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LONG PAPER

Virtual user models for the elderly and disabled for automatic simulated accessibility and ergonomy evaluation of designs

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Abstract This paper presents a framework for automatic simulated accessibility and ergonomy testing of virtual prototypes of products using virtual user models. The proposed virtual user modeling framework describes virtual humans focusing on the elderly and people with disabilities. Geometric, kinematic, physical, behavioral and cognitive aspects of the user affected by possible disabilities are examined, in order to create virtual user models able to represent people with various functional limitations. Hierarchical task and interaction models are introduced, in order to describe the user's capabilities at multiple levels of abstraction. The use of alternative ways of a user task's execution, exploiting different modalities and assistive devices, is supported by the proposed task analysis. Experimental results on the accessibility and ergonomy evaluation of different workplace designs for the use of a telephone and a stapler show how the proposed framework can be put into practice and demonstrate its significant potential.

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1 Introduction

Disability is part of the human condition. Almost everyone will be temporarily or permanently impaired at some point in life. Moreover, aging is strongly connected with difficulties in functioning. People with disabilities often face discrimination in and infringement of their rights on a daily basis. Inaccessible products and services create major barriers to participation and inclusion. Disabling barriers in various domains, such as workplace, transportation, living spaces, infotainment and health, contribute to poorer health outcomes, lower educational achievement, less economic participation, higher rates of poverty, increased dependency and restricted participation. Over the last years, special emphasis is given to the importance of an open and accessible to all society and the identification and removal of accessibility barriers. Within the European Community, disability is addressed as a human rights issue and as a matter of law.

Even though some environments, products and services are accessible to the majority of the population, including the elderly and disabled, ergonomy is another factor of great importance that has to be taken into account by the designers. When a product/service is accessible but not ergonomic, although it can potentially be used, the person using the specific product/service faces difficulties in usage, including great effort, pain, etc. Health problems may arise due to low ergonomy. Repetitive and forceful movements and vibrations that may occur when operating various devices can lead to various pathologies, mainly in the vascular, nervous and even cardiovascular system. Employees with or without disabilities often face stress and strain due to the poor design of the workplace. This may lead to physical and mental fatigue, as well as to reduction in motivation. Poor ergonomics are strongly related with reduced product quality. It has also been cited as the reason for failure in many ICT projects.

When people's needs and capabilities are considered during the design, implementation and operation of products and services, there are many benefits, including ease of use, ease of learning, satisfaction, trust and loyalty, safety and health, productivity and work quality, satisfaction and commitment. Moreover, accidents, injuries and illness, development costs, as well as need for redesign and recall, are significantly reduced. It can be considered that good ergonomics is good economics. On the other hand, when human aspects are not considered, this often leads to the development of inaccessible and non-ergonomic products and services. The lack of accessibility and ergonomy puts great barriers in the daily life of people with disabilities and even excludes them from many activities.

The incorporation of virtual humans with realistic interaction properties in the design of products and services can play a very crucial role in terms of their accessibility and ergonomy. Digital human modeling (DHM) and simulation have gained importance in the past few years and allow designers easily observe and evaluate the interaction of the designed product with a virtual user having specific needs and/or preferences. Simulation can be used to study and compare alternative designs or to troubleshoot existing systems. It offers to designers the opportunity to explore how a new system might behave before the real prototype is developed, or how an existing system might perform if altered, thus reducing development time and costs. But even if many remarkable researches in this direction can be found in the literature, to the authors' knowledge, a holistic framework including a formal definition of virtual users with disabilities, a detailed description of user tasks taking into account alternative modalities and the use of assistive devices, as well as a set of accessibility and ergonomy metrics, to be used in different simulation frameworks, has not yet been proposed.

The present paper introduces a framework for automatic simulated accessibility and ergonomy evaluation of virtual prototypes using virtual user models able to describe efficiently the interaction of virtual older and disabled users with the virtual prototype within a virtual environment. A set of accessibility and ergonomy metrics are also proposed. Experimental results on the accessibility and ergonomy evaluation of different workplace designs for the use of a telephone and a stapler show how the proposed framework can be put into practice and demonstrate its significant potential.

2 Related work

Toward the development of virtual humans, in recent years researchers have made significant progress by focusing their attention on biomechanically modeling various body parts, including the face [19], the neck [25], the torso [9], the hand [45] and the leg [22]. Surveys on behavioral modeling of virtual humans have also been conducted [49].

Algorithms for dynamical animation of digital humans have also been presented in the literature. Hodgins et al. [18] presented a set of motion algorithms allowing a rigid body to stand, run, turn at various speeds, ride a bicycle and perform vaulting. Other studies investigated different types of jumps, such as squat vertical jumping and countermovement jumping with and without arm swing [7]. Wooten [48] conducted research on improving methods for controlling dynamically simulated human figures. Parameterized basic controllers were developed, so that each controller could produce a variety of behaviors including leaping, tumbling, landing and balancing.

The simulation of virtual humans can be a powerful approach to support engineers in the product development process. Recently, research interest in using digital human modeling for ergonomics purposes has increased significantly [23]. Virtual human modeling reduces the need for the production of real prototypes and can even make it obsolete [6]. Lamkull et al. [24] performed a comparative analysis on digital human modeling simulation results and their outcomes in the real world. The results of this study show that ergonomic digital human modeling tools are useful for providing designs of standing and unconstrained working postures.

Additionally, the use of virtual humans and simulation in the automotive industry has shown great potential. Porter et al. [36] present a summary of applications of digital human models in vehicle ergonomics during the early years of personal computers, at which time few of the current commercial DHM software tools were available.

Existing available tools and frameworks provide designers with the means for creating virtual humans with different capabilities and use them for simulation purposes. DANCE [39], for instance, is an open framework for computer animation research focusing on the development of simulations and dynamic controllers, unlike many other animation systems, which are oriented toward geometric modeling and kinematic animation. SimTk's OpenSim [41] is also a freely available, user-extensible software system that lets users develop models of musculoskeletal structures and create dynamic simulations of movement.

One tool using virtual environments for ergonomic analysis is the VR ANTHROPOS [1], which simulates the human body in the virtual environment realistically and in real time. There are also many tools such as JACK [35], RAMSIS [31], SAMMIE [37], HADRIAN [30], SIMTER [27], Safework [11] and Santos™ [47], offering considerable benefits to designers who apply design for all approaches, as they allow the evaluation of a virtual prototype using virtual users with specific abilities. A list of software tools for ergonomics analysis is reported in [10]. RAMSIS and JACK are the most popular accessibility design software packages, focusing on automotive industry. Both RAMSIS and JACK have anthropometric data sets based on measurements taken from the healthy and the able-bodied groups.

The present paper contributes a holistic framework for automatic simulated accessibility and ergonomy evaluation of virtual prototypes, based on virtual user models that can sufficiently describe the elderly and people with various types of disabilities based on a hierarchical analysis of user tasks. A set of innovative accessibility and ergonomy metrics are also proposed.

3 Proposed framework

In order to support the automatic accessibility and ergonomy assessment of virtual prototypes, it is essential to describe all interaction components in an accurate and formal way. The tasks of the user, including alternative ways of execution through different modalities and assistive devices, as well as the simulation scenario to be executed, have to be defined at a high level of detail. The capabilities, possible functional limitations as well as some other characteristics of the virtual user, such as anthropometrics, that play a crucial role in the evaluation of the accessibility and the ergonomy of a design have also to be described accurately. Finally, the accessibility and ergonomy metrics that will be used for the evaluation of a virtual prototype have to be defined.

The proposed framework is based on the following six major building blocks:

(i) *Abstract User Models*: The Abstract User Models refer to a high-level description of potential user models. They are developed with respect to several specific disabilities and are broken down according to the disability category, that is, cognitive user models, physical user models and behavioral and psychological user models. An Abstract User Model includes several disability-related parameters like disability description, disability metrics and ICF functional abilities.

(ii) *Generic Virtual User Models*: A Generic Virtual User Model (GVUM) describes a set of users having a specific set of disabilities. In a Generic Virtual User Model the description is also augmented with actions (primitive tasks) that are affected by the specific set of disabilities. For instance, for users with hemiplegia actions that are affected by the disability could include gait, grasping, etc.

(iii) *Instance of a Generic Virtual User Model*: An instance of a Generic Virtual User Model describes an instance of a virtual user (e.g., Persona). All the disabilities of the user are included in the instance of a GVUM as well as the affected actions (primitive tasks). Several disability-related parameters are also included describing the severity of the disorder. For instance, the value of the gait cycle for a specific virtual user who suffers from spinal cord injuries is 2.1 s, etc.

(iv) *Primitive Tasks*: The primitive tasks define the *primitive human actions* and are related to the disability category.

(v) *Task Models*: The actions that are being systematically performed in the context of the virtual prototype to be tested are described within the task model. These tasks are developed using a hierarchical approach. Thus, high-level tasks are related to more complex abstract actions, for example, driving, and are broken down into simpler tasks, for example, steering, and primitive tasks, for example, grasping.

(vi) *Simulation Models*: A Simulation Model describes the simulation scenario to be followed during the simulation process. A Simulation Model may contain complex or primitive tasks.

The primitive tasks are the basis of the proposed framework, as they are the only common reference between the virtual user models, the task models and the simulation models. The “divide and conquer” approach for task analysis followed by the proposed framework, which allows the analysis of each complex task into primitives, offers great advantages for the entire simulation process. First of all, within a simulation framework that will be developed according to the proposed framework, only the primitive tasks have to be implemented biomechanically. Any possible combination of primitive tasks (constituting a complex task) is then supported without the need of extra implementation effort. Additionally, any possible simulation scenario could be supported for a virtual prototype by simply developing a new simulation model. As previously mentioned, a simulation model contains primitive tasks or complex tasks, which are analyzed into primitives following the task model hierarchy.

Figure 1 illustrates an outline of the proposed virtual user modeling framework and summarizes its most significant properties, while detailed analysis is provided in the following sections.

Figure 1 illustrates an outline of the proposed framework. The development of the user models can be performed in seven distinct but interrelated steps:

1. The Abstract User Models are initially formed by examining the current state of the art, existing standards and guidelines related to several disabilities. Moreover, this information is augmented utilizing the WHO ICF functional abilities framework.
2. The Task Models are developed reflecting the actions that are systematically performed by the users in the context of the virtual prototype to be tested. They follow a hierarchical structure from high-level tasks to low-level primitive tasks. It is very important to have a limited but sufficient number of primitive tasks, since they will be related to disabilities. For the development of the Task Models, alternative ways of tasks execution are considered, including different modalities and the possible use of assistive devices. The Task Models are used by the simulation platform in conjunction with the Simulation Models, which describe the simulation scenario to be followed during the simulation process with regard to the accessibility and ergonomy assessment of the virtual prototype for a specific virtual user.
3. The Generic Virtual User Models refer to a specific category of virtual users and can be comprised from one or more Abstract User Models, for example, a Generic Virtual User Model can include the propanopia and hemiplegia disabilities. They also include a description for how specific disabilities affect the execution of specific tasks (primitive or not) that are described in the task models.
4. Finally, an instance of a Generic Virtual User Model (virtual user, Persona) describes a specific virtual user with specific disability-related parameters.

Special attention should also be paid to the development of the virtual prototype to be tested. The virtual prototype has to be accurately defined as a virtual replica of the real prototype and to be functioning similarly to the real one.

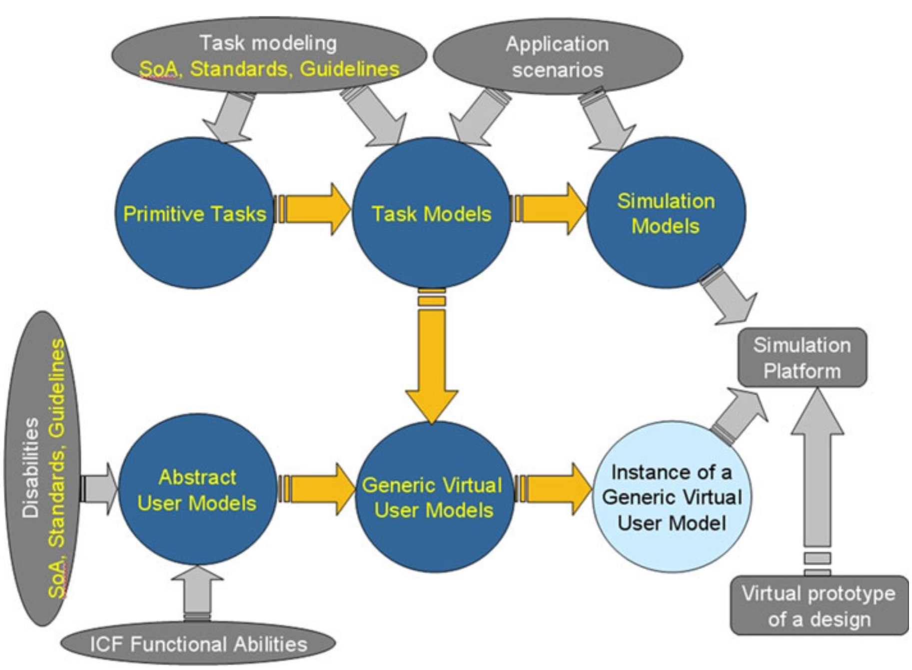
As it can be assumed by the above description, the proposed framework follows a top-down approach, where initially at the top level, the Abstract User Models refer to descriptions of specific disabilities. In the mid-level of the hierarchy, the Generic Virtual User Models refer to descriptions of specific classes of disabled users exhibiting the same kind of disability. At this point, the user models are also related to the Task Models that refer to actions performed in selected application scenarios. At the bottom level of the hierarchy, the instances of the GVUMs are generated for a specific scenario and for specific accessibility evaluation needs and requirements. In the following paragraphs all the proposed models are described, along with simple indicative examples.

3.1 Primitive tasks

3.1.1 Objective

The primitive tasks define *primitive human actions* and are related to the disability category. The number of primitive tasks should be limited, but also sufficient in order to efficiently model all systematically performed actions in the target application scenarios. The degree of primitiveness that will be adopted may vary and depends on the

Fig. 1 Architecture of the proposed framework



specific needs of each system that will be based on the proposed methodology.

3.1.2 Implementation

Concerning the implementation, each primitive task should contain a name as well as the category in which it belongs to. The list of primitive tasks may include tasks of different categories, such as motor, cognitive, perceptual, visual, hearing and speech. The following table (Table 1) lists some indicative primitive tasks.

3.2 Task models

3.2.1 Objective

Task models [20] describe the interaction between the virtual user and the virtual prototype. User tasks are divided into two categories: (a) primitive (e.g., grasp, pull, walk, etc.) and (b) complex (e.g., driving, telephone use, computer use, etc.). For each complex task, a Task Model is developed, in order to specify how the complex task can be analyzed into primitive tasks (as they have been defined by the designers/developers, according to the functionality of the prototypes to be tested in terms of accessibility). The Task Models are based on existing relevant stat of the art, standards and guidelines, but also on domain knowledge with respect to the target application scenarios.

Table 2 presents the task analysis for the complex task "close car door while seated." This complex task is analyzed in four primitive tasks that have to be executed sequentially.

3.2.2 Implementation

For the implementation of the Task Models, the taskModel element of UsiXML [26] language has been chosen, as it can describe the tasks of the user, much more accurately compared to other task modeling languages [15, 16] like GOMS, GTA and TOOD. Figure 2 presents a schematic description of the complex task described in Table 2, and the corresponding UsiXML source code is presented in Table 3.

Table 1 Primitive tasks: example

Primitive task's category	Primitive task
Motor	Push
Motor	Grasp
Motor	Pull
Motor	Walk
Motor	Sit
Cognitive	Select
Cognitive	Read

Table 2 Task model example: close car door while seated

Complex task	Primitive task	Body part	Object
Close car door while seated	Reach	Arm	Door
	Grasp	Hand	Interior door handle
	Pull	Hand	Interior door handle
	Push	Hand	Lock button

3.3 Abstract User Model

3.3.1 Objective

The Abstract User Models refer to a high-level description of potential user models. They are developed with respect to several specific disabilities and are broken down according to the disability category, that is, cognitive user models, physical user models and behavioral and psychological user models. An Abstract User Model includes several disability-related parameters like disability description, disability metrics and ICF functional abilities.

The Abstract User Models are initially formed by examining the current state of the art, existing standards and guidelines related to several disabilities. In particular, the definition of the Abstract User Models is based on the analysis of existing physical, cognitive and behavioral/psychological models of users with disabilities in the state of the art. Accessibility guidelines, methodologies and existing practices such as Human Factors (HF), Guidelines for ICT products and services, and "Design for All" methodologies are also analyzed for the definition of the Abstract User Models. Table 4 presents an example of an Abstract User Model.

3.3.2 Implementation

Ontologies are used to provide a powerful interoperable and extensible description of the Abstract User Models. An Abstract User Model stored in the ontology includes the type of user disability, user capabilities according to the ICF functional abilities framework, user needs, characteristics from cognitive user models, physical user models, behavioral and psychological user models, guidelines and standards.

The use of ontologies for specification purposes has significant advantages. The ontology can provide a common basis for communication and collaboration between heterogeneous artefacts and intelligent environments. It can

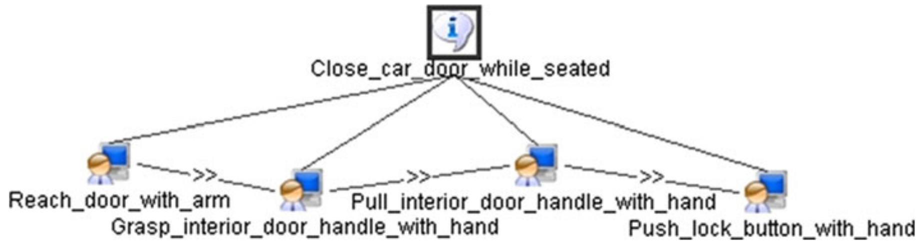


Fig. 2 Task Model example—the *root node* represents a complex task, while the *leaf nodes* represent primitive tasks. The *arrows* between the primitive tasks define that the primitive tasks should be executed sequentially

Table 3 Task model example (UsiXML source code): close car door while seated

```xml
<?xml version="1.0" encoding="UTF-8"?>
<taskmodel>
  <task id="st0task0" name="Close_car_door_while_seated" type="abstraction">
    <task id="st0task1" name="Reach_door_with_arm" type="interaction"/>
    <task id="st0task2" name="Grasp_interior_door_handle_with_hand" type="interaction"/>
    <task id="st0task3" name="Pull_interior_door_handle_with_hand" type="interaction"/>
    <task id="st0task4" name="Push_lock_button_with_hand" type="interaction"/>
  </task>
  <enabling>
       <source sourceId="st0task1"/>
       <target targetId="st0task2"/>
  </enabling>
  <enabling>
       <source sourceId="st0task2"/>
       <target targetId="st0task3"/>
  </enabling>
  <enabling>
       <source sourceId="st0task3"/>
       <target targetId="st0task4"/>
  </enabling>
</taskmodel>
```

also describe the basic conceptual terms, the semantics of these terms, and define the relationships among them. A fully semantic description of the Abstract User Models will allow the use of inference engines in the simulation environment. The use of ontologies to describe user models and their interrelationship will also ensure the openness and the accuracy of the models specified. In case that new Abstract User Models should be added, designers can take profit of existing Abstract User Models inheriting the properties of similar ones.

3.4 Generic Virtual User Model

3.4.1 Objective

A Generic Virtual User Model refers to a class of virtual users exhibiting one or more specific disabilities. The Generic Virtual User Models describes the tasks affected by the specific disabilities and their associated disability-related parameters. Table 5 presents an indicative example reflecting the main concept of a GVUM. As depicted in the example of Table 5, gait velocity ranges from 0.18 to 1.03 m/s and that is because the GVUM refers to a population group, not to an individual user.

In the following paragraphs the parameters of a GVUM are analyzed in detail.

The proposed GVUM aims to efficiently describe elderly and disabled people, in order to be used in various simulation frameworks performing accessibility and ergonomy assessment of virtual prototypes. Funge et al. [13] propose an abstract modeling hierarchy for the proper development of virtual humans, containing five layers: a) geometric, b) kinematic, c) physical, d) behavioral and e) cognitive, as depicted in Fig. 3. Geometric modeling represents virtual users as mannequins, with articulated body geometry, texture mapping and animation. The kinematic layer contains the representation of the virtual human using a set of rigid bodies hierarchically organized and connected by joints and defines user's motion without regard to the forces that cause the motion. Physical modeling takes into

Table 4 Abstract User Models: example

Disability category	Disability	Short description	Quantitative disability metrics	Functional limitations (*ICF Classification*)	Age-related
Motor	Spinal cord injuries (thoracic injuries)	Spinal cord injuries cause myelopathy or damage to nerve roots or myelinated fiber tracts that carry signals to and from the brain. The nerves that control a man's ability to have a reflex erection are located in the sacral nerves (S2–S4) of the spinal cord and could be affected after a spinal cord injury	*1. Gait parameters*: Weight shift: inability to effectively transfer weight between legs Step width: decreased step width Step height: decreased step height Step length: decreased step length Step rhythm: abnormal step rhythm Excessive plantar flexion during swing phase Delayed heel rise achieved less peak knee flexion in swing *2. Temporal gait variables*: Gait Cycle (s): 2.17 (1.05) Cadence (steps/min): 65.0 (23.1) Double support (%): 42.8 (10.2) Stride (m): 0.48 (0.13) Velocity ((m/s)/height): 0.27 (0.13) *3. Kinematic variables*: Hip excursion (°): 39.3 (9.0) Knee excursion (°): 38.1 (13.2) Ankle excursion (°): 25.0 (4.9) Hip velocity (°/s): 38.2 (17.5) Knee velocity (flexion) (°/s): 64.1 (41.8) Knee velocity (extension) (°/s): 83.8 (54.2) Ankle velocity (°/s): 48.1 (30.8)	S120: spinal cord and related structures, S1200: structure of spinal cord, S12000: cervical spinal cord, s12001: thoracic spinal cord, s12002: lumbosacral spinal cord, s12008: structure of spinal cord, other specified, s12009: structure of spinal cord unspecified, s1208: spinal cord and related structures, other specified, s1209: spinal cord and related structures, unspecified	Could be

Table 5 Generic Virtual User Models: example

Disability category	Disability	Affected primitive tasks	Affected primitive tasks' parameters
Motor	Hemiplegia	Grasp	The user is able to grasp objects, with size $\leq$ 3 cm $\times$ 3 cm $\times$ 3 cm
		Pull	The user can pull an object with max_Force: 5 N
		Walk	Gait velocity ranges from 0.18 to 1.03 m/s
			Abnormal step rhythm

account forces applied internally/externally to the virtual human when interacting with an environment. Variables like friction and collision with virtual objects are also considered. Behavioral modeling aims to model user's behavior when interacting with an environment. Cognitive modeling defines the user's ability to perceive and understand the environment.

In order to develop a GVUM for the objectives stated above, it is essential, first of all, to identify the human characteristics affected by various disabilities and then analyze how they could be simulated for accessibility and ergonomics purposes. The geometric, kinematic, physical, behavioral and cognitive parameters of the proposed GVUM are presented in the following paragraphs.

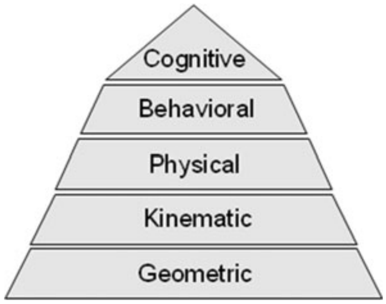


Fig. 3 The proposed GVUM in the context of the modeling hierarchy proposed by Funge et al. [13]

3.4.2 Structure

Geometric parameters

Anthropometric parameters

Anthropometry plays a crucial role in the design of accessible and ergonomic products and services. People with motor disabilities exhibit anthropometric variability, as disabilities often affect the anthropometric parameters of the person. In [28] the progression of ankylosing spondylitis (AS) is evaluated as a function of disease duration and exercise frequency in a group of patients who were observed and followed up for 6 years. The results revealed significant differences in the anthropometric measurements through the passing of the years.

Bradtmiller [4] points out that even if there are many studies on basic anthropometry of people with disabilities and of the elderly, most of them have relatively small sample sizes and refer to specific target groups (e.g., the US population) or focus on specific applications (e.g., seating). He also remarks that the plentiful anthropometric data available for the non-disabled population should not be used for design tasks where the intended user population has a variety of disabilities. Thus, since it would not be feasible to produce a generic anthropometric model describing people with disabilities, the proposed GVUM includes a set of configurable anthropometric parameters able to describe various disabled populations.

In the proposed GVUM, anthropometric parameters have been divided into three categories, according to the referred human body part: a) general, b) upper limb parameters and c) lower limb parameters. In the general anthropometric parameters set, the weight, stature, head length, head breadth, sitting height, bideltoid breadth and waist circumference are included. The set of the upper limb anthropometric parameters includes shoulder–elbow length, forearm–hand length, relaxed biceps circumference and flexed forearm circumference. Finally, the set of the anthropometric parameters concerning the lower limbs contains parameters such as ankle height, hip breadth, knee sitting height, buttock–knee length, foot length, foot breadth, thigh circumference and calf circumference.

3D representation

The proposed GVUM does not include the direct description of the 3D representation of the virtual human (using, for instance, the H-Anim specification), as the included anthropometric parameters stated above contain sufficient information concerning the 3D representation. It has to be mentioned that an avatar structured by articulated rigid bodies is supposed to be used for the 3D representation of the proposed GVUM.

Kinematic parameters

The detailed description of the kinematic parameters of the virtual user is within the scope of the proposed GVUM, as they are strictly correlated with motor disabilities. At the kinematic layer, the virtual user is modeled using a set of rigid bodies hierarchically organized and connected by joints.

Generic joint

Movable human joints are divided into four main categories, according to their degrees of freedom (DOF) [29]:

- *uniaxial*, having a single rotational DOF. When the motion axis is orthogonal to the bones, the joint is called *hinge*. The interphalangeal joints are typical examples of hinge joints. In case where the axis is parallel to the bones, the joint is called *pivot*. A typical example of a pivot joint is the proximal radioulnar joint.
- *bixial*, having 2 rotational DOFs. Typical examples include the knee and wrist joints.
- *poliaxial*, typically having 3 rotational DOF, such as the shoulder and hip joints.
- *plane* joints, having 6 DOF, such as the tibia and fibula.

Bones representation using rigid bodies

For the representation of the bones in the proposed GVUM, rigid bodies are used. A rigid body is similar to a system of particles in the sense that it is composed of particles. The main difference is that the relative positions among the particles composing a rigid body do not change. In the proposed GVUM the bones follow a hierarchical tree model. Each bone has one parent bone and various (or none) children bones.

As a joint connects two or more bones, the rotation of a joint results in the translation of the corresponding bones. The position of a rigid body is represented by the linear position, namely the position of one of its particles, specifically chosen as a reference point (typically coinciding with the center of mass), together with the angular position of the rigid body.

Range of motion (ROM)

One very common symptom of many disabilities, mainly motor, is the limited range of motion in various joints, resulting in accessibility and ergonomic problems that often are great barriers in a person's life. Ballinger et al. [2] aim to determine whether shoulder pain and the decreased range of motion, which are common problems of people with chronic spinal cord injury, can be predicted by demographic, injury-related, body weight and radiographic data over 3 years, as well as to determine the relationships among these shoulder problems and functional limitations, disability and perceived health. In this survey, it is reported that shoulder ROM problems were more common among men who were older, had acromioclavicular (AC) joint narrowing, had lower functional independence measure (FIM) scores and reported poorer health. Smith et al. [42] presented a detailed set of measurements and capabilities of the older adult regarding the range of motion that can be used in the design of accessible and ergonomic products and services.

The proposed GVUM describes the ROM of many joints referring to different human parts, as depicted in Fig. 4. Each rectangle on the shape represents a human part having its own properties. The proposed structure is a hierarchical one, where there are some basic containers, such as the containers for the upper and lower limbs, and each of them has its own children, representing the sub-parts of the human body. This hierarchical structure enables the easy

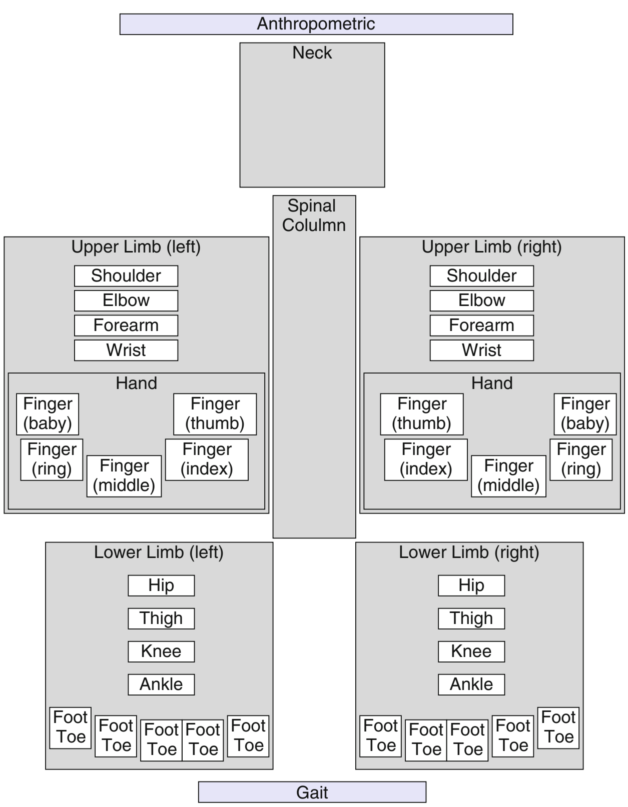


Fig. 4 Proposed GVUM structure—supported human parts

representation of the proposed GVUM using an XML or an ontology schema.

The kinematic parameters described within the proposed virtual user model concern the entire human body, including the upper and lower limbs, the neck as well as the torso.

The kinematic parameters concerning the upper limbs include shoulder flexion/extension abduction/adduction and internal/external rotation, elbow flexion/hyperextension, forearm pronation/supination, wrist flexion/extension and radial/ulnar deviation, hand pronation/supination and flexion/extension of each finger.

The kinematic parameters concerning the lower limbs include hip flexion/extension, abduction/adduction and internal/external rotation, thigh flexion/extension, knee flexion/extension, ankle dorsi/plantar flexion and eversion/inversion as well as flexion/extension of each toe.

There is also a set of neck parameters, including flexion/extension, left/right lateral flexion and left/right lateral rotation, as well as a set of parameters for the spinal column, including flexion/extension, left/right lateral flexion and left/right lateral rotation.

Physical parameters

The amount of force needed to be applied for a task's successful completion, when a user interacts with a product, is a crucial factor to be considered during the development of accessible and ergonomic products. Fransen et al. [12] compared mean isometric muscle strength data collected for 113 patients with knee osteoarthritis with published normative data for 131 asymptomatic subjects. The comparison showed that there is a decrease in knee extensor as well as in knee flexor force in patients with knee osteoarthritis compared with their age- and sex-matched asymptomatic peers. An analysis of force distribution in the hand during maximum isometric grasping actions and a comparison of grip strength between normal, leprotic and paralytic subjects is presented in [38]. In the case of subjects with leprosy, the grip strength decreased with the severity of the disease and was only about 50 percent of the normal subjects, while in hemiplegics the grip strength was only about one-eighth of the normal values.

The proposed GVUM includes force limits concerning both the upper and lower limbs.

Visual parameters

Visual functions deteriorate with age. Moreover, many surveys showed that cataracts at any stage of development may affect contrast sensitivity and glare disability [43]. Scotoma is another common type of vision loss that is often appeared in conjunction with other visual deficiencies, like glaucoma or cataract. Some visual disabilities, like glaucoma, are also correlated with scotomas. Functional defect progression of glaucoma is most commonly seen as a deepening of a scotoma, followed by defect enlargement, and less commonly by the formation of new scotomas [32].

The proposed GVUM includes a set of visual parameters, including visual acuity, glare sensitivity, spectral sensitivity, contrast sensitivity, blind spot count, blind spot size, blind spot area and blind spot opacity.

Hearing parameters

Hearing impairments lessen a person's ability to hear environmental sounds without amplification. Often they also diminish the ability to discriminate between sounds even with amplification. Hearing loss is a major public health problem. Age-related hearing loss is the most prevalent in human auditory disorders [44]. Epidemiological studies indicate that the hearing threshold and the prevalence of hearing disabilities increase with age [17].

The proposed GVUM describes the hearing threshold for various frequencies, as well as the resonance frequency for each ear.

Speech parameters

Though often overshadowed by the more salient skeletal aspects of movement impairment such as gait and upper limb control, speech impairment in Parkinson's disease (PD) is not uncommon. PD patients are often characterized by reduced intensity of voice, a tendency to increased and unvarying pitch, monotony of speech and an abnormal rate of speaking [34]. Disordered articulatory movements have been documented in people with PD through kinematic analysis of jaw movements [5].

The proposed GVUM includes variables for describing jaw movement and lip movement coordination as well as for voice pitch and syllable duration.

Cognitive parameters

Many disabilities affect cognition mainly in combination with other functional limitations, like motor. Bassett [3] reports that almost all patients with Parkinson's disease suffer from selective cognitive impairments, including difficulties with attention, concentration, problem solving, set-shifting and memory. Multiple sclerosis patients often experience cognitive dysfunction during the course of their disease. The most often affected domains are attention, memory and information processing speed. Grant et al. [14] examined forty-three patients with multiple sclerosis, and the results showed disturbances in short-term memory, learning and delayed recall.

The proposed GVUM contains a set of cognitive parameters including memory, visuospatial and perceptual abilities.

Behavioral parameters

Recent surveys revealed that there are relationships between disabilities and a patient's behavior. Siredíris [40] examined the presence of helplessness in students with learning difficulties and evaluated the role of goal orientations as antecedents of helplessness, negative affect and psychopathology. The results showed that students with learning difficulties displayed increased negative affectivity, lower positive affectivity, lower self-esteem and hopelessness, compared to typical students. People with intellectual disabilities often have symptoms like tearfulness, loss of interest, lack of emotional response, sleep disturbance, loss of libido, suicidal ideation, anxiety, social isolation and others. Sleep problems are common in children with intellectual disabilities [8]. Such problems may be divided into dyssomnias, such as settling difficulties, frequent night waking, excessive sleepiness and early waking, and unusual behaviors during the night (i.e., parasomnias), such as teeth grinding and night terrors.

The proposed GVUM contains a set of behavioral parameters like valence, emotional intelligence and physiological arousal.

Auxiliary parameters to reduce simulation complexity

Gait parameters

The design of accessible environments (e.g., workplace, home, etc.) should take into account human gait, which is affected by many different motor disabilities. Vieregge et al. [46] studied stride parameters between 17 patients with idiopathic Parkinson's disease (PD) and 33 healthy age-matched controls, and the results of their measurements showed that there were reductions in the value of gait velocity, stride length and cadence in the PD patients. They also compare their results with reductions in stride parameters for PD patients presented in other studies.

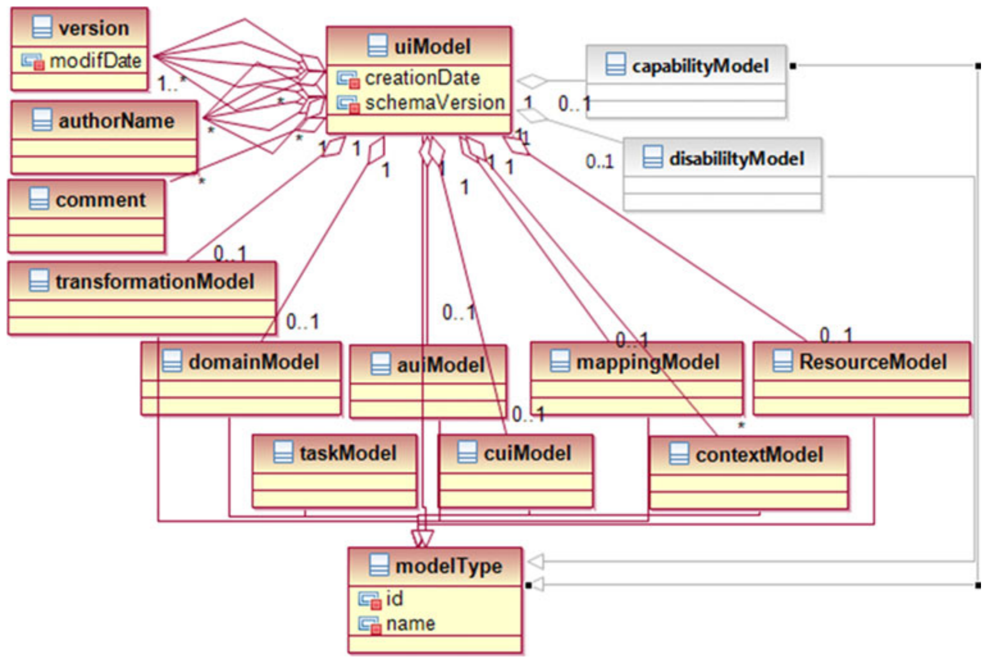
Although during gait simulation parameters such as step length and velocity can potentially be inferred given the kinematic and physical parameters, the proposed GVUM includes some parameters of that kind, in order to reduce the complexity of real-time gait simulation. In addition to reducing simulation complexity, this also enables the direct usage of gait-related measurements found in the literature regarding motor-disabled people.

The gait parameters supported by the proposed GVUM include step length and width, stride length, foot contact, gait cycle, cadence and velocity.

3.4.3 Implementation

For the development of user models that could be automatically used by software tools/modules/frameworks, the use of a machine-readable format is essential. For the implementation of the proposed GVUMs, the UsiXML language has been chosen, as it can sufficiently describe user tasks, has some primal support for user description and is easily extensible, due to its XML nature. Two new models are introduced [21] and added to UsiXML's uiModel (Fig. 5):

Fig. 5 uiModel—UML class diagram



- the *disabilityModel* (Fig. 6) and
- the *capabilityModel* (Fig. 7).

The *disabilityModel* describes all the possible disabilities of the user, as well as the tasks affected by the disabilities. Each *disability* element has a name and a type (e.g., motor, visual, etc.). Each *affectedTask* element has the following attributes:

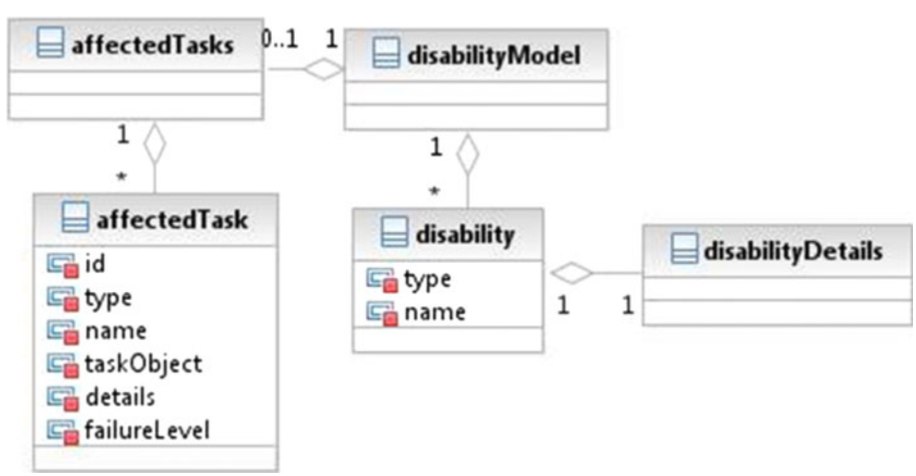
- *id*: task's unique identity
- *type*: the type of the task (e.g., motor, visual, etc.)
- *name*: task's name
- *taskObject* (optional): the name of the task object (e.g., "door handle" may be the task object for task "open door")
- *details* (optional): some details/comments concerning the execution of the task
- *failureLevel*: an indicator showing the failure level of the task due to the disabilities [accepted values: 1–5]—failureLevel = 5 means that the user is unable to perform the specific task

The *capabilityModel* describes in detail the physical, cognitive and the behavioral/psychological user characteristics. The majority of the parameters of the proposed user model concerns the physical characteristics, as most of them are measurable and independent from the environment, in contrast to the cognitive and behavioral/psychological ones.

More specifically, the *capabilityModel* contains the following basic elements:

(a) *general*: container for some general characteristics (e.g., gender, ageGroup);

Fig. 6 disabilityModel—UML class diagram



(b) *generalPreferences*: container for user's needs/preferences (e.g., preferred input/output modality, preferred sound volume, etc.);
(c) *anthropometric*: container for the anthropometric data (e.g., weight, stature, head length, sitting height bideltoid breadth, etc.);
(d) *motor*: container for the motor parameters (e.g., wrist/elbow/shoulder flexion, hip abduction, etc.);
(e) *vision*: container for the visual parameters (e.g., visual acuity, glare sensitivity, spectral sensitivity, etc.);
(f) *hearing*: container for the hearing parameters (e.g., resonance frequency, hearing thresholds, etc.);
(g) *speech*: container for the speech parameters (e.g., voice pitch, fundamental frequency, syllable duration);
(h) *cognition*: container for the cognitive parameters (e.g., memory, etc.); and
(i) *behavior*: container for the behavioral parameters (e.g., valence, emotional intelligence, etc.).

The UML class diagram of the proposed *capabilityModel* is presented in Fig. 7.

3.5 Instance of a Generic Virtual User Model

3.5.1 Objective

An instance of a Generic Virtual User Model (Virtual user, Persona) describes a specific virtual user with specific disability-related parameters including disabilities, affected primitive tasks and specific affected primitive tasks' parameters for the specific user. Table 6 presents an indicative example of an instance of a GVUM.

3.5.2 Implementation

The instances of GVUMs, in a similar way as the GVUMs, are expressed in UsiXML format, according to the proposed UsiXML extension, as described in Sect. 3.4.3. The only difference between a GVUM and an instance of a GVUM is that the first represents a population group, thus, the values of its parameters are ranges, in general, while the second refers to a specific user, thus, the values of its parameters are mainly absolute values.

3.6 Simulation models

3.6.1 Objective

A Simulation Model [20] refers to a specific product or service and describes all the functionalities of the product/service, as well as the involved interaction with the user. It actually describes the scenario to be followed during the simulation process. In Table 7, the main tasks and the subtasks that have to be executed during a simulation scenario example for the automotive sector are presented.

A Simulation Model may include three different types of tasks: (a) abstract tasks, (b) interaction tasks or (c) application tasks. An abstract task is a container having two or more children tasks, which are actually executed. An interaction task is a task performed by the virtual user, containing interaction between the virtual user and the virtual prototype. An example of an interaction task could be opening a door. An application task is a task performed automatically by the virtual prototype, without including any interaction with the virtual user. An example of an application task could be playing a musical theme when exiting an ICT application. The connection between the tasks within a Simulation Model can be established using a set of temporal operators defining the execution sequence, choice relationships, information passing, etc.

The leaves of the hierarchy tree representing a Simulation Model, which are actually the tasks that will be simulated during the simulation process, may contain complex tasks as well as primitive tasks. In case where a leaf node is a complex task, the information stored in the corresponding Task Model has to be exploited, in order to find out how the specific complex task is analyzed into primitives.

3.6.2 Implementation

As a Simulation Model actually describes a set of tasks with their temporal relationships, it can be developed using the *taskModel* of UsiXML, similarly to the Task Models. An example of a Simulation Model is presented in Fig. 8.

4 Novel accessibility and ergonomy quantification metrics for the evaluation of designs

The proposed framework, described in the previous paragraphs, aims to be used for the accessibility and ergonomy evaluation of virtual prototypes. According to the main concept on which the framework is based, a designer having more than one alternative designs of a virtual prototype assesses the accessibility and the ergonomy of each design using a set of virtual user models, representing virtual users with various disabilities. The proposed accessibility and ergonomy quantification metrics, which are used for the evaluation, are presented in the following paragraphs.

4.1 Accessibility metrics

In order to assess the accessibility of a virtual prototype, three distinct levels of simulation are proposed:

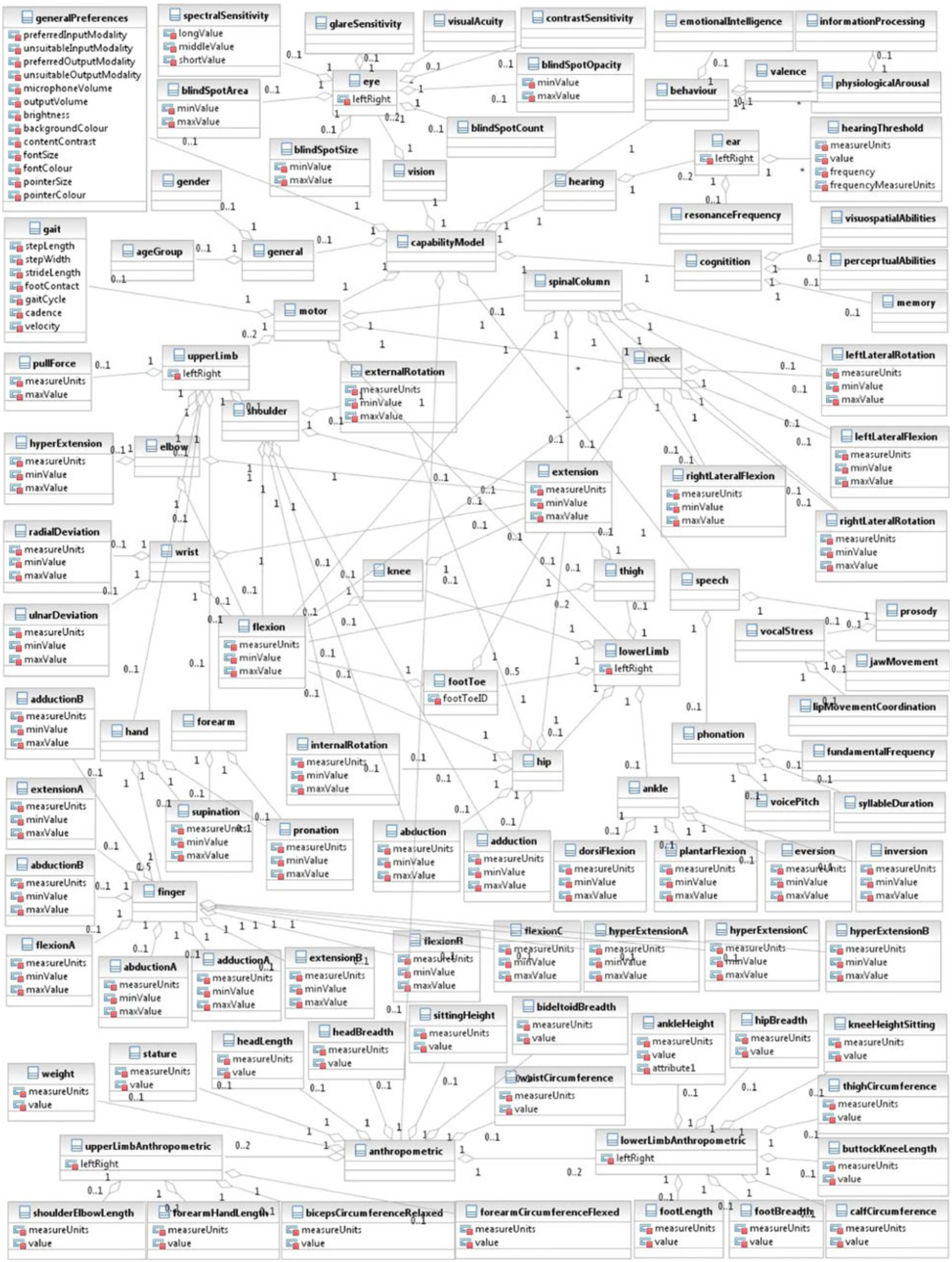


Fig. 7 capabilityModel—UML class diagram

Table 6 Instance of a GVUM: example

User ID	Disability category	Disability	Affected primitive tasks	Affected primitive tasks' parameters
User 1	Motor	Hemiplegia	Grasp	The user is able to grasp objects, with size ≤ 2.5 cm × 2.5 cm × 2.5 cm
			Pull	The user can pull an object with max_Force: 3 N
			Walk	Gait velocity : 0.9 m/s
				Abnormal step rhythm

Table 7 Simulation model example: automotive simulation

Scenario	Main tasks	Subtasks
Automotive simulation: assess the accessibility of the handbrake and the storage compartment	Use handbrake	Pull handbrake
		Release handbrake
	Use storage compartment	Open storage compartment
		Close storage compartment

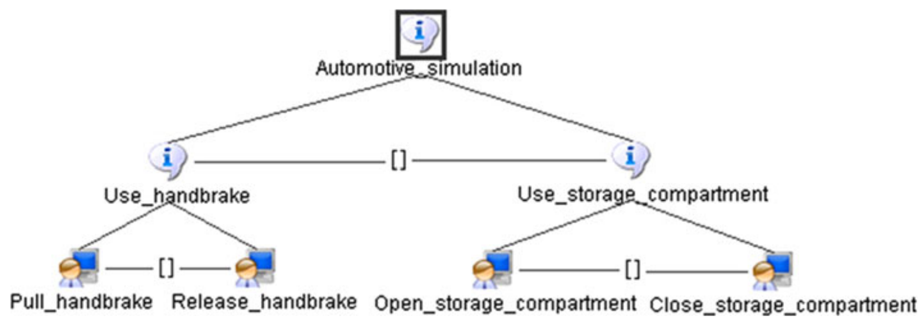


Fig. 8 A Simulation Model example representing some common tasks that can be performed in a car interior. The tasks of the same level are connected with choice relationship, which means that only one of the two can be executed at a time

- Level 0: data comparison–based simulation
- Level 1: kinematic simulation
- Level 2: dynamic simulation

When a simulation process runs at level 0, every task validation is done by simple data comparisons (examination of low-level constraints satisfaction). For example, if the virtual user has an upper limb length equal to x meters and the distance between the user's shoulder and an object is more than x meters, then the task fails. The level 0 simulation is the fastest of the three levels and refers to constraint satisfaction. It can be used only to exclude the feasibility of some basic actions, such as the reach action described above. Even if this first simulation level is pretty simplified, it can be very useful in cases where the simulation of a task is very difficult to be implemented, like in the case of cognitive tasks. For instance, if a virtual user is not able to read due to cognitive problems (as defined in the instance of a GVUM) and a Simulation Model contains the task "read," the simulation process will return failure for this task.

Level 1 simulation can be described as "kinematic simulation." Every algorithm that involves kinematic computations can be activated. All the kinematic parameters of the virtual user models are used, such as the body joint's range of motion and gait velocities. Regarding the virtual user's motor functionality, forward and inverse kinematics can be applied when performing the accessibility assessment. However, level 1 does not incorporate dynamics, thus cannot involve any kind of forces or torques constraints.

Level 2 simulation is the most advanced and complex simulation type. It involves both kinematics and dynamics. It expands the algorithms of level 1, by adding forward and inverse dynamics. Forces and torques are present; thus, concepts such as force exertion capabilities can be included in the simulation at this level.

At the end of the simulation process, the accessibility results will depict whether a specific virtual user is able or not to perform successfully each task included in the simulation scenario for each simulation level.

4.2 Ergonomy metrics

In order to assess the ergonomy of a design, it is proposed to use some common physics-based factors like joint torque, angular impulse and energy, as well as a set of novel anthropometric factors [33], including a RoM comfort factor and RoM-torque comfort factor.

4.2.1 Physics-based factors

Joint Torque When a body part is moved, or more precisely rotated, torques are generated by the musculoskeletal system. The joint torque that is generated at a time instant is given by:

$$\tau(t) = \tau_{\text{net}}(t) + \tau_{\text{force}}(t) = Ia(t) + r(t) \times F(t) \tag{1}$$

where $\tau_{\text{net}}(t)$ is the joint's net torque, I is the moment of inertia, a is the angular acceleration of the rotated body, $\tau_{\text{force}}(t)$ denotes the joint's internal forces, r is the vector from the joint's center to the body part's center of mass, $\times$ denotes the cross product, and F denotes the forces generated in every body joint, in order to keep its body parts connected. By computing each joint torque and averaging it through time, a measure of the demands of a human task in terms of strength can be created. This mean torque factor is given by:

$$\tau_{\text{mean}} = \frac{1}{n}\sum_{t=1}^{n} |r(t)|. \tag{2}$$

Angular Impulse (torque × time) In order to estimate fatigue, the calculation of the mean torque is not sufficient, as fatigue contains also a time duration sense that is not included in the definition of torque. Thus, by computing the time duration of a task and providing it to the τ_{mean}, the angular impulse results by the following equation:

$$I_{\text{ang}} = \tau_{\text{mean}} dt_{\text{task}} \tag{3}$$

where τ_{mean} is the joint's mean torque and dt_{task} denotes task's duration. The angular impulse that is generated at each joint enhances the torque measure of the strength demand for a task to strength and duration demand for a task, which is proposed as a fatigue measure.

Energy The kinetic energy produced by each joint at a very small time step dt is given by:

$$E_{\text{kinetic}}(t) = \frac{1}{2} I(\omega^2(t) - \omega^2(t-1)) \tag{4}$$

$$\cong \frac{1}{2}\tau(t)(\omega(t) + \omega(t-1))dt \tag{5}$$

$$\cong \tau(t)\omega(t)dt \tag{6}$$

where $\tau(t)$ is the joint's torque and $\omega(t)$ is the angular velocity of the rotated body part. Equation 6 is an approximation that stems from Eq. 5 assuming that $\omega(t) \cong \omega(t-1)$, when $dt \to 0$.

Moreover, the potential energy is given by the equation:

$$E_{\text{potential}}(t) = mgdz = mg(z(t) - z(t-1)) \tag{7}$$

where m is the body part mass, g is the acceleration of the gravity, and dz is the translation of the rigid body's center of mass in the vertical direction in this time step. By adding Eqs. 6 and 7 and averaging through time, an estimation of the total chemical energy consumed by the joint and its body parts can be made:

$$E_{\text{total}} \cong \sum_{t=1}^{n} (\tau(t) \cdot \omega(t)dt + mg(z(t) - z(t-1))) \tag{8}$$

4.2.2 Novel anthropometric factors

RoM comfort factor The distance of a joint's angle to the nearest limit (minimum or maximum) of its total range is proposed as a possible comfort metric of a specific degree of freedom (*DoF*) of a joint:

$$C_d(t) = \min(|\theta_{d,\max} - \theta_d(t)|, |\theta_{d,\min} - \theta_d(t)|) \tag{9}$$

where d is the id of the *DoF*, and $\theta_{d,\max}$, $\theta_{d,\min}$, $\theta_d(t)$ are the maximum, minimum and current angle of this *DoF*, respectively. In order to compute a comfort factor per joint, a simple addition of its respected *DoF* comfort values is proposed:

$$C(t) \leftarrow \sum_{d=1}^{m} C_d(t) \tag{10}$$

where m is the total number of *DoF* of the joint. C can be normalized to the interval [0,1] by using the following equation:

$$C(t) = \frac{2\sum_{d=1}^{m} C_d}{\sum_{d=1}^{m} (\theta_{d,\max} - \theta_{d,\min})} \tag{11}$$

Values near unit are considered more "comfortable" than the values near zero. The $C(t)$ factor changes only when the joint rotates. By taking the average of these $C(t)$ over time, the "RoM comfort factor" is given:

$$C = \frac{1}{n}\sum_{t=1}^{n} C(t) \tag{12}$$

RoM-torque comfort factor The factor in Eq. 11 can be enriched by including the joint's produced torque magnitude. This will result in a factor that includes the joint dynamic properties besides the kinematics and takes into consideration the fact that a torque of an uncomfortable posture has not the same fatigue impact of the same torque of a more comfortable posture. The proposed factor is referred to as "RoM-torque" comfort factor and can be calculated by the following equation:

$$C_\tau = 1 - \frac{1}{n}\sum_{t=1}^{n} \left(\frac{(1 - C(t))|\tau(t)|}{|\tau_{\max}|} \right) \tag{13}$$

where t_{max} is the joint torque having the maximum magnitude recorder in the task. C_τ is used to evaluate the overall body posture comfort considering the dynamics demands of the task.

5 Experimental evaluation of designs using the proposed framework

In this section, two evaluation scenarios are presented, in order to show how the proposed framework can be put into practice. According to the selected scenarios, a workplace designer performs accessibility and ergonomy evaluation of different designs of a virtual prototype for different virtual users with disabilities. The designer initially develops the designs of virtual workspace prototype to be tested, as presented in Figs. 9 and 15. Then, three instances of GVUMs are developed, according to the proposed methodology, corresponding to a user with no disabilities, an elderly (60–84 years old) with reduced range of motion in the upper limbs and a user with rheumatoid arthritis that has reduced range of motion in the shoulders. More details on the characteristics of each user model can be found in [33]. The Task and Simulation Models describing the interaction of the virtual user with the virtual prototype and the simulation scenario to be followed, respectively, are also developed (according to the approach described in Sects. 3.2.2 and 3.6.2). The simulation ran in fully dynamic level (Level 2), in order to allow the measurements of the proposed ergonomic human factors.

5.1 Telephone use

In this first scenario, the telephone use was simulated for two different designs one where there is a wall phone at the right of the seated virtual user and a second where the phone is on the desk. The scenario in both designs (Fig. 9) was described by one task: reaching the phone. The avatar was given a target time of 1 s to perform the reaching action.

The simulation results depicted that all virtual users managed to reach the phone in both designs, but the ergonomic factors showed that one of the two designs was more ergonomic than the other for a specific user. The human factors collected information only from the activated body regions, that is, the torso and the right arm. The results are presented in the following paragraphs.

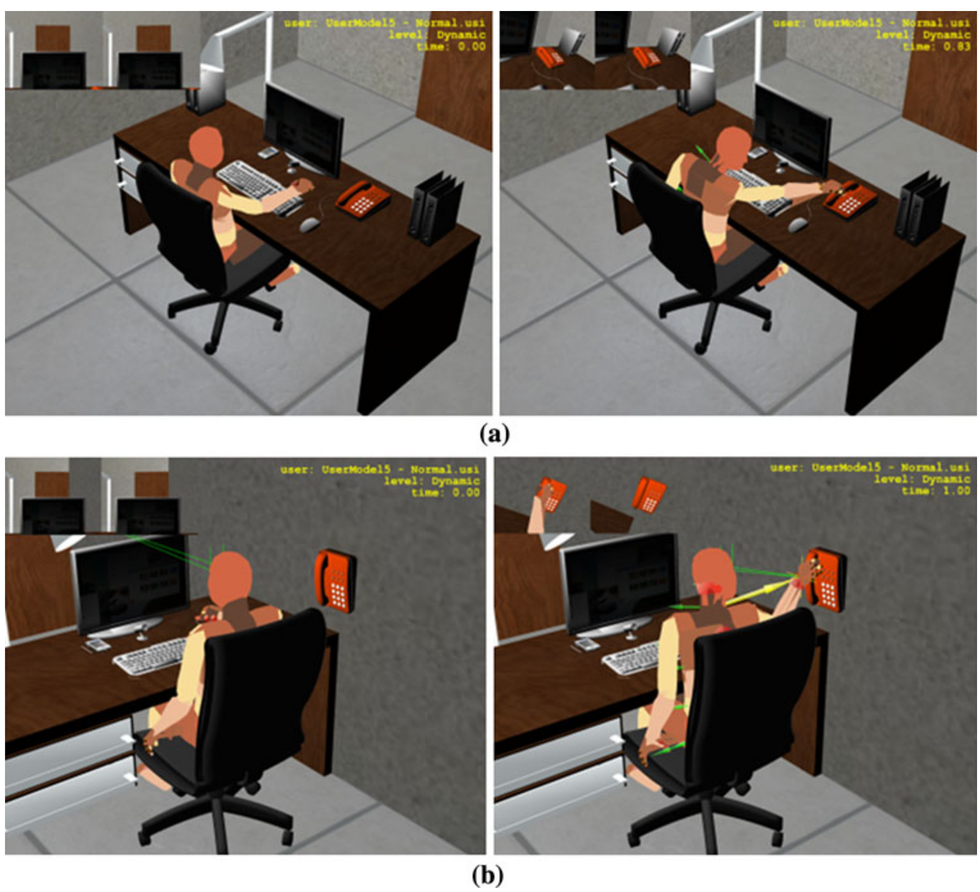


Fig. 9 Different designs to be tested for the telephone use: **a** telephone on the desk, **b** wall telephone

5.1.1 Mean torque

As depicted in Fig. 10, when the phone is placed on the desk, the torso area of all the three users requires more torque for the reaching action. This can be explained because the reaching of the desk phone requires more torso bending.

On the contrary, the wall phone can be reached by simply moving the arm (without involving the torso joints). Regarding the elderly user, it is noted that the mean torques are significantly lower, compared to the other two models. This is expected, due to the lower strength capabilities of the elderly user.

5.1.2 Angular impulse

The results of the angular impulse are almost identical to the results of the mean torque (Fig. 11), and this is due to the fact that the task duration time was $\sim$1 s for each simulation. As depicted in Eq. 3, when $dt_{task} \cong 1$, then $I_{\text{ang}} \cong \tau_{\text{mean}}$.

5.1.3 Energy consumption

As depicted in Fig. 12, all three users and especially the user with rheumatoid arthritis consume more energy in their torso regions when the phone is on the desk. This is due to the fact that more energy is consumed for maintaining the torso-bending posture while reaching the phone on the desk. The rheumatoid arthritis user requires more energy in the torso region when the phone is on the desk, because he/she needs to bend more than in the other design, due to his/her limited arm range of motion.

5.1.4 RoM comfort factor

Concerning the RoM comfort factor, as depicted in Fig. 13, the normal user presents slightly better comfort statistics in the torso and shoulder regions when reaching the phone on desk. This can be justified due to the fact that the user approaches his/her range of motion limits when reaching the phone on the wall. However, in the wall phone design the elbow region seems to be more comfortable. The user

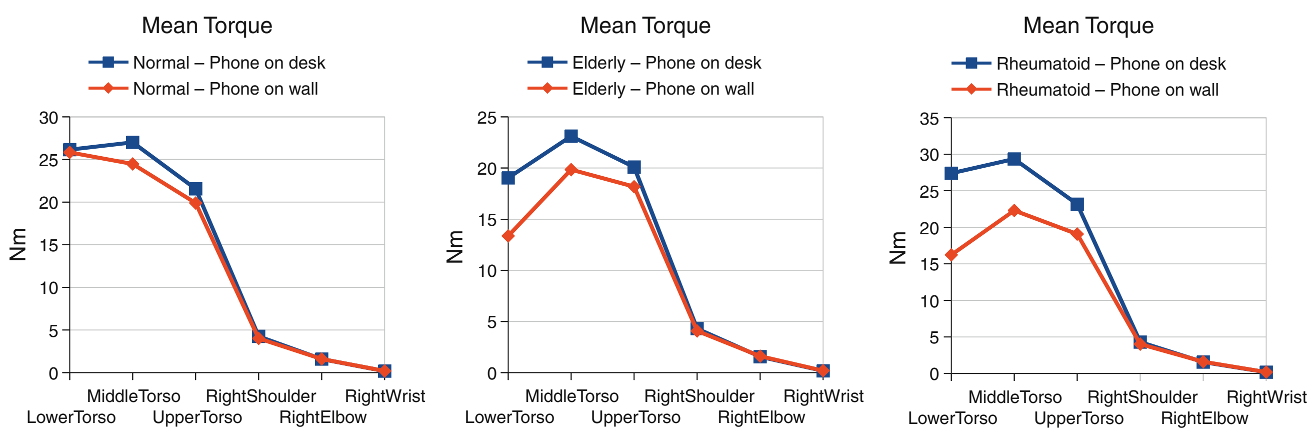


Fig. 10 Mean torque results for the telephone use

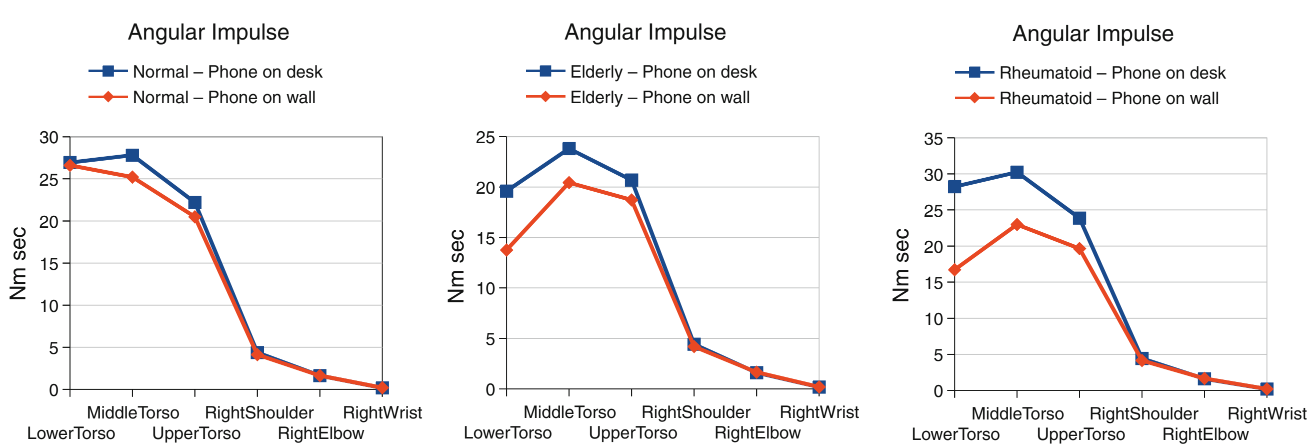


Fig. 11 Angular impulse for the telephone use

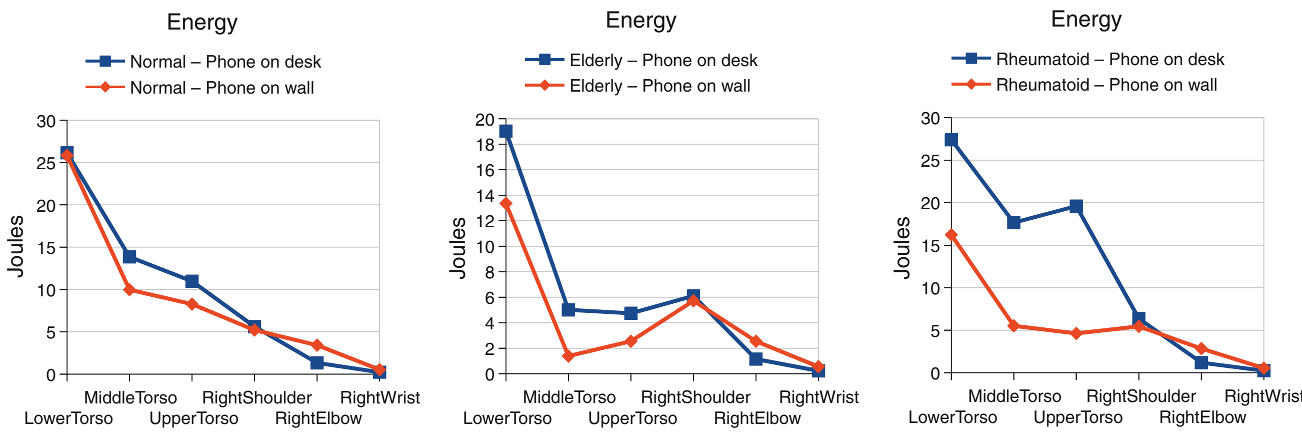


Fig. 12 Energy consumption for the telephone use

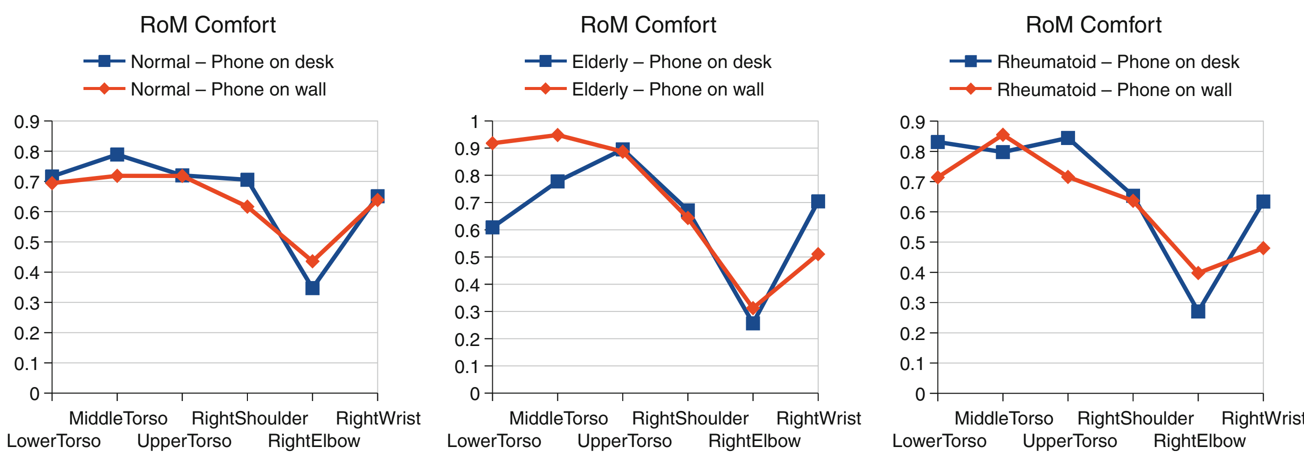


Fig. 13 RoM comfort factor for the telephone use

with rheumatoid arthritis presents better comfort factors in the lower torso, upper torso and wrist regions when reaching the phone on desk, comparing to the phone on wall, where the middle torso and elbow area present better comfort factors. Thus, for these two users the RoM comfort factor cannot provide a clear view on which design is better. Concerning the elderly user, the telephone use seems to be more comfortable when the phone is on the wall (especially for the lower/middle torso). This can be explained by the reduced torso flexion RoM of the elderly user.

5.1.5 RoM-torque comfort factor

Taking into consideration the torque and applying it into the comfort factor, as depicted in Fig. 14, the design where the phone is on the desk seems to be more comfortable for the normal user and the user with rheumatoid arthritis, in terms of torso-comfort. The torque comfort factor regarding the elderly user is greater in the case of the wall phone, because in this case no bending is required and bending is uncomfortable for the elderly user, due to the decreased torso flexion.

5.1.6 Evaluation result

In terms of strength and energy, the design where the phone is on the wall is less demanding for all the users. Regarding comfort, the design where the phone is on the desk seems to be better for the normal user and the user with rheumatoid arthritis, while the elderly user's body postures seem to be more comfortable in the case of the wall phone.

5.2 Stapler use

In the second scenario, use (Fig. 15) was simulated for seven different staplers with torque resistance 2.5, 5.0, 10, 15, 20, 25 and 30 Nm, respectively. The scenario consists of two subtasks: (a) reach the stapler with the right hand and (b) press it. The total target time for performing each task was set to 2 s.

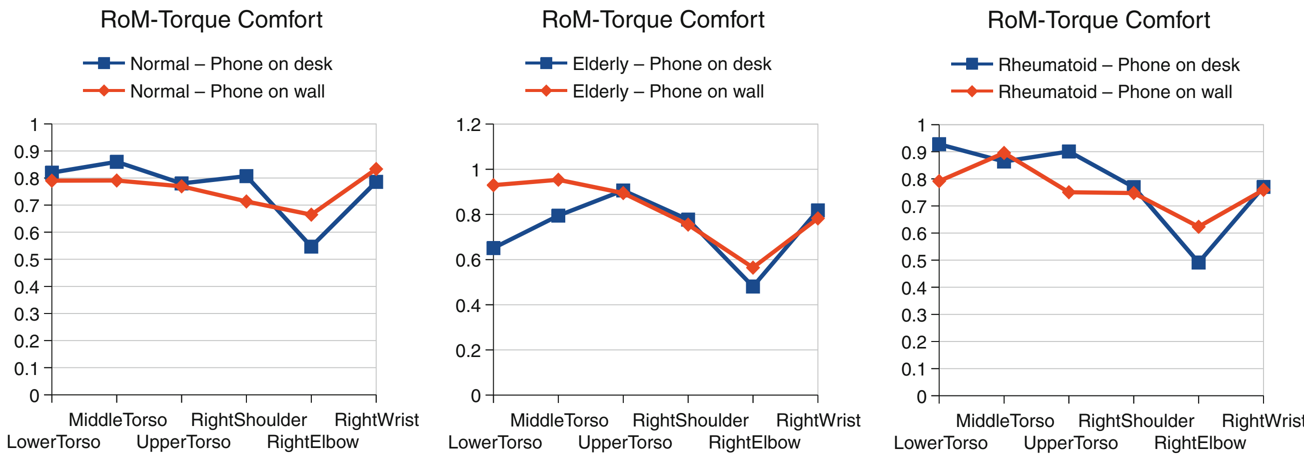


Fig. 14 RoM-torque comfort factor for the telephone use

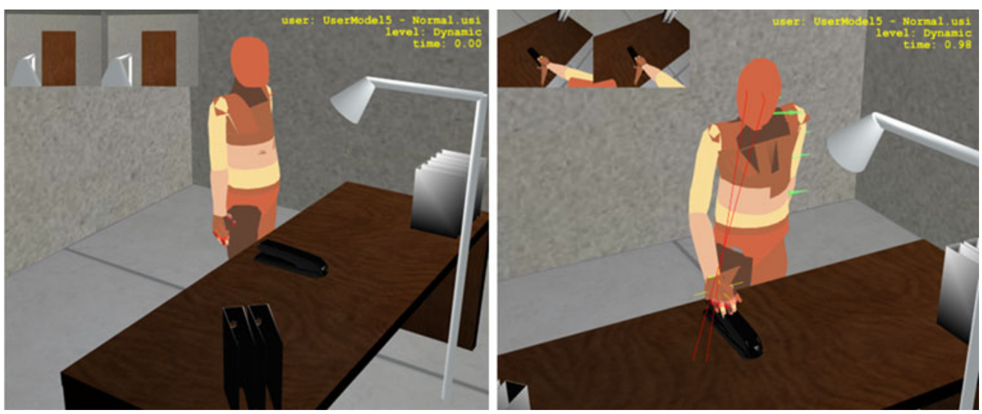


Fig. 15 Simulating the stapler use

Table 8 presents the simulation results concerning the accessibility of each design for each user. As depicted in Table 8, the normal user was able to use the stapler in all cases, except the one where the resistance was 30 Nm. The staplers with resistance equal to or greater than 15 Nm seemed to be inaccessible for the elderly user, while the staplers with resistance equal to or greater than 20 Nm found to be inaccessible for the user with rheumatoid arthritis.

Table 8 Accessibility results: stapler use

Stapler torque resistance (Nm)	Normal	Elderly	Rheumatoid arthritis
2.5	Pass	Pass	Pass
5.0	Pass	Pass	Pass
10	Pass	Pass	Pass
15	Pass	Fail	Pass
20	Pass	Fail	Fail
25	Pass	Fail	Fail
30	Fail	Fail	Fail

Concerning the ergonomy evaluation, the simulation results for the first two cases (stapler with resistance equal to 2.5 and 5 Nm, respectively), which were accessible for all the users, have been indicatively selected and are presented in the following paragraphs.

5.2.1 Mean torque

As expected, the mean torques appear higher in the stapler having resistance equal to 5 Nm (Fig. 16). It is also worth noting that the stiffer stapler requires more strength in the torso region, which was expected, as the increment in the required force requires extra effort in the body's torso region.

5.2.2 Angular impulse

As depicted in Fig. 17, and as expected considering the mean torque distributions, the angular impulse was greater for all the users, when the resistance of the stapler was equal to 5 Nm.

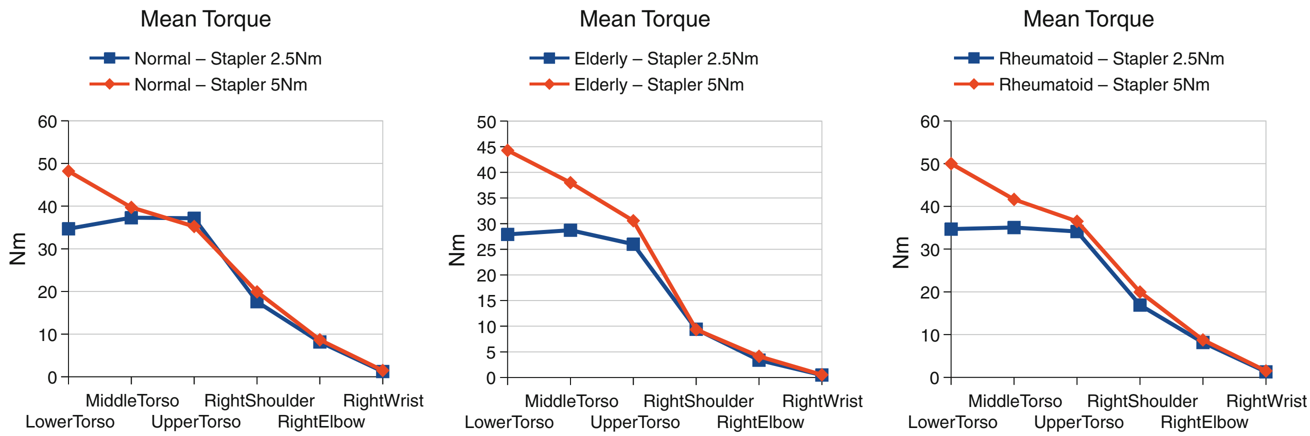


Fig. 16 Mean torque for the stapler use

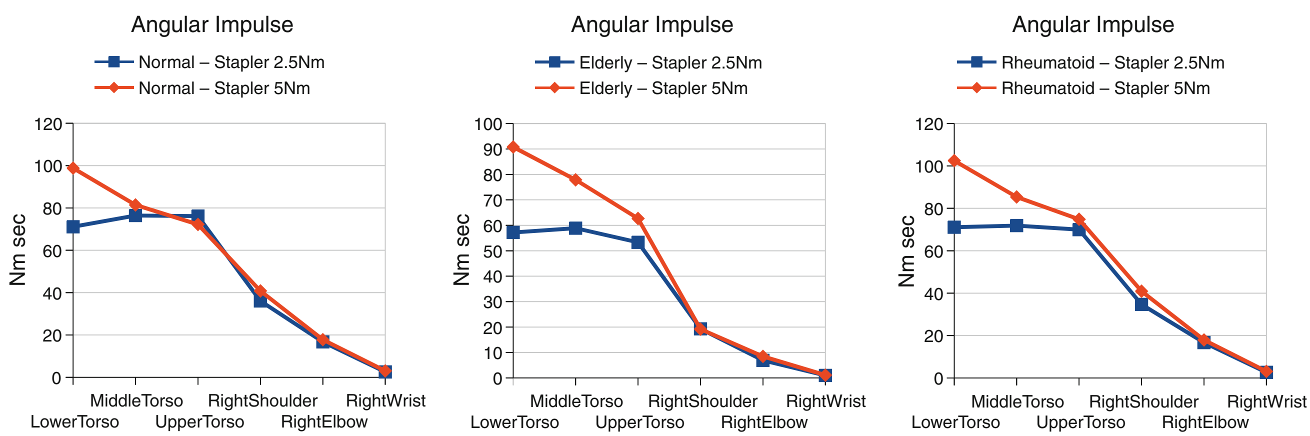


Fig. 17 Angular impulse for the stapler use

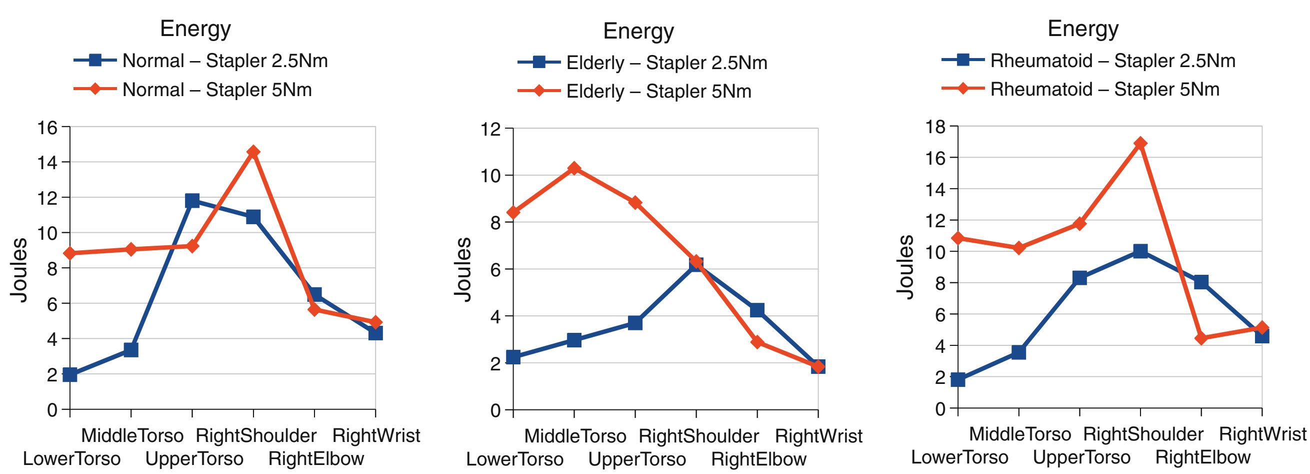


Fig. 18 Energy consumption for the stapler use

5.2.3 Energy consumption

Energy consumption diagrams (Fig. 18) reveal that the energy consumed by the torso and shoulder is higher in the stiffer stapler, while the energy consumed by the forearm is lower. Moreover, the total energy needed in the case of the stiffer stapler was significantly higher for all the users.

5.2.4 RoM comfort factor

Considering the RoM comfort factor results presented in Fig. 19, it is not clear which of the two designs is more ergonomic. This is due to the fact that the RoM comfort factor is based only on RoM information, ignoring any dynamic properties of the user.

5.2.5 RoM-torque comfort factor

It is already shown that the simpler RoM comfort factor could not distinguish the two stapler ergonomies. However, by including the torque metrics into the RoM-torque comfort factor, the use of the stapler with less resistance seems to more comfortable (Fig. 20).

5.2.6 Evaluation result

As expected, the ergonomy of the stapler with the lower resistance is better in general. Even a small change in the stapler's resistance results in significant changes of the physical human factors (mean torque, angular impulse and energy consumption). For instance, the elderly user consumes significantly more energy (around 18 Joules) in order to use the stiffer stapler.

6 Conclusions

This paper has presented a framework for automatic simulated accessibility and ergonomy testing of virtual prototypes using virtual user models. The proposed virtual user models describe virtual humans with focus on the elderly and people with disabilities. The concepts of the Abstract User Model, Generic Virtual User Model, instance of a Generic Virtual User Model, Primitive Task, Task Model and Simulation Model were introduced, describing the characteristics of the virtual disabled user, how a task of the user can be executed and the simulation scenario to be followed during the simulation process, respectively. The

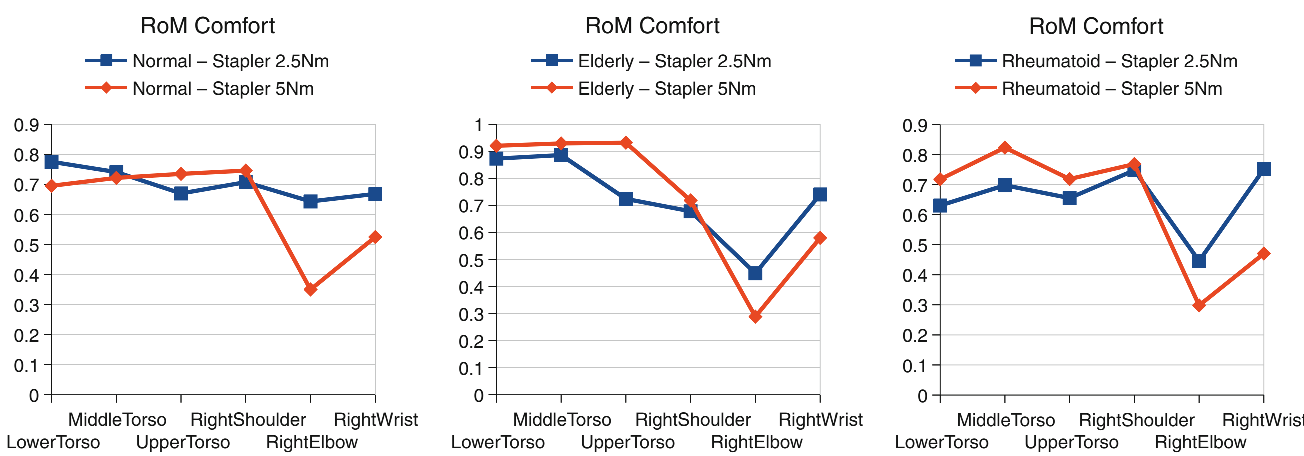


Fig. 19 RoM comfort factor for the stapler use

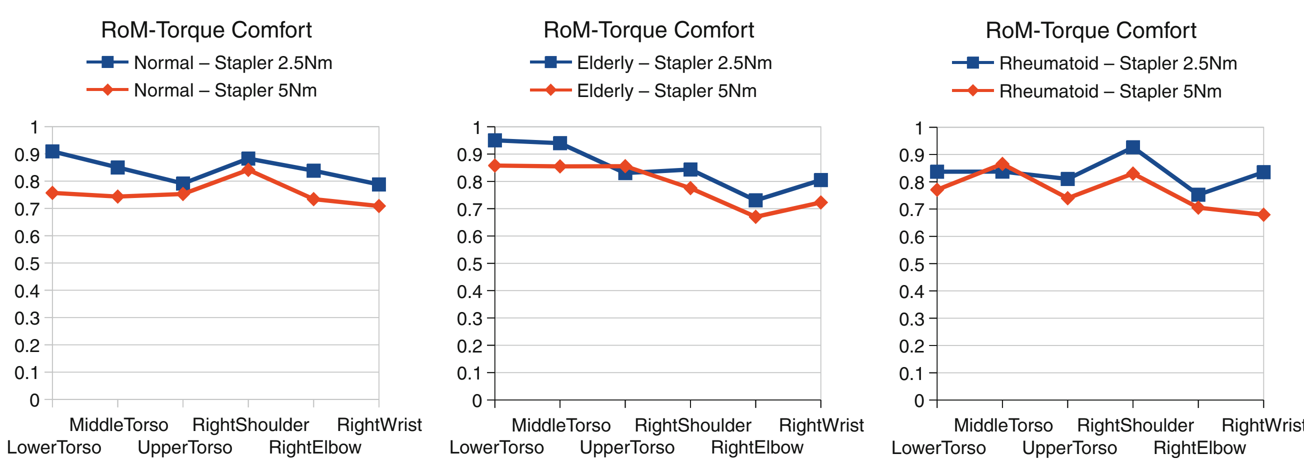


Fig. 20 Rom-torque comfort factor for the stapler use

entire framework is based on the definition of user's primitive tasks, which is the connecting point between all the models. Experimental results showed how the framework can be put into practice and reveal its significant potential.

The use of UsiXML for the implementation of all the models makes the framework very generic, as UsiXML can accurately describe the user interfaces to be evaluated, the user tasks, the simulation scenario to be executed, as well as the user (through the proposed extension described in Sect. 3.4.3), in an abstract way, which does not contain any implementation details. Another great advantage of the proposed framework is that there is no need for development skills for the elaboration of the models. The proposed framework could be used in various simulation platforms performing accessibility and/or ergonomy assessment of virtual prototypes. Some of the proposed models could also be used in adaptive user interfaces, where the user interface of an application could dynamically change, in order to fulfill user's needs/preferences. In this case some of the proposed models may be ignored (e.g., there is no need for simulation models).

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