Fashion and Textiles

REVIEW

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Revolutionising textile manufacturing: a comprehensive review on 3D and 4D printing technologies

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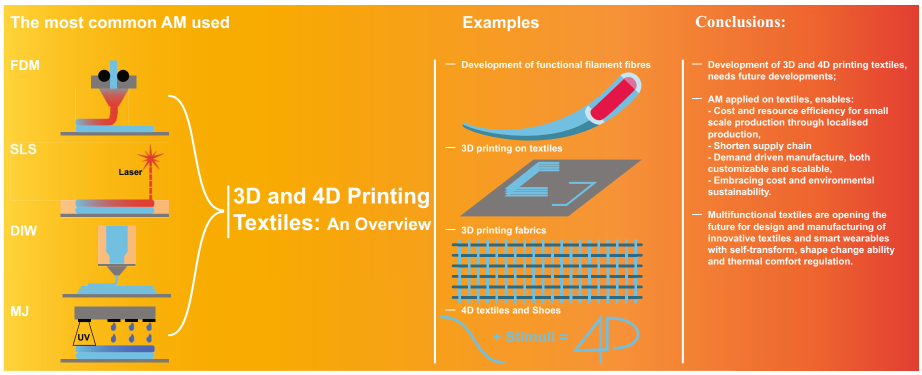
Abstract

An exhaustive and integrative overview of recent developments in 3D and 4D textiles based on Additive Manufacturing (AM) were provided in order to identify the current state-of-the-art. Despite all scientific progress, AM applied on textiles is a challenging technique and is still at an embryonic stage of research and technological development (R&TD), mainly due to the technological gap between featured prototypes and scalability in manufacturing. Despite its full potential across a range of different applications, such as development of functional filament fibres/wires, 3D printing on textiles, 3D printing completed garments and 4D textiles, needs future developments. Although, AM applied on textiles, enables cost and resource efficiency for small scale production through localised production, shorten supply chain and demand driven manufacture, both customisable and scalable, embracing cost and environmental sustainability. The opportunities and limits of 3D and 4D printing textiles are also discussed. Finally, the conclusion highlights the potential future development and application of the convergence of advanced computational design techniques, product customization, mathematical modelling, simulation, and digital modelling within multifunctional textiles.

Keywords: Textiles, 3D printing, 4D printing, 4D textiles, Fused deposition modelling (FDM), Selective laser sintering (SLS), Direct ink writing (DIW), Material jetting photopolymers (MJ)

Graphical Abstract



Introduction

Additive manufacturing (AM), also known as 3D printing, is defined by the ISO/ASTM 52,900:2021 as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" (ISO/ASTM, 2021).

Stereolithography was the first patented AM technology (U.S. Patent 4.575.330), by Charles Wall in 1984 (Hull, 1984). Since that, AM has undergone considerable development and has been moving beyond its original prototyping function and small-scale production to advanced manufacturing of functional components in industrial sectors such as aeronautics, automobile, biomedicine and textiles (Alghamdi et al., 2021; Tian et al., 2022). Nowadays, AM is an unavoidable area for the new industry revolution, also called Industry 4.0, due to its ability to address some of the most significant challenges of industry in this century, such as cloud manufacturing, near net shape products and their customization (Cerejo et al., 2021).

In this scope, the main advantages of AM, over conventional manufacturing process are: (1) geometrical flexibility, which allows to improve and optimize product functional and structural features, (2) microstructure-properties modification through metamaterials approach, (3) use of less raw material, (4) cost and resource efficiency for small scale production, (5) cloud manufacturing which shortens the supply chain due to a more localised production, with important sustainability benefits (Ali et al., 2019; Cabigiosu, 2020; Ford & Despeisse, 2016; Kabir et al., 2020; Keefe et al., 2022; Kim et al., 2019; Praveena et al., 2022; Ruckdashel et al., 2021; Vanderploeg et al., 2017). Huang et al. (Huang et al., 2013) stated that: *"AM is expected to become a key manufacturing technology in the sustainable society of the future".*

On the other hand, the main disadvantages of AM are: (1) post processing needs, (2) process variability influence the 3D object's reproducibility, (3) undesired porosity and anisotropic features that compromise the mechanical properties obtained, (4) size limitations on 3D objects to print and (5) slower build rate when it comes to mass customization (Cabigiosu, 2020; Chakraborty & Biswas, 2020; Faludi et al., 2015; Kim et al., 2019; Praveena et al., 2022).

The seven categories of AM, according to ISO/ASTM 52,900:2021 are: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat polymerization (ISO/ASTM, 2021). The four main classes of materials used in AM are resins and colloids, filament/paste, powder and solid sheet (Guo & Leu, 2013). Therefore, the selection of materials depends on AM technology adopted and ranges from thermoplastics, thermosets, hydrogels and conductive materials to rigid ceramics (Guo & Leu, 2013; Ligon et al., 2017).

The evolution of AM is clearly evident in recent applications across nearly every industry, such as in footwear ("Nike Flyprint is the First Performance 3D Printed Textile Upper," 2018), jewellery (Yap & Yeong, 2014) and fashion industry (Zarek et al., 2016b), since 2010 when Iris Van Herpen showcased her first 3D printed dress (Herpen, 2010) or with the completely 3D-printed ready-to-wear N12 bikini (Lim & Fashion, 2014), trigged by the low cost and product customization from wearer's body through a 3D scan (Spahiu et al., 2016) and design highly complex structures (Xiao & Kan, 2022).

Also, functional filament fibres are been embedded in wearable textiles, with new functionalities, such as capacitive soft strain sensor fibres for detecting elongational strains (Frutiger et al., 2015), flexible energy harvesting (Chen et al., 2020; Peng et al., 2019; Zhao et al., 2018), heaters (Park et al., 2019), piezoelectric and triboelectric nanogenerators (Dong et al., 2020; Park et al., 2018), flexible supercapacitors (Anjum et al., 2020), light-emitting (Grimmelsmann et al., 2016), light electroluminescence device (Tadesse et al., 2018), colour changing materials (Kan et al., 2015; Kao et al., 2016; León-Cabezas et al., 2017), thermal comfort regulation fibres (Chatterjee & Ghosh, 2020; Gao et al., 2017; Li et al., 2021) and tactile sensors based on triboelectric effects (Chen et al., 2021).

4D is opening new innovations and applications through research and technological development (R&TD) of programmable textiles materials and smart wearables with self-transform and shape change ability (Khan & Hassan, 2021; Leist et al., 2017; Rastogi & Kandasubramanian, 2019). 4D printing combines 3D printing with a time change element under the influence of an external stimulus. 4D printing can be applied to textiles—4D textiles, therefore 4D textiles are structures or textile products that can change shape or function over time. A particular stimulus is applied to active the switching process. Through this technology, garments or shoes (as an example) can change over time in terms of functionalities, shape or properties when exposed to a specific stimulus that triggers the response (Choi et al., 2015; Momeni et al., 2017).

Despite all scientific progress, AM applied on textiles is still at an embryonic stage of R&TD mainly due to the technological gap between featured prototypes and scalability in manufacturing (Gehrke et al., 2019). In addition, comfort is a widespread problem in textiles also the whole textile electronic should withstand washing, ironing and stretching over its life cycle (Paret & Crégo, 2019).

This paper aims to provide an exhaustive and comprehensive literature review of 3D and 4D print to highlight the full potential of these techniques based on textiles. The paper explores and discusses what research has been carried out and available products on the market until—2022.

The paper is organized into 5 sections. In Sect. "Additive manufacturing", the most common AM technologies used to create textile-based structures, are presented.

Sect. "3D and 4D printing textiles", developments and applications of 3D and 4D printing textiles, with a focus on four main topics: development of functional filament fibres/wires, 3D printing on textiles, 3D printing fabrics and 4D textiles, are detailed. The opportunities and limits of 3D and 4D printing textiles are explored in Sect. "4D textiles and shoes". Concluding remarks are finally given in Sect. "Conclusions".

Additive manufacturing

The most common AM technologies used to create 3D and 4D printing textiles, which include Fused Deposition Modelling (FDM™), Selective Laser Sintering (SLS), Direct Ink Writing (DIW) and Material Jetting Photopolymers (MJ) are depicted in the following subsections, as well as its basic principles and available materials. The main differences between these technologies are related to both, the method how the layers are processed and the materials used in the process, such as solid, powder and liquid-based methods (Pérez et al., 2020).

Fused deposition modelling—FDM™

FDM™ process was developed by S. Scott Crump in 1992 and patented in 1989 (U.S. Patent 5.121.329) (Crump, 1992). FDM™ is a material extrusion process which allows to build 3D objects layer-by-layer, from a filament spool, according to the CAD model. Since the FDM™ term is a trademark, the same technology is also known as Fused Filament Fabrication (FFF). This invention has transformed and catapulted the additive industry of 3D polymeric objects. Due to its simplicity and low cost, it is currently widely disseminated (for polymeric materials), both at industrial level and end users (Cerejo et al., 2021).

The first low cost commercial FDM™ 3D printing was introduced in 1996, with Genisys FDM™ printer and Actua 2100 3D printer (Wohlers & Gornet, 2016). FDM™ processing parameters such as nozzle and printing bed temperatures, printing speed, part infill pattern type, part orientation and density, raster angle and width, perimeters width, building orientation and layer thickness have a significant impact on quality, mechanical properties, build time and dimensional accuracy of printed objects (Jaisingh Sheoran & Kumar, 2020; Lay et al., 2019; Singh et al., 2020a, 2020b).

A broad range of standard, engineering and high performance filaments are available in FDM. Polycaprolactone (PCL), acrylonitrile butadiene styrene (ABS), polypropylene (PP), polycarbonate (PC), polyamide (PA), polylactic acid (PLA) and polystyrene (PS) are the most commonly FDM™ 3D printing materials (Parandoush & Lin, 2017). High performance filaments, such as polyetheretherketone (PEEK), TPU and silicone, show better mechanical, chemical and thermal properties than the commonly used plastic filaments (Sharma & Rai, 2022; Xu et al., 2021a; Zhang et al., 2020).

In order to improve the properties of the FDM™ printed objects, composite filaments with fibres and/or particles reinforced thermoplastics, have been developed (Cano-Vicent et al., 2021; Chatterjee & Ghosh, 2020). Composite filaments can be filled with electrically and/or thermally conductive nanoparticles, such as carbon black (CBs) (Hui Yang et al., 2017), carbon nanotubes (CNTs) (Ly & Kim, 2017), graphene (Geim, 2009), graphene oxide (GO) (Zhu et al., 2010), boron nitride (BN) (Joy et al., 2020) and silver nanowires/nanoparticles (Wei et al., 2015) with the aim to make them multi-functional materials, allowing its use on textile fabrics. FDM™ printed polymer composite objects are found to exhibit improvements in functional and structural properties compared to the unreinforced printed objects (Chatterjee & Ghosh, 2020).

Selective laser sintering—SLS

Under the U.S. patent 4.863.538, Deckard (Deckard, 1986) disclosed "a method and apparatus for producing objects by selective sintering", in 1986. SLS 3D printing uses a laser, which selectively melts the powdered material, fusing them into a 3D printed object. After the layer is completed, the building platform is lowered and a new layer of powder is added and melted on top of the previous layer. This process is repeated until the object is completely formed. SLS 3D printing does not require support structures (Guo & Leu, 2013; Kruth et al., 2003; Parandoush & Lin, 2017). Polymer powders based on nylon, PCL, PC, PLA, polyethylene terephthalate (PET) and TPU materials are available for SLS (Kafle et al., 2021; Kumar, 2003).

Direct ink writing—DIW

DIW was first developed by Cesarano and Calvert (Cesarano & Cavert, 2000) at Sandia National Laboratories in 1996 (U.S. Patent 6.027.326). DIW is an extrusion-based AM process, in which the filament-based suspensions or inks are continuously extruded out of the nozzle under controlled flow rates by the force of a piston, a screwing system or pneumatic pressure. Layer by layer, 3D objects are built, through filament solidification due to rheological transition from pseudoplastic to dilatant state or due to paste gelation (Chatterjee & Ghosh, 2020; Lewis, 2006; Xu et al., 2021b).

In DIW, inks materials such as polymers, biopolymers, ceramics or metal powders, hydrogels, organic monomers or nanomaterials, composite mixtures must meet stringent rheological parameters, which include its apparent viscosity, yield stress under shear and compression and also viscoelastic properties, in order to achieve the desired geometry and functional properties (Wan et al., 2020). DIW enables multi-material printing by using microfluidic printheads which, allows to switch or mix different materials, such as CNTs, graphene, polyvinylidene fluoride (PVDF), boron nitride, lithium iron phosphate nanoparticles, lithium titanium oxide nanoparticles, polydimethylsiloxane (PDMS) and polytetrafluoroethylene (PTFE) particles in order to 3D printing electrical, thermal, flexible filaments fibres for textile fabrics (Rocha et al., 2020).

Material jetting photopolymers—MJ

MJ is a 3D printing technology which allows to build 3D objects layer by layer, by jetting photopolymer or wax droplets through a thermal or piezoelectric mechanism, onto a build platform and solidifying them with ultraviolet (UV) light. This technology enables multi-colour and multi-materials 3D printing due to its multi-nozzle printhead, allowing printing hard and soft polymeric materials in a single process as well as providing high accuracy and smooth surface finish (Gülcan et al., 2021; Singh et al., 2020a, 2020b). Photopolymer resin materials can offer extreme durability, high rigidity and high temperature resistance and also can have similar properties to those of most common FDM™

3D printing thermoplastics materials, such as ABS, PLA and PC (Bass et al., 2016; Singh et al., 2020a, 2020b).

3D and 4D printing textiles

Recent developments and applications in 3D and 4D printing textiles have grown over the past decade focusing on four main topics: (3.1) development of functional filament fibres/wires which can be embedded into/onto textile fabric, (3.2) 3D printing on textiles (polymer-textile composites), (3.3) 3D printing fabrics completed garments or individual structures which might be assembled to create a flexible fabric and (3.4) 4D textiles and shoes, such as hybrid textile structures that can change shape and function over time when triggered by an external stimulus as temperature, light or other environmental stimuli (Chatterjee & Ghosh, 2020).

Development of functional filament fibres/wires

3D printing functional filament fibres have been developed through the addition of conductive electric materials in order to integrate them into textile fabrics for wearable and stretchable sensors (Gregory et al., 1989; Palanisamy et al., 2018; Tseghai et al., 2020), such as wearable lithium-sulfur bracelet battery (DIW and FDM™ based 3D printing) to energy storage and power supply electronic devices (Chen et al., 2020) or capacitive soft strain printing sensors based on multicore-shell fibre, consisting of concentric layers of alternating ionically conductive fluid and dielectric/encapsulant silicone elastomer in the form of filament fibre. Since it has a fibre shape, these sensors can be readily stitched or woven into textiles (Frutiger et al., 2015).

Researchers are combining both electrical, conductivity and elasticity of functional polymer fibres as well as the efficiency for integration into woven and knit textiles (Seyedin et al., 2020). Stretchable and flexible triboelectric nanogenerator fibres were woven into textiles for self-powered by Park et al. (Park et al., 2018). The authors argued that fibres can be manufactured on a large scale and can be used in textiles. Wang et al. (Wang et al., 2017) developed a high flexible, strength and electromechanical stable all-fibre lithium-ion battery by combining polymers inks for DIW. The inks containing CNTs as conductive, PVDF as a binder and either lithium iron phosphate nanoparticles for fibre cathodes or lithium titanium oxide nanoparticles for fibre anodes, were developed. Both fibre electrodes were coated with a gel polymer (insulation layer), twisted and bonded to form a quasi-solid electrolyte. Stretchable elastic fibres with a conductive core and insulative sheath were DIW printed by Chen et al. (Chen et al., 2021). The conductive core is composed by PDMS and graphene particles, while the insulator/triboelectric sheath is composed of PDMS and PTFE particles. The core-sheath fibre can perform the function of a tactile sensor through triboelectric effects and tolerate tensile strain greater than 300%.

Beyond conductive electric fibres, thermal comfort regulation fibres (Gao et al., 2017) and flexible thermoelectric fibres (Peng et al., 2019; Zhao et al., 2018) are under investigation. Continuous flexible thermoelectric fibres were realized by Pen et al. (Peng et al., 2019), through DIW printed composite inks of bismuth telluride micrograins and non-conducting polymer as a binder, followed by roller-pair compression. The low-power energy harvesting was demonstrated on wearable electronic textiles. Zhao et al. (Zhao et al., 2018) conducted experiments on a 3D-printed flexible and wearable hybrid fibre-shape integrated with an asymmetric supercapacitor and temperature sensor, providing both energy storage and temperature monitoring in a range between 30 and 80 °C, with a sensitivity of 1.95%°C^{-1}. Thermal textiles based on thermally conductive boron nitride and polyvinyl alcohol composite fibres have been explored by Gao et al. (Gao et al., 2017). These fibres that were DIW printed, exhibited excellent mechanical (355 MPa, mechanical strength) and thermal properties (55% increase in cooling effect compared with commercial cotton fabric) and were used in woven and knitted fabrics. Leon-Cabezas et al. (León-Cabezas et al., 2017) blended PLA, ABS and TPU with different additives in order to provide functional properties, such as colour change (thermo/photochromic change), luminescence, conductivity and antimicrobial for FDM™ 3D printing.

An example of functional filament fibres/wires available on the market is the ChroMorphous. ChroMorphous is a user-controlled and colour changing textile through micro wires waved into the textile fabric. The colours and patterns of fabric are controlled through electricity and a smartphone application. Physically colour changing wires are due to an engineering blend of temperature sensitive pigments, micro cooper wires, electric current to generate heat and a computer chip. The wire's change temperature causes embedded pigment to change colour. Applications: fashion, textiles for home, automobile, office and defence ("ChroMorphous—A New Fabric Experience," 2022).

3D printing on textiles (non pre-stretched fabric, therefore non 4D)

Direct printing onto textile fabric substrates has been used to obtain different and functional composite structures (Dopke and Nils Grimmelsmann, 2017; Pei et al., 2015; Spahiu et al., 2017). Rivera et al. (Rivera et al., 2017) have demonstrated a range of techniques for embedding textiles into FDM™ 3D printed functional and flexible objects, opening a new design space for the 3D printing community.

3D printing processing parameters, such as nozzle and printing bed temperatures (Eutionnat-Diffo et al., 2020; Grimmelsmann et al., 2018; Hashemi Sanatgar et al., 2017; Spahiu et al., 2018), nozzle and printing bed distance (decreasing the distance between both the adhesive forces increases) (Grimmelsmann et al., 2018; Spahiu et al., 2018), printing velocity (Hashemi Sanatgar et al., 2017; Kozior et al., 2020) and orientation of the infill layers (Kozior et al., 2018), textile fabric characteristics (thickness, material, fabric structure and density) (Eutionnat-Diffo et al., 2020; Korger et al., 2016; Pei et al., 2015) textile net (net-like fabrics increases the adhesion between both materials, since large mesh openings provides better wetting and impregnation between the molten polymer and yarns/fibres) (Sabantina et al., 2015) and filament polymer properties (Kozior et al., 2018; Pei et al., 2015) influence the adhesion between both polymer and textile fabric.

Although, some reported drawbacks, such as dimensional accuracy, non-uniform shrinkage, voids generation which leads to layer debonding following printing and slower building rate (Biswas et al., 2021; Hajare & Gajbhiye, 2022), experimental research aiming at increasing the adhesion of the textile fabrics by mechanical, thermal (Ironing and drying oven) (Kozior et al., 2018; Mori et al., 2014), physical (low pressure plasma treatments) and chemical treatments (washing, acetone and desizing) (Gorlachova &

Mahltig, 2021; Korger et al., 2016; Kozior et al., 2018) or by polymer coatings (ABS, PLA, poly(methyl methacrylate) (PMMA) coatings) (Meyer et al., 2019; Unger et al., 2018) have been carried out.

Korger et al. (Korger et al., 2016) observed that the higher the adhesion bonding, the more hydrophilic a textile fabric is. The hydrophilic pre-treatments promoted the form-locking connections of the polymer with the textile fabric. The above results are in agreement with the work of Kozior et al. (Kozior et al., 2018) and Gorlachova et al. (Gorlachova & Mahltig, 2021), the latter also reported that the less hydrophobic a polymer, the higher the adhesion on a hydrophilic fabric is.

Adhesion is critical for the resulting material structure properties and depends strongly on the combination of textile and polymer. In order to quantify the adhesion of 3D printing objects to a textile fabric, Malengier et al. (Malengier et al., 2018) proposed three test methods (perpendicular tensile test, shear test and peel test), which helped standardize and benchmark their research. Sanatgar et al. (Hashemi Sanatgar et al., 2017) have investigated the adhesion optimization between polymers and nanocomposites on textile fabrics. The adhesion strength was quantified according to ISO 11339:2010. Adhesion tests were performed by Korger et al. (Korger et al., 2016), as specified in standard DIN 53,530, to evaluate the average values of maximum strength. In another research work, Korger et al. (Michael Korger et al., 2020) evaluated the abrasion and wash resistance of FDM™ 3D printed different thermoplastic elastomers (TPEs), such as TPUs and thermoplastic styrene (TPS) onto different knitted and woven fabrics made of cotton, polyester or aramid. TPUs showed better adhesion due to their high polar interactions with fabrics, high durability against abrasion and fastness to washing, while TPS resulted in 3D printed objects with good quality, comfortable and flexibility. The wear resistance of FDM™ 3D printed PLA onto polyethylene terephthalate (PET) fabrics performed on ASTM D4966-12 was studied by Eutionnat-Diffo et al. (Eutionnat-Diffo et al., 2020). They reported that

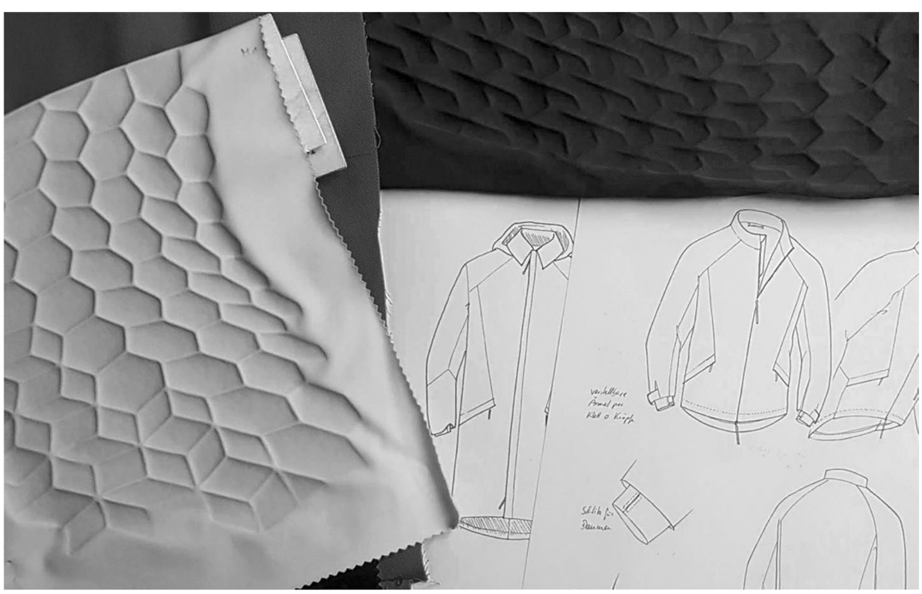


Fig. 1 Source: GRDXKN© ("GRDXKN 4D Printing Technology Structure Print—Functional Textile Solutions," 2022)

the 3D processing parameters, such as bed temperature and the textile fabric structure, defined by its weft density, weave pattern, roughness coefficient, fabric direction and yarn composition, had a significant impact on the adhesion, deformation, abrasion and tensile properties of 3D printed PLA onto PET fabrics.

A patented product based on 3D printing on textiles is the GRDXKN (Fig. 1). GRDXKN provides durability, flexibility, shock-absorbing, low weight, washability, protection to cooling down and abrasion-resistance. It is manufactured by printing a layer of polyurethane onto a fabric base, which reacts with heat and rises into a foam. The technology is available in multiple colour options and creates no waste production ("GRDXKN 4D Printing Technology Structure Print—Functional Textile Solutions," 2022).

3D printing fabrics

Attempts have been made to develop textile-like structures, such as woven or knitted structures (Beecroft, 2016; Partsch et al., 2015; Valtas & Sun, 2016). Melnikova et al. (Melnikova et al., 2014) combined the traditional approach of textiles structures with 3D printing technologies, SLS and FDM™, to print weft knitted structures. It was reported that SLS with Nylon powder provided a lack of structural flexibility, whereas FDM™ with soft PLA improved the flexibility, although it exhibited lower quality surface finish. Following the later research, Beecroft (Beecroft, 2019) evaluated the material performance of SLS Nylon (PA12) 3D printed weft knitted and interlocking structures. The structures exhibited both similar stretch and extensibility of weft knitted fabrics as well as the mechanical properties of the Nylon.

3D printed thin woven-like structures consisting of warp and weft were developed by Takahashi and Kim (Takahashi & Kim, 2019). By controlling the movement of an FDM™ printer head, the PLA filament is interlaced across the warp structures. Different patterns can be designed, through the control of the warp structures density and weaving/interlacing patterns, thus enabling users to create their own flexible fabric designs out of rigid PLA. Also, conductive or even more flexible materials than PLA can be employed. Forman et al. (Forman et al., 2020) introduced DefeXtiles, a thin, flexible and breathable FDM™ 3D printed quasi-woven fabric. Complex textile geometries are extruded perpendicularly to the bed, resulting in structures with a periodic gap between layers (small globs stretched along the print direction) and apparent warp-weft. Some explored applications were garment design, interactive objects, aesthetic patterning and actuators.

Chainmail structures consist of 3D printed micro or meso structures interconnected to create complex, foldable forms composed of thousands of articulated modules, which behave as a continuous textile (Gurcum et al., 2018). Chainmail patterns have been used in textile fabrics for garment production, such as Modeclix garment (Bloomfield & Borstrock, 2018) Voltage dress and venus dress (Koerner, 2017), both it were printed with a flexible material called TPU 92 with the SLS technology. Francis Bitonti in collaboration with Michael Schmidt and Shapeways factory, has created a tailored 3D printed garment for Dita von Teese, fully flexible and similar to chainmail. Made using SLS, the garment consists of 17 pieces and features about 3.000 unique articulated moving components, taking over 400 h to print. The garment was featured in New York Fashion Week in the fall of 2013 (Grain & Unver, 2016). The Nervous System project, co-founded by Rosenkrantz and Louis-Rosenberg (Rosenkrantz & Louis-Rosenberg, 2017), takes a new approach to chainmail structures by 3D printing. Unlike traditional fabric, the textile developed is composed of thousands of unique interlocking components to create a dynamical structure, fluid enough to be worn comfortably on the body. The 3D printed textile is not uniform; it varies in stiffness, drape, flex and pattern. Also the completed garment is customizable from the wearer's body through a 3D scan. Wang et al. (Wang et al., 2021) designed a SLS 3D printed nylon chainmail, which can switch between soft state to rigid state when vacuum packed, becoming more than 25 times stiffer. The chainmail is comprised of an interlocked array of octahedrons. In the soft state, the chainmail can freely bend, fold and drape over curved objects. Wearable exoskeletons, bulletproof vests and reconfigurable medical supports are some of the suggested applications.

Some research efforts have been focused on geometric structures. By using FDM™ 3D printing and exploring different geometric structures and materials (soft PLA, Nylon, TPU—Filaflex and Ninja flex), Spahiu et al. (Spahiu et al., 2020) designed a fully 3D printed dress. Both arrowhead shape structure and Filaflex filament, were selected for the final 3D printed model. Polymaker and Covestro jointly developed a processing technology to improve mass production of 3D printed wearable fabrics by combing three elements: flexible-materials specialized 3D printer and design software for fabric development. The design software allows users to create geometric patterns, moiré patterns, density gradients effects, shape changes and organic textures. Flexible materials based on TPU were also developed (Davies, 2022).

Bionic structures and 3D printing technology have been explored by Julia Koerner (Koerner, 2019, 2017) on the SETAE jacket and ARID collection. 3D printing SETAE jacket is inspired by both microstructure and colourful patterns of Madagascan Sunset Butterfly wings. The wing setae patterns were digitised through an algorithm, which translated the colour pixels into 3D bristle patterns. Also inspired by the crystalline formations of the Dead Sea, ARID collection is made of 38 3D printed objects, which can be assembled into a full dress or reconfigured into different combinations. The garment consists of a jacket, a skirt, a corset and a series of accessories.

In Table 1 are reported 3D printing garments available on the market or garments which were created for a fashion exhibition.

4D textiles and shoes

Skylar Tibbits introduced 4D printing concept in 2013 (Campbell et al., 2014). 4D is opening innovations and applications through R&TD of programmable textiles materials, smart wearables with self-transform and shape change abilities (Khan & Hassan, 2021; Leist et al., 2017; Rastogi & Kandasubramanian, 2019). According to Pein (Pei, 2014), 4D printing is defined as: "the process of building a physical object by additive layer manufacturing of stimuli-responsive composites or multi-materials system, which have the ability to change the shape/configuration, properties or functionality, when triggered by an external stimulus or through human intervention over a particular domain of time."

4D printing relies predominantly on the AM process and is also known as programmable materials or smart materials which are dependent on time-material-stimuli and structure–function correlations (Ali et al., 2019; Fu et al., 2022; Khare et al., 2017) as well as mathematical modelling and simulation (Pei & Loh, 2018; Zafar & Zhao, 2020).

Table 1 AM technologies, materials and features/applications with regard to 3D printing fabrics, are depicted

Ref	AM Technology	Materials	Research/Features/Applications
(Koerner, 2017)	SLS	TPU 92	Brand name: venus dress (Fig. 2)  Figure 2 Venus dress. Credits: Venus dress, Julia Koerner 2017. Photography: Tom Oldham Development state: fashion exhibition, 2013 Features: completed wearable 3D-printed dress

Table 1 (continued)

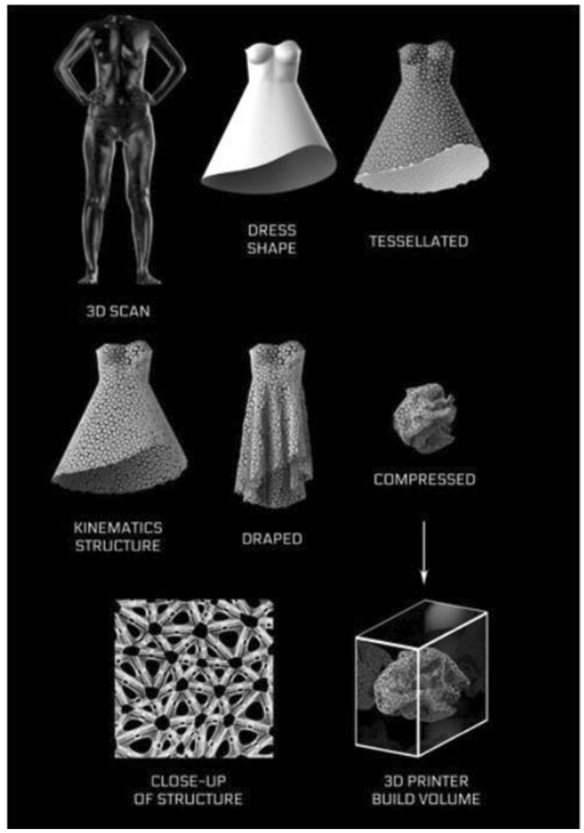
<table>
<tr><th>Ref</th><th>AM Technology</th><th>Materials</th><th>Research/Features/Applications</th></tr>
<tr><td>(Rosenkrantz & Louis-Rosenberg, 2017)</td><td>SLS</td><td>Rigid nylon</td><td>Brand name: kinematics dress and kinematic petals dress—nervous system (Fig. 3)


Figure 3 Nervous system
Development state: fashion exhibition
Features: computational geometry techniques with rigid body physics and digital fabrication are combined to create customized products. 3D printed hinge structures are interconnected to create complex, foldable forms composed of thousands of articulated modules, which behave as a continuous textile. The dress making process was: (1) 3D scan client, (2) sketch dress, (3) tessellate, (4) generate kinematics structure, (5) simulate draping, (6) compress into a smaller form for fabrication by 3D printing. It emerges from the 3D printer fully assembled</td></tr>
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Table 1 (continued)

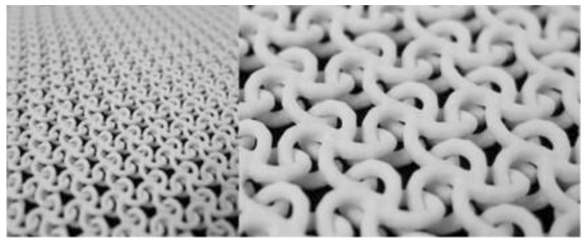
Ref	AM Technology	Materials	Research/Features/Applications
(Bloomfield & Borstrock, 2018)	SLS	Polyamide (PA12)	Brand name: modeclix (Fig. 4)  Figure 4 Modeclix. Credits: Mark Bloomfield, Shaun Borstrock University of Hertfordshire Development state: On the market Features: 3D printing fabric customisation through a structured system of additively manufactured links. The system allows the interchangeability of links to remove or add links to adjust the size and shape, repair or re-shape the garment design. Modeclix addresses principles of the circular economy: manufactured and scaled on demand, localised manufacture, enables repair, re-use and re-shape into different design
(Julia Koerner, 2019)	MJ	Flexible VERO multi-material	Brand name: SETAE jacket (Fig. 5)  Figure 5 SETAE Jacket. Credits: Setae Jacket for Chromorpho Collection Stratays, Julia Koerner 2019. Photography: Ger Ger Development state: fashion—chro morpho collection Features: both bionic structures and multi-colour 3D printing are explored. The jacket is composed of thousands of multicoloured bristle-like structures that move with the wearer's movement

Table 1 (continued)

Ref	AM Technology	Materials	Research/Features/Applications
("Danit Peleg," 2022)	FDM™	TPU—FilaFlex (brand of flexible 3D filament)	Brand name: Danit Peleg Development state: "The first fashion collection 3D-printed at home" Features: Danit Peleg's 3D printed fashion designs are based on three approaches: printing with a known pattern, printing textiles for dapping and printing objects that can be linked together. The lace-like textiles are based on filaflex's flexibility and mesostructured cellular materials designed by Andreas Bastian. Also, Peleg uses auxetic patterns in some of her garments. Both lace-like textiles and auxetic patterns can adapt to the body and have a more fabric-like behaviour Online sales: ready-to-wear 3D printed bomber jacket is available to purchase online. It takes about 100 h to print and is customizable through website options by selecting 3d printing fabric, lining fabric, typing back words, choosing the size and having a virtual fitting session
(Lim et al., 2014)	SLS	Nylon 12	Brand name: N12 Bikini Development state: on the market Features: N12 Bikini is a 3D printed ready to wear, is flexible and all closures are included

Therefore, 4D combines 3D printing with time change element under the influence of an external stimulus (Choi et al., 2015; Momeni et al., 2017) such as temperature (Ly & Kim, 2017; Pandini et al., 2020; Zarek et al., 2016a, 2016b), pressure (Ramuz et al., 2012), moisture (Ventcool fibre) (Dang & Zhao, 2021), stress (Gall et al., 2004), light (Boyle et al., 2017; Lendlein et al., 2005; Roppolo et al., 2017), magnetic (Ze et al., 2020; Zhang et al., 2021), electrical (Liu et al., 2009), pH (Han et al., 2012; Nadgorny et al., 2016) or chemical compound (Berg et al., 2014).

Some examples of 4D smart materials are shape memory polymers (SMPs) (Alshebly et al., 2021; Leng et al., 2011; Pyo et al., 2018), metamaterials (Bodaghi et al., 2017a, 2017b; Fan et al., 2021; Lei et al., 2019; Ryan et al., 2020) and hybrid laminates (Stapleton et al., 2019).

SMPs, such as polycaprolactone (PCL), polytetrafluoroethylene (PFTE), polyvinyl chloride (PVC) and ethylene–vinyl acetate (EVA), are examples of materials that can undergo reshaping and recovering their original shape upon application of an external stimulus (Suriano et al., 2019; Yu et al., 2015). SMP are attracting researchers attention due to their low cost, lower density, large recoverable strain and the opportunities to develop both 4D printing technologies based on 3D printing and 3D printing functional materials (Biswas et al., 2021; Subeshan et al., 2021). The primary research areas currently in focus concerning 4D textiles are smart materials (Shin et al., 2017), equipment design/development (Zhang et al., 2019) and mathematical modelling (Chung et al., 2017). Following are depicted some research works based on 4D textiles technology, both stimuli-responsive SMPs (1) thermoresponsive and (2) photoresponsive materials, (3) metamaterials and (4) hybrid laminates materials.

(1) Thermoresponsive shape memory properties of PLA (SMPLA) printed by FDM™ on a Nylon textile were explored by Leist et al. (Leist et al., 2017). Smart textiles were successfully programmed into a temporary shape through the application

of temperature (70 °C). Therefore, temperature allowed smart textiles to fold from 2D (initial shape) into 3D shape (deformed and fixed shape) and unfold to its initial shape (2D). Thermoplastic shape memory polyurethane (SMPU), was extruded as fibres and spun with a range of natural, synthetic yarns to produce an array of new yarns (SMPU yarns). Engineered woven textiles were manufactured with SMPU yarns. These smart woven textile designs for interior applications were able to change shape between an open and close woven structure (sunlight filter) under the influence of temperature (Chan Vili, 2007).

(2) Photoresponsive materials based on SMPU and photothermal carbon black (CBs) were explored by Yan et al. (Yang et al., 2017) in order to 3D printing of photoresponsive shape memory objects from a FDM™ printer. Similarly, Ly and Kim (Ly & Kim, 2017) investigated the properties of SMPU and its CNTs composites to develop smart textile and wearable products.

(3) Metamaterials are engineered materials whose properties are tailored by manipulating their internal physical structure rather than their chemical composition. Metamaterials are based on periodic patterns of geometrically designed "meta" cells. The material properties themself are not responsive to an external stimulus. There is a trend to use 3D printing technology to develop metamaterials (Braszkiewicz, 2021; Manen et al., 2021; Yu et al., 2018). Metamaterials with advanced functionalities, such as multi-stable mechanism (Haghpanah et al., 2016; Ren et al., 2021; Tao et al., 2020; Yang & Ma, 2019), phase transformation (Chen & Jin, 2018; Khajehtourian & Kochmann, 2020; Yang et al., 2016), auxetic structures (auxetic refers to solid materials with negative Poisson ratio) (Braszkiewicz, 2021; Lei et al., 2019; Pandini et al., 2020; Ren et al., 2018), shape-reconfigurations (Yang & Ma, 2020) and shock/impact energy absorbers (Chen et al., 2014; Ha et al., 2018; Hamzehei et al., 2022; Yu et al., 2019) have been exploited with novel 2D and 3D engineered structures. The optimized process can be obtained through geometric parameterization (cell size, cell orientation, strut thickness, etc.), finite element modelling (FEM) and physical testing (Wallbanks et al., 2022; Yang & Ma, 2019; Zheng et al., 2021). Metamaterials with performance-driven functionality printed by FDM™ were studied by Bodaghi et al. (Bodaghi et al., 2017a, 2017b). 3D printed polyurethane-based shape memory showed both shape-shifting by self-folding (1D to 2D) and self-coiling (2D to 3D) with potential use in mechanical or biomedical applications were demonstrated.

(4) Hybrid laminates consisting of 3D-printed patterns bonded or directly printed onto pre-stretched fabric are examples of 4D textiles (Han et al., 2020; Kycia, 2019; Schmelzeisen et al., 2017). Through parametric simulations, 3D printing patterns are analysed and optimised (Christie, 2017; Stapleton et al., 2019). When the pre-tension is released, the planar shape becomes a 3D geometry due to equilibrium forces between the fabric's restoring form and the opposed elastic stiffness of the pattern structure (Agkathidis et al., 2019; Berdos et al., 2020; Koch et al., 2021; Kycia & Guiducci, 2020). Some design studios and researchers have been exploring and designing three-dimensional hybrid laminates via FDM™ technology, such as Shapemode design studio with the project SIKKA (combination of flexible textiles and FDM™ 3D printing technology) ("Delta WASP 3MT Experiences the 3D Printed Tissue,"

2020) and Schmelzeisen et al. (Schmelzeisen et al., 2017), which redefined the concept of the hybrid laminate by introducing the time change element. Therefore by combining pre-stretched fabrics, 3D FDM™ printing and the time change element, 3D structures could have multiple change shapes in response to temperature, as external stimuli. "Active Membranes" based on hybrid laminates consisting of FDM™ 3D printed pattern of TPU 95 and PP fibres bonded onto pre-stretched fabrics were designed by Agkathidis et al. (Agkathidis et al., 2019). Through a parametric simulation, 3D printing of the fibre pattern (embossing material), pre-stretching the textile, lamination of the embossed pattern onto a pre-stretched fabric and release of the laminate pre-stretched, the planar shape is converted into a 3D geometry. The following advantages are highlighted: flexibility, low weight and adaptability. Fallowing the previous research, an algorithm was developed by Berdos et al. (Berdos et al., 2020), in order to predict the geometric pattern and the resultant behaviour of the composite material consisting of a pre-stretched fabric and a semi-elastic material in its 3D dimension state.

In Table 2 are depicted some prototypes based on 4D textiles and shoes.

Opportunities and limits of 3D and 4D printing textiles

AM (3D and 4D) is a disruptive technology which is shifting the manufacturing processes toward a digital and global factory, promoting a more localised production, allowing product customization and on-demand production of small batches (Ahmed et al., 2021; Sitotaw et al., 2020). For instance, in fashion, 3D printing is regularly being used and some examples are depicted in Table 1.

Direct printing onto knitted and woven fabrics made of cotton, polyester or aramid, materials such as ABS, PLA, TPU and Nylon have been used to obtain different and functional composite structures (Dopke & Nils Grimmelsmann, 2017; Pei et al., 2015; Spahiu et al., 2017).

In sports, Adidas 3D printing running shoes midsole, tailored to the athlete's foot by combining data, AM and bio-based materials are being brought into production. The 3D printing technology allowed the production of complex lightweight structures that optimise shock absorption and comfort (Yosra, 2022). Also, Nike 3D printed textiles for shoes upper, made by solid deposit modelling (SDM) with thermoplastic polyurethane (TPU) filament, are being used through translated athlete data into new textile geometries. The resultant fabric is a wire layer, flexible, lighter and breathable, which allows water to efficiently drain out ("Nike Flyprint is the First Performance 3D Printed Textile Upper," 2018).

4D printing market is expected to grow at a compound annual rate (CAGR) of 42.1% between 2021 and 2027, in which 4D textiles are anticipated to contribute to the overall market with a share of 20%. The major end-use applications of 4D printing technology are expected to rise from military and defence, aerospace and healthcare. However, once the technology becomes available for mass production, it can meet the demands of other industries including textiles, apparel and footwear ("Global 4D Printing Market—Global Forecast 2017 to 2027," 2021). Industry 5.0 (value driven) is projected to fuel the emergence of 4D printing through a smart approach to the design process rather than the technology-driven (Industry 4.0) (Xu et al., 2021c). Industry 4.0 is associated with smart

Table 2 4D textiles and shoes: AM technologies, materials and research/features/applications

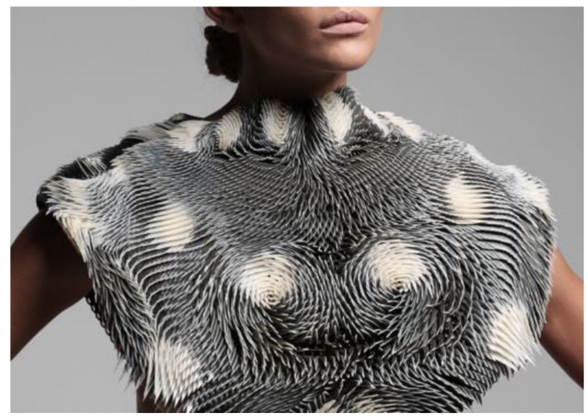
Ref.	AM Technology	Materials	Research/Features/Applications
(Farahi, 2016)	PolyJet 3D printing	PLA + Shape memory alloy (SMA)	Brand name: Caress of the Gaze (Fig. 6)  Figure 6 Caress of the Gaze. Photo credit: Behnaz Farahi Development state: Research/prototype Features: Interactive garment based on eye-gaze tracking technologies. The technologies employed enable the garment to move in response to the other people is gaze, through a camera and SMA actuators embedded in a 3D printed garment

Table 2 (continued)

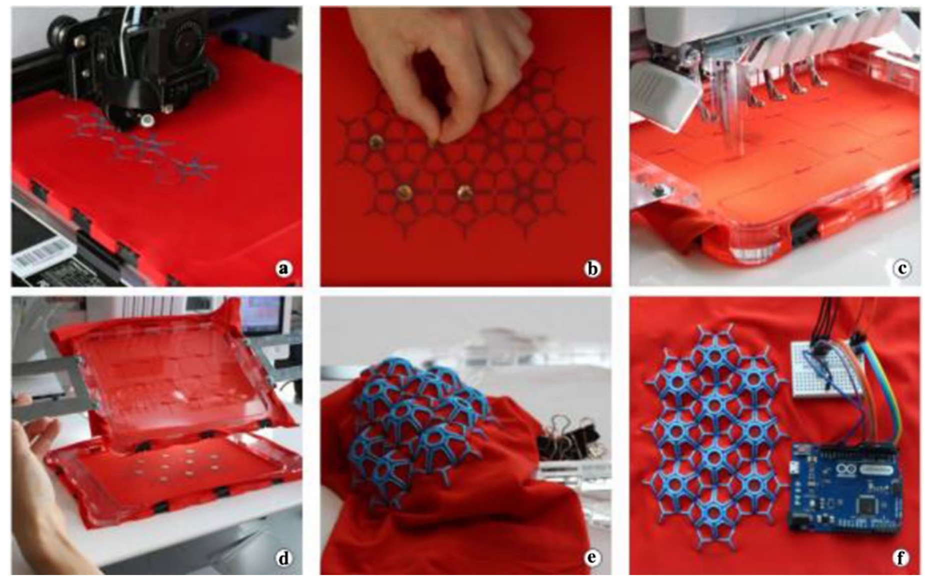
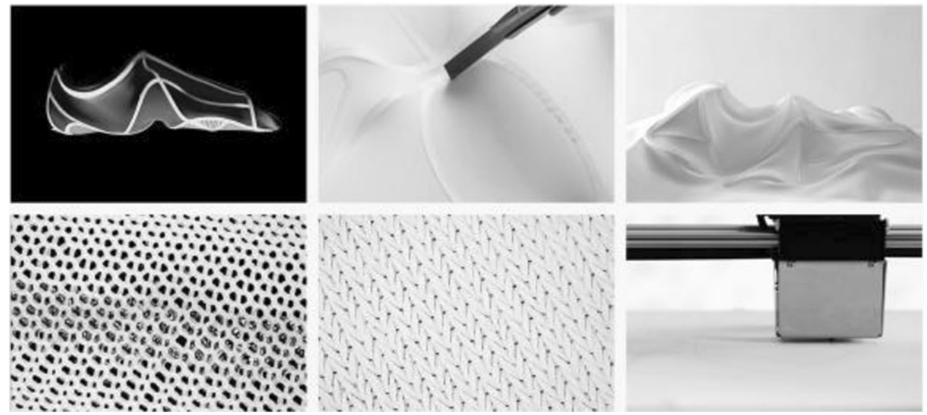
Ref.	AM Technology	Materials	Research/Features/Applications
(Goudswaard et al., 2020)	FDM™ (Physical components) + Embroidery Machine (Electromechanical components)	Filament: tronxy Flexible TPU + Stretch fabric: lycra	Brand name: FabricClik (Fig. 7)  Figure 7 FabricClik. Project credits: Maas Goudswaard, Abel Abraham, Bruna Goveia da Rocha, Kristina Andersen and Rong-Hao Liang, 2020 Development state: Proof-of-concept Features: A method for interweaving functional pushbuttons into fabrics through 3D printing and digital embroidery is explored. Made of two layers stitched together as textile-based pushbuttons: Button layer (1) 3D print star-like structures onto pre-stretched fabric and Circuit layer (2) embroider both conductive and insulation circuitry on a pre-stretched fabric

Table 2 (continued)

Ref.	AM Technology	Materials	Research/Features/Applications
(Guberan & Clopath, 2015)	FDM™	Not specified: plastic material with different layer thickness + Stretched fabric	Brand name: Active shoes (Fig. 8)  Figure 8 Active Shoes. Project credits: Christophe Guberan + Carlo Clopath, Self-assembly lab, 2015 Development state: Research/prototype Features: Self-transforming structures which reconfigure into pre-programmed shoe shapes. It contracts around the feet, shrinking in size. The objective was twofold: (1) tailor-made to the client' s foot and (2) meet the personal design preferences of each client
(Nachtigall et al., 2018)	FDM™	TPU—FilaFlex	Brand name: Customized 4D printed shoes Development state: finished—single user Features: A customized shoe is designed and 3D printed in order to meet specific needs of aesthetic and comfort. The geometry of the material is designed to support, flex and change with the movement of each foot. The manufacturing process was comprised by two stages: (1) the feet is scanned, the digital shoe design is generated using a 3D design software and (2) Printing process

factories, real-time and flexible production of personalized products (Wang et al., 2016; Zhong et al., 2017), whereas industry 5.0 is focused on sustainability (waste prevention and recycling), human-centricity, digitalization, manufacturing customization and artificial intelligence technologies in order to increase the flexibility and production efficiency (Nahavandi, 2019; Xu et al., 2021a, 2021b, 2021c).

Nowadays, the design and printing technologies of 4D textiles based on stimuli-responsive are still in their R&TD stage and remain a great challenge and opportunity for customized textiles, apparel and footwear (Ali et al., 2019). By changing the colour ("ChroMorphous—A New Fabric Experience," 2022), structure and texture (Ali et al., 2019), through a stimulus reaction, smart textiles can provide thermal comfort regulation (Gao et al., 2017). Most of the 4D textiles are developed in research institutions, in which the research areas fall into the development of new equipment and smart materials, mathematical modelling and research on deformation mechanisms (Ahmed et al., 2021; Biswas et al., 2021; Zhang et al., 2019). Also, 4D textiles are limited to experimental prototyping, such as the examples given in Table 2.

Some exceptions, are for instance, the commercially available SMPU membrane Diaplex® patented by Mitsubishi. Diaplex® is a non-porous "smart" membrane, which provides properties such as waterproof, windproof and breathability by changing its molecular shape upon low temperatures (the gap between the SMPU molecules decreases) and at temperatures above 10 °C through memory effect activation returns to its original shape (reverse molecular process). Diaplex® can be attached in multi-layer textile fabrics and can be provided as a membrane, pellets, filament and liquid (Thakur, 2017).

Furthermore, textiles are inhomogeneous, anisotropic, porous and deformable materials allowing free movement. These characteristics of textile structures determine their unique and different behaviour when compared to other engineering materials (Hashemi Sanatgar et al., 2017; McCarthy, 2016). Hence, researchers and designers have been rethinking woven and knitted fabrics with novel functionalities that cannot be obtained with the textile fabrics, promoting significant sustainability benefits and a sustainable future for materials (Kim et al., 2019; Zapfl, 2022).

In addition, the materials used in 3D printed fabrics results in stiff and rigid clothing, which are uncomfortable to wear and most are made by petroleum-based polymers, such as ABS, PLA and PU, while natural textile fibres (wool) as 3D printing materials are still in an early development stage (Perry, 2018). Therefore, research on new and existing materials and deposition/extrusion technology is required (Hashemi Sanatgar et al., 2017) to provide comfort, breathability and flexibility for the fabrics.

Nonetheless, TamiCare (TamiCare. Introducing COSYFLEX, 2021) developed an AM technology called CosyFlex to manufacture tailor-made fabrics, using liquid polymers, such as latex, silicon, polyurethane, teflon and textile fibres. TamiCare claims that its technology is environmentally friendly (recycled raw materials, bio-based "ingredients", reduced water usage, reduced carbon footprint and virtually no scrap), the products are manufactured on demand and the fabrics are engineered to exhibit high-performance and comfort.

Conclusions

In the current review, we have discussed the concepts of additive manufacturing, fused deposition modelling, selective laser sintering, direct ink writing and material jetting-photopolymers, recent developments and applications in 3D and 4D printing textiles with focus on four main topics, development of functional filament fibres/wires, 3D printing on textiles (polymer-textile composites), 3D printing completed garments or individual structures and 4D textiles and shoes. Finally, the opportunities and limits of 3D and 4D printing textiles are depicted.

Several research and R&TD projects specific to AM applied on textiles are underway both in the academic and industrial fields to overcome the current limitations, which will lead to the improvement of prototypes for industrial applications. The furthest scientific advances include 4D printing and its applications, opportunities and challenges in textiles, which are vast and are acknowledged by several research groups and experts in the field.

By combining advanced computational design techniques, product customization from the wearer's body through a 3D scan, mathematical modelling, simulation and digital modelling (3D printing), the successful way toward multifunctional textiles is paved, opening the future for the design and manufacturing of innovative textiles and smart wearables with self-transform, shape change ability and thermal comfort regulation, which enable the interaction both our bodies and external environment.

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Authors' contributions
All originated the research idea and JM carried out the research and wrote the manuscript. JD and FC read and revised the manuscript. All authors read and approved the final manuscript.

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