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An Ecosystem of Intelligent ICT Tools for Speech-Language Therapy Based on a Formal Knowledge Model

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Abstract

The language and communication constitute the development mainstays of several intellectual and cognitive skills in humans. However, there are millions of people around the world who suffer from several disabilities and disorders related with language and communication, while most of the countries present a lack of corresponding services related with health care and rehabilitation. On these grounds, we are working to develop an ecosystem of intelligent ICT tools to support speech and language pathologists, doctors, students, patients and their relatives. This ecosystem has several layers and components, integrating Electronic Health Records management, standardized vocabularies, a knowledge database, an ontology of concepts from the speech-language domain, and an expert system. We discuss the advantages of such an approach through experiments carried out in several institutions assisting children with a wide spectrum of disabilities.

Keywords:

Electronic Health Records; Rehabilitation of Speech and Language Disorders; Medical Informatics.

Introduction

The language acquisition process is closely related with intellectual, psychological and emotional development of children. In the same line, speech and language serve as cornerstones for human cognition and constitute tools to interact with the fellows of the social environment. Commonly, during the first 4 years of life, children make significant progress in learning language. However, in some cases there arise delays or differences in patterns of language acquisition, aspects that constitute warnings of developmental problems [1]. These delays or differences can be related with a wide spectrum of circumstances and can appear in different stages of life. In the case of children, some disabilities are related with the following periods [2]: prenatal (chromosomal anomalies and genetic metabolic and neurologic disorders, drug and toxin exposure, congenital infections, ...) perinatal (complications related to prematurity, periventricular leukomalacia, breech or high forceps delivery, multiple births, placenta previa, preeclampsia, ...), or postnatal (undernutrition and environmental deprivation, viral and bacterial encephalitides, poisoning, ...). On the other hand, the speech, language and swallowing disorders in acquired neurological conditions arise as a result of several conditions, such as traumatic brain injury, stroke, progressive neurological conditions (Parkinson's disease, multiple sclerosis, ...), dementia, head and neck cancer, and palliative care [3].

In the same line, in a world where 1 billion people live with some form of disability, the most recent estimates about People with Communication Disabilities (PWCD) shown a complex picture. For example, nowadays 60 million persons in the world live with disabling hearing loss (5.3% of the world's population) and 15 million suffer from stutter, and there exists a lack of rehabilitation services and healthcare related to Speech-Language Disorders (SLD) in most of the developed countries [4]. The situation is even more complex in developing countries due to lack of personnel, resources, and adequate services.

Over the last years, there have been several approaches to apply Information and Communication Technologies (ICT) to support Speech and Language Therapy (SLT). However, the existing approaches to provide support tools for SLT deal with very specific problems. The aphasia treatment field [5] proposes a computer gesture therapy tool (GeST) with the aim to improve the gesture production and/or spoken naming, whereas [6] it investigates the feasibility to incorporate the Semantic Feature Analysis technique in a mobile-web paired application in domestic and clinical settings. Some speech disorders like dysarthria have motivated the application of Automatic Speech Recognition (ASR) techniques for diagnosis tasks [7]. On the other hand, the application of Auditory Verbal Therapy (AVT) to develop several speech abilities in children with cochlear implants has been successfully applied through videogames [8] and multimedia programs [9].

Nevertheless, nowadays some of the most important issues of health care field are related to maintenance, sharing and portability of clinical data, a perspective based on specific domain knowledge, and the adaptability and standardized vocabularies. Accordingly, the aforementioned approaches rely on ad hoc solutions that use particular vocabularies, languages and own data structures. Only a few recent studies have used conceptualizations and classifications (e.g. ontologies) to support the operation of an expert system aimed at the initial diagnosis of language disorders [10].

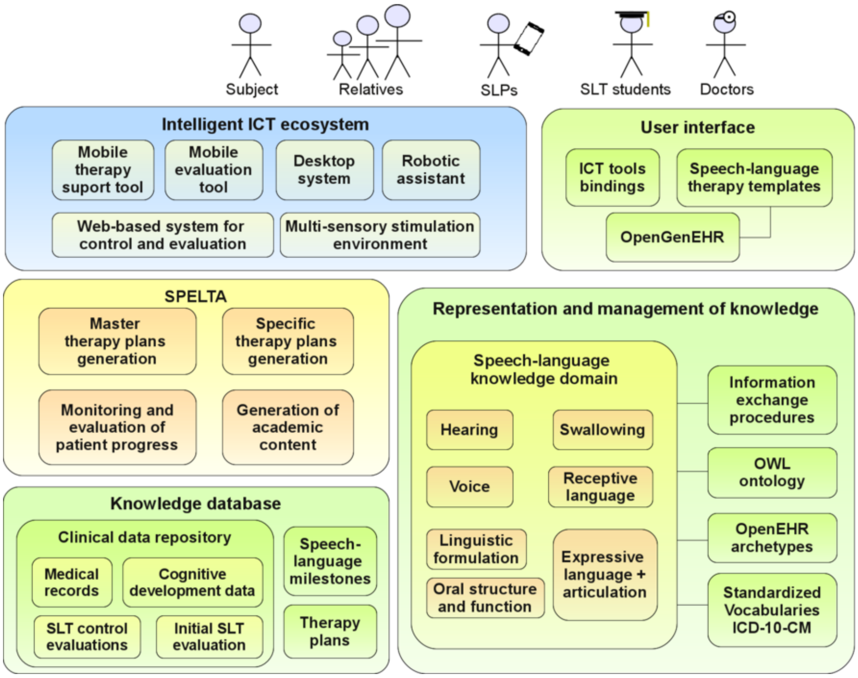

Figure 1– The high-level design and main components of our SLT ecosystem

Methods

SLT is a healthcare area that involves the active participation of different actors, such as doctors, Speech-Language Pathologists (SLP), SLT students, and patients/subjects and their relatives. Therefore, in this section, we present a complete backing ecosystem for SLT that considers these actors from a viewpoint that arises in a formal knowledge model. Likewise, this model is capable to provide an integrative perspective for ICT tools, specific SLT domain knowledge, standardized vocabularies, expert systems, and electronic health records management. Figure 1 shows a high-level model of the architecture of the proposed ecosystem for supporting SLT. This architecture allows building an integrative multi-layer framework for several therapy-related activities, users, knowledge management and portability, intelligent systems, and ICT tools. Some of the most relevant elements are described below.

The expert system layer (SPELTA)

The Speech and Language Therapy Assistant (SPELTA) is an expert system that provides the foundations to develop inference mechanisms for recommender and decision-support systems to assist in the preparation of therapy plans, the evaluation of exercise results, the generation of case studies, etc. Some of the most outstanding functionalities of SPELTA are the following:

- *Master therapy plans generation*: these kind of plans contain the general guidelines and activities that should be conducted with patients over a period of 6 months. Their aim is to develop some specific skills related to speech and language. In order to automatically generate a new master therapy plan, SPELTA uses a custom version of *Partition Around Medoids* (PAM) algorithm and KNN criterion (see more details in [11]). The PAM algorithm generates several clusters organized in two abstraction levels. The first level groups patients according to some elements of their profiles (cognitive developmental age, chronological age), medical record (diagnosis, related disorders/disabilities, and general medical condition), and the initial diagnostic of speech-language. In the second level several subclusters are created inside the general clusters, using the fine-grained evaluation of patient's speech-language skills.
- *Specific therapy plans generation*: these plans contain specific exercises and therapy activities that should be conducted with patients according to a weekly schedule. A set of specific therapy plans belongs to a master plan, and currently we are developing a semantic network using ontologies to represent the different relations between disabilities, disorders, and speech-language milestones and skills according to chronological and developmental age.
- *Generation of academic content:* the expert system is able to generate educational content for phonoaudiology students. These contents include tests about real and generated cases, training resources for decision making about therapy strategies, standardized vocabularies entries, etc.
- *Monitoring and evaluation of patient progress:* this feature of SPELTA allows to automatically analyze the patient progress and generate alerts for SLP when the master and specific plans are not effective.

Knowledge database

The knowledge database stores several information structures to support the data analysis tasks and inference process performed by the expert system layer:

- *Clinical Data Repository* (CDR): consolidates data from several clinical resources (medical records, cognitive development data, SLT control evaluations, initial SLT evaluation) and presents a unified view of patients. Our CDR uses standardized vocabularies from the American Speech-Language-Hearing Association [12].
- *Therapy plans*: these are data structures to represent either long term activities and exercises (master plans) and sets of activities scheduled according to patient's skills and therapy sessions (specific plans).
- *Speech-language milestones*: defines a set of skills according to chronological and developmental age (e.g. formal expressions of facts like "*from 1 to 2 years of normal development, a child must to be able to acquire new words on a regular basis, know a few parts of the body and point to them when asked*").

Representation and management of knowledge

In order to provide a comprehensive support for all therapy process, the model considers seven areas of speech and language: hearing, swallowing, voice, receptive language, linguistic formulation, oral structure and function (oral peripheral mechanism), and expressive language and articulation. The main processes, tests, evaluations, protocols, and therapy activities are modelled using ontologies and are implemented through OpenEHR archetypes. Figure 2 shows a screenshot of an archetype to conduct the Pure Tone Audiometry (PTA) test. As we can see, through this archetype it is possible to assess the patient's response to sound stimulation and voice commands, and determine if he/she is able to localize sound sources without visual stimuli.

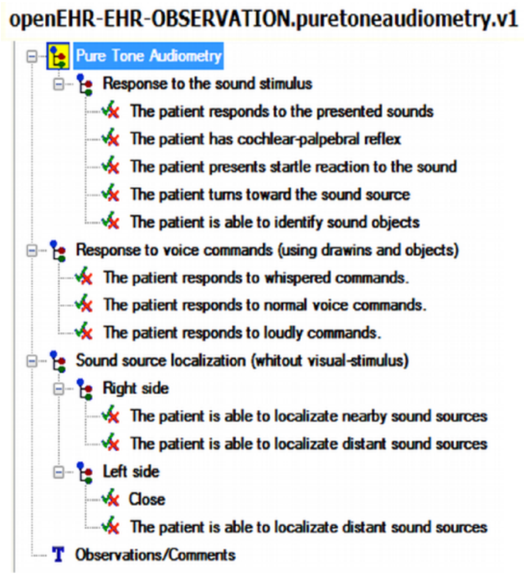

Figure 2– Partial view of the archetype that represents the Pure Tone Audiometry test

Intelligent ICT ecosystem

This layer incorporates a complete set of novel ICTs designed to support most of the SLT stages, and can easily add new tools using the bindings of the user's interface layer. Some of the most relevant elements are the following:

- *Multi-sensory stimulation ecosystem*: these kind of tools serve to support relaxation activities, early stimulation and several rehabilitation processes, for both children and adults, as was proved in [13] and [14].
- *Robotic assistant:* is a novel backing tool for therapy sessions, educational and ludic activities, and remote monitoring tasks. The robot has two main elements, an electronic displacement platform and a mobile device (Android-based tablet or smartphone). Using the mobile device the robot can tell stories, conduct exercises for motor rehabilitation (using a red glove to control a virtual hand), recognize voice commands, and interact with patients through different kinds of exercises based on multimedia resources (color discrimination, temporo-spatial notions, ...).
- *Support tools based on ICT:* through these tools the SLP is able to use desktop and web systems (Speech-language Maturation Assessment Tool, SPELMAT), and mobile devices to perform therapy exercises, assessment tasks, collection of information related with patients, registering the results of therapy sessions, report generation, and sharing data with other SLP. For example, Figure 3 (a) shows a screen capture of MOPHOC, a mobile application to support the learning process of phonetic code. This tool allows to conduct several kinds of exercises related with articulation (phonemic awareness, sentence construction, phonatory, …).

User interface

This layer contains the bindings to connect the ICT tools (Intelligent ICT environment) with the representation and management knowledge layer. Other important elements of this layer are the speech-language therapy templates generated using OpenGenEHR tool (http://www.openehr.org). These templates provide the interface to feed the different information structures related with clinical data. An example of a template to access personal data, conduct a hearing screening, conduct the PTA test, and other options is presented in Figure 3 (b).

Results

Once we have deployed the knowledge model, the information exchange mechanisms, and the main algorithms of the expert system, three pilot experiments were carried with the aim to validate the developed ICT tools with the support of five institutions of special education from Ecuador: Instituto de Parálisis Cerebral del Azuay (Institute of Cerebral Palsy of Azuay), Unidad Educativa Especial del Azuay (Unit for Special Education of Azuay), Fundación "General Dávalos" (General Davalos Foundation), Fundación "Jesús para los niños" ("Jesus for the kids" Foudation), and CEDEI School. These institutions are concerned about the health care, education, and rehabilitation of children suffering from different disabilities (cerebral palsy, dysarthria, dyslalia, athetosis, autism, Down syndrome, multi-disabilities, ...). In this line, for the first experiment, a team of 4 experts were provided with the mobile application MOPHOC to conduct several phonetic exercises and evaluations using articulatory phonetic tests. A total of 32 children were evaluated, and the system determined the error produced in the utterance production of phonemes, consonant clusters, diphones, and sentences (Table 1).

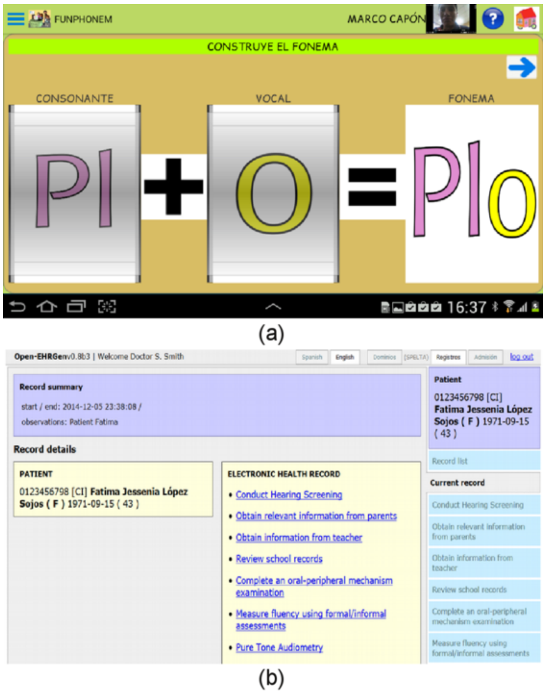

Figure 3– (a) A screen capture of the "articulation notebook" module of the MOPHOC application. (b) A screen capture from menu options of the archetype to conduct a speech evaluation for fluency

In this experiment, we also analyzed the time required to conduct the therapy and evaluation activities through the mobile application (MOPHOC). Also, we have verified an important reduction in the following activities: application of articulatory phonetics test (reduction from 30 to 15 minutes), planification of therapy activities using multimedia resources (5 minutes instead 30), and report generation (reduction from 30 to 5 minutes). These results have been validated by the experts, using manual version of PTA test.

Table 1– Most common articulatory errors detected by the system in the second group of children (32 cases)

Utterance	Average errors committed (%)
Consonant cluster	83
Sentence	77
Diphone	77
Phoneme	67

For the second experiment, a team of 6 experts was provided with the SPELMAT system to conduct evaluations on a different group of 53 children. This team of speech and language therapists had created 40 therapy plans to train the system, according to each child's profile. Each plan consists of five sub-plans to provide general therapy guidelines in 5 SLT areas: hearing, receptive language, linguistic formulation, oral structure and function, and expressive language and articulation, respectively (a total of 200 elementary plans). After that, the remaining 13 children's profiles were presented to the system, with the aim to generate a therapy plan for each (65 sub-plans). Therapists evaluated the outputs by giving each plan a rating of 1 if it was convenient and 0 otherwise, considering consistency, accurateness, and completeness. The last parameters were evaluated in the same way (1=correct, 0=incorrect); therefore, only if the three are correct, the accuracy will be 1. Table 2 shows the accuracy of SPELTA according to each area.

Table 2– Accuracy achieved in the generation of master therapy plans

Speech and language area	Plans correctly generated	Accuracy (%)
Hearing	13	100
Linguistic formulation	13	100
Oral structure and function	13	100
Receptive language	11	84
Expressive language+articulation	9	70
	Average	90

In the last experiment, we have conducted several activities to evaluate the robotic assistant as support tool for SLT. Some of the main goals were to analyze the response time of children during the relaxation activities and initial therapy, to test the robot response to the stimulation of motor skills, and to verify the robot's integration with the database of profiles and therapy plans. Some of the most relevant achievements were that the time needed to conduct the relaxation activities and initial therapy has shrunk from 40 minutes to 25, all the specialists have agreed on the usefulness of the robot, and children have shown high levels of motivation during their interactions with the robot.

Discussion

The results obtained with this study show that it is possible to automate several activities related with SLT, with the aim to provide a better service to patients suffering from several kinds of disabilities. In the same way, the use of mobile support tools allows to reduce significatively the time needed to conduct several activities related with therapy planification, assessment, and report generation. With these mobile tools, an SLP can perform several tasks from any place and assist his/her patients in a better way. Likewise, the use of expert systems based on clustering, allows SLP to discover "hidden populations" for those cases belonging to a group of subjects that suffer from the same disorders and have the same development cognitive age, but have deteriorations in different skills of the same speech-language area.

The management of electronic health record in conjunction with the concepts modeling based on ontologies have an important potential to represent the complex underlying relationships in SLT. With the use of these artifacts, it is possible to create knowledge databases for specific domains and provide efficient integration services for ICT tools and intelligent systems. The use of a model based on several layers, among other elements (archetypes, templates, ICT tools, etc.), provides a robust growing environment, able to easily incorporate new knowledge mainstays, actors, and supporting tools for sharing information through standardized languages and vocabularies.

Conclusion

In this paper we have presented a comprehensive model to support the most relevant task related with SLT. This model is designed to be adjusted or grow up according to requirements of the institutions where patients receive therapy and rehabilitation. In the same way, given that our model uses archetypes, templates and standardized vocabularies, all generated information can be shared and updated in an efficient way.

Likewise, using this model, it is possible to improve several process related to management of SLT information, given that a SLP can generate reports, visualize data, and analyze the patients' progress quickly and from any device (web, mobile or desktop). On the other hand, the expert system layer provides support in decision making for complex tasks, such as planning and scheduling of therapy sessions and activities according to specificity of each patient's profile. The SPELTA has achieved promising results, given that the generated therapy plans were deemed consistent, accurate, and complete by the experts. Only the areas of receptive and expressive language seem to demand a refined or alternative approach.

The following are proposed lines of future work:

- Extend the proposed model to cover some deeper areas of knowledge, like the automatic generation of specific therapy plans based on daily activities and considering these elements: the existing levels of granularity of the patient's cognitive development, the incidence of other disorders (cerebral palsy, athetosis ...), etc.
- Modify the distance measures to improve the accuracy of generated plans in the areas of receptive language, and expressive language and articulation.

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