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RESEARCH ARTICLE

A Domain Ontology for Gait Analysis and Decision Support on Gait-Related Diseases

TERRANCE MARTHINUS[1] AND OLAWANDE DARAMOLA[2], (Member, IEEE)
[1]Department of Information Technology, Cape Peninsula University of Technology, Cape Town 8000, South Africa
[2]Department of Informatics, University of Pretoria, Pretoria 0028, South Africa

Corresponding author: Olawande Daramola (wande.daramola@up.ac.za)

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ABSTRACT The complexity of diagnosing and treating gait-related diseases necessitates the existence of a domain ontology that can support intelligent decision-making by gait experts and medical personnel. This study describes the development of a domain ontology for gait analysis and decision support on gait-related diseases. The process for developing the ontology followed a custom ontology development process that is based on the hybridisation of the Ontology 101 (OD-101) development methodology and Methontology, ensuring a systematic and replicable construction of the ontology. The design of the Gait Analysis Domain Ontology (GADO) embraced thirteen dimensions, making it the most comprehensive domain ontology for gait analysis compared to previous efforts. The GADO was created using the Protégé ontology editor and was evaluated by using ontology verification and validation procedures. Ontology verification was conducted by using the Framework for Ontology Conformance Analysis (FOCA) to assess domain task fit through competency questions and content richness of the ontology. The results demonstrated GADO's suitability in representing the domain effectively. Ontology validation involved checking the structural and logical consistency of the ontology by using reasoners such as HermiT and Pellet and employing Description Logic and SPARQL queries to assess the ontology's ability to respond to domain-specific queries accurately. The validation process confirmed the GADO's effectiveness in facilitating the retrieval of relevant information. Thus, the GADO is positioned to enhance clinical decision support for gait-related diseases, thereby advancing the applications of ontology-enabled decision support systems.

INDEX TERMS Artificial intelligence, decision support system, domain ontology, gait analysis, gait-related diseases, ontologies, ontology development.

I. INTRODUCTION

Historically, the word ontology originated from the field of philosophy. It refers to "the nature of being or existence" [1]. In Computer Science, ontology transcends its philosophical roots of being and existence to a practical framework for defining and categorising concepts within a domain, facilitating shared understanding and interoperability. Ontologies in Computer Science, as Guarino [2] posits, are explicit specifications of conceptualisations that enable the structured representation of knowledge, important for decision-making and knowledge management.

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Gait analysis, the scientific study of human walking patterns, is gradually measured and interpreted through advanced computing technologies. This analysis is indispensable for evaluating and formulating treatment plans for patients with gait mobility concerns.

Modern technological advancements in mobile cloud computing, wearable sensors, and body markers have streamlined the assimilation and analysis of gait data, enabling gait experts to make informed decisions swiftly and remotely [3]. The integration of innovative technologies in the biomedical and digital landscapes has significantly advanced the capabilities for aiding humans with various diseases and their treatments [4]. This paper presents the development of a domain ontology for gait analysis that could aid intelligent reasoning and enable decision support systems focused on the treatment and management of gait-related diseases.

Biomedical research, where gait analysis is extensively applied, could benefit from ontologies that can encapsulate the domain's unique vocabularies and classifications. Well-structured ontologies can aid domain experts by providing decision support to enhance the accuracy and efficiency of patient treatment and well-being [5], [6].

Implementing an intelligent system using ontologies often involves leveraging the Web Ontology Language (OWL), which is endorsed by the World Wide Web Consortium (W3C), to create an ontology that includes classes, individuals, and relationships. OWL facilitates the exchange of procedural information within the semantic web, enhancing the design and deployment of knowledge structures. The semantic web, an enriched version of the current web, structures information to improve human-machine interoperability [7].

Ontologies, developed using formal languages like OWL, are grounded in Description Logics (DL), ensuring that logical formalisms are decidable and that DL reasoning tools can infer knowledge from the ontology. These reasoners are pivotal in processing ontologies, enabling the automatic derivation of implicit knowledge [8].

In recent years, ontologies have gained significant attention and use in various research areas. Lately, ontologies have been widely applied in knowledge engineering, artificial intelligence (AI), E-commerce, digital information sharing, database management, Bioinformatics, natural language processing (NLP), expert systems, and decision support systems. The need for gait experts to have better insight into clinical gait analysis has become increasingly significant, especially with the advent of big data and other innovative AI technologies. Now more than ever, developing and designing a suitable domain ontology that decision support systems can leverage for informed decision-making on the treatment of gait-related diseases is a necessity [9].

The Gait Analysis Domain Ontology (GADO) is aimed at assisting gait experts in the diagnosis and treatment of gait-related diseases. The contributions of this paper are as follows:

- It is the first attempt at developing a dedicated domain ontology to support gait analysis. To date, there is no such ontology or knowledge graph.
- It proposed the Gait Analysis Domain Ontology (GADO), which covers thirteen dimensions (aspects), making it the most extensive knowledge base on gait analysis so far, compared to previous efforts.
- It demonstrates the application of state-of-the-art methods for domain ontology design, development, and evaluation.
- It reveals the critical requirements for effective decision-support in the treatment and management of gait-related diseases.

The rest of the paper is structured as follows: Section II presents the background and related work, while Section III describes the methodology used to develop and evaluate the Gait Analysis Domain Ontology (GADO). Section IV discusses the results. Finally, section V concludes the paper with a summary and an outlook for future work.

II. BACKGROUND AND RELATED WORK

In this section, we provide an overview of the relevant theoretical context for this study and review related work.

A. GAIT ANALYSIS

Gait is a biological characteristic of a person, and the gait pattern is the manner or style in which a person usually walks [10]. Gait is a fundamental function that is crucial for human movement [11]. Gait analysis is a critical tool in the medical field, providing insights into the locomotive patterns of individuals, which can be indicative of various health conditions [12]. The gait process involves a systematic approach to collecting and analysing data on the manner a person walks, using a range of methods and equipment, from simple observational techniques to advanced motion capture systems. The significance of gait analysis extends to the diagnosis and monitoring of gait-related diseases such as Parkinson's disease, multiple sclerosis, arthritis, and musculoskeletal disorders. Gait-related diseases can manifest in distinctive types of gait patterns [13]. Gait analysis is crucial for identifying deviations from normal gait that may signal underlying gait-related diseases [14].

B. GAIT-RELATED DISEASES

Gait is a complex process involving the coordination of the human musculoskeletal system by the brain, culminating in body movement and postural stability. The gait coordination activity of the brain is a process that involves various components, such as the cortical brain regions, white matter tracts, and the peripheral nervous system [15]. According to [11], walking is a cognitive process that requires higher-level cognitive control by specific areas of the brain, particularly during challenging walking conditions that require executive function and attention. When these areas of the brain are affected by diseases, the control of posture and gait will be affected. Gait disorders are abnormalities in the movement pattern of a person, which can ultimately impair the ability to walk.

Gait disorders can be caused by several factors, including sensory ataxia, Parkinsonian, musculoskeletal disorders, neuromuscular and myelopathic disorders, arthritis (such as osteoarthritis and skeletal deformities), and brain dysfunction [16], [17]. Cognitive decline is closely associated with the severity of gait impairment and abnormality, particularly in older and younger persons with severe health conditions [18]. Gait impairments are known to be closely associated with Neurodegenerative diseases (NDD), which are a set of chronic diseases that involve the central nervous system, leading to severe disabilities that worsen with time until eventual death [19]. Examples of NDD include Alzheimer's Disease (AD), Multiple Sclerosis (MS), Parkinson's disease (PD), Huntington's disease (HD), dementia, Amyotrophic Lateral Sclerosis (ALS), Prion diseases, Spinocerebellar ataxias, Spinal Muscular Atrophy (SMA) [12]. Gait disorder is also associated with other neurological diseases such as Stroke or Transient Ischemic Attack (TIA) [15] and cerebral palsy [20]. Severe chronic cases of different diseases can also result in gait disorders in the patient. According to [16], apart from neurological conditions, gait disorders can be evident in persons with orthopaedic problems (e.g. osteoarthritis and skeletal deformities) and medical conditions such as heart failure, respiratory insufficiency, peripheral arterial occlusive disease and obesity.

There are different types of gait disorders, which include the following: Hemispastic gait, Paraspastic gait, Ataxic gait, Sensory ataxic gait, Cautious gait, Freezing gait, Propulsive gait, Astasia, Dystonic gait, Choreatic gait, Steppage gait, Waddling gait, Antalgic gait, Vertiginous gait, and Psychogenic gait disorder [16]. By using wearable technologies, gait experts can monitor patients with gait-related diseases and provide the required treatment plans to manage patients' health conditions [13], [19]. The development of an ontology for the gait analysis domain can revolutionise the way gait data is conceptualised and utilised.

C. ONTOLOGY

An ontology, by definition, captures the explicit formal specifications of a shared vocabulary of a domain and relationships that exist amongst the concepts [2]. It serves as a framework for integrating disparate data sources and providing a common understanding of the domain, which is essential for effective data analysis and knowledge management [21]. The diverse range of ontologies, encompassing top-level, domain, task, as well as application-specific ontologies, can cater to the multifaceted nature of gait analysis, ensuring a detailed depiction of knowledge of the domain [22].

In essence, a domain ontology serves as a comprehensive representation of the concepts and their interrelationships within a particular knowledge domain. This specialised type of ontology can be employed to describe a specific area of expertise, along with its associated terminology, relationships, and definitions. Domain ontologies foster a shared understanding of a particular field and its related concepts, thereby streamlining the sharing and exchange of information among collaborators. An ontology defines the structure of a given domain in a precise manner. Domain ontologies are particularly decisive for developing AI systems capable of reasoning about specific knowledge domains. Therefore, domain ontologies find applications in natural language processing (NLP), knowledge engineering, and semantic web development, where they play a pivotal role in establishing a shared understanding of the domain and facilitating the efficient interchange of information. This facilitation of a knowledge domain allows domain assumptions to be explicitly stated [23].

Ontology development is a detailed process that involves methods and tools designed to build, maintain, and evaluate ontological structures. This process includes the selection of appropriate ontology languages like OWL and Resource Description Framework (RDF), which provide the syntax and semantics for defining and relating the concepts within the ontology. Formal languages like Description Logics (DL) and First-Order Logic (FOL) underpin ontology development, providing the means to evaluate the logical structure and inferential power of the ontology. These formalisms are instrumental in ensuring that the ontology can support reasoning processes, namely those facilitated by ontology querying and ontology reasoners, which are essential for deriving meaningful inferences from the domain ontology [24]. SPARQL querying and reasoners are both tools that operate on ontologies, but they serve distinct purposes. SPARQL is a query language used to retrieve and manipulate data stored in RDF format. Reasoners, on the other hand, are tools that infer implicit knowledge from explicit facts and relationships specified in an ontology. These mechanisms generally interact with the ontology post-development.

D. ONTOLOGY DEVELOPMENT METHODS

The ontology development process has a similar goal to software engineering, which is to produce a functional artefact that meets stakeholders' expectations by following a systematic approach or methodology. Various ontology development methods and methodologies have been proposed in the literature [23], [25]. According to [25], although many ontology development methodologies exist, there is not a single and universally recognised methodology that is superior or a one-size-fits-all approach to ontology development. Selecting the most appropriate ontology development methodology depends on the desired outputs and expected deliverables. The process of ontology development has become significant in recent years, as ontologies have become the pillar of the semantic web. Existing methodologies like Methontology [26], Toronto Virtual Enterprise (TOVE) [27], Uschold and King's methodology [28], Ontology Development 101 (OD-101) [29], DILIGENT [30], NeOn [31], Modular Ontology Engineering (MOE) [32], as well as Agile Ontology Engineering Methodology (AgiSCOnt) [33], are prime examples of ontology development methods. Based on individual merits, each of these methodologies has its strengths and weaknesses, and it is essential to consider which is best suited for a particular ontology development task [25].

Fundamentally, the activities of the ontology development lifecycle are the following:

- *Feasibility study*: involves investigating whether the domain ontology is necessary, potentially useful, and viable to solve the problem at hand.
- *Domain analysis*: entails examining the sources of knowledge and domains of knowledge that are relevant for developing the envisioned ontology.

- *Conceptualisation*: identifying the concepts (terms, entities) and relationships among the concepts of the domain, which will be contained in the domain ontology.
- *Implementation*: actual creation of the domain ontology by using a specific ontology language format.
- *Maintenance*: updating the ontology and refining it after development to make it adaptable to new requirements.
- *Use*: entails using the ontology after the development in practical applications and other ontologies.

Ontology engineering activities can be broadly classified into 3 phases, which are pre-development (viz. feasibility study), classical development (viz. domain analysis conceptualisation, implementation), and post-development (viz. maintenance and use) [34]. The ontology support activities such as knowledge acquisition (KA), reuse, evaluation, and documentation are performed in parallel to the core development activities. There is no single ontology development methodology that covers all the phases of ontology engineering. Hence, based on specific requirements, a hybrid or adapted methodology might be useful in many instances.

E. ONTOLOGY EVALUATION

The evaluation of the ontology is imperative to ensure its quality and applicability. Ontology evaluation employs standard metrics to assess an ontology's fitness for the domain tasks, its correctness, and content richness. This rigorous evaluation is central for ensuring that the ontology not only accurately represents the domain knowledge but is also practical and reliable for end-users [35]. Ontology evaluation involves validation and verification procedures. Ontology validation ensures that the ontology is constructed correctly and complies with the established requirements, whereas verification guarantees that the ontology meets specific quality criteria and is built optimally [36].

F. RELATED WORK

This section reviews previous research on domain ontology development pertaining to gait analysis.

In recent years, there has been a growing interest in the use of ontologies for the representation and organisation of gait analysis. In [4], the GaitViewer, a web application designed for semantic analysis and visualisation of gait data, was developed. GaitViewer tackles the challenge of integrating and analysing heterogeneous gait data, such as joint angles and muscle activation, acquired from diverse clinical gait analysis systems. The authors facilitated semantic integration through ontologies. Ontologies were used to represent the meaning of gait data, enabling seamless exchange and analysis across different platforms. GaitViewer separates numerical data (stored in a NoSQL database) from meta-information (represented by ontology concepts). This separation enables efficient querying and retrieval of gait data based on semantic criteria. The tool employs parallel coordinate plots for visual analytics, allowing researchers to explore correlations between various gait metrics. GaitViewer highlights the potential of semantic integration and visual analytics to improve clinical gait analysis. The study is particularly relevant as it underscores the importance of semantic integration for effective gait data analysis.

In [13], a conceptual framework that can enable decision-making on the treatment of gait-related diseases in resource-limited settings was proposed. The framework was designed to leverage a suite of knowledge graphs and ontologies to provide decision-support for medical practitioners and also aid patients with information on self-management strategies. However, the paper did not include the implementation and validation of the proposed conceptual framework.

In a study by [37], the authors demonstrated the application of domain ontology in the construction of a decision-support data warehouse architecture for musculoskeletal lower limbs. The authors described the mapping of this ontology to data warehouse models for generic data mining. Data mining was explored as a foundation during the creation process since the focus was to create an ontology of lower limb gait disorders. Considering the size and complexity of biomedical ontologies, the authors adopted the OSMMI (Ontologie du Systeme Musculo-squelettique des Membres Inferieurs) as an ontology for their project. OSMMI is a generic ontology of the musculoskeletal system that focuses on aspects of posture, ligament, and articular contact. It is not dedicated to gait analysis. Hence, the approach by [37] failed to cover other aspects of gait analysis apart from lower limb gait disorders.

In [38] and [39], the use of fuzzy ontologies and sensor data for gait recognition was proposed. The authors addressed the limitations of traditional ontologies by handling non-specific and vague knowledge using flexible fuzzy datasets. The study analysed human gait patterns by employing a Microsoft Kinect sensor and a gait recognition algorithm. The paper demonstrated the interoperability and reuse of applications and data in gait analysis, potentially enhancing security surveillance systems. However, the developed ontology did not sufficiently embrace several aspects that are critical for decision support on gait analysis.

In [40], an ontology that describes the characteristics of human arm movement was developed to analyse gestural information. The goal of the ontological model is to improve the accuracy of intelligent systems in recognising gestural information contained in arm movements. The ontology was designed to serve several digital applications.

In [41], the authors proposed a knowledge-based framework for semantic gait interpretation and recognition. The study addressed limitations in current gait recognition systems, particularly their sensitivity to variations in clothing, footwear, and viewing angles. The authors introduced a human gait ontology, enabling the system to progress beyond simple classification and achieve a more comprehensive understanding of gait patterns. The proposed framework comprises three phases. The first phase involves knowledge acquisition, where an ontology is built to capture human gait concepts. This ontology incorporates intrinsic properties (age, sex, height), extrinsic factors (clothing, shoes),

TABLE 1. Comparative overview of related work.

Reference: Year	Artifact	Objective/Purpose	Domain	Focus	
				Gait analysis	Gait-related diseases
[37]: 2013	Application of a domain ontology (OSMMI)	Decision-support data warehouse architecture for musculoskeletal lower limbs	Lower limb gait disorders	No	No
[41]: 2015	Human gait ontology	To achieve a more comprehensive understanding of gait patterns beyond simple classification.	Human gait recognition for automated person identification systems	No	No
[4]: 2016	A web application. Ontology was used to represent the meaning of gait data	Semantic analysis and visualisation of gait data	Improvement of clinical gait analysis	Yes	No
[40]: 2019	Ontology for upper arm movement	Representation of characteristics of upper arm movement to understand gestural information	Human motion analysis	No	No
[38 & 39]: 2017, 2019	Fuzzy ontologies for human gait recognition	Representation of both Microsoft Kinect data and biometric features of individuals for personal identification	Human gait motion analysis and recognition.	No	No
* [42]: 2021	A proposal without a concrete implementation	Decision support for gait analysis and gait-related diseases	Gait analysis, clinical gait analysis, gait-related diseases	Yes	Yes
* Our Approach	Domain ontology for gait analysis (GADO)	Decision support for gait analysis and gait-related diseases	Gait analysis, clinical gait analysis, gait-related diseases	Yes	Yes
* same authors					

and locomotion concepts (stance, swing). It establishes a structured vocabulary for gait description and serves as the foundation for the subsequent learning (second) phase. In the learning phase, features are extracted from image samples, and classifiers are trained to recognise these encoded gait concepts. Finally, the categorisation (third) phase involves applying the trained classifiers to new gait sequences. The extracted gait concepts are matched against the ontology to identify the most likely gait class.

While these previous studies have laid the groundwork for integrating ontologies with gait analysis, there remains a gap in the explicit development of ontologies that are designed to cover several critical dimensions of gait analysis that will facilitate comprehensive decision support for gait experts and the treatment of gait-related diseases. This gap is particularly evident because none of the existing ontologies has embraced an integrated perspective of gait analysis covering as much as the thirteen dimensions, including gait pathology, gait equipment, gait technologies, gait measurement, gait disturbance, and gait-related diseases, that were covered in the design of our GADO. In a previous paper [42], we described how a domain ontology can support healthcare experts in the care of patients with diseases that are associated with human gait impairment and gait abnormality. The paper [42] described the process of developing such an ontology, but it lacks actual implementation and evaluation. However, it provided the necessary foundation for this study. A comparative overview of the related work and our proposed GADO is shown in Table 1

III. METHODOLOGY

We adopted a hybrid ontology development process that relied on the key concepts of the Ontology Development 101 (OD-101) methodology [29] and Methonthology [26] to develop the Gait Analysis Ontology (GADO). The OD-101 methodology offers a comprehensive strategy that encompasses all the simple and essential steps required for the successful creation of a domain ontology, ensuring quality, reusability, and pragmatism [25]. However, it does not sufficiently embrace the aspects of formalisation and evaluation. In comparison, the Methontology methodology emphasises formalisation and evaluation, which we consider critical for the development of the GADO. Hence, we adopted a customised iterative development process that is derived from the core aspects of OD-101 and Methontology. The phases of our adopted ontology development process consist of problem identification, design, development, and evaluation (see Figure 1).

The development process of Gait analysis Domain ontology (GADO) consists of the following activities:

A. IDENTIFY PROBLEM

This is the first phase of the ontology development process. The activities of this phase are described as follows.

1) DEFINE ONTOLOGY DOMAIN AND SCOPE

This initial step involved defining the domain and scope of the ontology, focusing on gait-related matters, and establishing a solid foundation for the ontology's structure.

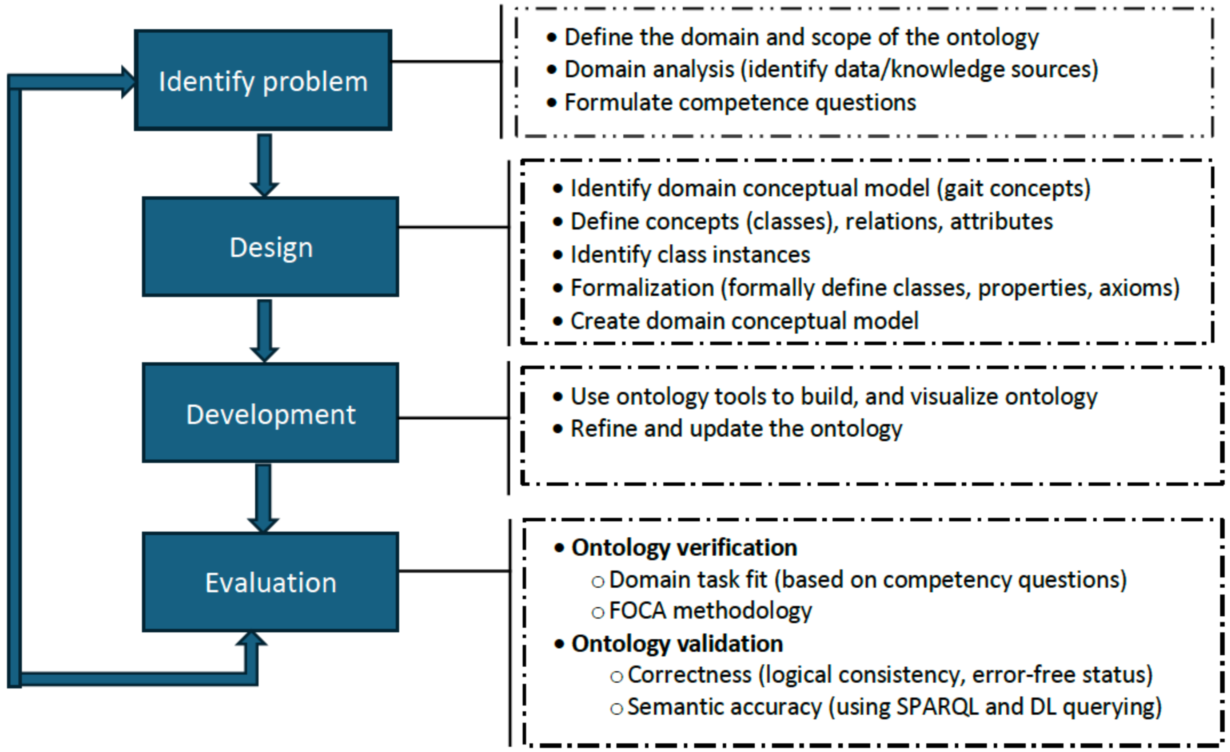


FIGURE 1. The Domain ontology development process for the GADO – derived from activities of OD-101 and methontology.

2) DOMAIN ANALYSIS

A robust domain analysis was undertaken, mining a rich array of secondary data sources that included medical databases such as Online Mendelian Inheritance in Man (OMIM®) [43], PubMed [44], the EMBL-EBI Ontology Lookup Service (OLS) [45], and the Human Phenotype Ontology (HPO) [46]. Key foundational texts in gait analysis and ontology engineering were also critically reviewed to establish a comprehensive knowledge base. The primary merit of secondary data in this context is the establishment of a shared understanding rooted in established knowledge. Peer-reviewed publications, medical databases, and authoritative texts on gait analysis serve as invaluable sources for obtaining this foundational knowledge [47]. These data sources provide a wealth of well-vetted information, ensuring the ontology's credibility and transparency and eliminating potential biases from subjective views [48]. In addition to the online web-based data sources, three published books were reviewed to provide broad and scientifically rigorous information for constructing the Gait Analysis Domain Ontology. These books supplemented and enriched the scope and requirements of the domain and ontology development process, which are:

- An Introduction to Gait Analysis, 4th edition [49]
- An Introduction to Ontology Engineering v1.5 [24]
- Handbook on Ontologies, 2nd edition [8]

3) FORMULATION OF COMPETENCY QUESTIONS

Driven by the insights from domain analysis, competency questions were formulated to set the ontology's functional benchmarks. The competency questions were designed to ensure the GADO's usefulness in supporting decision-making in the gait analysis and treatment of gait-related domains. These questions, detailed in Table 2, were essential for establishing GADO's domain coverage and ensuring its capability to support clinical decision-making. Interestingly, these very same competency questions were also pivotal in directing the development process and later served as a metric for ontology verification [50].

The process of eliciting secondary data sources was conducted to identify the key ontology concepts that pertain to the gait analysis domain. Hence, thirteen (13) core dimensions were identified from the requirements and competency questions and were considered necessary for adequate coverage of the gait analysis domain (see Table 3).

B. DESIGN

An extensive literature review and domain analysis helped identify the domain concepts and relationships, which were then organised and formalised into a conceptualised model.

Once the domain knowledge was gathered, the next step was to define the structure of the ontology. The core concepts of the ontology should fully and systematically represent the domain, laying the foundation for a robust and comprehensive domain ontology. Every focus area or concept was typically assigned to its class, with the greater knowledge area defined as the main class based on its level of abstraction and the lower-level knowledge point considered a subclass. Once identified, the concepts were organised into a structure that

TABLE 2. Competency questions of GADO.

	Competency Questions (CQs)
Q1	Who are the users of the domain for gait-related diseases?
Q2	What gait-related diseases are linked with geriatric (elderly) patients?
Q3	What are the most common types of gait-related diseases?
Q4	What are the typical neurological gait-related diseases that impact patients' gait?
Q5	Is there sufficient detail to differentiate between different types of gait-related diseases?
Q6	What current gait assistive technology solutions are available for gait disorders?
Q7	What types of non-pharmacological treatments are available for gait-related diseases?
Q8	To what extent can a decision support system for gait-related issues be useful/beneficial?
Q9	Who are the key role players in the execution of a gait-based process?
Q10	What are the types of gait disturbance that are generally associated with children?
Q11	What are the resources that require gait analysis?
Q12	What are the main etiological anatomies for gait pathologies?
Q13	What are the different gait dimensions for the domain?

TABLE 3. The GADO's gait dimensions.

Core Concept	Dimension description
Gait-based Process	This concept refers to the process by which the human body executes movement during walking or running for assessment.
Gait-related Disease	This refers to any medical condition that can affect an individual's gait.
Gait Analysis Equipment	This includes the equipment and resources used to analyse and measure the gait-based process.
Gait Analysis Method	This refers to the procedures and techniques used to assess and evaluate the gait-based process.
Gait Assistive Technology	This includes any devices, treatments, or technologies that are used to support and rehabilitate abnormal gait.
Gait Classification	It involves analysing and understanding the distinctive characteristics of a person's gait, such as stride length and cadence, to classify abnormalities or pathologies.
Gait Cycle	This concept refers to the complete cycle of movement executed by the human body during walking or running.
Gait Disturbance	This refers to any disruption or deviation from normal gait.
Gait Measurement Point	Gait measurement points are physical locations that analyse and measure how a person walks or moves.
Gait Parameters	This refers to any quantifiable aspect of the gait process, such as speed, step length, and width.
Gait Pathology	This refers to any abnormal condition or disease that affects a patient's gait.
Type of Gait	This refers to abnormal or improper gait categorised in different types of gait based on the symptoms or appearance.
Gait Person	This refers to the individual who is involved in the gait-based process, such as a gait patient or gait expert.

reflected their attributes and relationships. Each class was assigned a singular name that served as its identification, as shown in Figure 2.

The next step was to develop a taxonomy to organise the concepts and relationships logically. After that, the GADO's properties and axioms were defined to describe the characteristics of concepts and their relationships. Properties describe the characteristics of concepts, while axioms define the relationships between concepts [51]. Lastly, the conceptual model was developed to provide a high-level interpretation of the necessary concepts.

1) AN EXAMPLE OF A CONCEPTUAL MODEL: 'GAIT EXPERT' CLASS

The GADO is a structured knowledge base for information and data dissemination that aids in diagnosing and treating gait-related diseases [52]. A pivotal class in this ontology is the 'Gait expert', which acts as an agent interacting with various aspects of the gait analysis domain. The 'Gait expert' class is under the main concept or class of 'Gait person'. The 'Gait expert' class is an important concept in the Gait Analysis Domain Ontology because it represents the individuals who have the expertise to diagnose and treat gait-related diseases. The 'Gait expert' class includes individual instances like the Biomechanist, Orthopedist, Healthcare Practitioner, Podiatrist, and Physical Therapist. The 'Gait expert' class has the following key object properties, each defining a specific relationship with another concept in the ontology:

- **Administers**: *Gait expert→ Gait-based Process*
  [The Gait expert administers various gait-based processes like gait assessments or analysis.]
- **Facilitates**: *Gait expert→ Gait Analysis*
  [Involved in facilitating comprehensive gait analyses, possibly with specific gait analysis equipment and gait analysis methods].

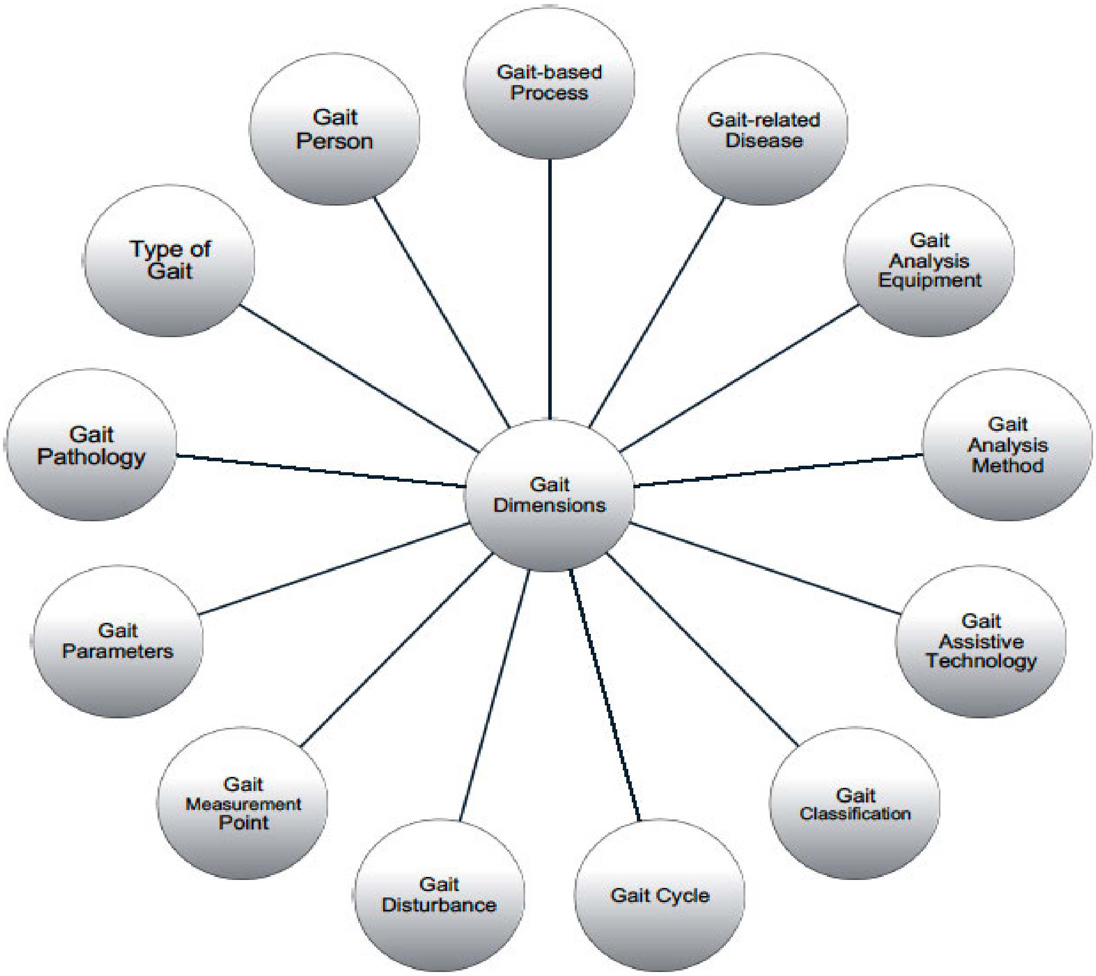


FIGURE 2. Gait dimensions covered in the gait analysis domain ontology (GADO).

- **Analyses**: *Gait expert→ Gait Data*
  [Responsible for examining gait data acquired from gait analysis activities.]
- **Observes**: *Gait expert→ Gait Cycle*
  [The Gait expert observes gait cycles to identify abnormalities or confirm normal gait patterns.]
- **Prescribes**: *Gait expert→ Gait Assistive Technology*
  [Based on the analysis, the Gait expert may prescribe assistive technologies like braces or walking aids.]
- **Treats**: *Gait expert→ Gait patient*
  [Ultimately, the Gait expert is involved in treating patients with gait abnormalities, overseeing their progress, and adjusting treatment plans accordingly.]

Figure 3 illustrates a conceptual diagram of the 'Gait expert' class and how it relates to other classes within the GADO, such as 'Gait-based Process', 'Gait Analysis' and 'Gait patient' as previously mentioned.

2) FORMALISING THE ONTOLOGY

Formalisation of the ontology involved translating the domain-specific conceptualisation into an unambiguous, machine-readable format. The formalisation of the ontology served to delineate explicit definitions for core concepts and to specify the permissible types of relationships among them. Utilising a formal language like Web Ontology Language (OWL) ensured that the Gait Analysis Domain Ontology (GADO) not only provides a common vocabulary but also supports automated reasoning for gait analysis. Hence, the conceptual model was formalised using the OWL ontology language. The resultant formalised ontology facilitates machine-based inferences, thereby enhancing the objectives of the GADO. Based on the core concepts for the GADO, a more enriched formalised ontology involves specifying classes and subclasses, as shown in Table 4, and then how the object properties relate to these classes.

Table 5 shows examples that attempt to articulate the relationships between some of these classes. These are just snapshot examples of the relationships that exist between some of the classes through object properties in the Gait Analysis Domain Ontology.

Table 4 shows examples of object properties that describe the relationships between specific classes in the Gait Analysis

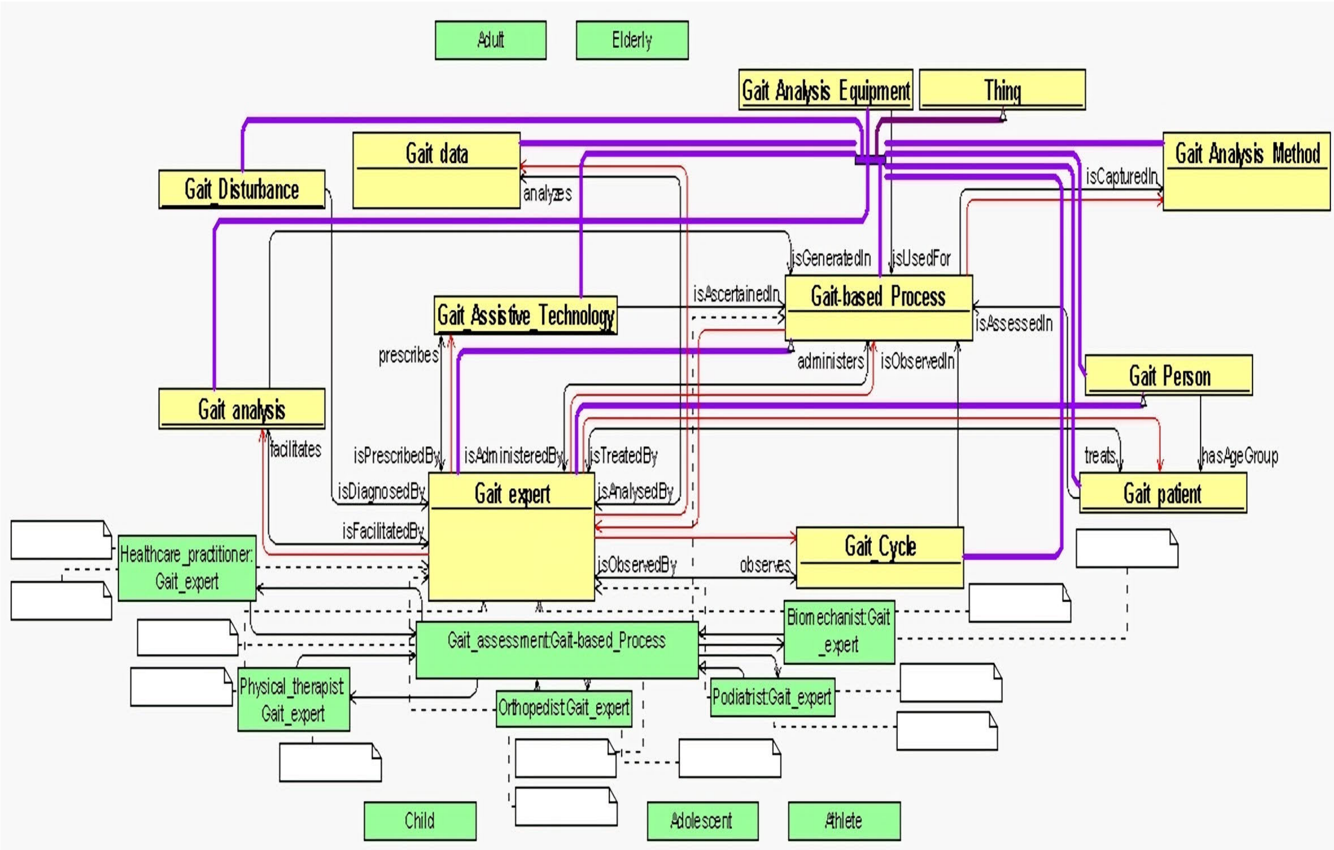


FIGURE 3. Conceptual model of the 'Gait expert' class.

Domain Ontology (GADO). Properties (object, data) and axioms were used to define the nature and characteristics of relationships between concepts (classes) in the ontology as part of the formalisation process.

C. DEVELOPMENT

The Gait Analysis Domain Ontology was implemented using Protégé 5.5.0. Classes, properties, relationships, and instances were defined to create a detailed representation of the domain.

1) USING PROTÉGÉ TO CREATE THE GADO

Protégé, a widely recognised and reliable open-source tool for creating and managing ontologies with a user-friendly graphical interface, was used to develop the GADO. Protégé's structured and machine-readable knowledge representation format made it well-suited for domain ontology development [53]. In addition, it also enabled the inclusion of annotations and labels to enrich the terms and concepts, improving the ontology's readability and providing supplementary information.

The GADO consist of a hierarchical structure, with each class or subclass embodying an individual concept or knowledge point associated with the domain. In the context of gait-related diseases, classes for various gait-related diseases, like Parkinson's disease, Neuropathy, and Hemiplegia, were created in the ontology, as well as classes for related main concepts like 'Gait Cycle', 'Gait Disturbance', 'Type of Gait'. This activity led to the creation of a hierarchical structure in which each class or subclass embodied a distinct concept or knowledge point associated with the domain. This hierarchical structure allows for a clear understanding and easier navigation of the concepts pertaining to the domain ontology.

Object properties were used to represent the relationships between concepts in the ontology. One such example is the object property ''isExhibitedBy'', which defines the relationship between the 'Gait patient' class and the 'Type of Gait' class. This property indicates that a gait patient can only exhibit one type of gait at a time. Basically, object properties also enabled the representation of meaningful relationships between classes in the ontology, making inferring and reasoning about the domain relatively straightforward. Data properties were used to represent the data attributes of each concept. Thus, the 'Gait person' class has data properties such as gender and age. These properties were used to describe the characteristics of the 'Gait person' concept and provided additional information about it. Data properties facilitated the development of a more intricate and comprehensive representation of the domain knowledge. Individuals, also known as instances, are specific objects or entities in the domain being

TABLE 4. The classes and a subset of subclasses.

Classes	Subclasses
Gait-based Process	Gait analysis, Gait data, etc.
Gait-related Disease	Parkinson's disease, Hemiplegia, etc.
Gait Analysis Equipment	Force plates, Electromyography, etc.
Gait Analysis Method	Motion systems, Kinematics, etc.
Gait Assistive Technology	Braces, Walking sticks, etc.
Gait Cycle	Stance phase, Swing phase, etc.
Gait Classification	Musculoskeletal, Neurological, etc.
Gait Disturbance	Gait ataxia, Falls, etc.
Gait Measurement Point	Foot progression angle, Stride length, etc.
Gait Parameters	Speed, cadence, etc.
Gait Pathology	Pathological gait and Geriatric gait
Type of Gait	Antalgic gait, Ataxic gait, etc.
Gait Person	Gait patient and Gait expert

TABLE 5. Some of the object properties relationships.

Object property	Description
isDetectedIn:	*Type of Gait* → *Gait Analysis Method* Meaning: A Type of Gait is detected in a particular Gait Analysis Method.
isMonitoredBy:	*Gait Patient* → *Gait Analysis Equipment* Meaning: A Gait patient is monitored by specific equipment.
affects:	*Gait Disturbance* → *Gait patient* Meaning: A Gait Disturbance negatively impacts the Gait patient.
isAssignedWith:	*Gait Person* (subtype: Gait Patient) → *Gait Assistive Technology* Meaning: A Gait Assistive Technology aids the Gait Patient.
isGeneratedIn	*Gait Analysis* → *Gait-based Process* Meaning: Gait Analysis is generated in the Gait-based Process.
isAdministeredBy	Gait-based Process → Gait expert Meaning: The Gait-based Process is administered by the Gait expert.

modelled. Individuals are the basic building blocks of ontology and can be both concrete and abstract concepts [24]. The GADO includes individuals to represent specific real-world instances of concepts in the domain ontology. The class 'Type of Gait' in the GADO has instances such as ''Ataxic gait'', ''Parkinsonian gait'', and ''Limp gait''.

The GADO is also annotated with descriptive information to enhance the understanding and meaning of its components and to provide additional context for users. These annotations or labels are added to individual classes, properties, or instances to provide descriptive clarity to the ontology's elements, supporting both human comprehension and machine interpretability.

The GADO was developed using an iterative approach, which allowed for the gradual improvement of the ontology, the inclusion of new concepts and relationships, and the refinement of existing ones. The ontology underwent multiple iterations, during which it was updated and revised to incorporate new information and integrate new knowledge, ensuring consistency, coherence, and a well-structured construction. Initial iterations focused on identifying key concepts and defining class properties. Subsequent iterations expanded the ontology with new classes, subclasses, and detailed relationships, incorporating the latest research findings and medical terms. Regular updates ensured the GADO's accuracy, coherence, and alignment with current domain knowledge, exemplifying this with the inclusion and detailed depiction of classes like 'Pathological gait' as shown in Figure 4. The incremental development process was key in crafting a comprehensive and reliable ontology for gait-related diseases, making the GADO more extensible and allowing new concepts and relationships to be added without difficulty.

D. GADO EVALUATION

The GADO was evaluated using ontology verification and validation, which are described next.

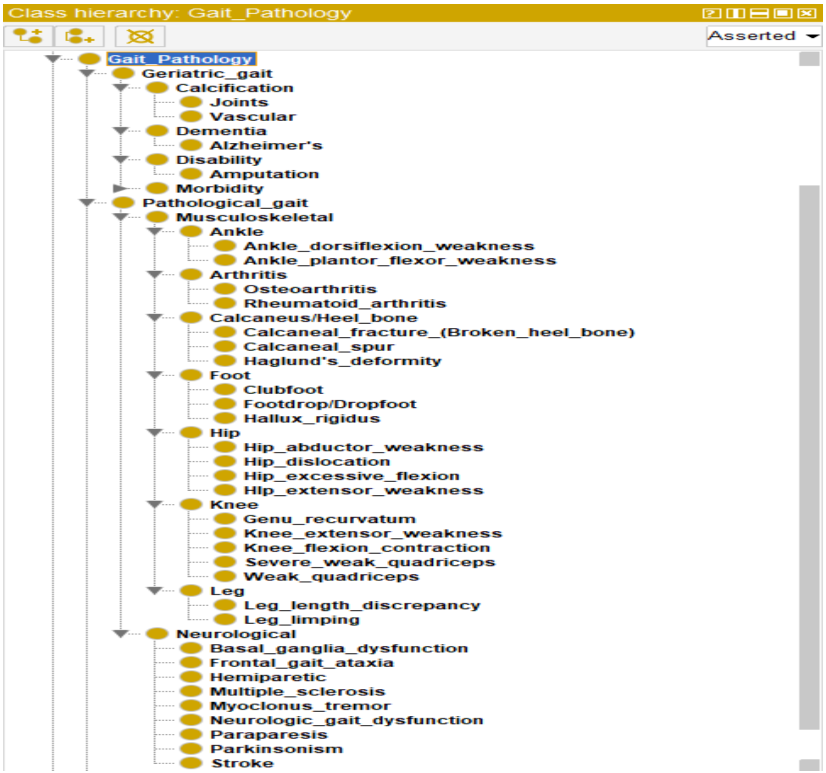


FIGURE 4. A view of the class hierarchy of 'Gait pathology.

1) VERIFICATION OF THE GADO

a: DOMAIN TASK FIT

The domain task fit of the ontology was assessed by evaluating its ability to meet the needs of its intended domain task and answer the competency questions. The goal is to ascertain if the ontology is aptly suited for its intended purpose and can be used to support diagnosis, treatment of gait impairments, and gait analysis tasks. The ontology was assessed against the competency questions previously defined in Table 1. This assessment helped to determine the correlation between the predefined competency questions and the concepts and relationships captured in the GADO (see Table 6). Our evaluation of the domain task fit of the GADO, based on predefined competency questions, confirmed its ability to support gait analysis and decision-making on gait-related diseases effectively.

b: CONTENT RICHNESS

The content richness of the Gait Analysis Domain Ontology was rigorously assessed to ascertain its expansive coverage of gait-related concepts. This evaluation was fundamental in determining the ontology's breadth and depth in encapsulating all pertinent aspects within the domain. The thorough annotation of key entities, including classes, subclasses, instances, objects, and data properties, was instrumental in achieving detailed representation. The annotations not only facilitated accurate and complete descriptions of the relationships among various concepts but, most importantly, ensured their logical consistency. The GADO's structural framework consisted of a significant number of entities, quantified by 2807 validated axioms. These were distributed across 214 classes, encompassing a wide range of gait-related concepts. The ontology contains 55 object properties and 23 data properties, integral in defining relationships and attributes within the domain. The ontology included 58 individual instances, further elaborated through 58 class assertions, 244 object property assertions, and 92 data property assertions. A total of 1540 annotation axioms were used to enrich the ontology. These annotations played a crucial role in providing detailed descriptions and comments, enhancing the clarity and understanding of each construct.

Figure 5 shows the metrics of the GADO providing a clear overview of the number of classes, properties, and axioms contained in the ontology.

c: FOCA METHODOLOGY

The FOCA methodology [54] was used to perform a structured evaluation, which facilitated an objective assessment of the ontology's design, construction, and implementation against predefined quality criteria.

The FOCA methodology is a comprehensive approach that combines quantitative and qualitative techniques [54]. An expert panel of four independent evaluators (see Table 7) participated in the evaluation, each with distinct backgrounds in academia, industry, and research, bringing a diverse range of expertise to the assessment process.

TABLE 6. Assessment of domain task fit based on answers to competency questions.

CQs	Answer
Q1	The domain users for gait-related diseases are gait experts, domain experts, and clinicians (all of whom are classes contained in the ontology).
Q2	Gait-related diseases associated with geriatric patients include dementia, osteoporosis, calcification, and muscle atrophy (all of which are linked to the Geriatric gait class in the ontology).
Q3	The most common types of gait-related diseases are Parkinson's disease, cerebral palsy, multiple sclerosis, and peripheral Neuropathy (all of which are classified as Gait-related diseases in the ontology).
Q4	Typical neurological gait-related diseases of patients include ataxia, dystonia, multiple sclerosis, Parkinson's disease, and Stroke (all of which are classified as neurological Gait-related diseases in the ontology).
Q5	Yes, the domain ontology contains up-to-date information on the current state of knowledge on gait-related diseases, including sufficient detail to differentiate between different types.
Q6	Current gait assistive technology solutions may include orthotics, canes, walkers, and therapy (all of which are listed as such in the ontology).
Q7	Non-pharmacological treatments available for gait-related diseases include physical therapy, rehabilitation therapy and gait training (all of which are listed as non-pharmacological treatments for gait-related diseases in the ontology).
Q8	A decision support system for gait-related issues can significantly provide healthcare professionals with accurate, evidence-based recommendations for the diagnosis, treatment, management, and informed decision-making of gait-related diseases (because the ontology contains information on all of these aspects).
Q9	Key role players in the execution of a gait-based process may include a gait expert, physical therapist, orthopaedist, and biomechanist (all of which are listed as key role players in the gait-based process in the ontology).
Q10	Gait disturbances generally associated with children include cerebral palsy, muscular dystrophy, loss of ability to walk in early childhood, and spina bifida (all of which are classified as Gait disturbances associated with children in the ontology).
Q11	Gait analysis requires resources such as motion capture systems, infrared cameras, force plates, sensors, and trained experts to perform and analyse the tests (all of which are listed as resources required for gait analysis in the ontology).
Q12	The main etiological anatomies for gait pathologies include musculoskeletal and neurological pathological gait (both of which are classified as etiological anatomies for Gait pathologies in the ontology).
Q13	Gait-based Process, Gait-related Disease, Gait Analysis Equipment, Gait Analysis Method, Gait Assistive Technology, Gait Classification, Gait Cycle, Gait Disturbance, Gait Pathology, Gait Measurement Point, Gait Parameter, Type of Gait & Gait Person (all of which are listed as gait dimensions in the ontology).

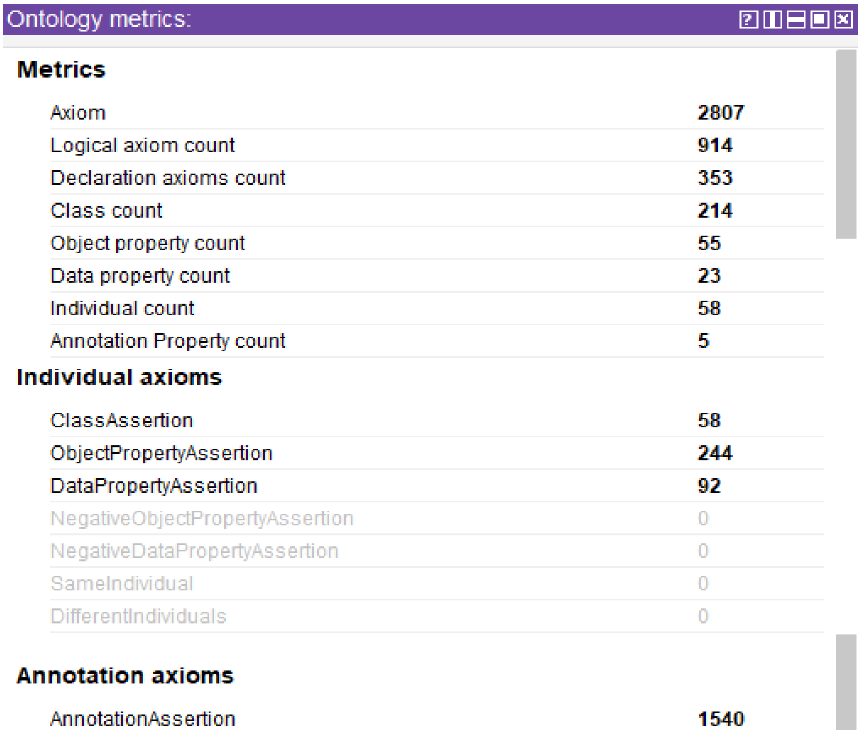
TABLE 7. Evaluators' profiles and background.

id	Description
P1	Academic background in Artificial Intelligence, intermediate expertise in ontology.
P2	Industry Systems Developer with advanced ontology design skills
P3:	Academic background as a Systems Developer experienced in ontology engineering
P4	Research in Knowledge Representation, expert-level skills in ontology

The FOCA methodology enabled an objective and goal-oriented analysis of the GADO, focusing on specific criteria representing five goals, such as *Goal 1: competency questions and reuse*, *Goal 2: ontology terms clarity*, *Goal 3: contradiction or invalid (re)use of terms*, *Goal 4: reasoning and reasoner performance*, and *Goal 5: ontology substantiation of the model against design specifications*. The FOCA methodology also involved assigning quantitative scores to specific questions related to each goal, which were then averaged to provide a mean score for each goal. This approach offered a concise and quantifiable view of how well GADO met each goal. A structured grading system was employed, where each evaluator assigned scores (either 25, 50, 75, or 100) to each question, reflecting their assessment of the ontology against each goal (see Table 8). The mean score for each goal was calculated by averaging the scores assigned by the evaluators to the questions related to that particular goal [54]. Based on the mean score for each goal, an evaluator's estimated total quality of the ontology is then computed using a beta regression model [55].

We obtained the estimated ontology quality by each evaluator (P1, P2, P3, and P4). Thus, for questions under Goal 1, if P3 gives a score of 75 to question 1, question 2 a score of 100, and question 3 a score of 100, the mean score for Goal 1 by evaluator P3 would be 91.67. The estimated total quality of the GADO was calculated for each evaluator based on the regression model [55], incorporating factors like mean goal scores and evaluator experience. This model considered the mean scores for each goal, along with other variables such as the evaluator's experience (experienced or not experienced) and whether all goals were assessed to determine the estimated total ontology quality assessment for each evaluator.

The FOCA beta regression model uses specific variables, including structural coverage (*CovS*), conceptual coverage (*CovC*), relationship coverage (*CovR*), concept property coverage (*CovCp*), level of expertise (*LExp*), and normalisation level (*Nl*), to calculate the overall quality (μ_i) of the ontology. Total quality verification was selected in this case because it evaluates all relevant aspects of ontology quality.


Ontology metrics:

Metrics

Axiom	2807
Logical axiom count	914
Declaration axioms count	353
Class count	214
Object property count	55
Data property count	23
Individual count	58
Annotation Property count	5

Individual axioms

ClassAssertion	58
ObjectPropertyAssertion	244
DataPropertyAssertion	92
NegativeObjectPropertyAssertion	0
NegativeDataPropertyAssertion	0
SameIndividual	0
DifferentIndividuals	0

Annotation axioms

AnnotationAssertion	1540

FIGURE 5. Ontology metrics for the GADO.

Based on the beta regression model [55], the total ontology quality can be calculated thus:

$$\mu_i = \frac{\begin{array}{l}\exp\{-0.44 + 0.03(Cov_s \times Sb)_i \\ +0.02(Cov_C \times Co)_i + 0.01(Cov_R \times Re)_i \\ +0.02(Cov_{CP} \times Cp)_i - 0.66LExp_i - 25(0.1 \times Nl)_i\}\end{array}}{\begin{array}{l}1 + \exp\{-0.44 + 0.03(Cov_s \times Sb)_i \\ +0.02(Cov_C \times Co)_i + 0.01(Cov_R \times Re)_i \\ +0.02(Cov_{CP} \times Cp)_i - 25(0.1 \times Nl)_i\}\end{array}}$$

For example, in order to determine the estimated total quality (μ) for P3, the following variables were considered:

- Cov_s : The mean value of goal 1.
- Cov_C : The mean value of goal 2.
- Cov_R : The mean value of goal 3.
- Cov_{CP} : The mean value of goal 4.
- $LExp$: The evaluator's experience, with 1 representing experienced and 0 not experienced.
- Nl : If a goal cannot be evaluated or any question cannot be evaluated, Nl is set to 1.
- $Sb = 1$, $Co = 1$, $Re = 1$, $Cp = 1$ because all goals were assessed.

These values were then substituted into the beta regression model to estimate the total quality of the ontology for P3. We have:

$$Cov_s = 91.67,\ Cov_C = 100,\ Cov_R = 87.5,\ Cov_{CP} = 100,$$
$$LExp = 1, Nl = 0,\ Sb = 1,\ Co = 1, Re = 1$$

Thus, the total quality μ for P3:

$$\mu_{P3} = \frac{\begin{array}{l}Exp(-0.44 + 0.03\,(91.67 \times 1) + 0.02\,(100 \times 1) \\ +0.01\,(87.5 \times 1) + 0.02\,(100 \times 1) \\ -0.66 \times 1 - 25(0.1 \times 0)\end{array}}{\begin{array}{l}1 + \exp(-0.44 + 0.03\,(91.67 \times 1) + 0.02\,(100 \times 1) \\ +0.01\,(87.5 \times 1) + 0.02\,(100 \times 1) \\ -0.66 \times 1 - 25\,(0.1 \times 0))\end{array}}$$

$$\mu_{P3} = \frac{\exp(6.525)}{1 + \exp(6.525)}$$

$$\mu_{P3} = \frac{680.7}{681.7} \approx 0.9985$$

Hence, the estimated total quality of the GADO is approximately 0.9985 for P3. The overall mean of estimated total quality for the GADO was calculated by aggregating the evaluation results from all evaluators. Since P1's total quality was 0.9977, P2's was 0.9949, P3's was 0.9985, and P4's was 0.9973, shown in Figure 6, the overall mean was 0.9971 (viz. average of P1, P2, P3, and P4). This overall mean provided a single, consolidated metric that reflected the GADO's quality as assessed by the panel of experts.

This mean value, being close to 1, indicates a high level of quality for the GADO, suggesting strong adherence to the FOCA evaluation criteria. This independent and impartial score implies that GADO is well-constructed, consistent, and accurately represents the domain knowledge, positioning it as a reliable resource in the field of gait analysis. The FOCA methodology enabled an unbiased evaluation of the GADO,

TABLE 8. Evaluators' scores for the GADO.

Evaluator Gradings	P1	P2	P3	P4
Goal 1				
Q1	100	100	75	75
Q2	100	100	100	75
Q3	100	0	100	0
Mean (CovS)	100	66.67	91.67	50
Goal 2				
Q5	100	50	100	75
Q6	100	100	100	100
Mean (CovC)	100	75	100	87.5
Goal 3				
Q7	50	75	100	50
Q8	50	100	75	100
Mean (CovR)	50	87.5	87.5	75
Goal 4				
Q9	0	100	100	100
Q10	100	100	100	100
Mean (CovCp)	50	100	100	100
Goal 5				
Q11	100	100	100	50
Q12	100	100	100	75
Q13	100	75	100	100
Mean	100	91.67	100	75

focusing on specific goals and metrics. Basically, it helped to quantify the ontology's strengths and weaknesses in a structured manner.

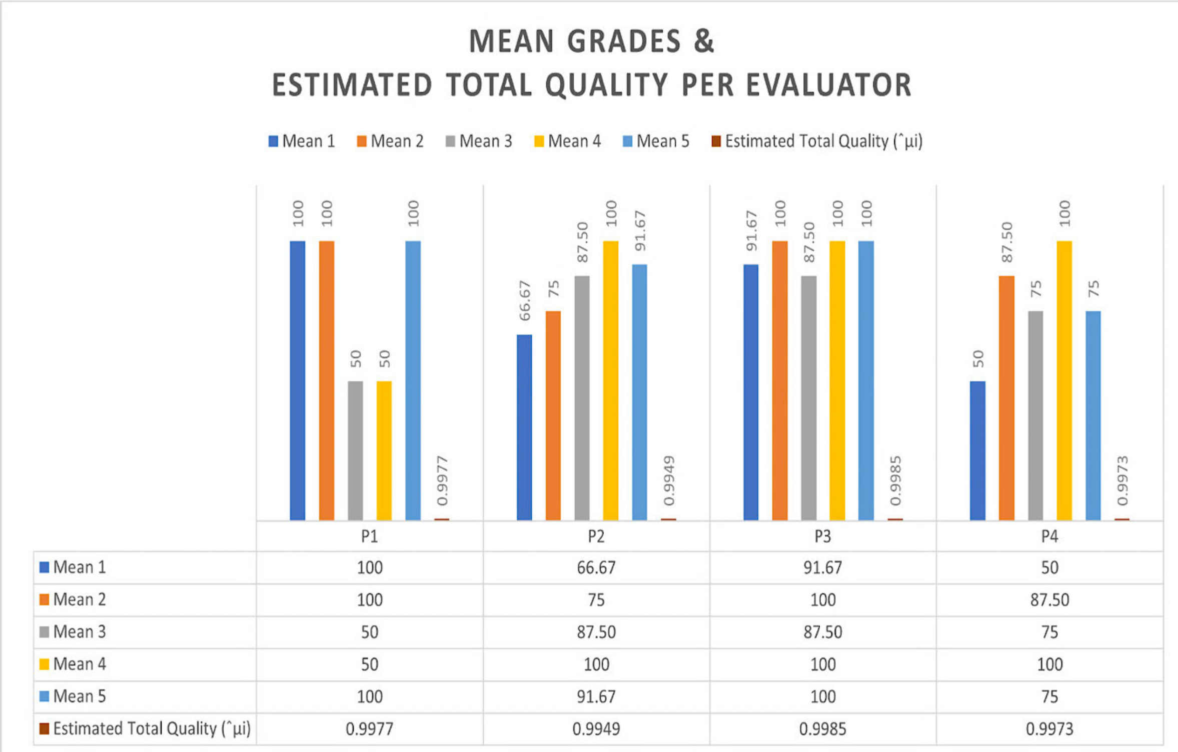
In addition to assessing the GADO using the FOCA evaluation methodology, the evaluators provided qualitative feedback on its design, documentation, and usability. The feedback was generally positive. They commended the GADO's well-structured design, clear documentation, and comprehensive coverage of the gait analysis domain. The evaluators also gave suggestions for improvement, such as the need to provide more explicit competency questions and examples and to further clarify some of the definitions in the evaluation document that was provided to them.

2) VALIDATION OF THE GADO

Ontology validation of the GADO entails ascertaining its correctness in terms of the structure and syntax of its components and its response to domain-specific queries.

a: CORRECTNESS

Ensuring the correctness of the GADO involved checking for errors in its syntax and structure. This process was carried out using the Protégé ontology editor, which incorporates tools for detecting and correcting such errors. We employed two ontology reasoners — HermiT and Pellet, to authenticate the logical consistency and error-free status of the ontology. Both HermiT and Pellet were able to successfully process the GADO, with the Pellet reasoner demonstrating significantly faster processing speeds compared to HermiT. This difference in performance is likely attributed to the Pellet reasoner's optimisations for handling large and complex ontologies. The HermiT reasoner completed the processing of the GADO in 18708 milliseconds, while the Pellet reasoner completed the task in 658 milliseconds, as shown in Figure 7, indicating a processing speed approximately 28.41 times faster. HermiT took 18050 ms (or approximately 18.05 seconds) longer than Pellet to process the GADO. In order to prove how much quicker the Pellet reasoner was compared to the HermiT reasoner, the speedup factor was calculated. The speedup factor is the ratio of the time the HermiT reasoner takes to process the ontology to the time the Pellet reasoner takes to process the same ontology.



	P1	P2	P3	P4
Mean 1	100	66.67	91.67	50
Mean 2	100	75	100	87.50
Mean 3	50	87.50	87.50	75
Mean 4	50	100	100	100
Mean 5	100	91.67	100	75
Estimated Total Quality (ˆμi)	0.9977	0.9949	0.9985	0.9973

FIGURE 6. Evaluators estimated total quality and mean grades.

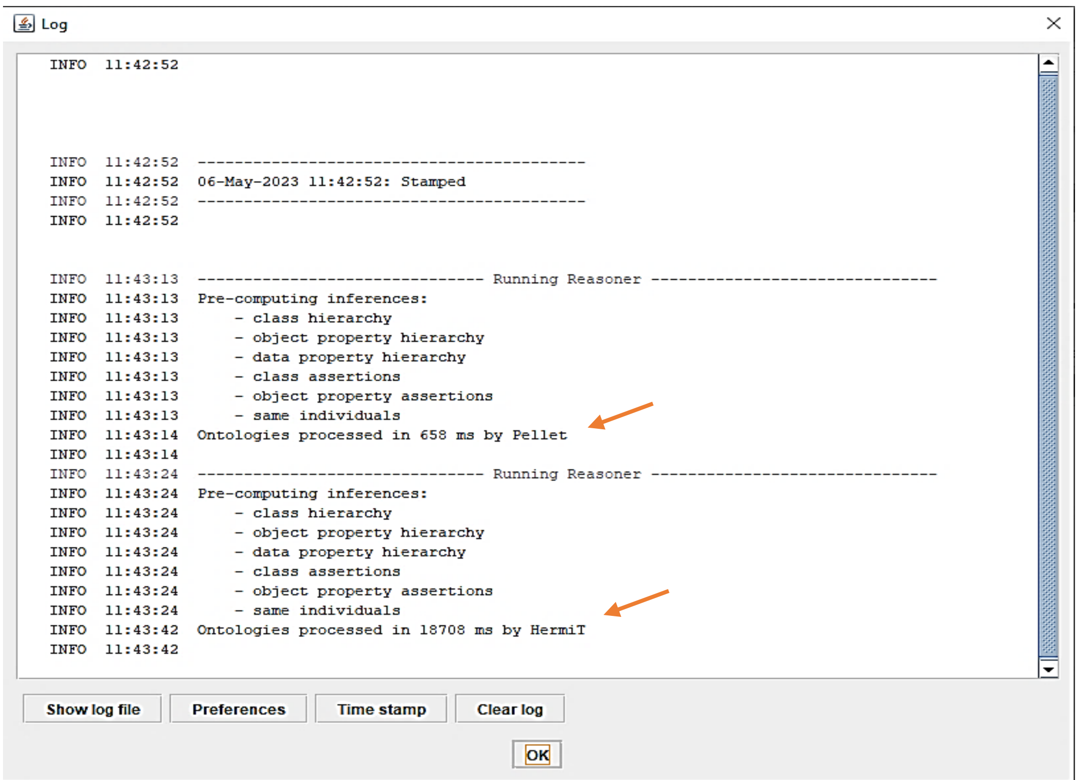


FIGURE 7. Log results of the Pellet and Hermit ontology reasoners.

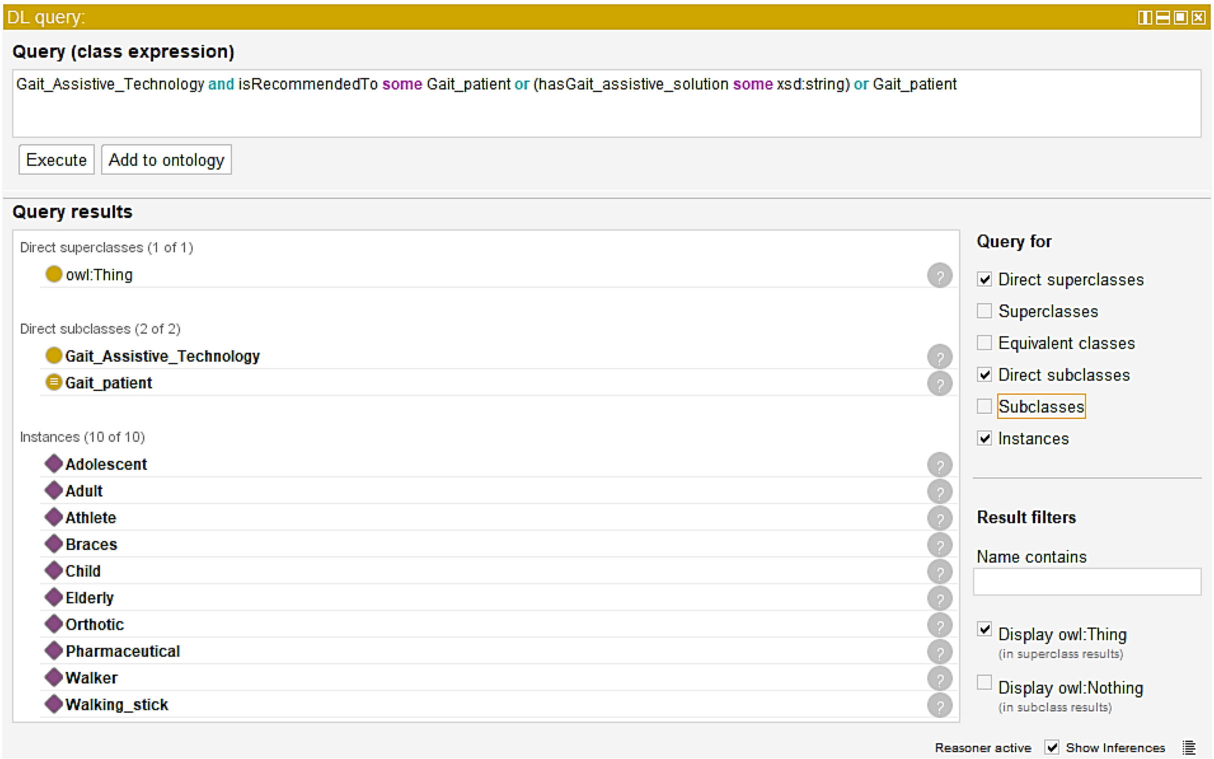


FIGURE 8. **The results of DL query.**

Speedup factor = time taken by HermiT reasoner / Time taken by Pellet reasoner

$$\text{Speedup factor} = 18708 \text{ ms}/658 \; ms$$

$$\text{Speedup factor} \approx 28.41$$

Therefore, the Pellet reasoner was approximately 28.41 times faster than the HermiT reasoner in processing the given ontology.

To calculate the difference in processing time between the two reasoners, we subtracted the time taken by Pellet from the time taken by HermiT:

$$18078 \text{ ms} - 658 \text{ ms} = 18050 \text{ ms}$$

This implies that the GADO is scalable and efficient, making it suitable for applications that require fast reasoning performance and capabilities.

b: DL AND SPARQL QUERYING

These tools were instrumental in validating the GADO's semantic accuracy and its capability to handle domain-specific queries effectively. DL queries were used to test the ontology's ability to answer domain-specific questions, and SPARQL queries were used to validate the data within the ontology. This step helped ensure that the ontology's data was consistent, precise, and aligned with real-world scenarios.

Description Logic (DL) Querying: DL queries were employed to evaluate and test the GADO by checking if the returned results corresponded to the expected outcomes. This activity helped to validate the ontology design and implementation, identify any errors and inconsistencies, and detect any potential omissions. Querying the ontology enabled us to check if it captured the required knowledge and whether it could answer the questions that needed to be answered. The following Protégé DL query was used to identify all gait assistive technologies that are recommended to at least one gait patient or have a gait patient who requires a gait assistive solution.

```
Gait_Assistive_Technology and
isRecommendedTo some Gait_patient or
(hasGait_assistive_solution some
xsd:string)or Gait_patient
```

The query utilised Description Logic expressions to define a complex class expression, effectively retrieving individual instances of 'Gait_Assistive_Technology' and 'Gait_patient' as shown in Figure 8.

SPARQL Querying: SPARQL queries were employed to validate the data within GADO, ensuring its consistency and accuracy. This process played a crucial role in maintaining the quality and reliability of the knowledge base. The queries effectively retrieved individual instances of 'Gait_patient' and 'Gait_Assistive_Technology', demonstrating the ontology's ability to represent and query knowledge accurately. Moreover, SPARQL queries enabled the researchers and evaluators to extract valuable insights from the ontology, leading to a better understanding of gait-related matters and their alignment.

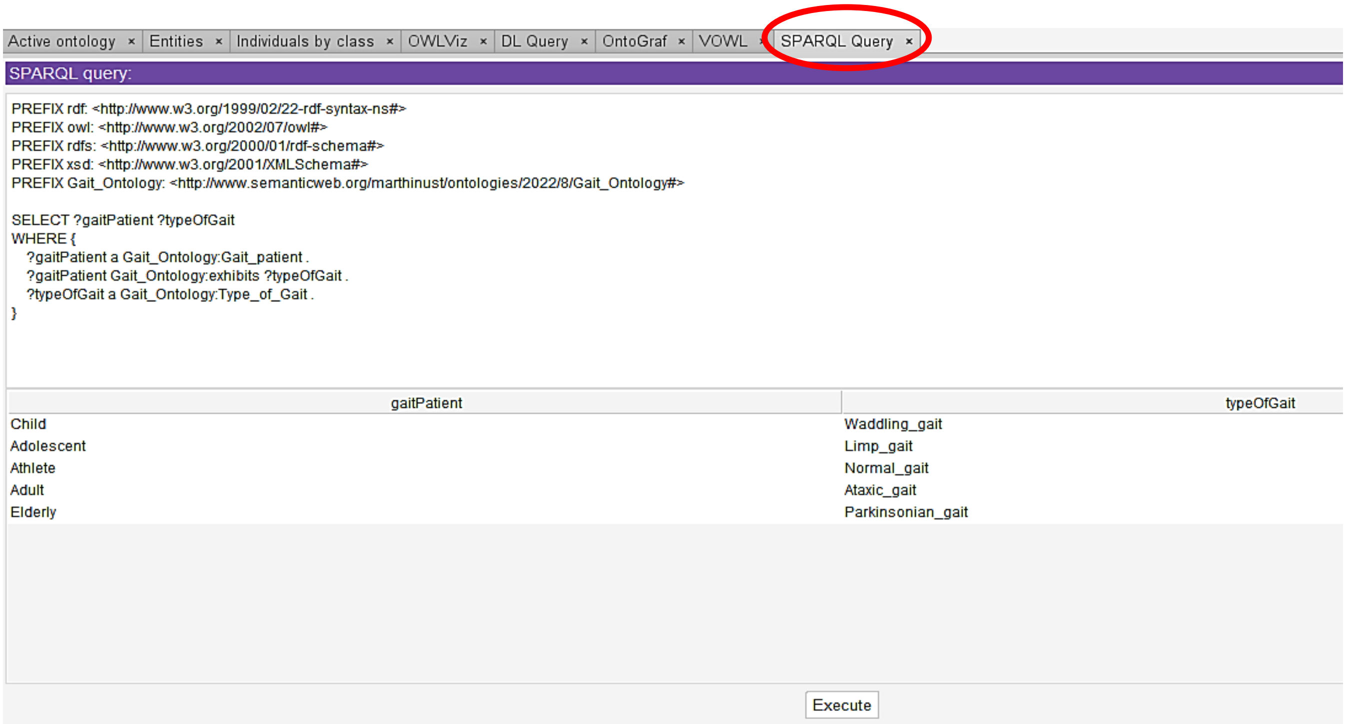


FIGURE 9. **SPARQL query for the type of gait exhibited by a gait patient.**

Two SPARQL queries were executed to illustrate the GADO's capabilities:

- Query 1: Identified gait patients and the type of gait they exhibit.
- Query 2: Retrieved gait patients and the gait assistive technologies assigned to them.

Query 1: This query retrieved all gait patients and the type of gait each patient exhibits, as shown in Figure 9.

```
SELECT ?gaitPatient ?typeOfGait
WHERE {
  ?gaitPatient a
Gait_Ontology:Gait_patient
  ?gaitPatient Gait_Ontology:exhibits
?typeOfGait
  ?typeOfGait a
Gait_Ontology:Type_of_Gait
}
```

Query 2: This query retrieved all gait patients and the specific gait assistive technologies assigned to them are shown in Figure 10.

```
SELECT ?gaitPatient
?assistiveTechnology
WHERE {
  ?gaitPatient a
Gait_Ontology:Gait_patient.
  ?gaitPatient
Gait_Ontology:isAssignedWith
?assistiveTechnology.
  ?assistiveTechnology a
Gait_Ontology:Gait_Assistive_Technology
}
```

The results of the queries showed that the GADO can correctly answer complex questions about gait patients, their type of gait exhibited, and the gait assistive technologies that are assigned to them. The fact that the GADO is able to answer a variety of domain-specific questions means that it can be used to extract valuable insights pertaining to gait analysis and gait-related diseases. These queries effectively demonstrated the ontology's ability to store, organise, and respond to complex queries related to gait analysis. Ultimately, the query results were consistent with the expected outcomes, demonstrating the validity and correctness of the ontology.

IV. DISCUSSION

Compared to existing gait analysis ontologies, the GADO[1] is unique because it is the first attempt at developing an otology dedicated to gait analysis. Although big ontologies such as Online Mendelian Inheritance in Man (OMIM) [43] and the Human Phenotype Ontology (HPO) [46] consist of concepts related to gait, such as gait abnormality and gait disturbance, these ontologies are not dedicated to gait analysis. For example, the HPO provides a standardised vocabulary of phenotypic abnormalities encountered in human disease.

[1] https://github.com/Kaapstud/gait-analysis-domain-ontology

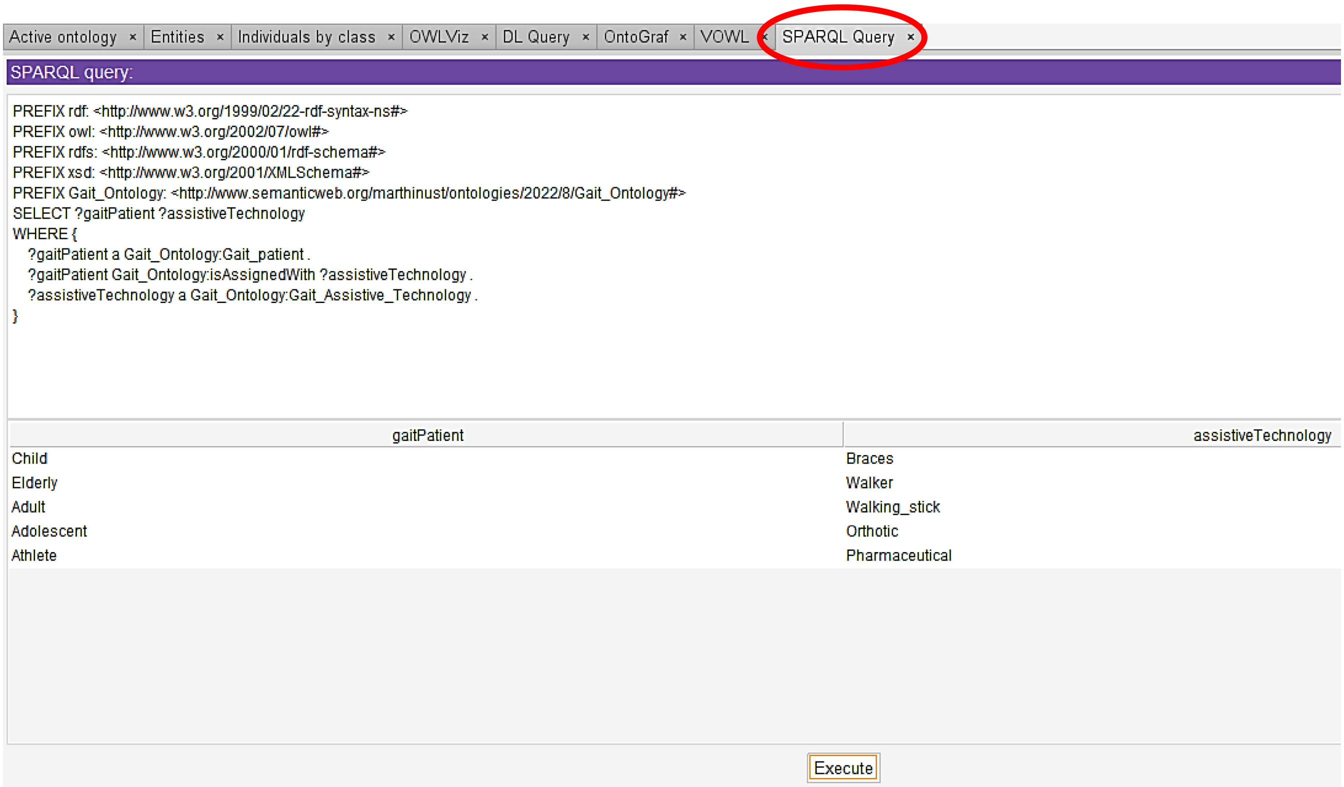


FIGURE 10. **SPARQL query listing gait patients and their assigned gait assistive technology.**

Thus, gait abnormality, which is a type of human phenotypic abnormality, is included, but other critical aspects of gait analysis were not covered. However, in the design of GADO, the classes and subclasses of the gait disturbance and gait pathology classes were based on the content of the gait abnormality class of the HPO. Emulating the concepts and relationships already defined in an established ontology like the HPO helped to ensure GADO's adequate coverage and completeness of knowledge representation in these two areas. In all, the GADO comprises 13 dimensions of knowledge representation about gait analysis covering 5 diverse aspects of gait analysis, which are process (gait-based process, gait cycle, gait analysis method), technology (gait assistive technology, gait analysis equipment), categorisation (gait classification, type of gait), measurement (gait measurement point, gait parameters), disease (gait-related disease, gait disturbance, gait pathology, gait person). Currently, no gait ontology has the level of coverage and diversity of the GADO.

The comprehensive knowledge representation afforded by the GADO makes it a suitable knowledge infrastructure to provide decision support for gait analysis and gait-related diseases. The semantic relationships that exist among concepts defined in the GADO are based on established knowledge as contained in standard textbooks, existing ontologies, and publications in academic databases (e.g., PubMed), which makes it suitable as a shared vocabulary on subjects/topics pertaining to gait analysis and gait-related diseases. Being an ontology means the GADO can be referenced by web and mobile applications that are aware of its existence to support computational operations such as semantic analysis of textual data, intelligent reasoning, information search and retrieval, and intelligent recommendation by querying its content.

A. LIMITATIONS OF THE STUDY

A limitation of our current implementation of the GADO is the lack of support for multilingual support as knowledge is only represented in the English language. Another limitation is the need to incorporate more domain expert knowledge in the creation of the GADO, particularly in areas such as gait rehabilitation and gait-oriented physiotherapy, where there is a shortage of experts in many developing countries of the world.

V. CONCLUSION AND FUTURE WORK

In this paper, we have presented the design and development of the gait analysis domain ontology (GADO). The aim is to provide a comprehensive domain ontology that can support decision-making on gait analysis and the treatment of gait-related diseases. The GADO is a structured representation of knowledge pertaining to gait analysis and gait-related diseases, enabling researchers, gait experts, and patients to understand better and manage gait-related diseases. We adopted a hybrid ontology development process that is derived from Ontology Development 101 (OD-101) and Methonthology, which involved a thorough domain analysis, ontology design, ontology development, and ontology evaluation. We also performed a rigorous evaluation of the GADO to assess its correctness, content richness, and domain task fit using ontology validation and ontology verification procedures.

This paper makes a significant contribution to the field of gait analysis and ontology development because i) it demonstrates the development of a dedicated domain ontology to support gait analysis covering thirteen dimensions (aspects), which is the most extensive compared to previous efforts; ii) it provides a deeper understanding of state-of-the-art methods in ontology development, and evaluation thereby advancing knowledge of ontology engineering; and iii) it reveals the critical requirements for effective decision-support for gait analysis and gait-related diseases.

Practically, the ontology constitutes an artefact that can enable intelligent reasoning and semantic capabilities for mobile apps and the computer algorithms that provide dynamic decision support for treating and managing gait-related conditions, ultimately contributing to improved patient well-being.

In future work, we will focus on expanding the scope of the GADO to include additional aspects of gait analysis, such as gait rehabilitation, gait-oriented physiotherapy, and gait analysis in sports. This endeavour will strengthen the capacity to support more clinical procedures and increase its relevance in a wider range of settings. In addition, actively engaging patients, caregivers, and healthcare professionals in the ontology development process will ensure a holistic and user-centric perspective. Their insights and experiences will be invaluable in refining the GADO to better address the specific needs and concerns of all stakeholders.

Furthermore, we will develop mobile applications and tools that leverage the GADO to support patient monitoring, treatment plan adherence, and decision-making by gait experts and medical personnel who care for patients with gait-related diseases.

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TERRANCE MARTHINUS received the B.Tech. degree from the IT Department, Cape Peninsula University of Technology (CPUT), where he is currently pursuing the master's degree, and brings more than 15 years of IT staff experience. His previous contribution to the field is his paper titled "On Domain Ontology for Decision Support in the Treatment of Gait-Related Diseases," which was published by IEEE at the 2021 21st International Conference on Computational Science and Its Applications (ICCSA). The paper introduces an ontology designed to offer decision support for treating gait-related diseases, employing a formal representation of domain knowledge. His research interests revolve around ontology engineering and knowledge-based systems, with a particular focus on gait-related diseases.

OLAWANDE DARAMOLA (Member, IEEE) is currently a Research Professor with the Department of Informatics, University of Pretoria, South Africa. He is the author of more than 100 journals, book chapters, and peer-reviewed conference papers in *Artificial Intelligence* (AI) and *Software Engineering*. His research interests include machine learning, knowledge-based systems, ontologies, big data analytics, and requirements engineering. He serves on the program committee of several international computing conferences. He is a Reviewer for several top computing journals that IEEE, Springer, and Elsevier publish.