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INVITED REVIEW

Potentials of 3D printing in nutritional and textural customization of personalized food for elderly with dysphagia

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Abstract

Elderly individuals commonly experience the risk of dysphagia or difficulties in eating and swallowing food safely. Three-dimensional (3D) food printing is a promising technique widely used in customized food development. This paper reviewed the potential of 3D food printing in nutritional customization and textural modification of personalized food for the elderly with dysphagia. 3D food printing can be used to re-formulate the food ink by combining more than one type of food materials to ensure high calorie and nutrient intake, improve sensory quality, and prevent malnutrition; thus, understanding the functional properties of such macronutrients compounds is essential to design food ink that meets personalized nutrient requirements. Hydrocolloids have been commonly used to modify the desired soft texture and consistent viscoelastic properties of 3D-printed elderly food, as well as improve printability and structural stability. The food standard guidelines have been established and used to categorize texture-modified foods to ensure easy to eat and safe swallowing for the elderly with swallowing difficulties. Finally, the production of personalized food using 3D printing may provide more food options, facilitate safe oral intake, and increase calorie intake to improve the healthy mealtime experience for the elderly.

Keywords 3D food Printing, Elderly nutrition, Dysphagia, Personalized food, Texture modification

Introduction

The global population is aging, and all societies are in the midst of the longevity revolution. According to the 2019 Highlight of World Population Prospects, the number of elderly over 65 years of age will double to 16% (2 billion) by 2050, compared to 9% (703 million) in 2019 [42]. South Korea is expected to be one of the world's most rapidly increasing aging populations in the next 40 years while the birth rate is declining, and nine in ten working-age persons will be senior people [47, 51]. Population aging will lead to a series of worrying issues for economic growth, fiscal sustainability, healthcare costs, and other social activities. Therefore, understanding their health conditions and investing in their basic needs (especially food supply and nutritional support) is crucial for maintaining a healthy lifestyle and reducing morbidity in aging societies [5].

Elderly individuals commonly experience the risk of dysphagia or difficulties in eating and swallowing food safely, which is caused by their physiological changes during aging development, including lost dentures, reduced salivary secretion ability (xerostomia), impaired anatomical coordination, muscle frailty, stroke, and other neurological diseases [19]. Elderly patients with dysphagic diagnostic may possibly face other severe eating problems associated with food choking, pulmonary aspiration, and bolus regurgitation. This may generate frustration,

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anxiety, and loss of appetite for the elderly while eating. Dysphagia in the elderly is increasingly recognized as a concerning healthcare issue that makes them suffer from the risk of malnutrition, starvation, dehydration, sarcopenia (decreased skeletal muscle mass), and altered gastrointestinal conditions. Therefore, besides medical and surgical treatments, applying the right choice of food and drink is a more important factor in ensuring the comfort of eating, safe swallowing, adequate nutrient intake, and easy-to-digest for the elderly.

Personalized food is specifically developed and commonly recommended to the elderly with swallowing difficulty for health improvement. Personalization of food in terms of customizing nutritional compositions and contents, modifying textural properties, and constructing attractive food shapes is coined as the solution to fit health conditions, preference patterns, dietary needs, and sensory sensitivities for the elderly [39]. Indeed, personalized food with nutritional customization should be reduced in saturated fat, cholesterol, sugar, and salt contents while enriching in protein, unsaturated fatty acid, essential micronutrients, other bioactive compounds, and pre-or pro-biotics to ensure sufficient calorie needs and necessary nutrient absorption to prevent malnutrition and degenerative chronic diseases. Moreover, soft food that is modified in texture, hydrated, blended, has reduced particle size or has added food hydrocolloids is ideal for easy-to-eat and safe swallowing [41]. However, this personalized elderly food is generally lumped together to form a soft puree or paste without a definite food shape,thus, it may not look good for appetite and sensory acceptance for the elderly.

3D food printing is an emerging manufacturing technique that allows the creation of various dishes that are more innovative, nutritious, safe, and appetizing. The 3D-printed food construction process is uncomplicated, quick, automated, and consistent. It starts from the preparation of food ink by formulating food ingredients into the targeted structures (dough, puree, or gelling forms), designing the desired food shape using any printing-related software, and performing the printing process by extrusion and deposition of food ink layer-by-layer to have recognizable and completed food shape, as shown in Fig. 1 [9]. In this case, owing to the feasibility of food ink customization, 3D food printing can be used to develop a new version of

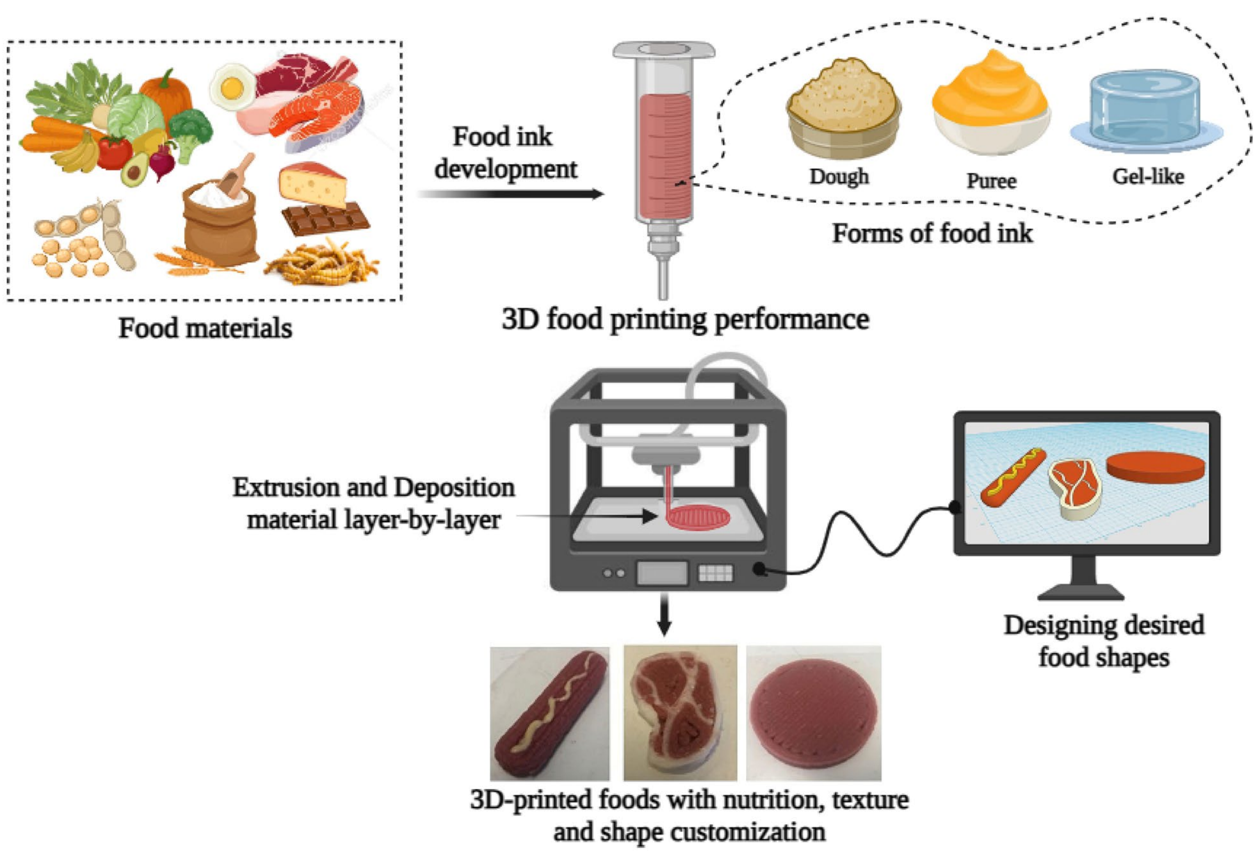


Fig. 1 The overall scheme of 3D printing technology in 3D-printed food production (modified from Pereira et al. [33])

personalized food with nutrition-added value, softening in texture, consistent viscoelasticity, improved functional properties, and visual appeal to provide more options, facilitate safe oral intake and satiety as well as improve the healthy mealtime experience for the elderly (Fig. 2). For example, the development of an easy-to-swallow 3D-printed mooncake from a combination of starch, Arabic gum, and soybean oil [45], easily digestible and functional 3D-printed food for elderly from pea protein hydrolysates [22], and a soft texture-modified 3D-printed food for elderly with swallowing difficulties from a mixture of plant-based and insect proteins [8].

This paper reviewed the insight potential of 3D food printing in nutritional customization and textural modification for personalized food production applied to the elderly with dysphagia. In this case, the composition and functional properties of essential macronutrients (protein, carbohydrates, and lipids) in personalized food ink customization were discussed. Personalized food characteristics, soft-texture modifying processes, texture-modified food classification based on the standard guidelines, and the challenges of personalized food development using 3D food printing were also reviewed.

3D food printing in nutritional customization

Aging and nutritional requirements

Instead of medication and physical activities, supplying the right diets and nutrients (an energy supplier and regulator of biological reactions in the body) are pivotal factors in promoting health, development, and longevity for the elderly facing age-related physiological changes and diseases, particularly dysphagic symptoms. Based on the Dietary Guidelines for Americans 2010, they recommend approximately 2000–2600 kcal per day for men $\geq$ 65 years of age and 1600–2000 kcal for women in the same age group [3]. It is important to recognize that many illnesses and complications secondary to the primary disease state are associated with diet and nutritional status. Indeed, inadequate nutrient intake causes elderly undernutrition and frailty and worsens their body's functional abilities, including the immune system, body mass, bone health, and cognitive functions. However, excess food intake may easily contribute to other chronic diseases such as obesity, diabetes, hypertension, or cancer. In this case, it is noteworthy to understand specific nutritional needs responding to a person's biological characteristics and health condition, as well as the composition, functionality, and appropriate amounts of essential macronutrients (protein, carbohydrates, and lipids) for the development

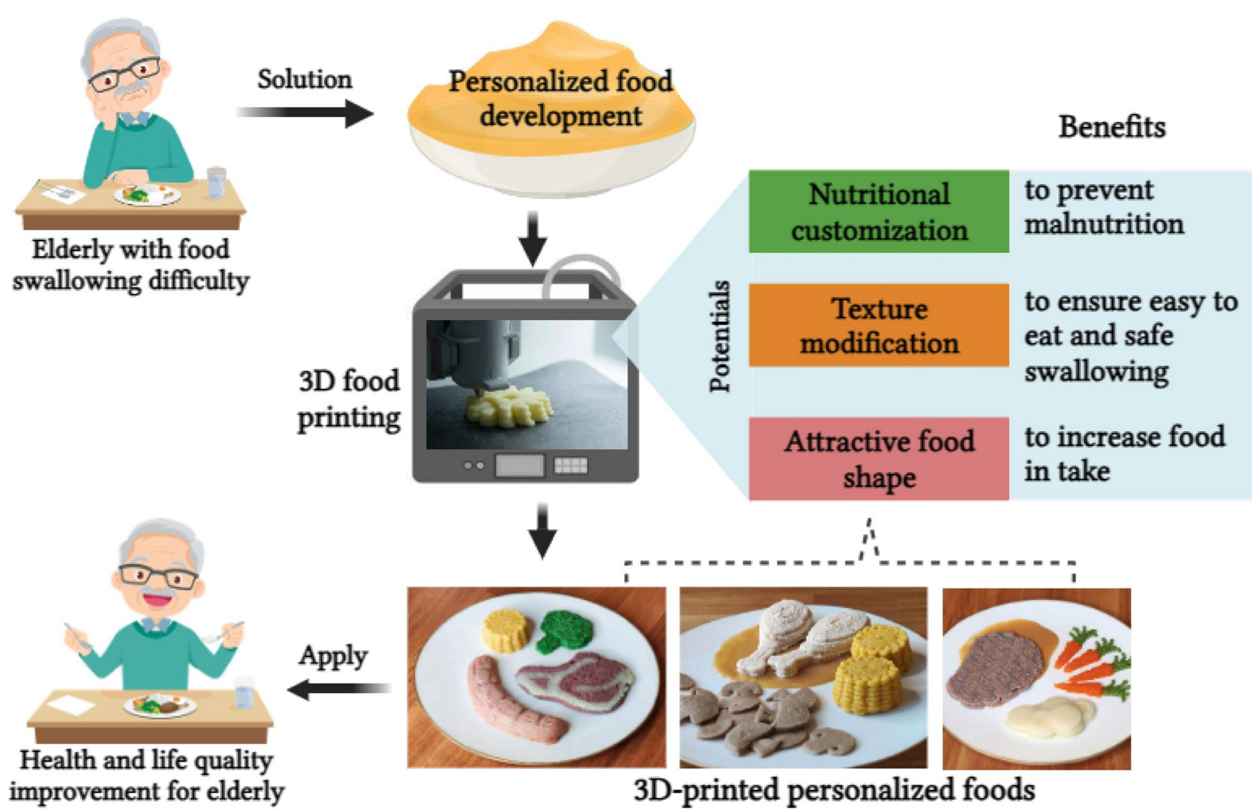


Fig. 2 Outline of texture-modified food development using 3D printing applied to elderly with dysphagia (modified from Lorenz et al. [27])

of a personalized diet that meets the right neeed of the elderly [4].

Nutritional compositions, functionalities, and sources

Because not all nutrient compounds and contents perform the same biological function, personalized food for the elderly should be re-formulated and customized by combining more than one type of food ingredients to ensure high nutrient-added value, improved sensory quality (such as texture, flavor, and appetizing visual aspect), and health benefits which can be facilitated by 3D food printing technology.

Proteins

Protein is one of the essential dietary macronutrients that play roles in supplying energy intake, involving muscle protein synthesis, balancing nitrogen losses from body waste secretion, and other biochemical processes to maintain body function and structure. In this case, a daily protein intake of 1.0–1.6 g per kilogram body weight is recommended for older adults to prevent sarcopenia and support optimal musculoskeletal health. Therefore, the personalization of elderly food should be in the form of a protein-dense diet formulated by high-quality proteins containing high amounts of essential amino acids (EAA) in their peptide sequences, digestibility, and bioactive activities. Protein supply in food can be obtained from animals, plants, and alternative sources, which provide important different protein patterns in terms of composition and functional properties. Meat (from beef, pork, and chicken), fish, and egg contain higher protein content of approximately 25%, 20%, and 12.6%, respectively. Moreover, they are an excellent source of EAAs, bioavailable minerals, vitamins, and healthy unsaturated fatty acids (particularly in fish) and provide a high source of energy intake, which is the essential nutritional material in the personalization of food for the elderly with dysphagia. Based on the potential of 3D printing in food ink reformulation, many researchers have proposed the development of a new form of high protein-dense food using 3D printing, for example, an appetizing pork leg product [11], hydrocolloid-combined beef pastes [12], and enzyme hydrolyzed-Alaska pollock fish surimi [29] as a personalized dysphagia food with new 3D-printed shapes, modified-soft texture, improved-protein-digestible properties, and maintained-protein-quality intake.

Plant-based proteins (from cereal grains and legume beans) and alternative proteins (from insects, algae, and fungi) have been examined as healthy, nutritious, and sustainable for food production. It also exhibited other crucial biological activities (antioxidant, anti-inflammatory, cholesterol-lowering, satiety, and anti-diabetic properties) and high water absorption and protein gelation properties for designing functional food and soft-textured puree for dysphagic elderly. However, both plant-based proteins and alternative proteins possess some drawbacks to human health, including low levels of some EAAs like lysine, tryptophan, and sulfur-containing amino acids for helping muscle protein synthesis in the body, less easily absorbed and digested when compared to animal proteins, allergic effects, bitter taste, and unfavorable smell. Interestingly, recent studies in the field of medicine have proven that a suitable combination of protein-rich diets (e.g., cereal protein + legume protein or legume protein + insect protein) could provide a complementary mix of the EAAs and nutrients needed for body maintenance and reduce the severity of other cardiovascular diseases like hypertension, heart disease, and obesity [21]. In addition, the strategy for the modification of the native globular structure of those plant proteins in interm of size changing, surface charge, hydrophobic/hydrophilic ratio, and molecular flexibility of the protein by using any physical, chemical, and enzymatic processes also helps to improve or create entirely new protein functionality. This can facilitate their use as ingredients in food formulation to confer flavor, color, odor, texture, structure, and digestible to food products [2]. In this case, food ink customization in 3D printing can manipulate the combination of multiple food materials into a unique food structure and appetizing look, which is an innovative and promising idea for customizing protein-rich diets from various sources of protein or structure-modified proteins (Table 1). For instance, the mixture of chickpea with mealworm proteins [8], pea protein with cricket powder [10], pea protein isolate with pea protein hydrolysate by enzymatic protein hydrolysis [22], and white mushroom with soybean protein isolate [48] have been proposed for customizing protein-rich food using 3D printing in the concept of amino acid contents balancing, food digestible improving, soft structure modifying, attractive food shape constructing as an easy-to-swallow food and increased protein intake for the elderly with dysphagia (Table 1).

Carbohydrates

Carbohydrates are a diverse group of molecules and a major supply of energy and nutrition in the human diet. However, different sources of carbohydrates are not considered equally healthy for human nutrition; it is based on the structural polymerization (mono-, di-, oligo- and polysaccharides) and food matrix, which can imply the level of digestibility, nutritional absorption, energy metabolism, and blood glucose release in the body. The blood glucose level is an important health issue that can cause other severe diseases like hypoglycemia (too low blood glucose level), hyperglycemia (too high blood

Table 1 3D food printing in nutritional customization for developing personalized food for the elderly with dysphagia

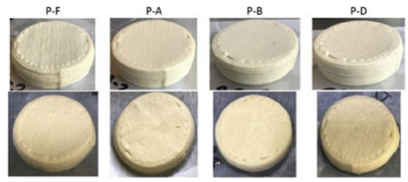
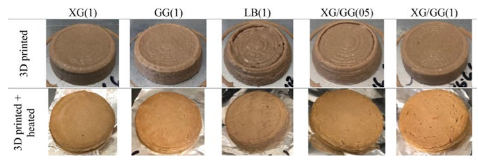
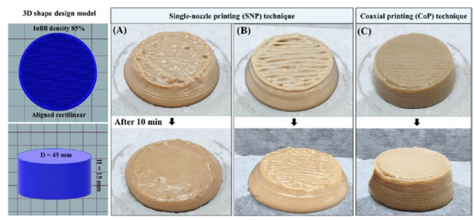
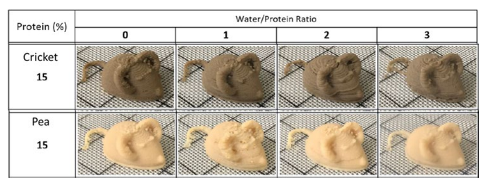
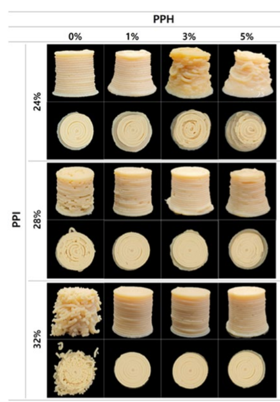
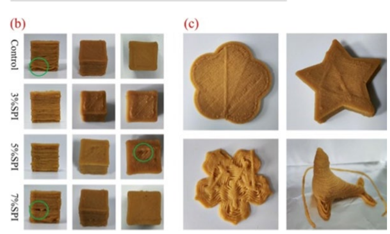
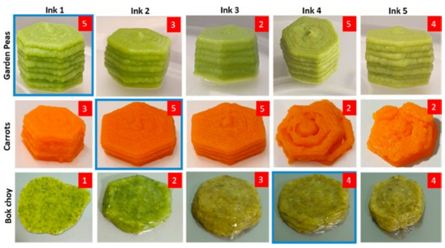
Nutrient base	Main source	Customization of food ink and its functionality	3D-printed personalized food	References
Protein	Pork leg meat	Pork meat puree was modified in nutritional value and texture properties by varying the contents of xanthan gum and guar gum blend		[11]
	Beef blade roast	Cooked beef paste was mixed with various hydrocolloid compounds, including xanthan gum, guar gum, *k*-carrageenan, and locust bean gum, to improve printability, texture, and calorie intake		[12]
	Chickpea + mealworm proteins	Food was prepared in the same proportion from a mixture of chickpea protein isolate and mealworm protein isolate gel for balancing essential amino acid contents and customizing the soft structure		[8]
	Cricket + pea proteins	3D-printed personalized mashed potato with the addition of cricket and pea powders was prepared for shape resolution, taste, and nutritional profile improvement		[10]
	Pea protein isolate + pea protein hydrolysate	Protein-enriched food was developed by incorporating pea protein isolate with pea protein hydrolysate, resulting in hardness reduction and food digestible properties improvement		[22]
	Soy + fungus proteins	Sustainably nutritious food was formulated from white mushroom mixing with different amounts of soy protein isolate for food intake, soft texture, and the muscle strength enhancement to patient with dysphagia		[48]

Table 1 (continued)

Nutrient base	Main source	Customization of food ink and its functionality	3D-printed personalized food	References
Carbohydrates	Vegetable + polysaccharide hydrocolloid	Low-starch-containing foods were prepared from a combination of fresh vegetables (garden pea, carrot, and bok choy) with various contents of xanthan gum to preserve nutrition vitamin intake, and visually appealing and texturally safe for consumption		[30]

glucose level), type II diabetes, obesity, and coronary heart disease [14]. In this case, applying the right choice of carbohydrate-containing foods that suit the body condition can prevent elderly patients from getting worse health problems. Therefore, the glycemic index (GI) is used to classify carbohydrate-containing foods according to their level of glucose release in the blood after two hours of consumption [37]. Foods classified as high GI include refined grain products (white rice, wheat), white bread, corn and potato, and table sugar due to their high content of easily digestible starch and free glucose. Low-GI foods include wholegrain products, legumes, sweet potatoes, and fruits containing high amounts of resistant starch and non-starch polysaccharides or fiber that are not digestible by human enzymes, which are positively linked to all kinds of health effects, including reduction of cardiovascular diseases, postprandial glycemia, and cholesterol absorption and improvement of digestive systems. Therefore, this may be an important scenario in designing a carbohydrates-rich diet, such as personalized elderly food using 3D printing as a nutritional customized technique [24]. has proposed research on reduced starch digestibility by controlling the interaction between starch and glycerol monostearate/stearic acid, enhancing enzymatic resistance within the 3D printing, and resulting in maintaining blood glucose concentration at a constant basal level. This structural modification of starch by combining rice with some of the foods that have a lower GI and higher resistant starch content has been proven to be the primary leading approach for reducing the GI of food. Pant et al. [30] has used 3D printing to develop low-starch-containing food ink from the combination of fresh vegetables (garden pea, carrot, and bok choy) with various contents of polysaccharide (xanthan gum), which preserved nutrition, vitamin intake, positive health effects, and visually stimulating and texturally safe for consumption by dysphagic patients (Table 1).

Lipids

Lipids are also important complex macronutrients that provide high-calorie content, nutritional profiles, and palatable sensory properties in food. Fatty acids, divided into saturated and unsaturated fatty acids, are known as the building blocks of lipid molecules and may differ greatly in their health impact [41]. Different fatty acids may differ greatly in their health impact. Dietary recommendations have mainly focused on decreasing total fat intake, in particular saturated fat, which is found predominantly in animal meat. Reduced saturated fat consumption can prevent the risk of cardiovascular disease and reduce serum cholesterol [16]. In this case, omega-3 fatty acids, which are known as the long-chain n-3 polyunsaturated fatty acids present in fish and other marine sources, seem to have several beneficial effects such as prevention of cancer and inflammation as well as improving eye, brain, and mental health [17]. It is considered a healthy fat that possesses nutritional and functional properties that can be used in the development of personalized food for the elderly to improve their quality of life. For example, 3D food printing research on using the emulsion gel, oleogel extracted from plant oil rich in unsaturated fatty acids, to replace saturated fatty acids in food can benefit consumer health, particularly the elderly. It has been shown that gel-like emulsion could be fabricated well-completed shapes using 3D food printing and used in various applications such as meat analogues cake decoration, or customized functional food [43].

3D food printing in texture modification

Characteristics of textured-modified food applied to elderly with dysphagia

For the elderly, eating and swallowing food are challenges because of their physiological changes, impaired coordination, muscle frailty, stroke, and other related diseases. Therefore, the development of personalized food with consistent rheological properties (liquid form) and specific texture characteristics (semi-solid form) specifically applied to the elderly with dysphagia is inevitable [15]. For semi-solid food, the texture properties recommended to the elderly should be avoided: fibrous structure, hard crumble, too high viscosity (firm), too low viscosity (watery), dry, springy, chewy, gummy, and gritty, which can cause difficulty for dysphagia elderly to eat and swallow [28]. Indeed, texture-modified food that is softened in texture by moisturizing, reducing particle size, or mixing with food hydrocolloids is commonly recommended for elderly patients. Moreover, these semi-solid foods are commonly designed in the form of minced and moist food, puree, jelly, pudding, or mouse with texture modification to be soft, adhesive, mushy, smooth, and homogeneously uniform without water separation, any lumps, or visible particles to ensure the comfort of eating and safe swallowing [41]. Textured-modified foods can be disintegrated in the mouth by a tongue-palate compression, eliminating teeth mastication and chewing process, as well as stimulating the development of a cohesively swallowable bolus and preventing the risk of pulmonary aspiration and food choking. In addition, it may also influence consumers' perception of satiety, satiation, and safety; thus, it can increase food intake and prevent undernutrition [8]. However, soft textured-modified food is generally lumped together without a definite food shape, which may not look attractive and appetizing to the elderly to consume the food, leading to the limitation of the food to be served.

3D-printed food with soft texture modification

Owing to the possibility of food ink customization, 3D food printing has been used to design food with balanced nutrients and specific texture properties that meet personalized nutrition requirements and health conditions. Recently, 3D-printed textured-modified food, specifically applied to the elderly with swallowing difficulty, has drawn many researchers' interest in producing healthy and safe food with an attractive shape to improve their mealtime experiences [32].

Food ink preparation is the essential process leading to the development of 3D-printed textured-modified food. During the preparation process, raw food materials may initially undergo physical processes such as blending or homogenizing to reduce the particle size and induce paste uniformity [40]. For example, after reducing the particle size of steamed fish and carrot pulp using a colloid mill, the fish-carrot paste possessed a suitable texture for dysphagia patients [13]. Moreover, the addition of hydrocolloids (like polysaccharides), starch, or other binding agents or additives is commonly required to achieve the desired texture and consistency and increase the functionality of personalized food. The interactions between the macronutrient compounds present in food and added hydrocolloids can alter the entire structure, texture, rheological and sensory properties of food [36]. More importantly, for printability, food ink should be designed to obtain viscoelastic properties that possess liquid-like behavior during extruding and recover to a solid-like structure after depositing to support its own printing structure and stability [7]. Thus, adding food hydrocolloids not only modifies the texture but also helps to create a new constructive shape for food during 3D food printing performance.

Hydrocolloids, such as xanthan gum, gelatin, pectin, carrageenan, agar, konjac glucomannan, or alginate, are polymers that can absorb water to form gels or viscous solutions, which are commonly mixed with food materials for 3D-printed textured-modified food production applied to elderly with dysphagia [49]. Pant et al. [30] have proposed the development of a new form of 3D-printed personalized food from fresh bok choy, garden peas, and carrots by the addition of hydrocolloids such as xanthan gum, kappa carrageenan, and locust bean gum with nutritional preservation, texture modification, and attractive food shape improvement. They discussed that using fresh vegetables in 3D food printing can be beneficial for the elderly with dysphagia and other swallowing disorders in hospitals and nursing homes. Liu et al. [23] has investigated the feasibility of the texture modification and printability of dysphagic food using shiitake mushrooms with various gum additions, including Arabic gum, xanthan gum, and k-carrageenan gum subjecting in 3D food printing performance. Xing et al. [50] also showed the effect of gum incorporation with black fungus-based 3D printed foods as a dysphagia diet. Qiu et al. [35] has proposed the investigation of 3D printing of apple and edible rose blends as a dysphagia food by mixing xanthan gum and basil seed gum at a ratio of 2:1 for printability and safe swallowing of the blends. Yun and co-workers have developed a kind of 3D food printing ink containing abalone powder and soybean protein, with gelatin being included to adjust the texture in order to meet the criteria for elderly-friendly foods [53].

With the potential to create soft textures with a more attractive appearance than regular meals, 3D food printing has overcome the typical diet for dysphagia elderly, promising to increase the patient's appetite, improve their oral intake, ensure eating comfortable and safe swallowing, and serve various food options which can prevent worsening nutritional status [32]. Generally, it is a major challenge for the elderly to consume meat because animal meat possesses a firming and chewing texture after cooking, which is not a suitable texture for them. With the potential for texture modification using 3D food printing, Dick et al. [11] have proposed the feasibility of the soft textured modification of 3D-printed pork meat as dysphagia food by incorporating hydrocolloid. The results have shown that the addition of xanthan gum and guar gum positively affected the rheological and micro-structural properties of 3D-printed cooked pork paste and significant textural differences were also recorded. Thus, this hydrocolloid incorporated 3D-printed pork and was categorized as a potential transitional food with a suitable texture for people with swallowing difficulty. A similar study by [12] determined printability and textural assessment of modified-texture cooked beef pastes that can ensure the safe swallowing the dysphagia patients. Another interesting study by [44] has created plant and animal protein-based formulations for the 3D printing of hybrid meat analogs with soft textures by mixing pea protein isolate and chicken mince and printing into a 3D chicken nugget shape. The development of texture-modified chicken surimi incorporated with mealworm protein using 3D printing may also be a promising soft-textured and nutrition-added value as a personalized food for the elderly [7].

Standard guidelines and methods to ensure safe food for the elderly with dysphagia

Texture-modified solid foods are basically classified foods into various levels based on their textural and rheological properties and prepared by following standardized guidelines, recipes, and equipment [40]. This section embarks on a comprehensive journey, unraveling the intricate tapestry of two pivotal frameworks, International Dysphagia Diet Standardization (IDDS) and Universal Design Food (UDF), that have been widely used to categized the level of texture-modified foods for the elderly and people with dysphagia and ensure the safe consumption, as shown in Fig. 3.

International Dysphagia Diet Standardization (IDDS)

The IDDSI is a global standard guideline to describe and characterize thickened drinks and texture-modified foods and provide easy testing methods that allow for consistent food production applied to people with swallowing difficulties. Dysphagia diets can be classified into eight levels (0 to 7) [18]. Because the pressure exerted by the human tongue during swallowing is around 17 kPa, it is equivalent to the pressure exerted by using a fork pressure test of foods at levels 4 to 7 [38]. The characteristics of texture-modified foods classified in levels 4 to 7 are described in this review.

Level 4 (pureed form) does not require chewing but is cohesive enough to hold its shape on a spoon. Level 5 (minced and moist form) is soft and moist foods without water separation, but small lumps (around 2 to 4 mm in size) may be visible within the foods and require minimal chewing. Level 6 (soft and bite-sized form) is soft, tender, and moist without water separation and can be mashed or broken down with pressure from a fork or spoon; chewing is required for this class of foods. Level 7 is regular foods with various textures (for example, hard, crunchy, and naturally soft).

Dysphagia diet classification that carefully takes food texture into account is necessary for providing dysphagic patients with the most appropriate foods, thereby contributing to their safety and health. Recently, the IDDSI framework has been widely used to determine the level and characterize 3D-printed soft food for the dysphagic

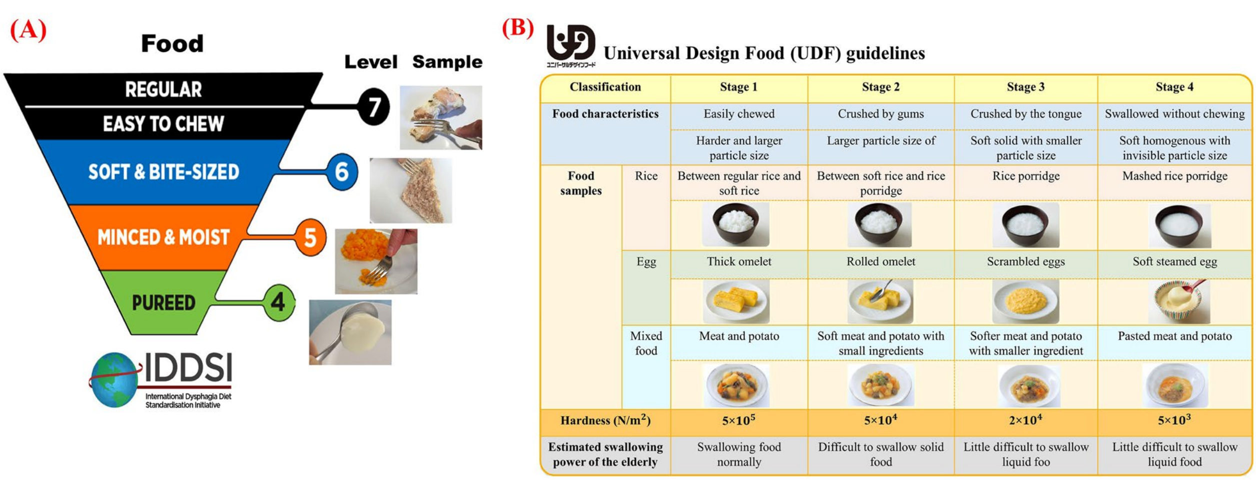


Fig. 3 The characteristics and classification of texture-modified foods according to two different standard guidelines: **A** International Dysphagia Diet Standardization (IDDS) classifying food into levels 4 to 7 (modified from IDDSI 2019 [18]); **B** Universal Design Food (UDF) classifying food into stages 1 to 4. Cited and modified from the IDDSI [18] (https://iddsi.org/framework) and the Japan Care Food Conference [20] (https://www.udf.jp/about_udf/section_01.html)

Table 2 International Dysphagia Diet Standardization (IDDS) tests on 3D-printed food with modified texture for patients with dysphagia

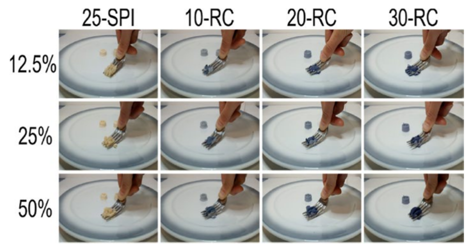
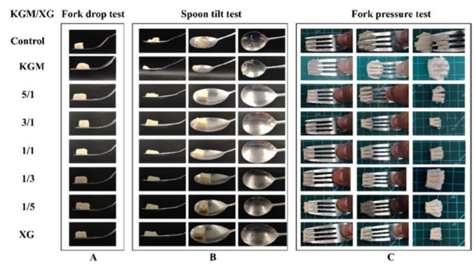
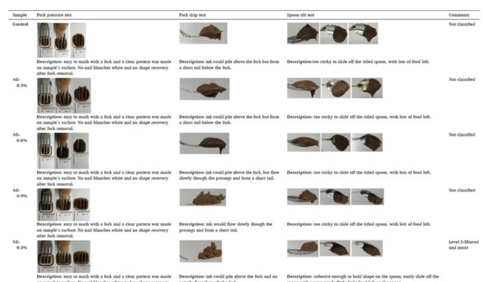
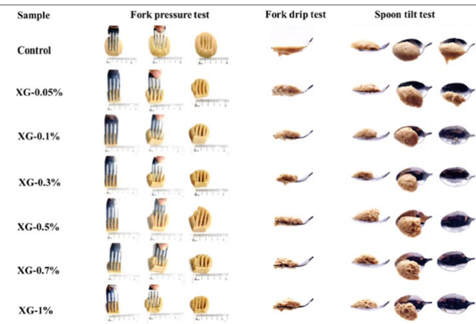
Optimal formulation	IDDSI testing of 3D-printed food	Food characteristics and level classification	References
25 w/v % of soy protein isolate (SPI) with various content (10, 20, and 30 wt %) of red cabbage (RC) subjecting to infill rate (12.5, 25 and 50%) during 3D printing performance		• All the printed structures were easily mashed with a fork and did not recover their original shape after the removal of the fork • 12.5% infill rate sample in level 5 • 25 and 50% infill rate samples in level 6	[6]
Fish paste with different konjac gum (KGM)/xanthan gum (XG) ratios (12/0, 5/1, 3/1, 1/1, 1/3, 1/5, 0/12, w/w)		• All the fish pastes were piled on the fork and did not flow or drip through the fork tines • The fish pastes conformed with the description of the potential transitional foods (level 5/6/7)	[52]
Black fungus (*Auricularia auricula*) powder with different concentrations (0.3%, 0.6%, 0.9%) of gums: k-carrageenan gum (KG), xanthan gum (XG) and Arabic gum (AG)		• Control and gum-containing samples would flow slowly through the fork prongs and form a short tail below the fork • All the 3D-printed foods in level 5 as minced and moist foods with texture-modified	[50]
15% (w/w) mung bean protein (MBP) and (5% (w/w) rose powder (RP) with different concentrations (0%, 0.6%, 0.9%, 1.2%, and 1.5% (w/w) of flaxseed gum (FG)		• All the printed samples were deformed without difficulty, and a clear pattern of the prongs was left on the surface of the cubes after the fork pressure tests • 3D-printed samples met level 4 as pureed/extremely thick foods	[34]

Table 2 (continued)

Optimal formulation	IDDSI testing of 3D-printed food	Food characteristics and level classification	References
Pea protein isolate (PPI) by incorporating XG at various of 0.05, 0.1, 0.3, 0.5, 0.7, and 1% (w/w)		• The sample without XG flowed gradually from the fork's prongs and formed a short tail below the fork • XG-containing samples prevented the flow of inks through the fork's prongs and could pile above the fork that met level 4 as pureed/extremely thick foods	[25]

elderly to ensure that it is easy to eat and swallow, as shown in Table 2. Carranza and co-authors [6] have developed vegetable-containing protein-based food from a combination of soy protein isolate and red cabbage with different internal 3D structures (infill rates of 12.5, 25, and 50%) for texture medication and further conducted IDDSI test. They observed that all the printed structures were easily mashed with a fork and did not recover their original shape after the removal of the fork. The 12.5% infill rate sample could be categorized as level 5, where minimal chewing is needed before swallowing, while samples with higher infill rates (25 and 50%) were exhibited as level 6 with chewing requirements. Yu and colleagues [52] observed the behaviors in konjac gum/xanthan gum 3D-printed fish pastes. The authors indicated that the samples fulfill the description of the potential transitional food levels: 5 (minimal chewing is needed), 6 (chewing skills are required), and 7 (there is a requirement to be able to bite appropriately sized food pieces and chew them) within the IDDSI framework. Xing and co-authors [50] observed that all black fungus-based 3D printed foods passed the fork pressure test and were categorized as level 5-minced and moist dysphagia food according to the IDDSI guideline. Qiu and co-workers [34] have prepared dysphagia-oriented foods containing mung bean protein (MBP) and rose powder (RP) with different flaxseed gum concentrations via 3D printing. For IDDSI analysis, all the printed samples were deformed without difficulty, and a clear pattern of the prongs was left on the surface of the cubes after the fork pressure tests, which met level 4 as pureed/extremely thick foods.

Universal Design Food (UDF)

Japan and South Korea appear in a rapidly aging society; a variety of nursing-care foods are currently under development and demonstrate physical properties that are suitable for the health condition of elderly patients. In this case, food texture (including hardness, adhesiveness, and cohesiveness) is a key parameter in customizing and categorizing elderly food [15]. The [20] established a standard UDF method to measure and classify semi-solid foods into four stages based on their hardness values. Each stage indicates the different characteristics of food that are particularly applicable to the elderly who have different difficulties in food mastication and swallowing. Stage 1 (hardness $\leq 5\times10^5$ N/m^2) refers to softened food that is easy to chew but unsuitable for persons with impaired dental functions such as weakened muscles, loss of natural teeth, and declined movement coordination. Stage 2 (hardness $\leq 5\times10^4$ N/m^2) refers to foods that can be easily crushed by gums and are suitable for the elderly without natural teeth. Stage 3 (hardness $\leq 2\times10^4$ N/m^2 and viscosity $\geq$ 1500 mPa.s) refers to foods that can be easily crushed by the tongue, which is suitable for the elderly who sometimes have difficulty swallowing water and liquid food. Finally, the fourth hardness level (hardness $\leq 5\times10^3$ N/m^2 and viscosity $\geq$ 1500 mPa.s) refers to foods that are easy to swallow without chewing requirement [20, 31]. Moreover, the texture profiles in terms of the hardness of foods must be measured by following the standard UDF protocol. For example, a standard UDF container (40 mm in diameter and 25 mm in depth) is used to place the food sample, and a texture analyzer equipped with a 500 N load cell and attached to a 20 mm diameter cylindrical probe is needed for a double compression test, with a clearance of 5 mm from the bottom of the sample container at a speed of 10 mm/s and a time between compressions of 5 s. The hardness value can be obtained and expressed in units (N/m^2) [7, 20].

Recently, this Japanese UDF guideline has been applied to determine the specific stage of 3D-printed soft foods to ensure eating safety for the elderly. For example, 3D-printed chicken surimi incorporated with 50% (w/w) mealworm protein gel as texture-modified food for the elderly exhibited a hardness value of $4.13\times10^4\pm0.61$ N/m^2, corresponding to stage 2 of the UDF guideline [7]. 3D-printed chickpea-mealworm protein mixture incorporating 5.5% (w/w) sodium alginate possessed a hardness value under 5×10^3 N/m^2, corresponding to stage 4. This 3D-printed texture-modified food could be applied to the elderly with dental loss, weak masticatory efficiency, and difficulty swallowing liquid food [8]. The 3D printing of abalone (*Haliotis discus hannai*) protein incorporation of various contents of potato starch as texture-designed food production for the elderly was demonstrated. The result has shown that the hardness values of texture-modified abalone protein paste were in the range of $3.70\pm0.4\times10^4$ to $6.36\pm1.3\times10^4$ N/m^2, responding in stage 2 of the UDF guideline [54].

Challenges of personalized food development using 3D food printing

As described above, 3D food printing is beneficial in the production of personalized food for the elderly with preserved nutrients, modified texture, and customized 3D-printed food shapes. However, most printed food is ready-to-eat food, which is in contrast to the particular consumption habits of the Asian culture, where people prefer to eat warm and hand-made food. This poses new challenges for printing inks and printing technology [49]. Moreover, another important challenge is related to the printability and self-support structure of texture-modified food ink. Generally, food ink with a soft texture and low viscoelastic properties exhibited inaccurately deposited layers and poor deformation-resistant ability, leading

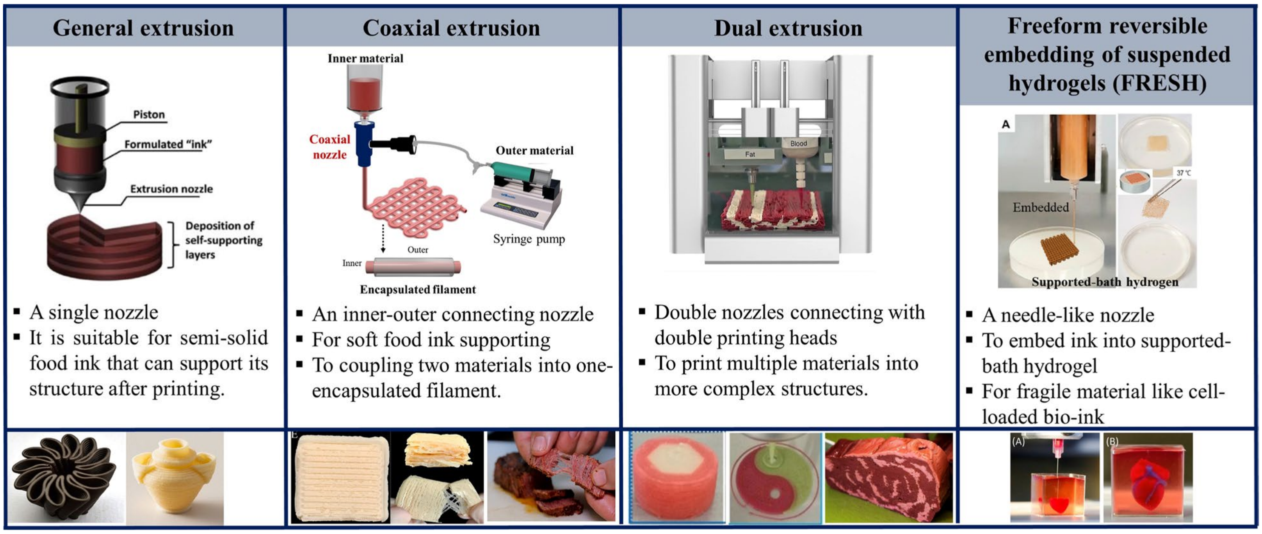


Fig. 4 Different extrusion-based 3D printing techniques based on the adjustment of nozzle type and printing head used in food production (modified from Chao et al. [8],Wen et al. [46])

to food products with poor printing resolution and non-shapable [1]. The limitations of 3D printing soft-textured food also include the limited types of printable food materials, printing difficulty with low resolution, and reduced food structural integrity. This traditional printing technique lacks functional supporting systems and only depends on the physical strength of the food ink; thus, adding a high content of starch or hydrocolloid into food ink is required. This can result in a rigid and adhered texture and reduce the main nutritional content of the food [8, 46]. Therefore, the exploration of the new potential of other extrusion-based 3D printing techniques that are suitable for printability of soft food ink. Due to the possibility of nozzle adjustment, extrusion-based 3D printing can be classified into four printing techniques with different textures and viscoelastic properties of materials and types of nozzle utilization, as shown in Fig. 4. There are general extrusion (a single-nozzle type), coaxial extrusion (an inner-outer connecting nozzle), dual extrusion (double nozzles connecting with double printing heads), and freeform reversible embedding of suspended hydrogels (FRESH) (a needle-like nozzle) [25]. Chao and co-workers [8] have investigated the printability and structural stability of soft-textured food (inner material) supporting fragile structures by sodium alginate (outer material) using a coaxial 3D printing technique. This texture-modified food still exhibited a soft texture and appreciated rheological properties that can applied to the elderly with dysphagia. Wang and colleagues [45] also exhibited the potential of using a dual nozzle-3D printing technique in the production of a multi-material-containing mooncake by subjecting two different food materials (dough ink and red bean) to more complex structures. This easy-to-swallow food was rated as level 4 based on the IDDSI analysis and framework.

Author contributions

CC & HKN: Conceptualization, Software, Validation, Formal Analysis, Investigation, Writing—Original Draft. HWK: Resources, Writing—Review & Editing. HJP: Supervision.

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Availability of data and materials

The datasets used during this study are available from the corresponding author, [Hyun Woo Kim], upon reasonable request.

Declarations

Conflict of interest

This paper has no conflicts of interest, and the results reported in this manuscript have not been published elsewhere, nor have they been submitted for publication elsewhere.

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