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A Knowledge-based Decision Support System for recommending safe recipes to individuals with dysphagia

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A R T I C L E I N F O

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A B S T R A C T

Background: Dysphagia is a disorder that can be associated to several pathological conditions, including neuromuscular diseases, with significant impact on quality of life. Dysphagia often leads to malnutrition, as a consequence of the dietary changes made by patients or their caregivers, who may deliberately decide to reduce or avoid specific food consistencies (because they are not perceived as safe), and the lack of knowledge in how to process foods are critics. Such dietary changes often result in unbalanced nutrients intake, which can have significant consequences for frail patients. This paper presents the development of a prototypical novel ontology-based Decision Support System (DSS) to support neuromuscular patients with dysphagia (following a per-oral nutrition) and their caregivers in preparing nutritionally balanced and safe meals.
Method: After reviewing scientific literature, we developed in collaboration with Ear-Nose-Throat (ENT) specialists, neurologists, and dieticians the DSS formalizes expert knowledge to suggest recipes that are considered safe according to patient's consistency limitations and dysphagia severity and also nutritionally well-balanced.
Results: The prototype can be accessed via digital applications both by physicians to generate and verify the recommendations, and by the patients and their caregivers to follow the step-by-step procedures to autonomously prepare and process one or more recipe. The system is evaluated with 9 clinicians to assess the quality of the DSS's suggested recipes and its acceptance in clinical practice.
Conclusions: Preliminary results suggest a global positive outcome for the recipes inferred by the DSS and a good usability of the system.

1. Introduction

Healthcare 5.0 paradigm, a research direction fostering a patient-centric approach leveraging on Artificial Intelligence (AI) applications and systems, aims at providing patients with access to personalized solutions [1]. In such contexts, the role of expert knowledge is essential in avoiding the risks related to "black box" models – i.e., the lack of transparency that may hinder the adoption of AI-based solutions in healthcare [2,3]. In particular, for clinical Decision Support Systems (DSSs) the lack of transparency in the decision-making process may significantly hinder the adoption of AI-based technologies [4,5]. The role of clinical experts is perceived as pivotal, particularly when patients safety is on the line. A possible solution to this problem consists in the adoption explainable AI (xAI) tools, for which the possibility to provide human-understandable explanations of the inferences generated by a machine could prove essential for the adoption of digital technologies in healthcare [6]. In such contexts, knowledge-based systems can support clinical personnel and patients in different ways. A part of such systems aims at replicating human (clinical) expertise to provide remote aid for specific problems to patients. However, these systems may require to be developed with experts' support to be effective: for some impairments or diseases, the lack of agreement among experts and the adoption of local (national or regional) standards may hinder the development of fully-functional systems.

A relevant condition characterized by the adoption of local clinical practices and nation-dependent knowledge is dysphagia. Dysphagia is a

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common condition characterized by an impairment in swallowing that limits the patient's ability to eat thus often leading to malnutrition [7–10]. Dysphagia is very common, particularly in patients older than 50 and those who have faced surgical interventions to the mouth or the neck. Moreover, it is a consequence of neuromuscular diseases [11]. Dysphagia is diagnosed by clinical personnel (Ear-Nose-Throat (ENT) specialists, and otolaryngologists) relying on different clinical scales according to the clinical standards in force in a country. Its treatment often consists of suggesting dietary modifications; such recommendations are also depending on.

Indications in daily meal preparation can support dysphagic patients (or their caregivers); however, such indications are provided by clinical personnel [12]. Patients following per-oral nutrition may find it difficult to daily adjust their meals according to the consistency limitations introduced by the clinicians, which may result in patients relying on a handful of dishes (perceived as safe) with the risk of incurring malnutrition [10] Furthermore, the modification of foods' textures and consistencies is not a standardized activity – it depends on local clinical practices and cultural habits – and it relies on patients' education and adherence to the nutrition therapy [13].

In this regard, knowledge-based systems can support dysphagic patients in identifying and applying the best strategies to adjust their diet according to clinical suggestions and maintaining a nutritional-balanced diet without risks. To this purpose, this paper introduces a novel ontology-based Decision Support System (DSS) developed in close collaboration with clinical personnel. The system leverages expert knowledge formalized into a domain ontology [14] to suggest recipes that can be safely consumed by patients according to their health condition. The DSS can be accessed via digital applications by the clinicians – to generate and verify the patient-tailored recommendations – and by the patients and their caregivers – who have access to the step-by-step procedures to autonomously prepare and process one or more recipes. In this way, the application answers the need for a patient-based response to his/her dysphagic condition while enabling clinicians to maintain control over – and intervene in – such a delicate decision-making process.

The remainder of this paper is organized as follows: Section 2 provides an overview on the dysphagia and on the clinical scales adopted to measure it. Section 3 summarizes some of the relevant works in the field of formalizing dysphagia and providing nutritional recommendations for dysphagic patients. Section 4 describes the ontology underlying the DSS and its testing, illustrating the reasoning capabilities of the system and highlighting the role of clinical experts. Section 5 illustrates the user and clinician applications and their functioning, while Section 6 presents the results of a preliminary validation with 9 clinicians. Section 7 discusses the results and highlights some of the limitations of this work. Finally, the Conclusions summarize the main outcomes of this work and sketch the future research directions.

2. Dysphagia and the role of clinical expert knowledge in its management

The difficulty in swallowing one or more food consistencies can have different causes, ranging from neurological diseases to surgical interventions' outcomes; dysphagia is also related to the ageing process. The two risks associated to dysphagia are *penetration*, which consists in the passage of food materials into the larynx – but not below the vocal folds – and *aspiration*, which consists in the passage of food materials below the vocal folds. In both cases, the patient may intervene by expelling (through cough) the materials penetrated or aspirated. However, dysphagia may also cause them not to perceive the intrusion of materials in the airways, resulting in pneumonia or asphyxiation. In its most severe cases, dysphagia may require patients to follow non-per-oral nutrition, with maximum assistance from caregivers or clinical personnel.

Due to the impact dysphagia has on everyday life, patients or their caregivers may try to change their diet deliberately and autonomously (i.e., without medical advice) with the aim of avoiding those food consistencies known for causing cough or asphyxiation [10]. Such unsupervised changes can result in malnutrition, also caused by a partial or total absence of one or more essential nutrients [15]. Moreover, it was noticed how dysphagia impacts on daily habits, in particular for elderlies: the lack of knowledge in processing foods to meet the changes entailed by dysphagia may aggravate malnutrition [7–9]. The first therapeutic line when facing dysphagia is to adjust a patient's diet, modifying food consistencies and textures [12]. Nevertheless, clinical indications may not be sufficient to help patients in day-by-day meal preparation activities, as they lack indications on how to dilute or thicken fluids, process solid consistencies, etc. As a result, patients tend to restrict their diet to a limited set of recipes they acknowledge as safe or they can reproduce autonomously at home [10].

The key for introducing modifications in a dysphagic patient's diet is the evaluation of the disease. However, there is no consensus regarding the clinical scales to be adopted to measure dysphagia. From the one hand, the disease can be measured by different perspectives [16], while from the other hand several scales have been developed over the time [17]. As a result, there is no uniformity in the adoption of a specific scale in clinical practice. The fragmented scenario regarding the knowledge on dysphagia measurement and food consistencies is also evident by the different initiatives that took place over the years with the aim of standardizing terminologies for food consistencies. For example, the *Terminology for foods and liquids consistencies*, which the Italian Study Group on Dysphagia developed (part of the European Study Group for Dysphagia and Globus, later renamed as European Society for Swallowing Disorders) [18] and the *International Dysphagia Standard Initiative* (IDDSI framework) [19] both aim at the same goal.

To pursue the goal of this work – developing an ontology-based DSS aimed at providing dysphagic patients with a set of recipes they can safely consume according to their health condition – we relied on the Italian clinical practice, which adopts two clinical scales to measure dysphagia and its outcomes – namely, the Dysphagia Outcome and Severity Scale (DOSS) [20] and the Penetration-Aspiration Scale (PAS) [21].

2.1. The Dysphagia Outcome and Severity Scale (DOSS)

DOSS is adopted in clinical practice to assess the *level of severity* of the dysphagia in patients. It investigates three factors: (level of

Table 1
A table summarizing the factors investigated by the DOSS clinical scale and the values indicating, for each factor, the patient's status (source [20]).

Factor	Range	
Level of independence	7	Normal
	6	Modified independence
	5	Distant supervision
	4	Intermittent supervision
	3	Total supervision
	2	Maximum assistance
	1	Non-per-oral nutrition
Level of nutrition	7	Full oral nutrition
	6	
	5	
	4	
	3	
	2	Non-oral nutrition
	1	
Diet modification	7	Normal consistency
	6	
	5	1 diet consistency restriction
	4	1$<$ diet consistency restrictions $\leq$ 2
	3	$>$2 diet consistency restrictions
	2	Artificial nutrition
	1	

independence, level of nutrition, and level of diet modification), scoring each of them from 1 to 7, according to the criteria summarized in Table 1. The output of this scale consists of one integer number ranging from 1 to 7, which is comprehensive of the three aspects investigated by DOSS.

2.2. The Penetration-Aspiration Scale (PAS)

In order to identify the food consistencies that may be critical for patients, the PAS scale proposes a model that, for each food consistency, asks the clinicians to evaluate whether or not there is penetration or aspiration of materials, whether these phenomena occur below, to, or above folds. The food consistencies being analyzed are Liquid (Li), Semi-solid (Se), Semi-liquid (SeLi), and Solid (So). They are recognized in Italy as a clinical standard in the "Terminology for foods and liquids consistencies" (reported in Appendix A). For each consistency, an integer score ranging from 1 (no penetration, no aspiration) to 8 is given (aspiration below folds with an absence of a reflexive or conscious attempt to expel bolus, also known as "Silent Aspiration"). The output of this scale is a score for each of the four food consistencies. Fig. 1 illustrates the PAS scale structure.

2.3. Formalizing clinical expert knowledge for dysphagia

The exploitation of expert knowledge in for clinical DSSs is no novelty [22]. In particular, domain ontologies are widely adopted as a means to achieve health data and personalized recommendations in several clinical contexts. Ontology's reasoning capabilities can be exploited to infer nutritional recommendations for a variety of users, including patients. Moreover, reasoning with ontologies presents similarities with the human cognitive process of decision-making with inferences, thus making it easier to exploit them in AI applications [23] and avoiding the opacity of "black-box" purely data-driven models [24]. Taking into account the vast expertise of ENT doctors working with dysphagic patients every day and the peculiarities each patient may present in his/her dysphagic conditions (as described in the previous subsections), semantic modelling and reasoning with knowledge formalized relying on clinical experts seems an approach capable of avoiding the "lack of transparency" stigmas characterizing clinical DSSs [4,5]. Ontologies and semantic reasoning seem to be promising in tackling the issue of providing dysphagic patients with tailored food items, taking into account their health condition and the severity and limitations generated by it. This entails the formalization of clinical expert knowledge pertaining to dysphagia and its assessment using ontological languages – a research issue rarely faced in previous research – in close collaboration with clinicians, who can actively monitor and participate in the ontology development process. We adopted AgiSCOnt [25] as an ontology engineering methodology since it fosters cooperation among clinical personnel and ontologists and foresees a validation phase aimed at checking the developing ontology before using it in applications.

3. Systematic literature review

To identify works relevant to the field addressed in this paper, a systematic literature review following the PRISMA approach [26] was conducted.

3.1. Research Questions (RQs), databases search, and quantitative results

Two research questions guided the search in Clarivate ISI Web of Science, PubMed, Scopus, and ProQuest databases:

- RQ1: Identifying papers addressing dysphagia or swallowing disorders and difficulties using a semantic ontology-based approach, able to formalize in a knowledge base or graph one or more aspects of the disease (search keyword: *(dysphagi* OR "swallowing disorders" OR (swallowing AND difficult*)) AND (ontolog* OR semantic OR "knowledge graph")*)
- RQ2: Identifying papers presenting decision support systems devoted to tackle one or more aspects of dysphagia (or swallowing disorders and difficulties)'s management, including nutrition (search keyword: *(dysphagi* OR "swallowing disorders" OR (swallowing AND difficult*)) AND ("decision support system")*)

Following the PRISMA approach, the searches related to RQ1 and RQ2 were conducted on papers' Title, Abstract and Author keywords records, limiting the search to conference proceedings papers, journal articles, and book chapters published between 2000 and 2024 (to include those works accepted for publication in 2023 but expected to be published in the following year). The date range selected corresponds to the years in which the Ontology Web Language (OWL) was released (2004). Considering the specific RQs and the focus on the ontological modelling of dysphagia and DSSs for the management of such disease,

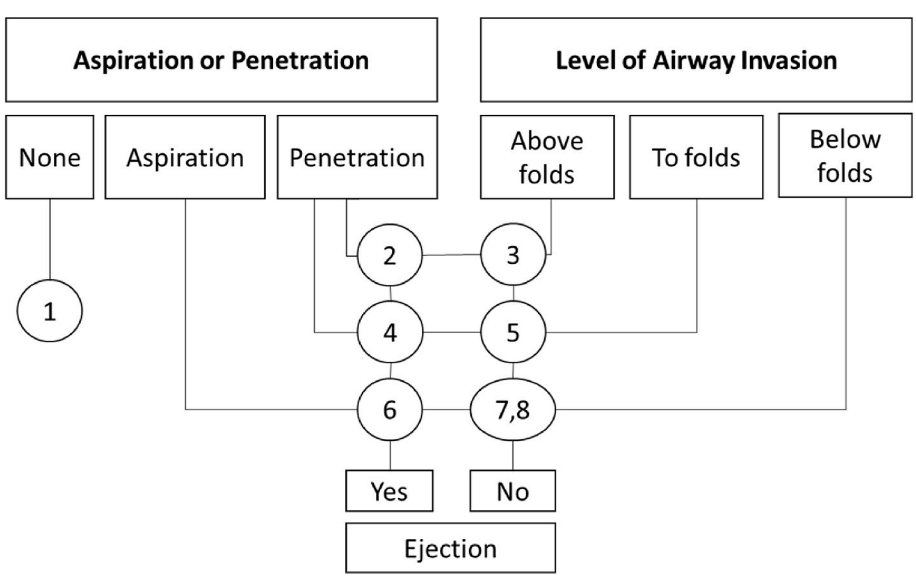

Fig. 1. A schematic representation of PAS scale score system (adapted from Ref. [21]).

the search was limited to works written in the English language and to the following subject areas: Computer science, Engineering, Medicine, Mathematics, and Decision sciences. The process of retrieval, screening, and selection of relevant works is summarized in Fig. 2.

The retrieval of papers from databases pertaining to the two RQs identified 127 articles, which were reduced to 7 after the screening process. The full-text reading of papers brought to the exclusion of one paper, allowing to identify 6 pertinent works. The corpus of records identified for this review includes 5 journal articles [27–31] and 1 conference proceeding paper [32]. Papers are dated between 2019 and 2023 (see Table 2).

3.2. Considerations from the papers reviewed

The review results underlined that a limited number of works address the two RQs. In particular, Table 2 summarizes the solutions described in each included article, identifying the types of patients addressed (whether they are generic dysphagic patients or patients affected by particular neuromuscular conditions entailing dysphagia), their main aim, and if the solutions adopted ontology-based modelling or supported the decision-making process for the intended aim.

Interestingly, all the retrieved works can provide an answer to RQ2. In contrast, only one article (partially) answers to RQ1: in fact, the adoption of domain ontologies is limited only to one article – Barbalho et al. [30] –, which relied on ontologies to develop a monitoring system for the follow-up of dysphagic patients. The system captures the movements and acoustic signals generated during the feeding process (e.g., chewing, swallowing, etc.) and leverages ontologies to classify the foods (into solid, liquid, or pasty materials) to record the meals (and their consistencies) consumed by the patient. Among the reasons that might explain the absence of domain ontologies as techniques underlying the included works, two seem to play a role: the first one is that dysphagia (as described in the previous Section) is a condition described by a variety of scales and usually is a consequence of neuromuscular disease (for which, several domain ontologies already exist [33]); the second reason is the current exploitation of AI-based and data-driven techniques in recent years, both for diagnostic [34] and therapeutic purposes [35]. Not by chance, the selected articles are concentrated in the past 4 years: more than half of the included works rely on data-driven AI techniques to draw inferences on some of the aspects of dysphagia. In particular, it is worth observing that 67% of the articles established the aim of diagnose the dysphagic condition [28–31], while two aimed at providing inferences related on therapies [27,32]. The adoption of AI techniques is transversal to both types of solutions, whether they are employed to process acquired data for diagnostic or therapeutical purposes.

Although the results are only partial, this review also marks a few research gaps. The first one is the quasi-total absence of nutrition therapies for dysphagic patients. Of all the articles, only [30] addresses the problem of food consistencies (although limited to what the patient already consumed) and their safety for patients' dysphagic condition, while Suh et al. [27] focused on the type of nutrition an ASL patient may or may not undergo. A second shortcoming characterizing the included works is the role of expert knowledge. All solutions described in Table 1 leverage expert knowledge combined with inferences gathered from data. However, none seem to be based on clinical practice nor rely on existing clinical scales to assess dysphagia or classify food consistencies.

Differently from existing solutions, our DSS tackles the problem of nutrition in dysphagic patients following per-oral nutrition, leaving diagnostic aspects to clinical personnel. Contrary to the solutions adopting AI-techniques and taking into account the risks related to food consistencies (as described in Section 2), the development of a knowledge-based system was preferred to other existing AI approaches. The system stems from the Italian clinical practice and leverages two clinical scales. Moreover, the proposed system integrates a step-by-step recipe preparation function to support dysphagic patients in preparing safe meals autonomously. To the best of the authors' knowledge, the proposed DSS is the only example of a digital application tackling recipe recommendations for dysphagic patients following per-oral nutrition.

4. Dysphagia Recipe Recommender: ontology engineering process

As mentioned above, the Agile, Simplified and Collaborative Ontology engineering methodology (AgiSCOnt) [25] was selected for this engineering process. Its lightweight but structured iterative process for ontology engineering (OE) was already experienced in previous health-related engineering processes [36]; therefore, the methodology was also deemed useful for this specific context. AgiSCOnt's articulates the OE into three phases:

a) *Domain analysis and conceptualization*: this phase consists in the development of the Ontology Requirements Specification Document (ORSD) [37], including the list of Competency Questions (CQs) [38], and culminates with the domain representation into a conceptual map. These activities are conducted by domain experts with the support of ontologists.
b) *Development and test*: The outcome of the previous phase is developed into a formal ontology after selecting the ontological languages. The prototypical ontology is then tested to check whether it answers all the CQs.
c) *Ontology use*: in this phase, the ontology is tested against a set of experts-generated use cases to evaluate if further modifications are necessary; it is then exploited as part of an application.

The experts directly involved in this process were: an ontologist, a biomedical engineer with previous experience in OE, a senior neurologist with decades of expertise in treating dysphagia, and two ENT specialists – the first with specific expertise in treating dysphagia and the second with specific expertise in diagnosis and treating of dysphagia in elderly patients characterized by chronic and neuromuscular conditions.

4.1. Domain analysis and conceptualization

The first phase is devoted to knowledge elicitation through domain analysis, and it is aimed at producing a conceptualization of the domain at hand. Clinical experts involved in the OE process pointed out the role and functioning of DOSS and PAS scales and how they were used in clinical practice. Since the aim of the DSS is providing dysphagic patients with a set of recipes that are considered safe according to the severity of their condition and in line with the consistencies they can safely swallow, the two scales were considered adequate to the purpose. Recipes to be suggested serve as an output for patients who can live independently (or to patients that are not completely independent but can rely on caregivers) and have to face dysphagia and its consequences on meal preparation and consumption. These recipes require food processing aimed at modifying their consistency and texture by adding one or more ingredients and crushing or diluting them [39]. Therefore, patients (and their caregivers) need to learn new food preparation techniques to prepare safe dishes. Taking into account the lack of generalized guidelines for foods' consistencies modification [13,40], clinical personnel suggested adopting an Italian book published specifically for neuromuscular patients affected by dysphagia and edited by professional chefs together with dysphagia and neurology experts.

In such a book, the recipes are thoroughly described and characterized by nutritionally-balanced compositions [41]. Each recipe contains nutrition facts, a step-by-step textual guide, and pictures to help patients and caregivers prepare dishes. Leveraging the expertise of clinical personnel participating in the development of this DSS, each recipe composing the book was associated with a single food consistency (among those described in the *Terminology for foods and liquids consistencies*: Semi-liquid A, Semi-liquid B, Semi-solid C, Solid D, Solid E –

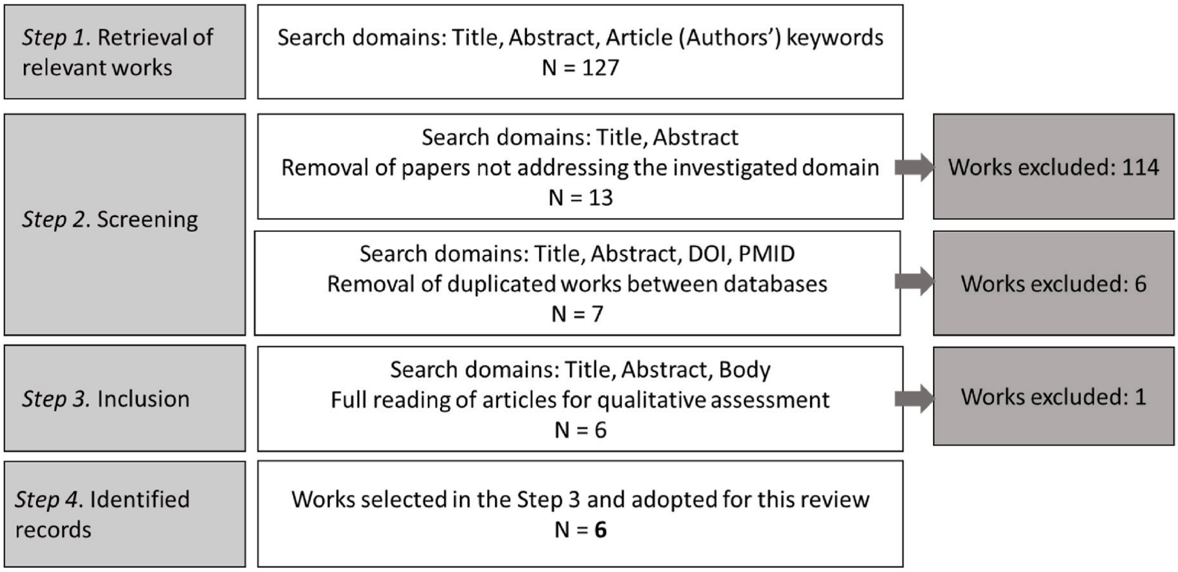

Fig. 2. The PRISMA flow diagram adopted in this review process.

Table 2
The synthetic descriptions of the solutions described in each of the included papers.

Ref.	Year	Patient	Description	Main aim	Ontology	DSS
[27]	2019	Patients with amyotrophic lateral sclerosis (ASL)	After assessing a correlation between pulmonary function and pharyngeal pressure in ALS patients using previously collected data, significant high resolution manometry (HRM) parameters during pharyngeal swallowing are assessed (between ASL patients and the control group). HRM parameters are adopted to predict the appropriate feeding type (ranging from Fully oral to Tube feeding) for target patients via logistic regression.	Therapy	–	✓
[28]	2021	Geriatric patients	An XAI clinical DSS to assess geriatric patients' risk of developing some symptoms (among which, dysphagia) related to geriatric conditions. It exploits results from questionnaires related to each of the four conditions and performs a SWOT analysis to predict one or more of the symptoms associated with the conditions. It adopts receiver operating characteristics analysis to assess DSS's performance (accuracy, sensitivity, and specificity).	Diagnosis	–	✓
[29]	2021	Dysphagic patients	An ML approach to elaborate sensors' data (swallowing and respiratory dynamics acquired via flexible mechano-acoustic sensors) into a multidimensional metric for the identification of unhealthy behaviors. Using Random Forest classifier, it recognizes the frequency and severity of poor swallowing to assess a patient's probability to fall into a dysphagia severity class (none, mild, moderate, severe).	Diagnosis	–	✓
[30]	2021	Dysphagic patients	A system (based on mobile devices) to capture mastication and swallowing movements and acoustic signals to classify them, to provide information regarding the detailed list of foods consumed and assess the level of patient's dysphagia. A domain ontology is adopted for acquired data classification.	Diagnosis	✓	✓
[31]	2022	Dysphagic patients	A system for home diagnosis of dysphagia leveraging the acquisition of speech signals. Using a throat vibration sensor, the system extracts relevant features related to dysphagia, and acquired data are analyzed and classified with an integrated ML classifier.	Diagnosis	–	✓
[32]	2023	Patients suffering from Eosinophilic Esophagitis (EoE)	An ML approach to support patients suffering from EoE in the elimination of six or one food causing them dysphagia. By elaborating on histological data and patient-reported outcomes, the ML infers several features to assign patients a therapy (eliminating six foods or eliminating one food).	Therapy	–	✓

Appendix A). This is pivotal, as dishes characterized by several consistencies may cause patients problems swallowing.

However, this may not be enough to guarantee patients' safety. Therefore, clinical personnel reviewed each recipe and its consistency to assess the safety conditions under which a dysphagic patient can consume it. Therefore, they attributed each recipe DOSS and PAS scores to indicate the minimum requirement a patient must fulfill to safely consume the recipe. The clinicians decided a recipe could be deemed safe for a patient if suitable under a severity perspective (DOSS scale) and, simultaneously, a consistency perspective (PAS scale). However, clinicians in charge of patients with dysphagia might grant individual patients some exceptions if they assess they can tolerate other recipes. The full list of annotated recipes can be observed in Supplementary materials (Table S1).

The results of this phase consist in a set of formal documents to state the aim of the ontology using the Ontology Requirements Specification Document (ORSD) [37], including the list of Competency Questions (CQs) [38] (Appendix B). From a conceptual perspective, the domain was schematized in a conceptual map (Fig. 3) and prompted ontologists to define the criteria that make a recipe eligible for a patient.

Taking into account the target users of the system, the condition for a recipe to be eligible as appropriate for a patient consists in:

- *C1*: the patient's DOSS score being equal or higher than the score defined by clinicians (dysphagia severity condition)
- *C2*: the patient's PAS score for the specific consistency being less than or equal than the one defined by clinicians (consistency condition).

A recipe is safe under the perspective of dysphagia severity if it

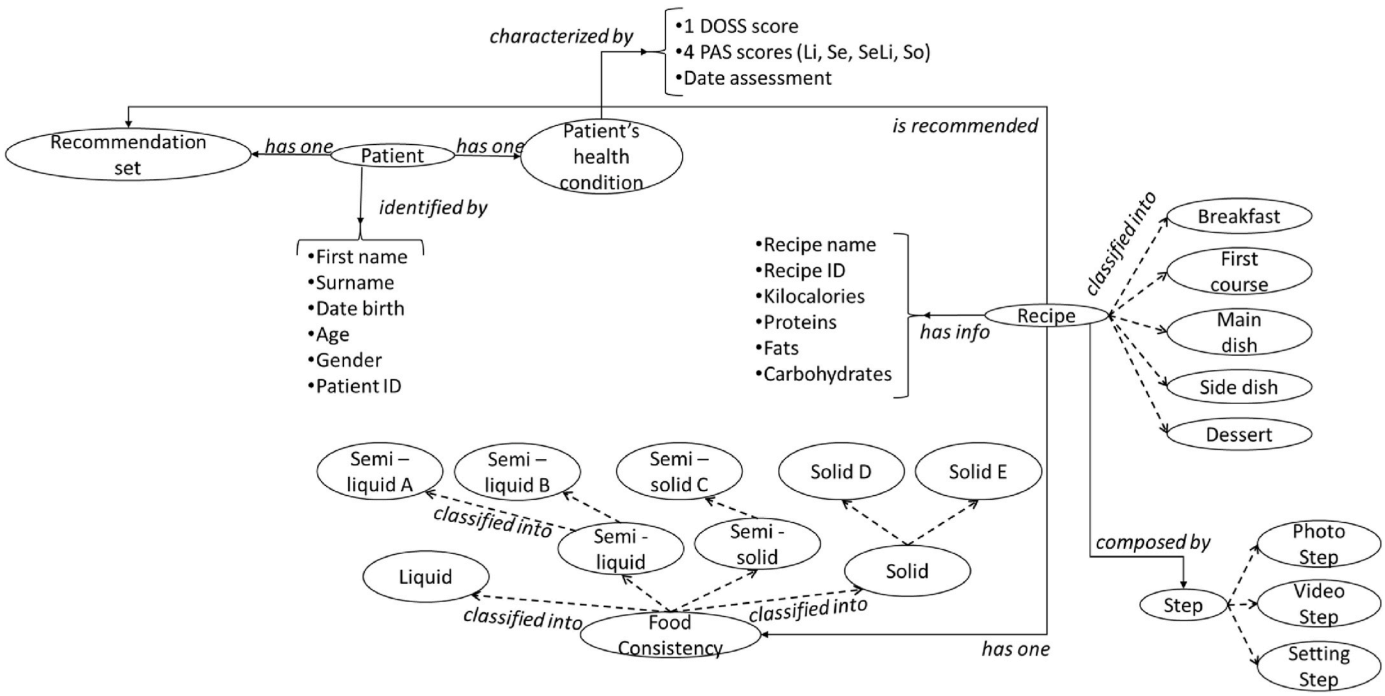

Fig. 3. The Conceptual map developed by the team involved in the dysphagia DSS ontology engineering process.

satisfies condition *C1*, while it is safe under the consistency perspective when it satisfied condition *C2*. Therefore, a recipe is completely safe – thus, it can be suggested to a patient – if it satisfies $C1 \wedge C2$.

4.2. Development and test

The development phase took advantage of the outputs of the previous step. In particular, considering the need to develop rules to indicate the severity (DOSS) and consistency (PAS) scores that prevent patients from consuming specific recipes, the OWL profile selected was OWL 2 DL [42]. The ontology was developed using the Protégé ontology editor [43], which also allows for illustrating most of the results in a graphical form and is available online[1]; in this way, it was possible to involve domain experts in validating different authoring choices.

The TBox of the Dysphagia ontology (prefixed as dis:) is structured in 24 classes, which reproduce the concepts illustrated in the Conceptual map (Fig. 3) – with the addition of the meta-class owl:Thing class. Classes representing fundamental concepts in the ontology are restricted: for example, a patient (called dis:User to avoid stigmatization) is any entity that holds at least 1 dis:isInHealthCondition relationship with an object that is-a dis:Health_Condition – reusing a documented ontology design pattern (ODP) [44].

Similarly, a dis:Recipe is an object that dis:isComposedOf of some dis:Steps, and that has exactly 1 dis:FoodConsistency and exactly 1 dis:recipedID integer value.

Each class is labelled with rdfs:label annotations to provide both English and Italian description of the concepts' names. Furthermore, classes describing consistencies adopt the annotation property dis:description to provide a string reporting the consistency, according to the *Terminology for foods and liquids consistencies*, and some dis:example providing a string with examples of foods that fall into that consistency (as reported in Appendix A).

The ontology adopts 13 object properties and 20 datatype properties to describe individuals. The owl:FunctionalProperty predicate was adopted to model subjects that must have only one single object – for example, the fact that one recipe can have one and only one consistency.

Also, for object and datatype properties, annotation properties are adopted to allow human users to quickly comprehend the relationships that populate the ontology.

The ABox consists of 124 individuals, which are used to represent 13 patients and an equal number of dis:Health_Condition and dis:Recipe_-Recommendation, 60 recipes, and some of their steps – so far, not all of the recipes have been completely represented with dis:Step, as it is a process that requires the preparation of videos and pictures (see further Section 5).

To conveniently represent the logical dependencies among the dis:Step composing a dis:Recipe, the ontology reused the Content ODP *Sequence* [45]. This ODP is fully documented and available as a "reusable building block"; it allows to represent the notion of transitive and intransitive precedence and their inverses, and it is used to represent processes. The reuse of this ODP enables the possibility of linking the dis:Step that composes the sequence of operations that need to be enforced for a patient to prepare a dis:Recipe (Fig. 4 provides an example of the use of the ODP Sequence for a dis:Recipe and its dis:Step).

Each dis:Recipe is also classified according to the course type it is supposed to belong to (dis:Breakfast, dis:First_Course, dis:Main_Dish, dis:Side_Dish and dis:Dessert). This can help patients identifying the type of dish for their daily needs, supporting them in composing their meals.

As recipes' instructions may contain key activities – especially those related to grinding solid foods to get a semi-solid or liquid consistency – that are pivotal for altering the texture of the dish, the team deemed it essential to provide short videos illustrating these delicate activities. As a consequence, the TBox of the ontology reflected this need by classifying dis:Step into dis:SettingStep (which presents the ingredients and their quantities, the preparation and cooking time), dis:PhotoStep (which provides a representative picture of the step), and dis:VideoStep (which provides a video illustrating the step). Each step is completed with a dis:stepDescription, providing a textual description of the instructions.

The ontology needs to represent the conditions under which a patient may or may not consume a specific recipe: these conditions were stated

[1] Publicly available at: https://www.stiima.cnr.it/wp-content/uploads/dysphagia.txt.

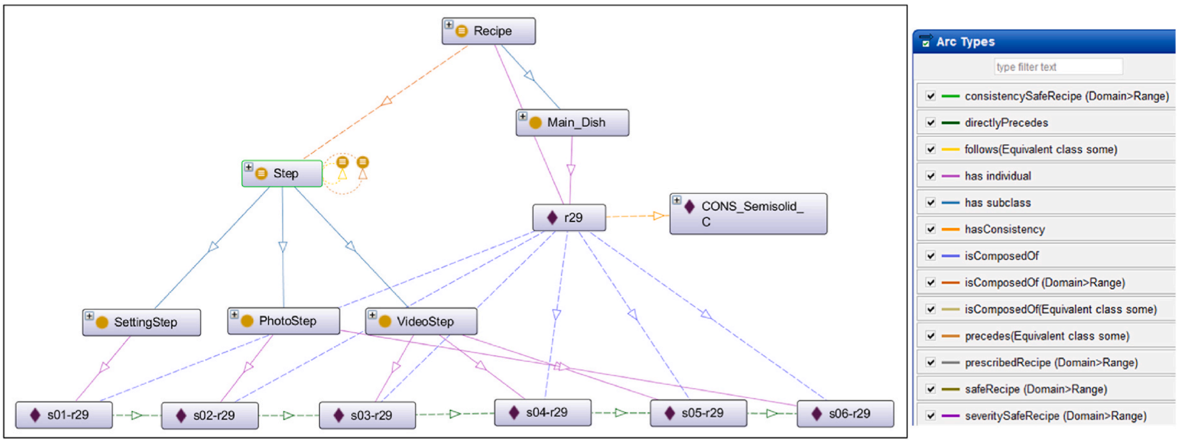

Fig. 4. An excerpt of the Dysphagia ontology illustrating a recipe (the individual dis:r29) that dis:isComposedOf its six dis:Step, each of which:directlyPrecedes its successor.

by the clinical personnel involved in the OE process. During the previous phase, clinicians investigated whether it was possible to state general rules preventing patients from consuming a recipe basing on to the recipe's specific consistency. It was possible to identify a set of general rules preventing food characterized by a specific consistency to be consumed by patients with DOSS and PAS scores not adequate (for example, recipes having a dis:liquid_A consistency are not recommended for patients with a dis:PAS_Li $\geq$ 7). For each recipe, the minimum DOSS and PAS scores for a patient to be safely allowed to eat a dish was stated, then rules were developed taking into account recipes' similarity. These considerations are translated into the ontology using rules using the Semantic Web Rule Language (SWRL) [46]. Recipes are evaluated for a dis:severitySafeRecipe perspective:

User(?u), isInHealthCondition(?u, ?hc), DOSS(?hc, ?x), greaterThanOrEqual(?x, 3), Recipe(?r), hasConsistency(?r, ?c), Semi-liquid_B (?c), isRecommended(?u, ?rec) -> severitySafeRecipe(?rec, ?r)

And for a dis:consistencySafeRecipe perspective:

User(?u), isInHealthCondition(?u, ?hc), PAS_SeLi(?hc, ?x), lessThanOrEqual(?x, 2), isRecommended(?u, ?rec), Recipe(?r), hasConsistency (?r, ?c), Semi-liquid_B(?c) -> consistencySafeRecipe(?rec, ?r)

As the rules illustrate, the comparison is performed by comparing the DOSS and PAS scores describing a patient's health condition. If the antecedent holds true, then also the consequence is true. These consequences are constituted of a triple in the form *dis:user's_recommendation dis:consistencySafeRecipe dis:rXX* or *dis:user's_recommendation dis:severitySafeRecipe dis:rXX*. Then, another SWRL rule models the safety condition ($C1 \wedge C2$):

User(?u), isRecommended(?u, ?rec), severitySafeRecipe(?rec, ?r1), consistencySafeRecipe(?rec, ?r2), recipeID(?r1, ?id1), recipeID(?r2, ?id2), equal(?id1, ?id2) -> safeRecipe(?rec, ?r1)

This ensures that the only recipes being inferred as dis:safeRecipe by the ontology have been evaluated under both severity and consistencies perspectives through the respective scales. SWRL rules also allow to represent some exceptions – e.g., the case of dis:r07, which, contrary to other recipes that have a dis:Semi-solid_C consistency, is indicated for patients with a DOSS score higher or equal to 4.

User(?u), isInHealthCondition(?u, ?hc), DOSS(?hc, ?x), greaterThanOrEqual(?x, 3), isRecommended(?u, ?rec), Recipe_Recommendation(?rec), recipeID(?r, ?id), notEqual(?id, 7), Recipe(?r), hasConsistency(?r, ?c), Semi-solid_C(?c) -> severitySafeRecipe(?rec, ?r)

User(?u), isInHealthCondition(?u, ?hc), DOSS(?hc, ?x), greaterThanOrEqual(?x, 4), isRecommended(?u, ?rec), Recipe_Recommendation(?rec), recipeID(?r, ?id), equal(?id, 7), Recipe(?r), hasConsistency(?r, ?c), Semi-solid_C(?c) -> severitySafeRecipe(?rec, ?r)

In this case, a patient characterized by a DOSS severity equal or greater than 3 can eat any semi-solid recipe, with the sole exception of the recipe with id equal to 7, because that recipe requires a DOSS score greater than or equal to 4 – i.e., recipe 7 is recommended for patients with a lower dysphagia severity.

The ontology makes use of 14 SWRL rules, which can account for all the characteristics of the recipes that the clinical personnel have identified during the previous step with AgiSCOnt.

The recommendation is represented as an individual – instance of the class dis:Recipe_Recommendation. After reasoning with a DL reasoner, the inferences materialize as triples in the form *dis:recommendation dis:safeRecipe dis:recipe*. However, also dis:consistencySafeRecipe and dis:severitySafeRecipe are reported. This is important to illustrate to clinical personnel which recipes have been selected as completely safe and which are safe only under one perspective (severity or consistency). In this way, it is possible to query the ontology to find out only the dis:safeRecipe, but also dis:severitySafeRecipe and dis:consistencySafeRecipe.

To exemplify the reasoning process, let us consider a patient P whose health condition is characterized by a DOSS score equal to 4 and a PAS score for liquids (dis:PAS_Li), semisolid (dis:PAS_Se), and solid (dis:PAS_So) equal to 3 (and semiliquid dis:PAS_SeLi consistency assessed to 1). P can follow an oral nutrition but needs to care for some consistencies, as they may generate discomfort and threaten his health. For this patient P, recipe r22 "Banana and pistachio milkshake" (with a consistency equal to "Semiliquid_A″) is inferred to be a dis:safeRecipe since its consistency is deemed safe. This happens because the comparison between P's DOSS value and r22's consistency enables the fact that r22 is a dis:severitySafeRecipe, thus respecting condition C1:

User(?u), isInHealthCondition(?u, ?hc), DOSS(?hc, ?x), greaterThanOrEqual(?x, 3), Recipe(?r), hasConsistency(?r, ?c), Semi-liquid_A (?c), isRecommended(?u, ?rec) -> severitySafeRecipe(?rec, ?r)

and also because P's semiliquid PAS score allows to consume foods with r22's consistency:

User(?u), isInHealthCondition(?u, ?hc), PAS_SeLi(?hc, ?x), lessThanOrEqual(?x, 2), isRecommended(?u, ?rec), Recipe(?r), hasConsistency (?r, ?c), Semi-liquid_A(?c) -> consistencySafeRecipe(?rec, ?r)

Therefore, the rule representing the safety condition ($C1 \wedge C2$) also holds true.

On the contrary, r15 "Asparagus, butter, and sage green semolina gnocchi" with its "Solid_D″ consistency is inferred to be a dis:severitySafeRecipe, but is not inferred to be a dis:consistencySafeRecipe; therefore, $C1 \wedge C2$ is false, and as a consequence, P's recommendation reports r15 only as a dis:severitySafeRecipe.

Similarly, recipes respecting P's restrictions on PAS consistencies can be inferred as dis:consistencySafeRecipe (C2), but they can be inferred as dis:safeRecipe only if they also respect C1.

The reasoning process can be schematized as follows:

```
start
Get user's PAS and DOSS values
Get number of recipes R {R1, … Rn}
while R > 0:
    ** Compare user's DOSS (C1) **
        Check if user's DOSS ≥ Rn's severity safety parameter
        then rec dis:severitySafeRecipe Rn
    ** Compare user's PAS values (C2) **
        foreach user's PAS(p) > 1
            Check if user's PAS(p) ≤ Rn's consistency safety parameter
            then rec dis:consistencySafeRecipe Rn
    **Check if (C1 ∧ C2) holds to determine safe recipes**
    if (rec dis:severitySafeRecipe Rn) AND (rec dis:consistencySafeRecipe Rn)
    then rec dis:safeRecipe Rn
Get the triples composing user's dis:Recommendation rec
end
```

4.3. Ontology use

The ontology resulting from the previous phase was checked under an ontology evaluation perspective using the Ontology Pitfall Scanner! (OOPS) [47] before its use. This ontology evaluation approach supports ontologists in the identification of common pitfalls, such as the use of polysemous elements, synonymic classes, improper use of "is a "relationships, incorrect definition of properties (including domain and range definitions, properties features such as functionality and inverse), lack of annotations and basic information, lack of disjointness, the inclusion of cycles (or loops) in the class hierarchy, etc. OOPS! is also available as an online tool [48] to support the community of ontologists. The test run on the Dysphagia ontology did not identify any pitfall among those searched with OOPS!

As the adoption of use cases and tests is pivotal in AgiSCOnt to verify and further modify the target ontology, the third phase foresaw the test of the developed ontology with 13 patients (and their health conditions, presented in Appendix C) provided by the clinical personnel. To ensure patients' anonymity, the datatype properties developed to identify patients (i.e., dis:FirstName, dis:Surname, dis:Age, dis:dateOfBirth) were not compiled. Users were identified exclusively by the dis:patientID, while the name attributed to owl:Individuals representing them was provided by clinical personnel. Not all health conditions were complete (some of them lacked one or more PAS scores), while three patients were out of the scope of the ontology – as they rely to non-oral nutrition: for these patients, the ontology was expected to retrieve no inferred data. The ontology was then queried to identify the dis:safeRecipe with SPARQL and the results were analyzed by clinical personnel to assess whether all results were in line with the expectations and the clinical recommendations. As mentioned, two patients (ID 05 and ID 13) were linked to a dis:recommendation individual that did not provide any inference. Similarly, a third patient (ID 3) is also characterized by a severe health condition, which also lacks data regarding three consistencies (PAS scores); thus, the few inferences characterizing his/her diet were only related to dis:consistencySafeRecipe – but were disregarded as the patient is fed via non-oral nutrition, as pointed out also by the lack of dis:safeRecipe inferences. Clinical personnel confirmed that these three patients are characterized by a level of severity that requires non-oral nutrition. The ontology was tested using the snapSPARQL plugin for Protégé [49] and the Stardog Enterprise RDF triple-store (with the SL reasoning type, as it supports both OWL 2 DL and SWRL) [50].

Considering the positive results of the testing phase, the OE process is concluded and the developed ontology is adopted as the backbone of a prototypical digital application (as illustrated in the following Section 5).

5. Digital applications

The exploitation of the DSS in a real clinical context requires the implementation of a tool that can be easily used by the target users – here clinicians and patients with dysphagia – through which they can access the results of the reasoning – here the nutritional recommendations. In this regard, we have designed two digital applications: one that allows the clinical personnel to generate a personalized list of recipes based on the patient's assessment; and the other that works as a digital recipe book supporting the final user, i.e., the patient and/or the caregiver, in following a more varied, but safe, diet at home. The two applications are interconnected in a single framework: the Clinician app generates the personalized configuration – based on the output of the ontology– that sets the adaptation of the Patient application.

5.1. Clinician application

After assessing the patient's condition, in terms of severity of the dysphagia and safe consistencies, the clinical personnel can generate the personalized recipe list through the application installed on his/her laptop. Such an application is based on a simple and intuitive graphical user interface (GUI) through which the user can create a patient profile, visualize the list of recipes automatically generated by the DSS, and generate the final list. The expected usage of the application is as follows (see Fig. 5):

1) First, the clinician logs in the application by inserting username and password in the specific fields. By authenticating, the clinician has access to all the already registered patient profiles.
2) After authentication, the clinician can create a patient profile by inserting in the required fields the following data: personal info, DOSS and PAS scores. The application also allows to modify an existing patient profile, e.g., in case the severity of the dysphagia has changed over time and an update of the safe recipes list is necessary. By clicking the "Generate recipe list" button, the profile is created and the request for generating the personalized configuration is sent to the DSS (Fig. 4a).

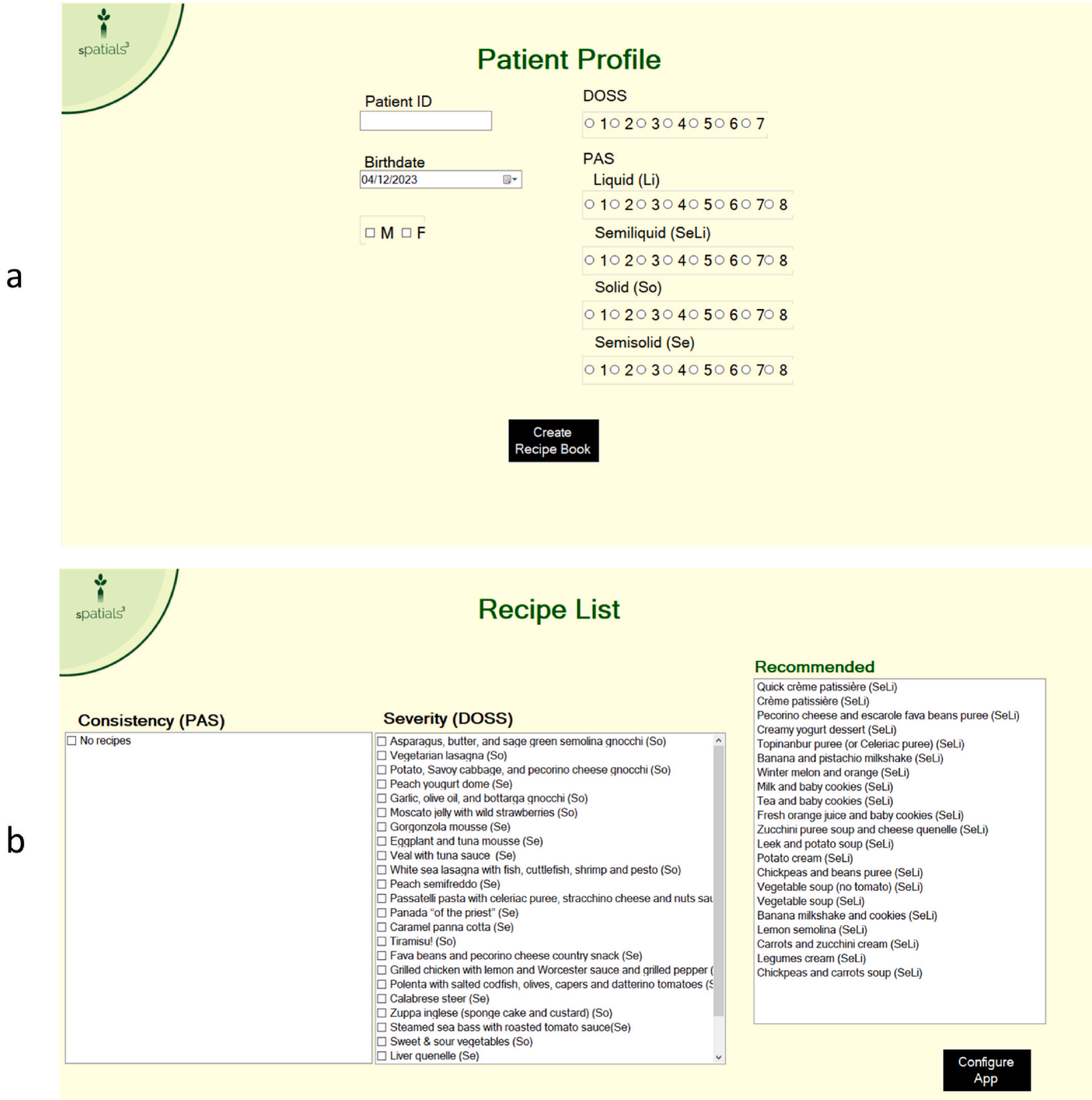

Fig. 5. The GUI of the clinician application for specifying patient's DOSS and PAS scores (a) and the list of recipes inferred by the DSS (b): on the right column, the list of dis:safeRecipe inferred, while on the left columns, the lists of PAS- and DOSS-safe inferred recipes.

3) The subsequent panel shows three lists of recipes (Fig. 4b). The "Recommended" list refers to the recipes that are considered safe (dis:safeRecipe) for the given patient, because they satisfy both the severity and the consistency criteria. The two lists – "Consistency (PAS)" and "Severity (DOSS)" on the left side of the panel include the recipes considered safe based only on either the PAS or the DOSS DOSS score, respectively. This information is made explicit because, according to his/her experience and the specific condition of the patient, the clinician is allowed to add one or more of such recipes to the list of recommended ones. By selecting the "Configure App" button, the clinician confirms and approves the recipe list that constitutes the final configuration.

5.2. Patient application

Once the personalized configuration (consisting in the list of recipes inferred and selected by the clinician) is generated, the patient can access the digital recipe book helping him/her or his/her caregiver prepare the recipes. Such an application represents an extension of an existing system, the Home Interactive Interface (HIC) – an ubiquitous projected GUI designed for the smart home that allows controlling appliances, comfort metrics and providing support for performing activities of daily living especially to frail individuals [51]. In particular, for the purpose of this work, we focused on a specific section of the HIC application aimed at helping the dwellers during meal preparation. Its main functionalities are reported in Fig. 5.

The patient application shows the user the list of available recipes, i.e., those included in the configuration and thus considered safe (Fig. 6a). After selecting a recipe from the dropdown list, a first panel illustrates a general overview of the recipe (corresponding to the dis:SettingStep in the ontology): the preparation and cooking time, the number of persons for whom the recipe has been created, the list of ingredients and respective quantities, and a sample image of the meal (Fig. 6b). By selecting the "START" button, the application shows in subsequent panels the main steps needed to prepare the meal. On the left side of the panel, text instructions illustrate each step, while on the right side of the panel either an image or a video shows the expected result of the given step or reproduces its execution (Fig. 6c and d). The instructions and the images of the recipes have been reproduced by following those included in the recipe book [41]. For some recipes, especially those characterized by more complex steps, ad-hoc videos have been recorded and uploaded to the application. To ease the usage process, the GUI only allows to navigate through the selected recipe by means of the "NEXT" and "BACK" buttons, or to return to the Home panel of the app. When a video is provided, the GUI also includes the buttons to control the video playback (as shown in Fig. 6c).

5.3. Integrated system architecture

The aforementioned applications are interconnected via a robust system architecture (Fig. 7). However, there are some restrictions and differences in their information access, modification permissions, and flow of data. The Patient application must provide the list of recipes selected tailored for a specific user, which was retrieved from the DSS. Nevertheless, it does not grant DSS access to the users (nor allow them to modify) their health conditions within the DSS. The data flow is only one-way, directed from the DSS layer to the Patient application.

On the other hand, the clinician application has access to the DSS with permission to modify the ontology, reason over new input data, and get a new set of recipes based on the latest modification for the patient. This allows the patient to navigate their application easily without any concern regarding the structure of the ontologies behind the system. If a patient's health condition has changed over time, which is likely to occur in progressive diseases such as neuromuscular, the clinician is able to then modify the ontology according to the most recent patient's assessment and update the Patient application according to the new reasoned data coming from the DSS. Similarly, if a patient reports specific issues related to the consumption of one of the suggested recipes, the clinician, after evaluating the situation, can modify the Patient application's output. In this way, the patient application is always updated according to the latest feedback coming from the patient and it will be further and further tailored and customized as they keep using the application. However, the previous health condition will be stored in a JSON file and exported to the clinician prior to any modification for further analysis. When the clinician modifies the patient information, the application generates a SPARQL query DELETE to remove the previous data, followed by another SPARQL query INSERT to insert the new information into the ontology. The SPARQL queries run over the Stardog reasoner and populate the result tables with a new set of recipes tailored for the new condition of the patient specified. Finally, the application generates a SPARQL query SELECT to retrieve all the safe recipes suitable for the patient exported in the form of a JSON file which will later update the Patient application.

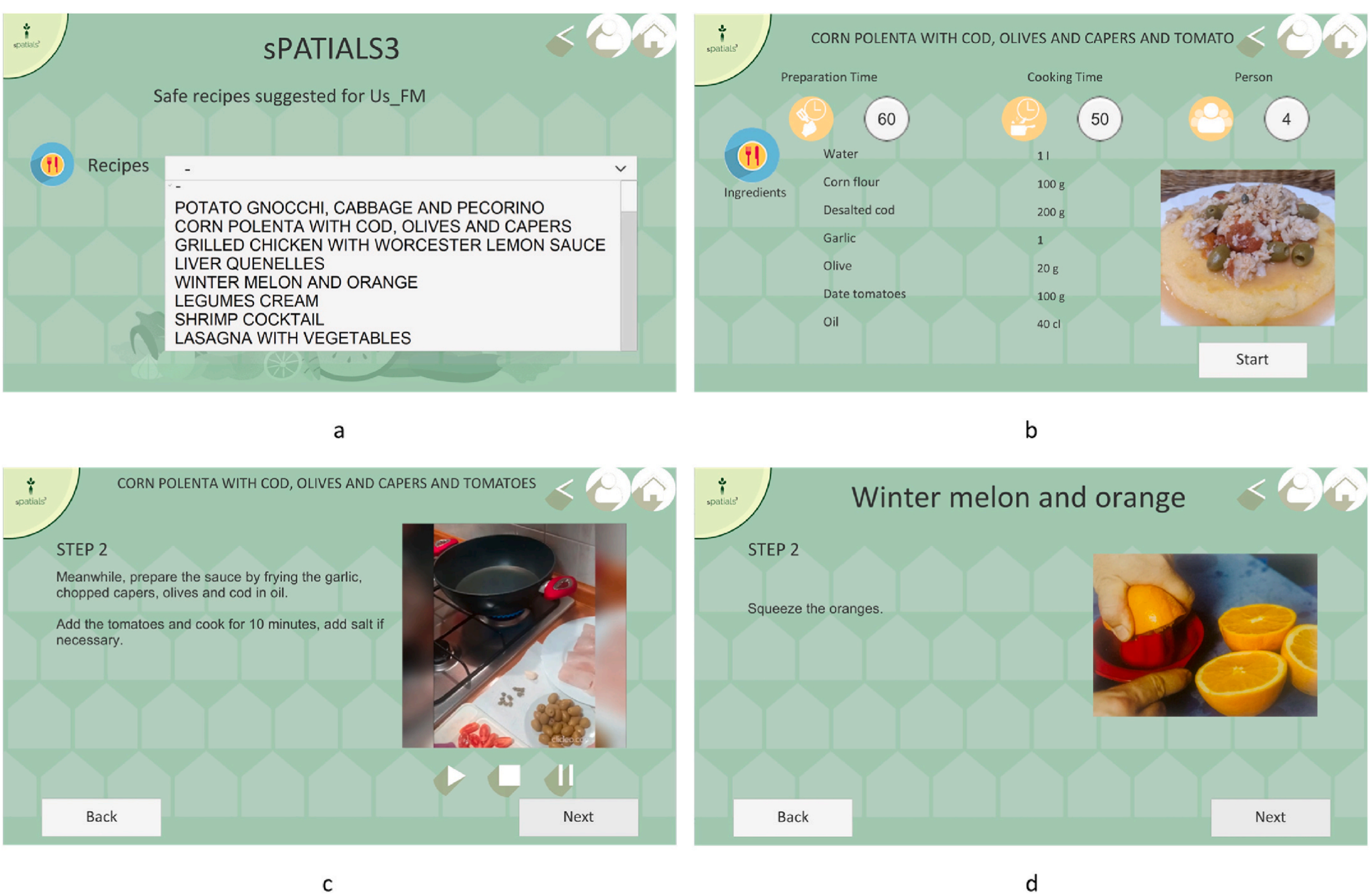

Fig. 6. Screenshots of the patient application showing its main functionalities (a: recipe selection; b: setting step of the selected recipe; c: textual and video instructions; d: textual and pictorial instructions).

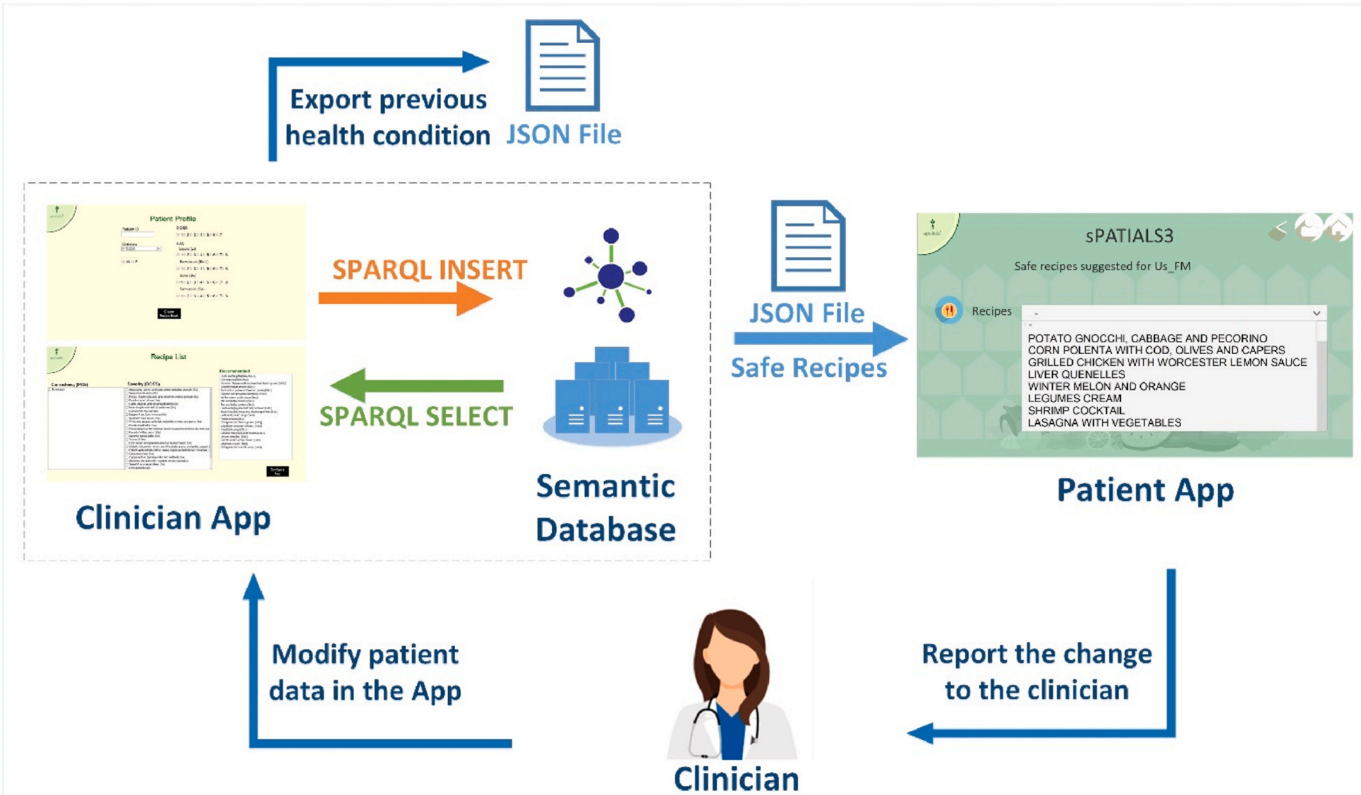

Fig. 7. Conceptual architecture of the integrated system and data flow among the clinician application, patient application and semantic database.

6. Preliminary evaluation of the DSS

A first evaluation of the system, consisting of the inferences generated by the DSS and the two digital applications presented in Sect. 5, was performed. The evaluation was carried out involving 9 clinical nutrition experts with a focus on dysphagia, and had the goals of:

1. Verifying that the recipes inferred by the DSS were suitable for the needs of specific patients; in other words, this goal is set to investigate whether the ontology-based DSS provides clinicians-approved and inferred recipes to the Clinician application.
2. Evaluating the ease of use and the perceived usefulness of the Clinician application.
3. Evaluating the ease of use and the perceived usefulness of Patient application.

6.1. Methods

The three objectives indicated above led to three distinct steps of the evaluation that were performed in a single experimental session. To reach as many experts as possible – and considering that such experts are clinical personnel involved in hospital activities – we carried out the experiment as a group session. Thus, all participants were explained the research activities conducted and at the end of each test phase, participants responded to questionnaires individually. Therefore, during the first phase of the experiment (E1, concerning goal 1), the researchers briefly explained the problem and the proposed solutions (ontology-based DSS and application); in particular, researchers stressed the knowledge-based reasoning capabilities underlying the inference capabilities of the DSS, and the applications that participants were asked to evaluate. The workflow consisting of the clinician inserting the patient's dysphagic condition with DOSS and PAS, the ontology-based DSS performing tailored inferences, and the Patient application retrieving the inferred recipes was explained.

For E1, each participant was provided with the following data regarding the health condition of three patients (real and anonymized). The three patients are examples of dysphagic patients, and one of them presents incomplete data related to one of the PAS consistencies:

- CDC – DOSS: 5. PAS_So: 1; PAS_Li: 1; PAS_SeLi: 1; PAS_Se: 1
- MA-MI – DOSS: 5. PAS_So: 1; PAS_Li: 8; PAS_SeLi: 1; PAS_Se: 1
- RU-MA – DOSS: 4. PAS_So: 1; PAS_Li: 1; PAS_SeLi: unknown; PAS_Se: 1

which consist of the patient's evaluation with DOSS and PAS scales. Therefore, a list of ten DSS-inferred recipes for each of the three patients (CDC, MA-MI, RU-MA, whose health conditions are presented in Appendix C) was presented. Each participant was asked to indicate whether, with respect to his/her clinical experience, the suggested recipes were suitable for each patient's condition, choosing "yes" or "no". During the activity, a copy of the paper recipe book was available for consultation so that participants could check the recipes' processes and consistencies.

The aim of the second part of the experiment (E2) was to evaluate the Clinician application. Participants were shown a video displaying the expected use of the application and how the clinicians should interact with it to enter patient data (DOSS and PAS evaluations) and automatically generate the list of suitable recipes. Participants could also see how to add or remove recipes from the list of those inferred. Thus, clinicians rated their degree of agreement with four statements on a 5-point Likert scale. The statements were:

- The application is easy to use
- The application is useful
- The application promotes a more varied diet
- If I had this application I would use it

These ad hoc questions were selected to measure the degree of agreement with respect to the perceived usefulness, the perceived ease of use, the extent to which the application actually does what it was designed to do, and the intention of use. Three of these four sentences were adapted from the Technology Acceptance Model questionnaire (TAM3 [52]). Furthermore, two open questions were proposed: "Why do you think the application is useful?" and "Do you have any suggestions to improve it?".

Finally, in the third part of the experiment (E3) each participant was shown a video of the patient's application, displaying the expected interaction (including clips pertaining the preparation of a recipe, illustrating how to process food to modify its texture). Participants were asked to score the degree of agreement with five statements on a 5-point Likert scale. These statements were:

- I think the application is easy to use for dysphagic patients
- I think the application is useful for dysphagic patients
- I think patients would need a lot of training before learning how to use the app properly
- I think most people would quickly learn to use the application
- I think dysphagic patients would use this application

Again, these sentences were adapted from the TAM3 questionnaire.

Finally, participants were asked to indicate their age, gender, occupation, and years of experience. The results of the experiment are presented in Section 6.3. In addition, all spontaneous comments were recorded (Table 4).

6.2. Participants

A total of 9 participants (all females) were recruited from the clinical staff who deal specifically with patients with dysphagia (in particular: 3 nurses, a neurologist, a physician, a physiatrist, a respiratory physiotherapist, a dietician, and a speech therapist). All participants work in the Centro Clinico Nemo, a specialized center for neuromuscular diseases located within the Niguarda General Hospital in Milan. According to Ref. [53], the number of expert participants needed for a usability evaluation has been reached. Therefore, all clinicians involved are experts in the pathology being studied and work in the same team, despite specializing in different aspects; the choice was made to have a heterogeneous but representative sample of users who would use the system (clinicians) and who can give expert opinions regarding the needs of patients with dysphagia. The participants' average age was 35.5 years (S.D. 9.13), with an age range of 22–46 years old. The sample reported an average work experience of 10.75 years (S.D. 7.89; range 1–24). Participants could respond by contributing according to their specialization but could not discuss choices or exchange opinions to avoid risks of bias.

Table 3
The agreement (score and ratio) for each recipe inferred and patients (represented with IDs). Each patient was evaluated for ten recipes (if the cell is blank the corresponding recipe was not selected for the specific user during the test).

Proposed recipe		Agreement (%)		
Name	Consistency	CDC	MA-MI	RU-MA
Asparagus, butter, and sage green semolina gnocchi	SO (D)	55,6		
Raspeberry blancmange	SE (C)	100	88,9	100
Stuffed cannelloni crepe with potato, leek and tomato sauce	SO (D)	77,8		
Creamy yogurt dessert	SELI (B)	100		
Potato, Savoy cabbage, and pecorino cheese gnocchi	SO (D)	44,4	77,8	44,4
Caramel panna cotta	SE (C)	100		
Carrots and zucchini cream	SELI (B)	88,9	55,6	
Polenta with salted codfish, olives, capers and datterino tomatoes	SO (D)	55,6	88,9	44,4
Porchetta rabbit	SE (C)	100		
Meatballs with fresh tomato sauce	SO (D)	66,7		
Meatballs	SO (D)		100	
Topinanbur puree (or Celeriac puree)	SELI (B)		100	
Veal with tuna sauce	SE (C)		100	77,8
Winter melon and orange	SELI (A)		22,2	
Panada "of the priest"	SE (C)		88,9	100
Moscato jelly with wild strawberries	SO (D)		88,9	44,4
Calabrese steer	SE (C)			100
Vegetarian lasagna	SO (D)			33,3
Sweet & sour vegetables	SO (D)			22,2
Tiramisu!	SO (D)			44,4

Table 4
The spontaneous comments and observations produced by participants during E1.

Comment 1	The system should propose substitute foods in case of an unwanted food.
Comment 2	It is not easy to evaluate the proposed consistencies for each recipe. For some of them, I would prefer to try them first before assessing their suitability for a patient.
Comment 3	In general, I would consider the app useful, but I would prefer first to verify the clinical adequacy in person […] even for appropriate recipes, there might be the risk that a patient does not follow the instructions properly and the resulting recipe has not the appropriate consistency.
Comment 4	It is hard to rely on DOSS and PAS classified recipes because I did not take part to the classification process […] I cannot trace back the DOSS and PASS classification process […] I should try the recipe myself before assessing them.
Comment 5	There should be the possibility for the patient to give feedback to the clinician about the perceived consistency of a recipe […] in this way the clinician can intervene on the list of recipes or modify its consistency

6.3. Results

The results related to the evaluation of the inferences generated by the DSS (tailored list of recipes – E1), the ease of use and usefulness of both digital applications (Clinician – E2 and Patient – E3) are illustrated below. Given the sample size, mode, minimum, and maximum scores are reported for E2 and E3.

6.3.1. Evaluation of the recipes proposed by the DSS

The experts had to indicate whether a given recipe was correct to propose to the dysphagic patient and, therefore, adequate for the specific clinical condition or whether it was incorrect because it was inadequate. The answers evaluated as adequate were assigned a score of 1, while the answers evaluated as inadequate received a score of 0. The following tables show the results in terms of the percentage of agreement. (Table 3).

The results are not homogeneous. In the case of the first patient (CDC), most of the recipes scored more than 66,7% agreement, obtaining the agreement of 6 judges out of 9. The recipes suggested to the second patient (MA-MI) are considered very suitable, obtaining high scores of agreement (except for recipes "Winter melon and orange" and "Carrots and zucchini cream"). In the third case (patient RU-MA) only 4 recipes are judged adequate by more than half of the participants (therefore, at least 5 out of 9).

Participants' spontaneous comments (Table 4) can suggest hypotheses to explain these results.

In particular, participants lamented that the recipes proposed in the book were not well-known; although the recipe book was physically present during the test and it could be consulted, the constraints related to the time available did not allow the participants to adequately read all the preparations of the recipes and therefore to evaluate their adequacy (see comments 2 and 4). This was stated by some participants as the reason that led them to be more cautious in evaluating recipes.

6.3.2. Evaluation of the clinician application

Participants rated the Clinician application as easy to use (mode: 4; min: 4; max: 5), useful in clinical practice (mode: 4; min: 3; max: 5), and helpful in varying the diet (mode: 4; min: 4; max: 5). With respect to using the application in their work, the clinicians expressed a neutral judgment (mode: 3; min: 3; max: 4). This latter aspect can be better understood by considering some spontaneous comments that emerged during the explanation of the test procedure (Table 4). Firstly, several clinicians have reported that the application can be useful but would not use it without personally verifying the adequacy of the proposed recipes (comments 3 and 4 in Table 4). Furthermore, several clinicians have observed that, even in the case of correctly inferred recipes, the patient could make a mistake in preparing the recipes at home.

An interesting insight emerged from the comments. A participant suggested proposing substitute ingredients in case of unwanted food (comment 1 Table 4).

6.3.3. Evaluation of the application for patients

Physicians rated the Patient application as easy to use (mode: 4; min: 4; max: 4) and useful for varying nutrition (mode: 4; min: 3; max: 5). They think that patients would need some training before learning to use the app (mode: 5; min: 2; max: 5), but that they would learn quickly (mode: 4; min: 3; max: 5) and would probably use it (mode: 4; min: 3; max: 4). No further suggestions were given.

7. Discussion and limitations

This Section discusses the main findings of this work and contextualize them in theoretical framework and open research challenges in the adoption of intelligent tools in clinical practice.

7.1. Discussion of experiments' results

Experiments' results allow highlighting some considerations about the proposed DSS. In E1, participants recognized a global positive outcome for the recipes inferred by the ontology. For patients CDC and MA-MI, clinicians voted that 9 recipes were properly identified as suitable. However, for patient RU-MA the inferences generated by the ontology resulted in only 4 recipes being accepted by the participants as suitable. RU-MA's health condition lacks the PAS score for semi-liquids (A and B), which contributes to explain some participants' reluctance in assessing recipes. Moreover, participants found it difficult to properly assess a recipe without having a direct experience of it: as reported in Table 4 (Comments 3 and 4), when not sure about a patient's health condition, clinicians would like to have more details about the single recipes before expressing their opinion. The lack of knowledge related to the recipes could have been overcome by consulting the recipe book – however, participants did not make use of the book they had at their disposal due to lack of time. The lack of confidence in determining the suitability of a recipe seems to fall under the general low levels of knowledge of nutrition care for patients with dysphagia [54]. Also, recent literature highlights that clinicians working with dysphagia cannot rely on systematized practices, especially regarding foods' consistency and texture modification, and nutritional management [13,40]. Thus, it might be safe to assume that for an incomplete health condition (such as RU-MA's) participants were not confident enough to certify the suitability of recipes, with the aim of safeguarding patient's wellbeing.

Nonetheless, these results show the necessity to provide clinical personnel with an in-depth training on the DSS, detailing them the process of selecting recipes' consistency and explaining in detail the criteria (and the rules in the ontology) adopted to match recipes with patient's DOSS and PAS evaluations. Moreover, the training session could underline some technical aspects of the proposed DSS.

The results in E2 showed us the good usability of the application, which was evaluated as easy to use, useful for the clinician and for the patients in supporting them for a more balanced and varied diet. However, clinicians remain hesitant with regard to an application they considered "unfamiliar" and for which the clinicians feel they cannot intervene. First, participants underlined a concern pertaining the fact that a recipe is proposed without first being approved by the clinician. Second, clinicians fear that patients may not carry out a recipe and its steps properly – which might result in a damage for patients. These concerns are in line with generalized resistance clinicians reserve to innovative technology applications [55]. In this sense, it is possible to work on a better communication with the operators, showing how the applications work alongside and not in their place, supporting them in their daily choices and thus also lightning the workload in terms of time. In addition to this, interesting implementation suggestions emerged from the participants in E2 – e.g., to propose new recipes to be added to the list of the inferable ones; to take into account patients' tastes and other limitations (e.g., intolerances, allergies, clinical restrictions, etc.) so as to satisfy any preferences or needs of end-users.

The results that emerged in E3 indicate that, in the opinion of clinicians, the application would be extremely easy to use and useful for the patient and his/her caregiver. No further suggestions or comments have emerged about this point that could indicate desirable modifications.

7.2. Discussion on the system

Experimental results – although promising – highlight some limitations of the DSS: first, the clinical personnel need to be more involved in understanding how recipes are classified (in terms of DOSS and PAS scales) and how the ontology-based system retrieves the inferred results. The participatory involvement of clinicians for the proposed DSS is crucial to increase its adoption and to gather precious feedback to further detail the matchmaking process between a dysphagic patient and suitable recipes, thus providing him/her with more tailored options. Therefore, the Clinician application should be supported by a "User Manual" and a training session aimed at explaining to clinicians how the system works and how to interact with it to modify a health condition. This could potentially increase their level of confidence in the system. Nonetheless, clinicians recognized that the Patient application could have a significant role in supporting dysphagic patients. Similarly, patients – in particular, older ones – may also need a dedicated "User manual" or training sessions, since patients' education plays a pivotal role in their adherence to nutrition therapy for dysphagia [13].

Compared to existing diagnostical systems (Section 3), which can leverage vast amounts of data, recipe suggestions is still a clinicians-dependent (also culture-dependent) activity. Therefore, the ontological approach for identifying a logical taxonomy of dysphagia, related foods consistencies, and recipe recommendation was deemed the most appropriate and safest approach to support the automatization of recommendations. Such an approach heavily relies on clinical personnel's expertise and knowledge, which also enables keeping patient safety during meals one of the DSS's priorities.

While Relying on expert knowledge engineering could partially support overcoming the "black box" issue characterizing purely data-driven AI applications, it requires the conceptualization underlying the application – i.e., the ontology and its inference rules – to be shared, discussed, and agreed-upon the widest number of clinicians. The issue pertaining the shareability of a conceptual model characterizes OE as a discipline [56], and may result in difficulties in updating the ontology [33] – ultimately leading to the non-adoption of the DSS. In fact, the lack of agreement with a DSS's results and the perceived opacity of the system's functioning are among those factors hindering the adoption of a system in clinical practice pertaining several healthcare domains [57–60]. However, transparent explanations of the DSS's functioning, demonstrations, and training can rise clinical personnel's acceptance of such systems, tackling both the issue pertaining [59,60]. Relying on an agile OE methodology could support the continuous elicitation of new information that can contribute to enhance the quality of the developed ontology [61]. By the incorporation of experts' feedback – foreseen in agile approaches – the ontology underlying the system is seen as a "living" representation of the domain at hand, which could potentially result in updates of the applications.

With regard to the patients' perspective, as mentioned in Section 5, the application should grant them the possibility to provide clinicians with feedbacks on specific recipes: in this way, domain experts would be enabled to suggest and cooperatively discuss recipe's DOSS and PAS requirements modifications. This aspect would further increase the collaborative approach, thus strengthening the shareability of the knowledge base underlying the applications. Moreover, including patients' feedback in the development activities of a system can foster patients' adherence to the nutrition therapy generated with the DSS [22].

8. Limitations, conclusions and future works

This work introduces a prototypical knowledge-based DSS aimed at supporting patients affected by dysphagia in following a nutritionally-balanced and varied diet. The system tackles the issue of modelling clinical knowledge in the field of diet modification for dysphagic patients with the aim of providing patients with a set of tailored recipes, suitable for their specific condition and supervised by clinical personnel. The prototypical DSS leverages collaborative ontology engineering to avoid purely data-driven AI applications' "black box" problem, enabling clinicians to maintain a pivotal role in the delicate matter of modifying dysphagic patients' diet by relying on their clinical practice. The preliminary validation of the system with clinical personnel proved that the system is perceived as useful and easy to use, although clinicians underlined the need to better familiarize with the recipes described and proposed by the DSS.

While the collaborative development of the knowledge base underlying the system is one of the advantages of the proposed solution, it constitutes also a potential limitation: the adoption of the DSS depends on the shareability of its ontology. Therefore, leveraging agile approaches, the discussion and feedback collection from domain experts is pivotal to enable the domain ontology's evolution – and, ultimately, the system's enhancement. Moreover, although the Patient app was rated useful and easy to use by clinicians, it has not been validated by real patients, yet. Therefore, it will be advisable to have it evaluated by the patients themselves, to understand if – from their perspective – the application is judged as useful and easy to use as it was for the Clinician application, and if there are desirable modifications that could improve the interaction and an effective daily use.

However, in this case, a preceding test with clinical personnel involved in the day-to-day management of dysphagic patients is essential since it enables the possibility of gathering expert feedback before administering the application to patients – who may experience discomfort if clinicians do not validate the inferred recipes before using the DSS. Thus, a preliminary validation with patients can occur in a clinician-supervised safe environment (to ensure participating patients' safety) to assess dysphagic patients' opinions on the use of the proposed system. Also, the current prototype of the DSS has been designed to include the possibility of gathering patient's feedback regarding a recipe he/she prepared so that the clinicians can be informed about possible swallowing problems and intervene in modifying the DOSS and PAS requirements for it. A prospective advancement consists in the possibility of gathering patients' recipes feedback to compare and refine recipes' classification. This feature will be tested and strengthened in the future release of the application, together with an increased list of recipes. Furthermore, the application, appropriately modified after the suggestions obtained in this first validation, will be tested with other hospital ENT teams, to collect further insights from the experts.

From an ontology perspective, two future directions will be pursued. The first consists of linking each recipe with the list of allergens recognized by the European Union so that – by specifying a patient's food allergy to one or more allergens – it is possible to avoid retrieving recipes that could harm patient's safety. In this regard, many ontologies describing foods could be adopted to support this task. Moreover, it is important to extend the usability of the DSS outside the European context: to this regard, a mapping between the Terminology for foods and liquids consistencies and the International Dysphagia Standard Initiative (IDDSI framework) [19] will be performed to enable clinicians adopting a different scale to understand how recipes are classified. Thus, the mapping may support the scalability of the DSS also to countries adopting the IDDSI, enabling the harvesting of more feedback about the DSS from different contexts.

Declaration – ethical approval

All clinicians participating to the experiments depicted in the paper signed a written informed consent form to participate; all clinicians participating to the experiments depicted in the paper signed a written informed consent for publications of the results, collected anonymously.

CRediT authorship contribution statement

Daniele Spoladore: Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Methodology, Investigation, Conceptualization. **Vera Colombo:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Vania Campanella:** Writing – original draft, Methodology, Investigation, Conceptualization. **Christian Lunetta:** Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Marta Mondellini:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Atieh Mahroo:** Writing – review & editing, Writing – original draft, Visualization, Software, Data curation. **Federica Cerri:** Writing – original draft, Supervision, Funding acquisition. **Marco Sacco:** Writing – original draft, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compbiomed.2024.108193.

Appendix A. The Terminology for foods and liquids consistencies [62]

Consistency	Category	Radiology	Phoniatrics	Description	Examples
Liquid		Fluid 1 (thin cordial, 1–2 cP)	–	Liquids	Water, tea, coffee, infusion, etc.
Semi-liquid	A	Fluid 2 (thickened cordial, 100–300 cP)	*Nectar* (51–350 mPa s)	Fluid and homogeneous; blended; sifted; cannot be eaten with a fork	Tomato sauce, vegetable soup, fruit smoothie, drinking yogurt, milk-based beverage,
Semi-liquid	B	Fluid 3 (bario standard *Nectar*, 200–4000 cP)	*Cream* (351–1750 mPa s)	Fluid and homogeneous; blended; sifted; cannot be eaten with a fork; it falls in drops more than pouring; cannot be arranged in layers	Creamy yogurts (with no solid parts), basic pastry creams, vegetable cream, mashed potatoes, sorbet, etc.
Semi-solidi	C	Fluid 4 (thin barium)	*Pudding* (1750–4000 mPa s)	Fluid and homogeneous; blended; sifted; cannot be eaten with a fork; it keeps its shape in the dish; can be arranged in layers; does not require chewing	Pudding, meat- or fish-based baby food, mousse, polenta, flan, panna cotta, etc.
Solid	D	Fluid 5 (thickened barium, 900–30000 cP)	$> 10^{12}$ Pa s	Moist; not blended; not sifted; can be easily cut into pieces or smashed with a fork; it requires limited chewing	Baked apple, soufflé, omelette, slush, boiled egg, cooked vegetables (non-filamentous), meatloaf, etc.
Solid	E	Fluid 5 (thickened barium, 900–30000 cP)	$> 10^{12}$ Pa s	Regular food with no modifications; it requires significant chewing; it cannot be easily cut into pieces or smashed with a fork	All foods that are not modified

Appendix B. The Competency Questions (CQs) developed for the Domain analysis and Conceptualization phase of the ontology engineering process and their representation as SPARQL queries. The queries were run in Protégé using the snapSPARQL plug-in

Competency Questions (CQs)	SPARQL queries answering the CQs

1. What are the information characterizing the patient?
The information characterizing the patient are: the first name, the surname, the date of birth, the age, the gender (to be selected between "male" and "female"), an ID provided by clinical personnel, and a health condition.
	SELECT ?prop WHERE {
	{?prop a owl:DatatypeProperty .
	?prop rdfs:domain dis:User .}
	UNION
	{?prop a owl:ObjectProperty .
	?prop rdfs:domain dis:User .}
	}

2. How is a patient's health condition assessed?
Patient's health condition is assessed in a specific day and time by clinical personnel and, for the purpose of this DSS, it reports the DOSS scale score and the PAS scores (one for each food consistency, if available) evaluated by clinical personnel during visits
	SELECT distinct ?prop ?hc WHERE {
	?hc a dis:Health_Condition .
	{?prop a owl:DatatypeProperty .
	?hc ?prop ?x .}
	}

3. What is the recommendation provided by this ontology?
3a. How are recipes found to be recommendable by the ontology?
The recommendation provided by this ontology foresees, for each patient, a list of recipes that are inferred to be suitable according to his/her health condition. The inference takes advantage of DOSS and PAS scores characterizing patients' health conditions; these values are compared with requirements represented for each recipe (requirements concerning the severity of the dysphagia – assessed with DOSS, and the issues with specific food consistencies – assessed with PAS). If a patient's health condition meets all the requirements represented for a recipe, then he/she is suggested that recipe.
	SELECT distinct ?prop WHERE {
	?prop a owl:ObjectProperty .
	?rec a dis:Recipe_Recommendation ;
	?prop ?x .
	}

4. How are recipes characterized?
4a. How many consistencies does a recipe have?
Recipes are characterized by a set of information consisting of the name of the recipe (in Italian), the recipe unique ID, the amount of kilocalories it provides per portion, the amount of proteins, carbohydrates and fats it provides per portion; each recipe is also associated to one and only one food consistency and is categorized as Breakfast recipe, First-course recipe, Main dish recipe, Side dish recipe, or Dessert recipe. Each recipe is described through a set of steps which needs to be followed in a precise order to get the recipe.
	SELECT distinct ?prop WHERE {
	{?prop a owl:DatatypeProperty .
	?prop rdfs:domain dis:Recipe .}
	UNION
	{?prop a owl:ObjectProperty .
	?prop rdfs:domain dis:Recipe .}
	}

5. What are the food consistencies that recipes can have?
According to the *Terminology for foods and liquids consistencies* a food can have one among these five consistencies: Semi-liquid A, Semi-liquid B, Semi-solid C, Solid D and Solid E.
	SELECT distinct ?cons WHERE {
	?recipe a dis:Recipe ;
	dis:hasConsistency ?cons .
	}

6. What are the steps composing a recipe characterized?
6a. Which are the steps composing a recipe?
The steps composing a recipe are all provided with a textual description, which consists in the instruction a patient must follow; moreover, the Steps can be classified as: Setting Steps (which provides the list and amount of ingredients with a representative picture of all of them); Photo Steps (which provides a picture illustrating the content of the step); Video Steps (which provides a short video illustrating the content of the step).
	SELECT distinct ?recipe ?step WHERE {
	?recipe a dis:Recipe ;
	dis:isComposedOf ?step .
	}
	ORDER BY ?step

Appendix C. A table representing the patients and their health conditions used to validate the inferences performed by the ontology. Blank values correspond to a lack of data

User	Patient ID	DOSS score	PAS scores			
			PAS Liquid	Semi-liquid (SELI A & B)	Semi-solid (SE C)	PA Solid (SO D & E)
CDB	1	5	5	1	1	1
CDC	2	5	1	1	1	1
CO-LO	3	1	–	–	1	–
FM	4	6	1	1	1	1
FO-MA	5	1	7	7	3	7
GIO-PA	6	5	3	1	1	1
MF	7	6	1	1	1	1
PA-LE	8	7	1	1	1	1
ROPRO	9	5	3	1	1	1
RU-MA	10	4	1	–	1	1
MA-MI	11	5	8	1	1	1
SOCE	12	4	3	1	3	3
VB	13	2	6	1	6	6

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