Rehabilitation Robotics Ontology on the Cloud

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***Abstract*—We introduce the first formal rehabilitation robotics ontology, called REHABROBO-ONTO, to represent information about rehabilitation robots and their properties; and a software system REHABROBO-QUERY to facilitate access to this ontology. REHABROBO-QUERY is made available on the cloud, utilizing Amazon Web services, so that 1) rehabilitation robot designers around the world can add/modify information about their robots in REHABROBO-ONTO, and 2) rehabilitation robot designers and physical medicine experts around the world can access the knowledge in REHABROBO-ONTO by means of questions about robots, in natural language, with the guide of the intelligent user-interface of REHABROBO-QUERY. The ontology system consisting of REHABROBO-ONTO and REHABROBO-QUERY is of great value to robot designers as well as physical therapists and medical doctors. On the one hand, robot designers can access various properties of the existing robots and to the related publications to further improve the state-of-the-art. On the other hand, physical therapists and medical doctors can utilize the ontology to compare rehabilitation robots and to identify the ones that serve best to cover their needs, or to evaluate the effects of various devices for targeted joint exercises on patients with specific disorders.**

I. INTRODUCTION

As the number of rehabilitation robots increase, the information about them also increases, but most of the time in unstructured forms (e.g., as text in publications). This makes it hard to access the requested knowledge (e.g., the flexion/extension range of motion (RoM) of ASSISTON-SE [1]) and thus automatically reason about it (e.g., finding the rehabilitation robots that target shoulder movements and also have at least 210° RoM for the flexion/extension movements of the shoulder).

Also, due to interdisciplinary nature of rehabilitation robotics, sometimes requested knowledge requires integration of further knowledge from related disciplines (e.g., physical medicine). Consider, for instance, finding rehabilitation robots that can be used to treat a patient with rotator cuff lesions. For that, we need to know 1) that rotator cuffs are muscle units for moving the shoulder, and 2) that, for patients with rotator cuff lesions, abduction and flexion movements of the shoulder should not have more than 90° RoM. Then we can look for relevant rehabilitation robots.

On the other hand, there are efforts, e.g., by European Network on Robotics for Neurorehabilitation, for standardizing terminology as well as assessment measures for rehabilitation robots. Given the growing number of different approaches introduced by various research groups and the variability of results available, the development of such a standardization would be a critical step forward in the field, helping robotic rehabilitation technology become widely understood and accepted as a useful tool.

Motivated by these challenges and efforts, we have designed and developed the first formal rehabilitation robotics ontology, called REHABROBO-ONTO. Ontologies are formal frameworks for representing knowledge in a structured form, to aid access to relevant parts of the knowledge and automate reasoning over it. Unlike databases, ontologies allow representation of incomplete knowledge, can easily be extended by new information (e.g., with new sorts/features of rehabilitation robots); ontologies developed by different parties at different locations can be integrated; and reasoning (e.g., query answering) can be automated over concepts and their relations represented in these ontologies. Therefore, it is not surprising that more and more knowledge-intensive systems (including Semantic Web [2] that is planned to provide automated services to Web by giving meaning to concepts) rely on ontologies to enable content-based access, interoperability, and communication across the Web.

REHABROBO-ONTO represents knowledge about rehabilitation robotics in a structured form, and allows automated reasoning about this knowledge. It is open-source and available on the cloud via Amazon Web Services (in particular, Amazon Elastic Compute Cloud)[1] so that every rehabilitation robotics researcher can easily add information about his/her robot to it, and every rehabilitation robotics researcher and every physical medicine expert can access information about all available rehabilitation robots. REHABROBO-ONTO has been designed in a way that enables integration with other medical ontologies, such as ontologies that capture rehabilitation protocols, patient data and disorder details. Considering the standards of World Wide Web Consortium (W3C), REHABROBO-ONTO is represented in OWL (Web Ontology Language) [3], [4].

To facilitate such modifications and uses of REHABROBO-ONTO, we have also developed a Web-based software (called REHABROBO-QUERY)[2] with an intelligent user-interface. In this way, experts do not need to know the underlying logic-based representation languages of ontologies, like OWL, or Semantic Web technologies, for information entry, retrieval and modification. REHABROBO-QUERY also utilizes Amazon Web Services for cloud computing.

We utilize Amazon Elastic Compute Cloud (Amazon EC2) for both developing and maintaining REHABROBO-ONTO, and for querying REHABROBO-ONTO via REHABROBO-QUERY. Amazon EC2 is a web service that provides resizable compute capacity in the cloud, and makes web-scale computing easier for developers. Considering the possibility of various researchers from around the world add/modify/query

[1] http://aws.amazon.com/ec2/
[2] http://hmi.sabanciuniv.edu/?page_id=781

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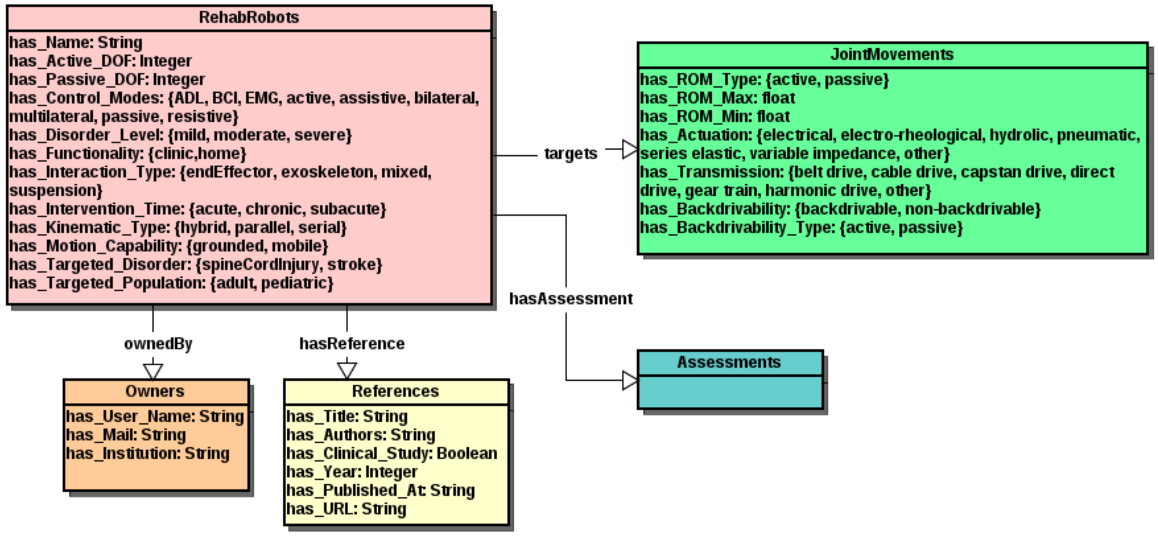

Fig. 1: REHABROBO-ONTO with main classes.

REHABROBO-ONTO via REHABROBO-QUERY, and the possibility of integrating various sorts of knowledge on the web related to rehabilitation robotics, Amazon EC2 provides a reliable environment for development and maintenance of REHABROBO-ONTO and REHABROBO-QUERY.

The ontology system consisting of REHABROBO-ONTO and REHABROBO-QUERY is of great value to robot designers as well as physical therapists and medical doctors. On the one hand, robot designers can benefit from the system, for instance, to identify robotic devices targeting similar therapeutic exercises or to determine systems using a particular kind of actuation-transmission pair to achieve a range of motion that exceeds some threshold. Availability of such information may help inspire new designs or may lead to a better decision making process. The ontology can also be utilized to group similar robots by quantifiable characteristics and to establish benchmarks for system comparisons. Overall, an ontology designed to specifically meet the expectations of the overall rehabilitation robotics effort has the potential to become an indispensable tool that helps in the development, testing, and certification of rehabilitation robots. On the other hand, physical therapists and medical doctors can utilize the ontology to compare rehabilitation robots and to identify the ones that serve best to cover their needs, or to evaluate the effects of various devices for targeted joint exercises on patients with specific disorders.

A preliminary version of REHABROBO-ONTO is described in our earlier paper [5]. This paper is different from [5] in the following ways: 1) we describe the current version of REHABROBO-ONTO, that significantly improves the preliminary version by including information about assessment measures, and related references, and physical therapies; 2) we describe our software REHABROBO-QUERY (not described in [5]), and present some examples to show its uses; 3) we discuss the advantages of utilizing Amazon Web Services allowing cloud computing (also not discussed in [5]).

II. REHABROBO-ONTO

Ontologies are formal frameworks for representing knowledge in a structured form, to aid access to relevant parts of the knowledge and automate reasoning over it. An ontology can be viewed as a graph where nodes denote concepts (e.g., rehabilitation robots, joint movements) and the edges between the nodes denote relations between the corresponding concepts. For instance, an edge from a node that denotes "Upper Extremity Rehabilitation Robots" to a node that denotes "Rehabilitation Robots" may characterize the "is-a" hierarchy relation; whereas an edge from a node that denotes "Rehabilitation Robots" to a node that denotes "Joint Movements" may characterize "targets" relation.

We have designed our ontology (Figure 1) considering four main concepts (or thematic classes):

- `RehabRobots` (representing rehabilitation robots and their properties),
- `JointMovements` (representing targeted joint movements and their properties),
- `Owners` (representing robot designers who add/modify information in the ontology about their own robots),
- `References` (representing publications related to rehabilitation robots),
- `Assessments` (representing assessment measures for rehabilitation robots).

These concepts are related to each other by the following relations:

- a rehabilitation robot `targets` joint movements,
- a rehabilitation robot is `ownedBy` a robot designer,
- a rehabilitation robot `hasReferences` to some publications,
- a rehabilitation robot `hasAssessment` with respect to some evaluation measure.

As seen in this figure, each class has its own properties. `RehabRobots` have the following properties about rehabilitation robots:

- name
- active degree-of-freedom: integer
- passive degree-of-freedom: integer

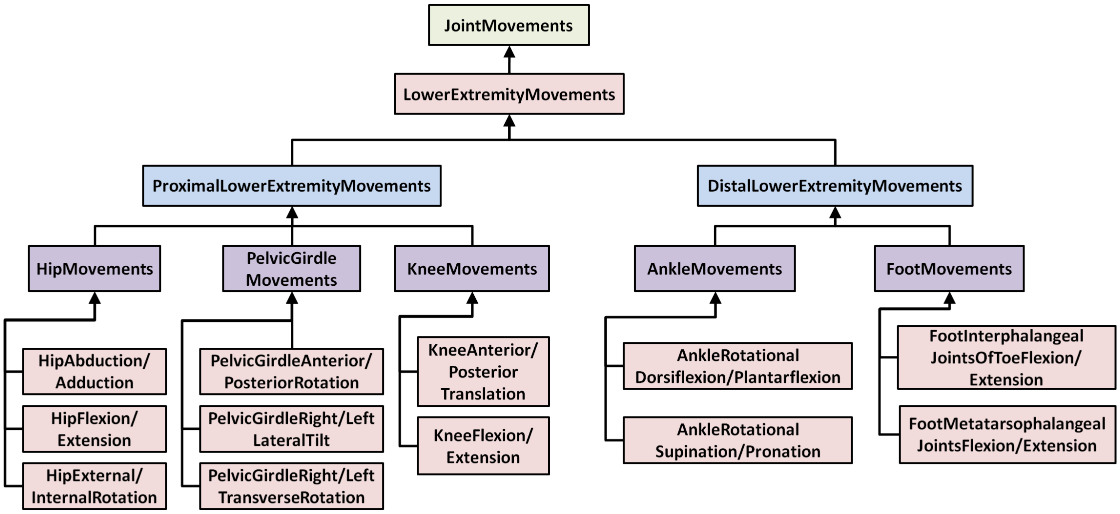

Fig. 2: Hierarchy of lower extremity joint movements targeted by rehabilitation robots.

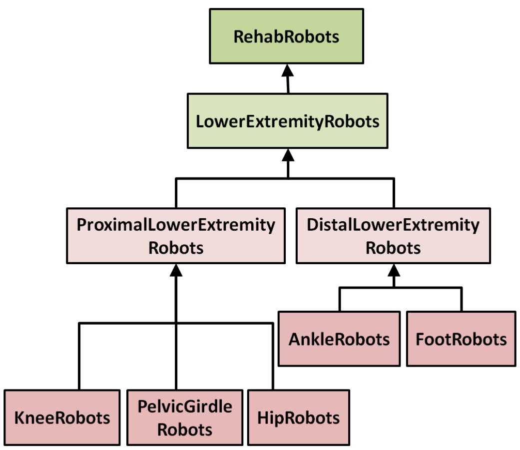

Fig. 3: Hierarchy of lower extremity rehabilitation robots.

- control modes: bilateral, active, passive, resistive, assistive, ADL, multilateral, EMG, BCI, other
- disorder level: mild, moderate, severe
- functionality: clinic, home
- interaction type: end-effector, exoskeleton, suspension, mixed
- intervention time: acute, subacute, chronic
- kinematic type: parallel, hybrid, serial
- motion capability: grounded, mobile
- targeted population: pediatric, adult
- targeted disorder: stroke, spline cord injury

`JointMovements` have the following properties about the joint movements targeted by the rehabilitation robots:

- RoM type: active, passive
- minimum RoM: float
- maximum RoM: float
- actuation: electrical, hydrolic, pneumatic, series elastic, variable impedance, electro-rheological, other
- transmission: harmonic drive, belt drive, cable drive, direct drive, capstan drive, gear train, other
- backdrivability: backdrivable, nonbackdrivable
- backdrivability type: active, passive

Considering various sorts of rehabilitation robots and various sorts of joint movements, `RehabRobots` and `JointMovements` classes have subclasses; some of these subclasses are illustrated in Figures 2 and 3. Maintaining such a hierarchy aids not only compact representation of knowledge about rehabilitation robots (by avoiding repetitions) but also efficient reasoning about it.

We have designed `Assessments` also as a hierarchy of evaluation metrics (Figure 4): movement quality assessments, effort assessments, psyhomotoric assessments, muscle strength assessments, kinematic assessments. Each assessment subclass has its own subclasses. For instance, `MovementQualityAssessments` class contains the following subclasses: bi-manual coordination, combined task coordination, compensation, dexterity, interlimb coordination, single joint coordination, visuomotor coordination.

The other concepts, `Owners` and `References`, do not have hierarchies. Though, for owners, we keep their contact information; and for references, in addition to their traditional descriptions, we also keep information about whether they contain results of some clinical studies.

Based on the design of these classes, their properties, subclasses, relations between classes, we need to represent the ontology formally using a logic-based ontology language. Considering the standards of W3C,[3] we have decided to represent the ontology in the logic-based ontology language OWL, in particular, in OWL/XML format. With such a choice of language, we could use the ontology editor PROTÉGÉ [6] to construct REHABROBO-ONTO.

III. REHABROBO-QUERY

To make REHABROBO-ONTO open-source so that robot designers can add/modify information about their robots, and that both rehabilitation robotics experts and physical medicine experts can ask queries over it, we have designed a software system, REHABROBO-QUERY (Figure 5), with an intelligent user-interface. With such an interface, the user is guided via tabs to add/modify information in REHABROBO-ONTO and ask queries in natural language; so the users do not

[3]http://www.w3.org/standards/

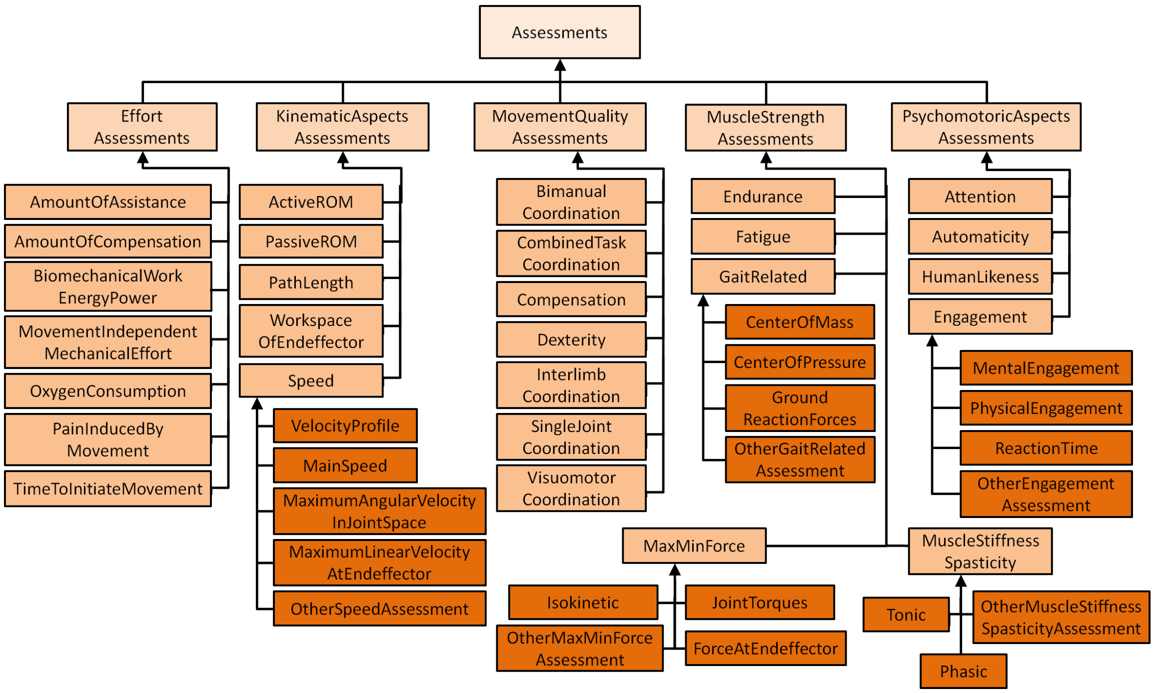

Fig. 4: `Assessments` with its properties.

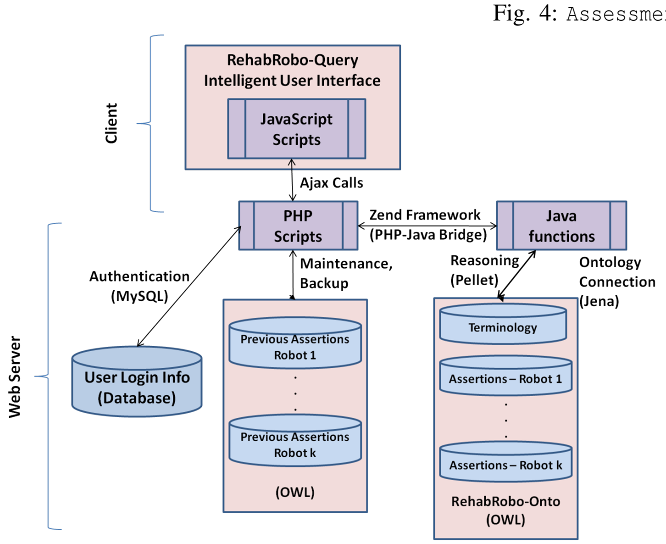

Fig. 5: An overview of REHABROBO-QUERY.

have to know about the underlying logic-based formalism, the reasoner used for answering their questions, or Semantic Web technologies.

For reliable development and maintenance of REHABROBO-ONTO by various robot designers from around the world, and to make use of web-scale computing for efficient queries that may require integration with other ontologies on the web, we have made REHABROBO-QUERY available via a webpage[2] hosted by a Web server running on Amazon EC2 services.

The overall system architecture for REHABROBO-QUERY on the cloud is illustrated in Figure 5.

A. *Adding/modifying knowledge in* REHABROBO-ONTO

Some snapshots of the user interface of REHABROBO-QUERY for adding new information to REHABROBO-ONTO ontology about the rehabilitation robot ASSISTON-SE are shown in Figures 6 and 8.

When the user adds information about his/her robot, it is stored (in OWL/XML syntax) as an assertion in a unique file. The terminology of ontology (that consists of classes, their properties and relations as described in the previous section) is kept in a separate file, also in OWL/XML syntax. The ontology REHABROBO-ONTO consists of the terminological part and the assertions of the robots.

Users are not allowed to modify the terminological part of the ontology, but only assertions about the robots. When a user wants to make modifications on the assertions about a robot, REHABROBO-QUERY displays the list of robots that the user is authorized to make changes about. If the user wants to make changes on another robot, the permission of its owner is required via REHABROBO-QUERY.

When users make changes on REHABROBO-ONTO via REHABROBO-QUERY, the updated information is saved as a set of assertions in OWL/XML format in a new file; the files containing previous assertions are marked as “modified”. Likewise, when users delete some assertions about their robots, the relevant files are simply marked as “deleted”. Note that in both cases, REHABROBO-QUERY keeps the information about the robot before modification/deletion as well; these files may be needed if the user accidentally deletes his/her robot from REHABROBO-ONTO, or modifies it incorrectly.

After adding, modifying, deleting information in REHABROBO-ONTO, REHABROBO-QUERY allows users to provide feedback about the system. To prevent automated access to the system by computer programs, Google reCAPTCHA[4] is used.

Only registered users can add/modify/delete information to/in/from REHABROBO-ONTO. Registered users and their

[4]http://www.google.com/recaptcha

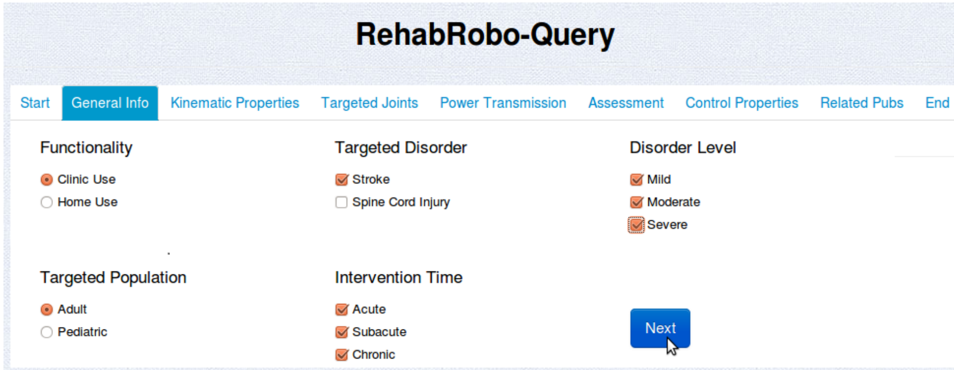

Fig. 6: REHABROBO-QUERY: Adding to REHABROBO-ONTO general information about the rehabilitation robot ASSISTON-SE.

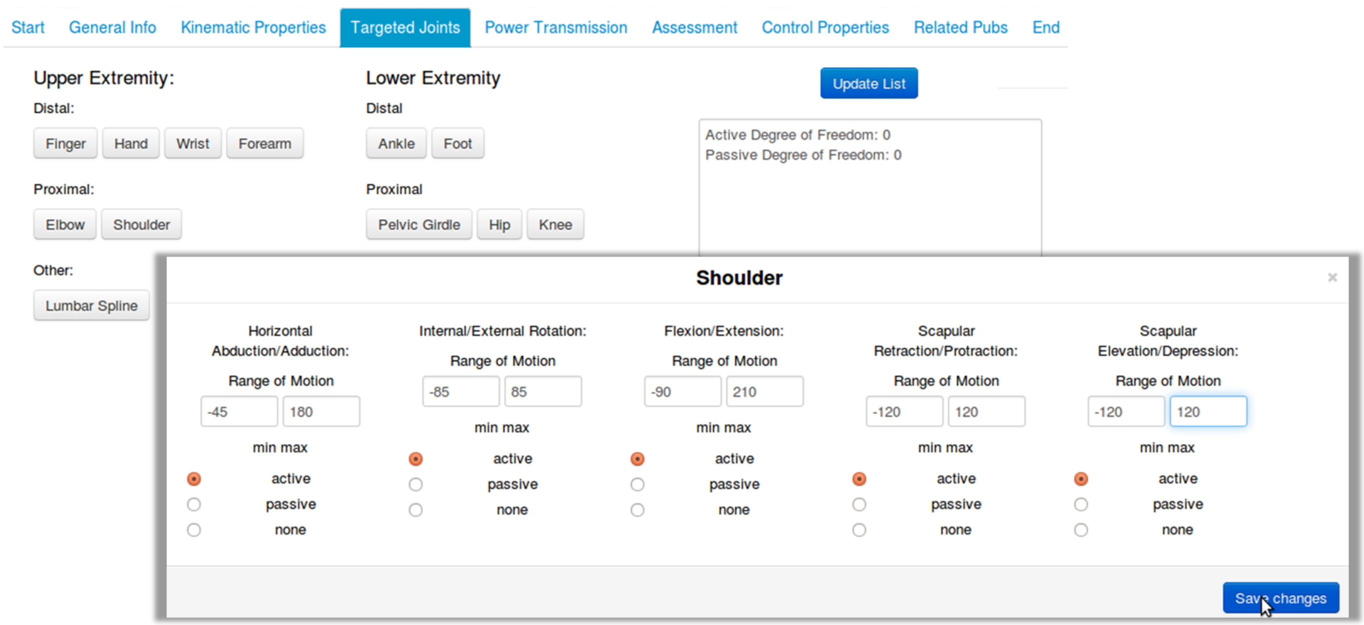

Fig. 7: REHABROBO-QUERY: Adding to REHABROBO-ONTO information about the RoM of targeted joint movements of the rehabilitation robot ASSISTON-SE; the lower inset illustrates these values for shoulder movements.

passwords are administrated by a database. For security, access to this database utilizes encryption via a cryptographic hash function.

Both the user database and the rehabilitation robotics ontology are stored on the server. The assertions are added/extracted to/from REHABROBO-ONTO using JENA,[5] a Java framework with various utilities for ontology management.

B. Answering questions about rehabilitation robots

Reasoning over REHABROBO-ONTO is done by means of answering questions posed by the user in natural language. Here are some example queries:

- What are the rehabilitation robots that target shoulder movements and that have at least 210° RoM for the flexion/extension movements of the shoulder?
- What are the rehabilitation robots that target wrist movements and that have at least 2 active degrees of freedom?
- What are the shoulder robots that target flexion/extension movements and that do not target elevation/depression movements?
- What are the ankle robots that target movements with electrical actuation and with cable drive transmission?
- What are the publications that are about rehabilitation robots that target wrist movements with more than 1 active degrees of freedom, and that report results of clinical studies?

These queries are transformed into the formal query description language SPARQL, also an official W3C Recommendation. Thanks to availability of the description logics reasoner PELLET [7][6] in JENA, answers to these queries can be computed automatically.

IV. DISCUSSION AND CONCLUSION

We have designed and developed the first formal rehabilitation robotics ontology, called REHABROBO-ONTO, to represent information about rehabilitation robots; and a software system REHABROBO-QUERY to facilitate access to this

[5]http://jena.apache.org/

[6]http://clarkparsia.com/pellet

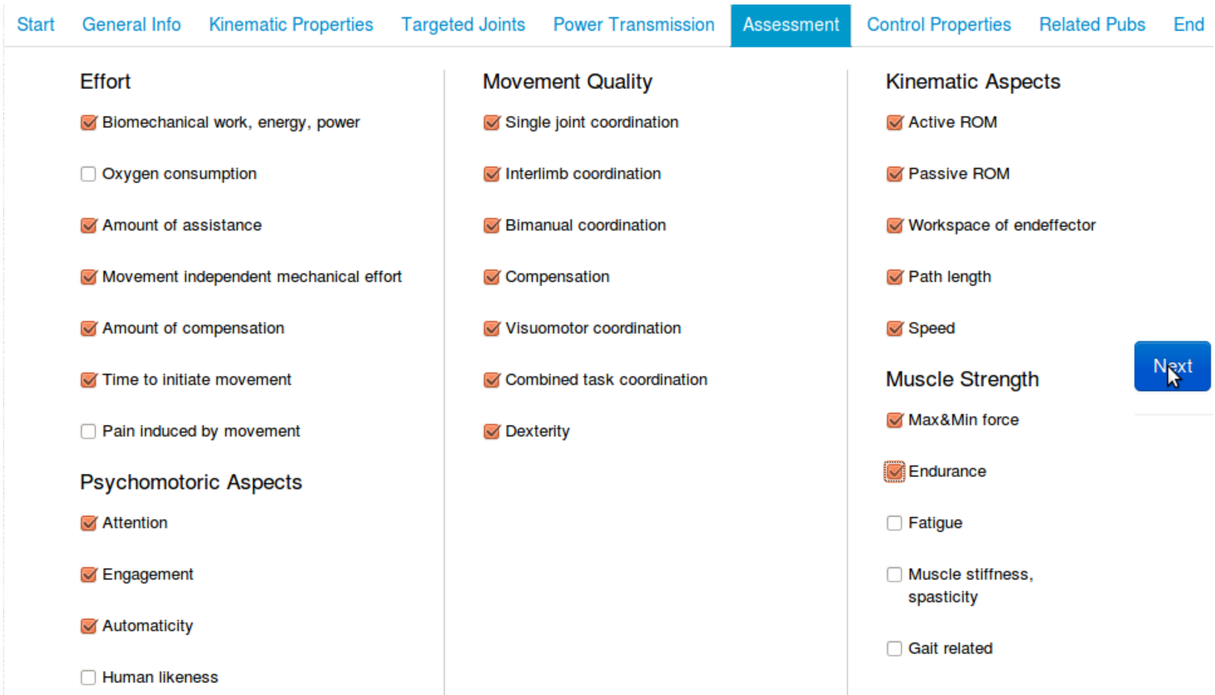

Fig. 8: REHABROBO-QUERY: Adding to REHABROBO-ONTO information about assessment metrics for the rehabilitation robot ASSISTON-SE.

ontology. We have made REHABROBO-QUERY available on the cloud, utilizing Amazon EC2 Web services, so that rehabilitation robot designers around the world can add/modify information about their robots in REHABROBO-ONTO, and rehabilitation robot designers and physical medicine experts around the world can access the knowledge in REHABROBO-ONTO by means of questions about robots, in natural language, with the guide of the intelligent user-interface of REHABROBO-QUERY. The users do not have to know about the underlying logical formalism of the ontology or the formalism to represent queries; they do not have to know about the use of the technologies for computing answers to their questions.

By means of such queries over REHABROBO-ONTO, right rehabilitation robots for a particular patient or a physical therapy can be found or designed; this further paves the way for translational physical medicine (from bench-to-bed and back) and personalized physical medicine. REHABROBO-QUERY aids exchange of information across rehabilitation robots researchers over the world, and thus to improve the state-of-the-art; it allows to identify "gaps" in functionality of rehabilitation robots, that can further improve research efforts. Furthermore, having a structured formal representation of knowledge about rehabilitation robots, allows answering complex queries that requires integration with other knowledge resources (e.g., patient databases, disease ontologies).

The importance of designing and developing ontologies for robotics is emphasized by IEEE-RAS Ontologies for Robotics and Automation Working Group.[7] The group has initiated the design and development of ontologies for several sorts of robots [8] (e.g., mobile robots [9], urban search and rescue robots [10]). However, none of the existing robot ontologies have been designed to target rehabilitation robots and, without further customization, they fail to capture many important aspects of rehabilitation robots, including the interoperability with the existing ontologies in physical medicine. Furthermore, none of them is open-source where the researchers are allowed to contribute and access. In that sense, our work contributes to efforts towards designing and developing robotics ontologies.

[7] http://www.ieee-ras.org/industrial/standards.html

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