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Core reference ontology for individualized exercise prescription

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"Exercise is medicine" emphasizes personalized prescriptions for better efficacy. Current guidelines need more support for personalized prescriptions, posing scientific challenges. Facing those challenges, we gathered data from established guidelines, databases, and articles to develop the Exercise Medicine Ontology (EXMO), intending to offer comprehensive support for personalized exercise prescriptions. EXMO was constructed using the Ontology Development 101 methodology, incorporating Open Biological and Biomedical Ontology Foundry principles. EXMO v1.0 comprises 434 classes and 9,732 axioms, encompassing physical activity terms, health status terms, exercise prescription terms, and other related concepts. It has successfully undergone expert evaluation and consistency validation using the ELK and JFact reasoners. EXMO has the potential to provide a much-needed standard for individualized exercise prescription. Beyond prescription standardization, EXMO can also be an excellent tool for supporting databases and recommendation systems. In the future, it could serve as a valuable reference for developing sub-ontologies and facilitating the formation of an ontology network.

Introduction

Background. Research has shown that physical activity can help reduce the risk of diseases and mortality from diseases, including cardiovascular disease[1–6], cancer[3–5,7,8], type 2 diabetes[3–5,9], and AIDS[4,10]. In addition to these benefits, people of different age groups, *i.e.*, children, adolescents, adults, and older adults, can all benefit from regular physical activity[3,4,11].

Physical activity, including exercise, is an excellent way to treat some diseases[12–14]. Exercise has been prescribed in some countries for patients with multiple sclerosis[15], patients with type 2 diabetes[16], stroke survivors[17], and cancer survivors[18,19]. Today, exercise prescriptions are usually based on the FITT-VP model (frequency, intensity, time, type, volume, and progression)[20]. However, compared to personalized exercise prescriptions, homogenized exercise prescriptions have several shortcomings. Homogeneous exercise prescriptions may not effectively enhance cardiorespiratory fitness in adults[21]. In contrast, personalized exercise prescriptions are safe and can significantly improve physical fitness and quality of life for lung cancer patients undergoing chemotherapy[22]. Additionally, athletes require more tailored exercise prescription guidance[23–26]. Personalized prescriptions based on preference and adequate plans can moderate the effect of the intention-behavior gap of physical activity[27]. Prescriptions must be individualized based on health status, family history, current activity, preferences, psychological factors, contraindications, and goals[28–31].

Related work. Ontologies are a useful tool and guidelines to support exercise medicine and prescriptions. Ontologies have many definitions, and Ontology Development 101 is "a formal, explicit description of concepts in a domain of discourse, properties of each concept describing various features and attributes of the concept, and

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Item	Count
Axiom	9732
Class count	434
physical activity	103
classes related to physical activity	104
personal status	152
other classes	75
Maximum depth	9
Maximum number of children	27
Average number of children	4
Classes with a single child	20
Classes with more than 25 children	2
Subclass of	564
Equivalent classes	27
Disjoint classes	32

Table 1. Metrics of Exercise Medicine Ontology.

restrictions on slots"[32]. Data standardization is a challenge for precision medicine and healthcare[33]. Ontologies can provide a controlled vocabulary and support the retrieval, aggregation, and reason of knowledge[34]. Ontologies have many applications in the field of exercise medicine, such as category activity status[35], recommendation system[36], clinical decision support system[37], and risk assessment system[38]. Kostopoulos *et al.*[39] proposed an ontology-based framework to support personalized exercise prescription[39], but the ontology is unavailable now. Currently, three physical activity- or exercise-related ontologies are available in the NCBO BioPortal, and they have all made contributions to the physical activity domain. The Ontology of Physical Exercises (OPE, https://bioportal.bioontology.org/ontologies/OPE) describes an exercise in 5 dimensions for treatment and prevention. It focuses primarily on aspects of the musculoskeletal system and includes only a handful of classes related to physical activity and exercise equipment. It contains health outcome classes but lacks personal health information. Physical Activity Ontology (PACO, https://bioportal.bioontology.org/ontologies/PACO) contains the concepts of describing physical activity and supporting data interoperability[35]. It can only describe physical activity without any other content (health status, etc.), which does not conform to our concept of exercise medicine. The last ontology is OPTImAL (http://bioportal.bioontology.org/ontologies/OPTIMAL), an application ontology used to model patient adherence to physical activity and exercise[40].

Since these current ontologies focus mainly on physical activity itself and lack concepts related to exercise medicine, such as individual health status and family history, we developed Exercise Medicine Ontology (EXMO), a core reference ontology for exercise medicine. EXMO includes personal health information, physical activity, tests, equipment, and other related items. It is built following the principles established by the Open Biological and Biomedical Ontologies (OBO) Foundry[41]; therefore, it has good compatibility and scalability for other OBO ontologies. Meanwhile, none of the existing physical ontologies met all quality criteria by OBO Foundry[34]. EXMO provides a core vocabulary for exercise medicine and can also help establish standards for exercise prescription. As a core reference ontology, EXMO will be extended to sub-ontologies specific to diseases such as cardiovascular diseases, cancer, or type 2 diabetes and will be included in the ontology network of exercise medicine, which will support the personalized exercise prescription.

Results

EXMO design and metrics. The latest release of EXMO, version 1.1, encompasses a comprehensive framework consisting of 434 classes and 9732 axioms, offering a rich and detailed structure. A detailed breakdown of these metrics can be found in Table 1. The hierarchical structure of the significant classes is visually depicted in Fig. 1, providing an overview of the ontology's fundamental organization. Within this framework, physical activity is categorized as a subclass of the process, and exercise, leisure physical activity, moderate-to-vigorous physical activity, recreational activity, and sedentary behaviour are subclasses of physical activity. Further, we classify exercise into aerobic exercises, anaerobic exercises, home exercises, outdoor exercises, and so on. Specific exercises, such as bicycling, swimming, and badminton are categorized to the next level. Additionally, the characteristics of exercise (exercise frequency, exercise intensity, exercise time, type of exercise, exercise volume, and exercise progression) are classified as a subclass of process. Health status and disease are also essential classes. Health status contains the classes about personal characteristics of health such as body fat mass, body mass index, obesity, and waist circumference. Common chronic diseases such as cancer and cardiovascular system disease are subclasses of disease. EXMO also includes other relevant classes such as exercise equipment, physical fitness testing, and their respective subclasses.

EXMO validation and evaluation. EXMO successfully passed the consistency validation with the ELK[42] and JFact[43] reasoners, with no inconsistencies detected.

Domain experts evaluated EXMO and confirmed that it could answer the competency questions (CQs) set up during the initial development phase, thus fulfilling its original objectives. The answers to these competency questions are shown below, and SPARQL queries are in the supplementary.

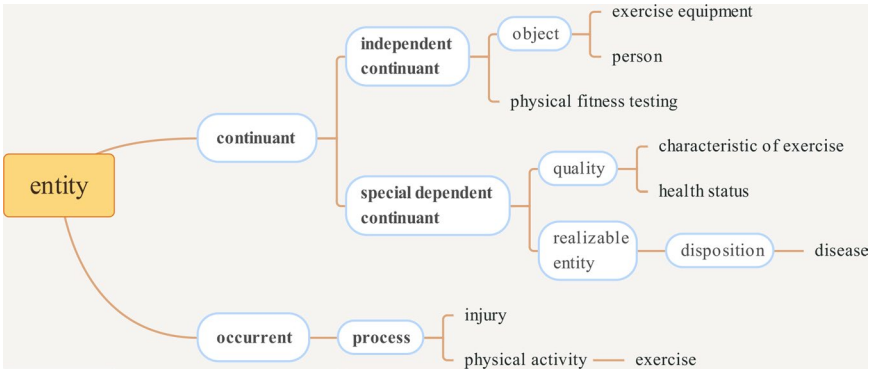

Fig. 1 Major hierarchical structure of Exercise Medicine Ontology.

	EXMO	OPE	OPTImAL	PACO
Axiom	9732	3863	3170	1153
Class count	434	634	142	224
Classes with no definition	115	634	142	217
Usage	reference	reference	application	reference
Synonym	√	×	×	×
Top-level ontology	BFO	—	—	—
Health status	√	×	×	×
Physical activity	√	√	×	√
Exercise equipment	√	√	×	√

Table 2. Physical activity and exercise-related ontologies.

CQ1. What is an exercise prescription? An exercise prescription commonly refers to the specific plan of fitness-related activities that are designed for a specified purpose.

CQ2. What information is included in the exercise prescription? An exercise prescription is an exercise plan that contains information on exercise frequency, exercise intensity, type of exercise, exercise time, exercise volume, exercise progression, warm-up exercise, cool-down exercise, monitoring, adjustment, safety, and risk management.

CQ3. Which testing should be conducted before prescribing for exercise? Body composition testing, cardiopulmonary exercise test, cardiovascular endurance testing, drop jump landing, flexibility testing, functional movement screen, general health evaluation, hop test, range of motion testing, selective functional movement assessment, strength and endurance testing, and Y-balance test.

CQ4. What harm might physical activity cause? Physical activity might cause athletic injury and muscle hypertrophy.

CQ5. Which neurotransmitters can be released when doing physical activity? Dopamine, endorphin, serotonin, norepinephrine, adenosine triphosphate, and glutamate.

CQ6. What causes muscle hypertrophy and who is prone to it? Physical activity may cause muscle hypertrophy. Adolescents and pregnant women are prone to it.

CQ7. What exercise equipment can be used in strength training? Barbell, dumbbell, kettlebell, medicine ball, and weight machine.

CQ8. What can a pulse oximeter measure? Pulse oximeter can measure oxygen saturation.

Discussion

EXMO includes the main categories of exercise medicine (health status and physical activity) to describe the core problem of exercise prescription: different groups need appropriate ways to exercise[21,44–46]. To the best of our knowledge, EXMO is the first core reference ontology within the field of exercise medicine. We compared EXMO with three other ontologies related to physical activity or exercise (as shown in Table 2). We provided definitions for classes where recognized definitions were available; however, the other three ontologies contained few definitions, making it difficult for users. Although EXMO has a lower class count than OPE, it sufficiently meets the requirements of a core reference ontology. Furthermore, EXMO encompasses all three sub-domains needed for our purposes. However, the other three do not and cannot provide good help for personalized exercise prescriptions. The integration of a top-level ontology enhances EXMO's compatibility and scalability.

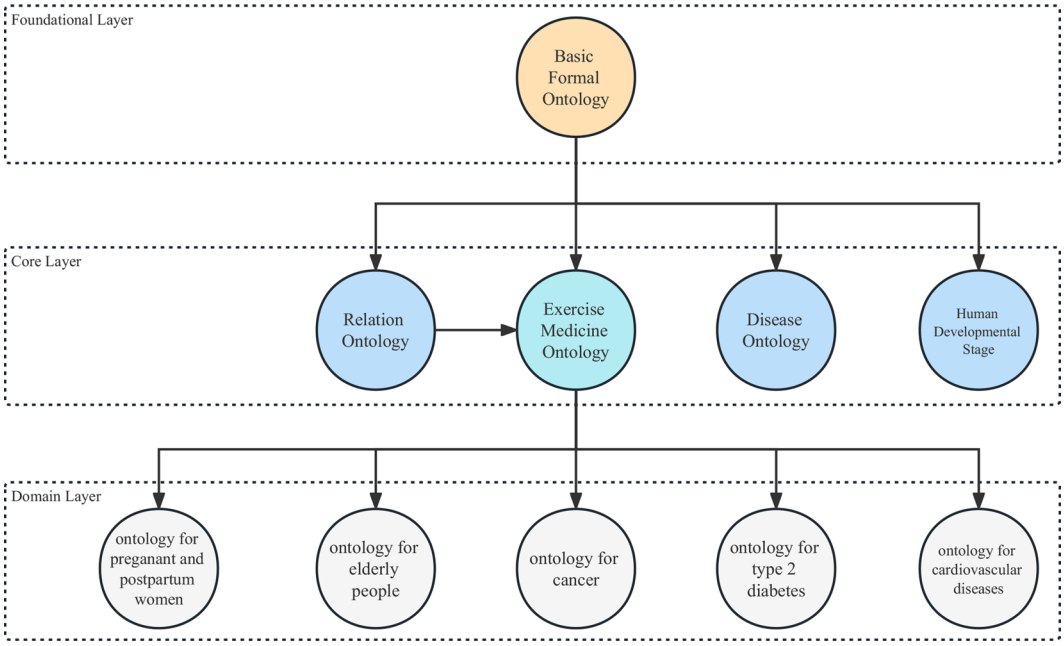

Fig. 2 Ontology network of Exercise Medicine Ontology.

As a reference ontology, EXMO provides a core vocabulary and contributes significantly to the standardization of exercise prescriptions. It does this by providing rich information encompassing personal health status, associated tests, physical activity, exercise equipment, and other relevant terms. This wealth of data helps create more accurate and effective exercise prescriptions. Furthermore, EXMO's robust framework offers an ideal foundation for developing an exercise prescription database and recommendation system. With the support of EXMO, these tools provide personalized, data-driven recommendations, increasing the effectiveness of exercise medicine and paving the way for a new level of personalized healthcare.

In our future efforts, we plan to expand the scope of EXMO by constructing sub-ontologies based on its framework, ultimately leading to the creation of an integrated exercise medicine ontology network. As shown in Fig. 2, the Basic Formal Ontology serves as the top-level ontology. At the core layer, we find both the Exercise Medicine Ontology and other OBO ontologies, including the Relation Ontology and the Disease Ontology. The domain layer, meanwhile, is populated with sub-ontologies tailored explicitly to various demographic groups, such as pregnant and postpartum women, individuals living with type 2 diabetes, and cancer survivors. Using EXMO as the core ontology allows these sub-ontologies to share common concepts, thus facilitating a more streamlined and efficient knowledge-sharing process. This interconnectivity and shared understanding among the sub-ontologies underpins the potential of this network to improve individualized exercise prescriptions and health outcomes[47]. In addition, we will develop a knowledge base and knowledge graph based on EXMO and its ontology network, and the knowledge graph can be used to build explainable artificial intelligence models[48].

Methods

We built the Exercise Medicine Ontology following the comprehensive guidelines of the Ontology Development 101 methodology[32] and the principles established by the OBO Foundry[41]. This meticulous approach ensures a thorough and standardized development process, providing a robust and reliable foundation for the ontology.

Figure 3 illustrates the workflow of building EXMO. Our expert team comprises clinicians, health management experts, sports experts, and informaticians. During the first six months, we held monthly meetings with the experts. After defining the ontology domain, we integrated classes from existing ontologies and supplemented them with terms from guidelines, databases, and literature. Throughout the process, we organized meetings with experts from various fields every three months. However, when specific challenges arose, we consulted the relevant experts promptly. During the evaluation phase, we modified EXMO and held monthly meetings. This iterative refinement continued until the ontology successfully passed expert evaluation and consistency validation. After three rounds, EXMO v1.0 successfully passed consistency checks and expert evaluation.

Domain and aim. Before we started developing the ontology, we discussed with our expert team to determine the domain and aim of EXMO. To precisely delineate EXMO's scope and goals, we addressed four key questions—domain, purpose, application, and user—derived from the Ontology Development 101 methodology. Our goal is to develop an ontology within the domain of exercise medicine, with a primary focus on exercise. Exercise refers to a form of physical activity that is typically performed regularly and intentionally to promote or maintain health. Given the close relationship between exercise and physical activity, EXMO also incorporates terms relevant to physical activity. Figure 4 illustrates the scope and goals of EXMO. As a foundational reference, EXMO v1.0 focuses only on core terms and key relationships. Specific details, such as disease types and stages, tailored exercise recommendations, or specific values (e.g., normal blood pressure ranges), are excluded from

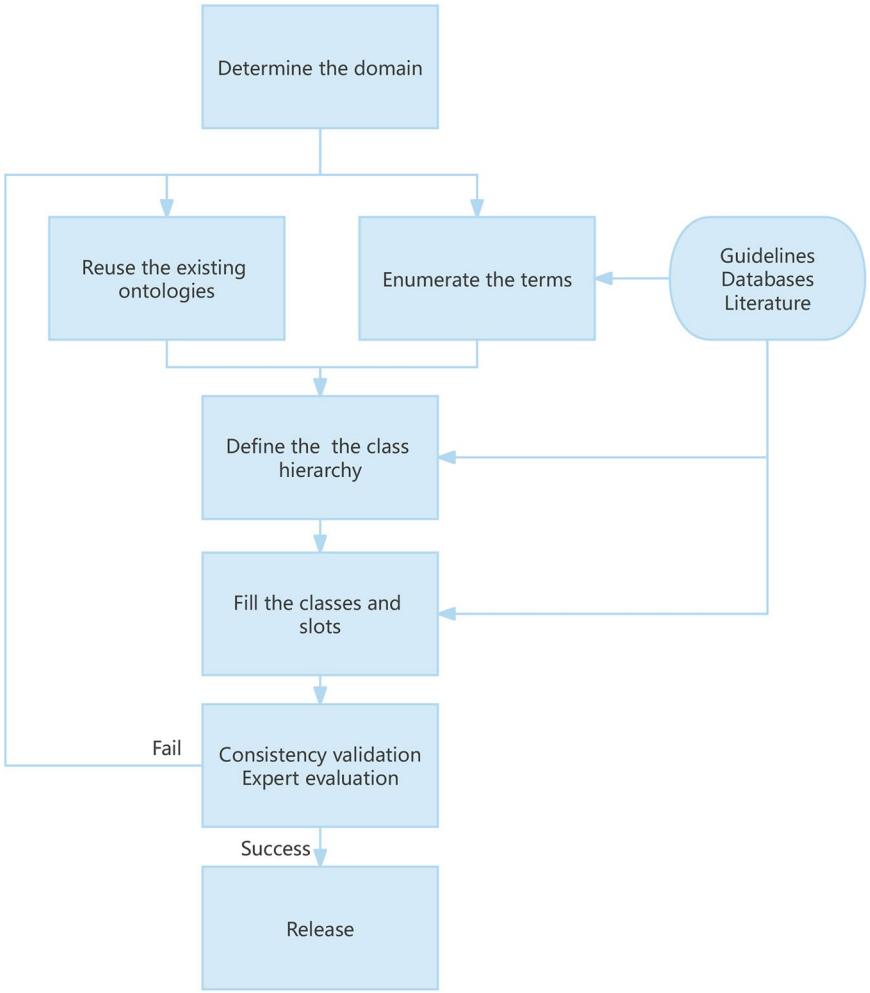

Fig. 3 Workflow of Exercise Medicine Ontology.

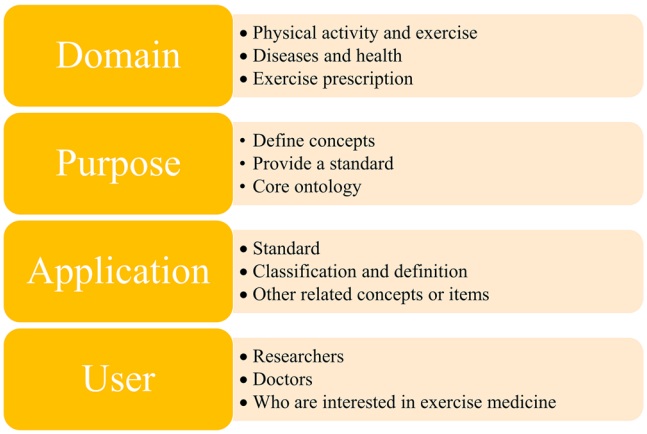

Fig. 4 Domain, purpose, application and user of Exercise Medicine Ontology.

this version. These elements will be addressed in future updates or through an extended ontology network. To guide the ontology's design, we selected 1–3 representative questions covering key aspects, including exercise prescription, health status, the effects of exercise, and exercise equipment. For exercise prescription, we identified two fundamental questions: What is an exercise prescription? And what information does an exercise prescription contain? (CQ1 & CQ2). For health status, we addressed questions related to exercise prescription (CQ3) and equipment (CQ8). Questions about the benefits and risks of exercise were captured in CQ4 to CQ6. Regarding

	Source	Usage
Ontology	Basic Formal Ontology	Top-level ontology
	Relation Ontology	Reuse relation
	Disease Ontology	Reuse disease
	Human Developmental Stages	Reuse human stage related concepts
	Ontology of Physical Exercises	As a reference
	OPTImAL	As a reference
	Physical Activity Ontology	As a reference
Guideline	WHO guidelines on physical activity and sedentary behaviour	Extract some concepts and relations between them
	National Fitness Guideline (China)	
	Physical Activity Guidelines for Americans	
	Physical Activity and Exercise Guidelines for All Australians	
	UK Chief Medical Officers' Physical Activity Guidelines	
	The National Guidelines on Physical Activity for Ireland	
	Physical Activity Standards for Health Promotion 2013 (Japan)	
Database	Medical Subject Headings	Extract some concepts and their definitions, as well as the relations between them
	National Cancer Institute Thesaurus	
	PubMed	
	Systematized Nomenclature of Medicine–Clinical Terms	
	Unified Medical Language System	
	Wikipedia	

Table 3. Main sources of classes and their definitions in Exercise Medicine Ontology.

exercise equipment, we focused on identifying equipment used for strength training (CQ7). These competency questions are used to assess and evaluate EXMO's capabilities.

Concepts from domain knowledge. In the domain of exercise medicine, it is imperative to include concepts related to personal health status, family history, disease, physical activity, the FITT-VP principle, equipment, and other related concepts.

We used the Basic Formal Ontology (BFO, https://basic-formal-ontology.org/)[49] as the top-level ontology for EXMO. Following the principles of the OBO Foundry, all relationships are derived from the Relation Ontology (RO, https://oborel.github.io/)[50]. Furthermore, we included classes from the Disease Ontology (DO, https://www.disease-ontology.org/)[51] to cover diseases and from the Human Developmental Stages (HsapDv, https://github.com/obophenotype/developmental-stage-ontologies/wiki/HsapDv) for human stages. However, because existing physical activity-related ontologies are built not under BFO, we did not directly reuse the classes from them but used them as references.

Identifying terms within the domain. To ensure a comprehensive understanding of the domain, we meticulously curated fundamental concepts from physical activity guidelines, scientific articles, and databases. These were further enriched through insightful discussions with experts in the respective fields. A comprehensive list of these sources is provided in Table 3 for reference. We conducted a search on PubMed using the keywords "exercise prescription [ti]" for exercise prescription literature, "exercise medicine[ti]" for exercise medicine literature, and " exercise [majr] OR physical activity[ti] OR sports medicine[ti]" for recent studies related to exercise or physical activity. Concepts that may not have been covered in other sources were primarily extracted by reviewing titles and abstracts. After selecting candidate terms, we engaged experts in discussions regarding the selection of these terms.

Ontology development. The Ontology Development Kit (ODK)[52] facilitated the creation of the EXMO project. We edited EXMO in the OWL2 language using Protégé Desktop[53]. In addition, the ROBOT tool[54] was used to extract, merge, reason, and convert the ontology, streamlining the process and ensuring the efficient and robust development of the EXMO framework.

After enumerating the concepts, we implemented a top-down process to establish the hierarchy of classes. First, we identified the most common synonym from the databases to serve as the class name. We then incorporated definitions, synonyms, and cross-database references derived from the databases. Within EXMO, synonyms are meticulously and rigorously classified into exact synonyms (same meaning), broad synonyms (similar meaning but broader), and narrow synonyms (similar meaning but narrower). This meticulous classification ensures the precision of data retrieval and cross-referencing, instilling confidence in the robustness of the EXMO framework. In addition, we have integrated relationships between classes using the imported RO, further enriching the complexity and utility of the data network within EXMO. Axioms such as SubClassOf and EquivalentTo are defined by searching sources such as databases and literature and discussing with experts.

Data availability

EXMO is available at https://github.com/DarkKnight0-0/exmo and https://bioportal.bioontology.org/ontologies/EXMO.

Code availability

No custom code was used.

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Author contributions

X.L. prepared the data, built and evaluated EXMO, and wrote the manuscript; Y.Y., H.Z., K.Z., M.J., C.Y., Y.C., J.W. and T.T. prepared the data and built EXMO; T.B., D.L. and S.R. prepared the data and evaluated EXMO; J.M.R. and B.S. conceived and supervised the work. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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