame design [169]. In the process, they have used a computer interface that is trained to support data acquisition [169]. The approach enhanced the various shape characteristics in correlation to the impact users' emotional responses (as shown in **Figure 8d**). To prove the relationship between the type of users' reaction and the preference of the eyeglass frame, some social experiment researchers' claim that eyeglass frames are the target product, including the design features regarding personality traits that are indicated by facial outlines [170]. To shade light on the correlation of eyeglass frames and the behavior psychology, Chih-Hsing Chu *et al.* proposed a computational framework for personalized eyeglass frame design based on parametric face modeling data [171]. An enormous piece of 3D facial models is gathered by non-contact scanning trained data (as shown in **Figure 8g**) The data includes different dimensions of the face geometry and can be utilized by the design. The main ambition of the models is not only to adjust the frame design in real time but also to evaluate whether or how the design style fits individual facial characteristics based on their behavior traits [171]. The findings infer that how the algorithm enhanced the design by utilizing big, collected data. The data collection for the eyeglasses frame shows there is a strong relationship between the optimum design and users' facial features in terms of the cultural comfy as well [172] [173].


(a)
Weight Reduction
Machined Titanium Inserts
Cellulose Acetate Propionate with Walnut Wood Finish
Comfortable Frame Design
Optimise Logo - Stainless Steel
UltraClear SuperClean Lenses
Classic/Stylish Frame Design
(b)
(e)
(c)
(f)
(d)
(g)
01
R09
L08
07
R12
10
11
L01
04
06
L02
02
08
L04
09
16
L05
17
12
L06
13
05
L03
03
R10
R11
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L07
15

Figure 8: (a). Lightweight eyeglass frame produced using generative design. *Reproduced with permission, Copyright @2022 Google* (b). Application Spotlight: 3D-Printed Eyewear. *Reproduced with permission, Copyright @2022 Google.* (c): Lightweight generative designed eyeglass frames. *Reproduced with permission, Copyright @2022 Google.* (d): computational framework for personalized eyeglass frame design based on parametric face modeling[171]. *Reproduced with permission, Copyright @2017 Advanced engineering information.* (d) Lightweight eyeglass frame. *Reproduced with permission, Copyright @2022 Google.* (f): MorphSensor embedded inside the eyeglass frame with an integrated blue light sensor and microcontroller. *Reproduced with permission, Copyright @2022 Google.* (g) The data acquired from user for the parametric CAD [171]. *Reproduced with permission, Copyright @2017 Advanced engineering information.*

9. Fundamental Limitations

3D printing of complex samples with intricate features is an intensive design process and involves expensive materials usage. Recently, the eyeglass frame structure has shown a remarkable development of smart three-dimensional (3D) lightweight structures, which are expected to possess self-shaping, self-folding and self-unfolding performances [174]. However, AM technology is still suffering from a fundamental limitation that cannot be compromised with the prototype's functionality. 3D printing technology has an issue with the types of material usage. For instance, the use of stainless steel metal and blending of the nanomaterials into polymers to enhance the mechanical strength is still challenging [77][175]. Plus, the incorporation of nanomaterial and nanocomposite into polymers can cause aggregation that may induce some cavities inside the 3D printed sample that can propagate fatigue that diminish the mechanical strength effectively [176][177][178]. Increasing the durability of eyeglass frames using nanomaterial composites requires in-depth research in AM.

Moreover, during the printing process, a lack of discontinuities in DLP printers arises when a new layer of polymer materials is deposited. Similarly, shrinkage porosity occurs due to the discontinuities that appear when the liquid polymer changes into a solid. The main reason behind the shrinkage porosity is that the polymers cannot compensate for the shrinkage or density change during the solidification since the material undergoes a liquid-to-solid phase transformation. Another possible challenge with the technology is the void formation due to the entrapped spherical shape of air inside the resin that could not escape because of the high speed of the printing process [178][179]. In the FDM, DLP, and SLA printing techniques, part warpage often arises due to the buildup of residual stress and relaxes when the sample part is removed from the build plate.

From a chemical perspective, some materials used for frames manufacturing cause various health risks. For example, researchers from the University Of California School Of Medicine discussed the allergic contact dermatitis (CD), an itchy inflammation caused by direct contact with a material from eyeglasses frames [180]. According to reported myriad of cases in the survey they conducted, the primary materials that can cause the CD allergies are nickel, phenol-formaldehyde, rubber, plastics, and ethylene glycol monomethyl ether acetate (EGMEA) [180]. These compounds are included inside the materials used for manufacturing of the eyeglass frames using AM. In the survey, they collected detailed data from across the world. According to the analysis, materials that cause the inflammation CD are part of the eyeglass frames that are widely used in the AM to enhance mechanical properties, aesthetic purposes, and research goals. Some of the materials are metals such as cobalt and nickel, plasticizersabietic [115][181][182][183][184]. Besides, solvents such as EGMEA and methylethylketoneare are some of the commonly used chemicals that cause CD. In addition to the above, UV stabilizers dyes such as anthraquinone brown-black dye paraphenylenediamine paraaminophenol solvent yellow 3, red 26, red 481 are among the top materials that cause the CD [182][180].

Additional research from dermatologists and skin specialists revealed that some materials used for eyeglasses frames can also cause inflammation behind the ear [185][186][187]. This is a case of erythematous or fissured plaques, an area of clearing in a flat confluent growth of bacteria or tissue cells in the retroauricular area that is an auricular region of the ears on the neck. Also, some materials can irritate the skin, such as granuloma fissuratum (i.e. thickening of the skin in response to low-grade, chronic pressure/rubbing caused by eyeglasses) on the nose near the inner ocular canthus(i.e. corner of the eye where the upper and lower eyelids assemble)[188]. So proper skin therapy should be involved before any eyeglasses are worn. Moreover, authors including M.Šitum *et al.* from the University Hospital Center, Department of Dermatology and Venereology, Zagreb, Croatia, contended the CD consequences of using titanium metal for eyeglass frames [115]. According to clinicians, CD allergy due to eyeglass frames is abnormal; sometimes, it could be experienced at any age [115]. The study addresses several further questions on CD from eyeglass frames that should be presumed in patients with retroauricular dermatitis on contact with the skin. M.Šitum *et al.* also discussed a myriad of materials that could cause CD, including metals, cosmetics, plastics, rubber, solvents, antioxidants, dyes, and waxes; in which some of them are included inside an eyeglass frame [115]. From the study perspective, 3D printing could also be the source of the CD as well. Since it has been discovered that UV stabilizers and nickel from eyeglass frames are the most common allergens; thus, the 3D printed eyeglass frames using the UV source printers could be a source of CD. Besides, M.Šitum *et al*. also noted that palladium or titanium, a common eyeglass frames materials, were also reported they can cause an allergic CD [115]. The authors also remarked that most plastic glasses are fabricated either using traditional or 3D printing techniques from zyl or propionate that include other materials, such as nylon, carbon, polycarbonate, optyl, and polyamid sources of the CD [115]. Some of the common procedures to test the allergic behavior of titanium eyeglass frames are using patch (epicutaneous) tests on contact allergens [115]. Although topical corticosteroid therapy can also be used to test the allergen behavior, the results are quick clinical resolution and do not prevent recurrences. Some researchers also suggested that modifying the frame material is the sole solution for these patients to avoid the eyeglass frames' allergenic infection. However, the existing research has not discussed alleviating manufacturing techniques' challenges. Also, hypoallergenic eyeglasses (i.e. relatively unlikely to cause an allergic reaction) can be produced using 3D printing/AM.

10. Conclusions and Recommendations

In this article, we reviewed the literature on the fabrication of eyeglass frames, with a particular focus on AM fabrication methods. AM involves the fabrication and optimization of eyeglass frames using a 3D CAD model CAD. Unlike the subtractive or traditional manufacturing processes, AM is a layer-by-layer process. In comparison to the subtractive process, AM provides substantial advantages in terms of material waste, cost, and ability to produce complex morphology of a sample. The subtractive/traditional manufacturing technique begins with a big block of material and subtracts till the final desired outcome is obtained with more wasted scarps. On the other hand, with the AM process, materials are deposited layer by layer, with zero waste. Again, when it comes to the eyeglass frame, it offers freedom to design a frame structure and is more economically feasible than conventional manufacturing due to the reduced tools and storage costs. Therefore, AM has been employed in many eyeglass frame applications, including commercial products. It also works hand in hand with the generative design to optimize the final product. The AI-trained CAD software can optimize the morphological structure, mechanical properties, and amount of material used. It also provides a new opportunity for designers to develop a new appealing eyeglass frame brand in commercial entities. Adding nanomaterials can enhance the mechanical properties of the eyeglass frame. However, blending nanomaterials with metals and polymers of the frame has some issues. As mentioned above, some materials are chemically cytostatic and can be allergenic to the eye and skin. Nevertheless, choosing the proper AM techniques can overcome cytotoxicity and blending nanomaterial options to make the eyeglass frame product viable mechanically and chemically.

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