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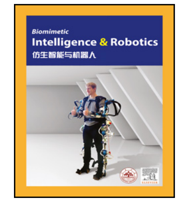

User-centered development and performance assessment of a modular full-body exoskeleton (AXO-SUIT)

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ABSTRACT

This paper presents the design and preliminary performance assessment of a full-body assistive exoskeleton (AXO-SUIT) for older adults. AXO-SUIT is a system that consists of separate lower-body and upper-body modular exoskeletons, which can be combined to form a full-body system to provide flexible physical assistance as needed. The full-body exoskeleton comprises 27 degrees of freedom (dof), of which 17 are passive and 10 active. It can assist people in walking, standing, carrying and handling tasks. A user-centered design approach was adopted throughout the development of the exoskeleton. This paper describes the design process of AXO-SUIT, involving a review of user needs, a kinematic and kinetic motion study, and innovative system design. Tests with the developed systems were conducted on selected end-user subjects, covering both performance evaluations at different levels and useability testing. End-user testing results show the effectiveness of the exoskeleton in providing flexible physical assistance.

1. Introduction

Exoskeleton technology has advanced into many application domains, including medical care/rehabilitation, industrial applications and for military applications [1–3]. In recent years, there has been increasing interest in wearable exoskeletons to meet the challenges and opportunities presented by the aging population [4–6]. Demographic changes worldwide are expected to bring a strong demand for robotic technologies like exoskeletons to assist older adults so they can remain active, independent, and have a high quality of life [7].

Many assistive exoskeletons have been developed. An overview of exoskeletons that were developed by commercial organizations and research laboratories can be found in [8]. While most exoskeletons have been developed for either upper limbs or lower limbs, very few were designed for the full body [9–12]. A well-known full-body exoskeleton is the hybrid assistive limb (HAL) designed for nursing care and/or elderly assistance [11]. HAL does not operate with a gripper, but rather loads are manipulated by the user's hand. The system is also light, weighing 23 kg and able to manipulate 15 kg in each arm. However, HAL is a single system and not of two modules like AXO-SUIT. Two full-body exoskeletons reported are the Body Extender (BE) [13] and XOS2 [14]. Both systems act to provide external forces to the human, where loads are transferred directly through the exoskeleton from a mechanical connection to the ground. Hence, only a small part of the load is exerted on the human. It is noted that BE is designed for heavy material handling and weighs 160 kg, while XOS2 is for military applications and weighs 95 kg. Another full-body exoskeleton developed at the University of Bremen has 30 active joints and weighs 41 kg [15].

It is noticed from the state-of-the-art that most systems of full-body exoskeletons are powerful but heavy, and hence are not suitable for the elderly. Moreover, there is generally a lack of data on their performance assessment in the literature. The focus of this research is thus to develop an exoskeleton, namely AXO-SUIT, to provide general physical assistance for older adults to perform activities of daily living. Moreover, comprehensive performance assessment will be conducted, covering both objective measurements and subjective feedback to emphasize the critical role of user-centered design and user involvement in human–robot system development.

This paper presents the design and testing of the AXO-SUIT exoskeleton, adopting a user centered design approach. The paper provides an overview of the system development of AXO-SUIT by extending the authors′ work reported in [16], where the full-body exoskeleton AXO-SUIT was introduced. In this paper more details on user involvements in both conceptual design and also end-user testing are provided. Section 2 describes the end-user centered design approach, in which design requirements were obtained through end-user involvement. Section 3 presents the design and construction of AXO-SUIT including mechanics and electronics. Preliminary performance assessment results are described in Section 4. Finally, Section 5 details the conclusions from this work.

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Table 1
Characteristics of end user questionnaire study participants (n = 34).

Variable	Primary (n = 31)	Secondary (n = 3)
Age (years)	71 (59–86)	29 (27–29)
Gender (%females)	77.4%	66.6%
Height (cm)	165 (152–189)	170 (169–179)
Body mass (kg)	72 (45–110)	60 (58–75)

2. User-centered design approach

AXO-SUIT was designed and developed with a user-entered design approach, taking into account end-user needs from the start of the system development. A range of methodologies were used for this to ensure that appropriate end user input was obtained. For this purpose, questionnaires, focus groups, and interviews, organized in three stages of the research, were performed. For Stage 1, a questionnaire study was undertaken among end users in each partner country. For Stages 2 and 3, end user demonstration events/focus groups were undertaken to obtain feedback on AXO-SUIT designs and physical prototypes, as well as end user opinions on matters relating to its commercialization. End users were engaged in the AXO-SUIT project to provide vital input and feedback on:

- Functional requirements;
- Product design;
- Commercialization strategy.

Primary end users, namely, adults aged 50 years and over with mild-to-moderate limitations in ability to perform activities of daily living, were prioritized for inclusion in end user engagement activities. A limited number of secondary end users (individuals in direct contact with primary end users e.g. family, friends, formal/informal care-givers) were also included. End user requirements were established at the outset of the project, prior to commencing the AXO-SUIT design, and also revisited during the project to ensure that a user-centered focus was maintained.

2.1. Questionnaire: Functional Requirement

A questionnaire study was undertaken among end users to collect user needs regarding physical assistance. Thirty-four participants completed the questionnaire study: twenty in Ireland, six in Sweden and eight in Denmark, as listed in Table 1. Details of the questionnaire content and methods have been published previously [17].

In this project, end user functional and design requirements were sought via a cross-sectional questionnaire study of primary and secondary end users. The questionnaire included items on basic participant demographic information, health-related quality of life, and a series of sub-sections in which participants ranked the priority of lower body, upper body, and full-body motions for which they wished to obtain physical assistance.

In summary, most primary users lived with a spouse (59%), while others lived alone (23%), with relatives (9%), in shared accommodation (6%), or in a nursing home (3%). Regarding residence type of the primary users, single-storey homes (53%) and two-storey homes with stairs (41%) were most common, with relatively few primary users living in two-storey homes with an elevator/stair lift (3%) or apartment (3%). The lower body, upper body and full body motions for which participants ranked the highest priorities for assistance are presented in Table 2.

The design implications and technical feasibility of assisting the tasks identified were discussed among the AXO-SUIT consortium before finalizing the target motions to assist. To further inform this decision-making process, human motion data were gathered for ten of these tasks on twelve participants, to aid the specification of the range of motion and torque requirements at joints of the proposed prototypes. Therefore, questionnaire results combined with biomechanical data and expert review were used to inform the functional goals, design and technical specifications for the AXO-SUIT prototypes.

2.2. Motion analysis to inform kinematic and kinetic requirement

To further explore the specific functional requirements of the main activities identified, a laboratory study of three-dimensional (3D) human kinematics and kinetics during simulated versions of the activities detailed above were conducted.

To design a feasible and efficient testing protocol for the laboratory study of 3D motion and force data, the specific activities for which data were to be collected were agreed upon by the AXO-SUIT consortium. These activities were chosen in line with the available results from Questionnaire 1, taking into account the laboratory resources available for data collection. The ten activities selected for simulation in the laboratory are described in Table 3.

Motion data were acquired using a two-camera Codamotion mpx64 motion analysis system (Charnwood Dynamics Ltd., Leicestershire, UK) at a sampling rate of 100 Hz. A thirty-marker set up was used to obtain full-body kinematic data, with markers placed on specific anatomical landmarks of participants. Force data were acquired at a sampling rate of 200 Hz using an Accugait (Advanced Mechanical Technology Inc., Watertown, MA, USA) portable square force plate, embedded in a portable walkway.

All data were recorded via the Codamotion ODIN software package, and exported in c3d file format. These c3d files, along with anthropometric data, were then imported into the AnyBody Modelling System (Version: 6.0.4.4327; AnyBody Technology A/S, Denmark) to create simulations of the participants performing the tasks. The MoCap_FullBody model from the AnyBody Managed Model Repository was used as the basis for the human body model in the present study. The AnyBody Modelling System generates a comprehensive array of biomechanical output data from each task simulation, such as individual muscle forces, joint contact forces, metabolism etc. In this part of the study, we were primarily interested in obtaining joint position data (range of motion or ‘‘ROM’’) and joint moment or torque data for the major upper and lower limb joints of the human body. These data were used to inform the ROM and torque requirements of the main joints of the AXO-SUIT upper-body and lower-body subsystems. Fig. 1 shows the AnyBody model of the full-body motion. One motion study result are displayed in Fig. 2. The greatest ranges of motion were observed at the hip and knee joints during walking, and were similar to (or less than) the ranges of motion seen during sit-to-stand. On the other hand, the greatest ranges of joint torques were seen at the right (dominant) hip and ankle joints, particularly in the sagittal plane i.e. hip flexion/extension, ankle plantarflexion/dorsiflexion.

Results from the motion analysis were used to define design specifications for the different modules, as listed in Table 4.

3. AXO-SUIT system development

Based on the design requirements specified, AXO-SUIT was designed to give assistive physical supplementary strength at the joint level. To make the system effective, flexible and reliable, a modular approach was adopted. The AXO-SUIT exoskeleton is shown in Fig. 3. The system consists of two main subsystems, namely, the lower-body (LB-AXO) and upper-body (UB-AXO) systems. Each subsystem is able to work independently to provide assistance as needed. Moreover, each subsystem has a number of modules, which enables the joint level assistance. The total weight of the FB-AXO is 25 kg, which includes a 3 kg Li-ion battery that can power the suit continuously for approximately 1 h. A detailed description of the system is available in [18]. We outline here briefly each subsystem for completeness.

Table 2
Highest priority lower body, upper body and full body motions, as ranked by participants in questionnaire.

Ranking	Lower body	Upper body	Full body
1	Sit-to-stand	Lifting/dropping without grasping	Getting up from kneeling
2	Walking and turning	Reaching to the side overhead/opposite shoulder	Getting up from squatted position
3	Standing	Carrying an object in front with both arms	Carrying small objects with one hand
4	Bending down to the floor	Pushing/pulling horizontally	Bending over/stooping to the floor/ground

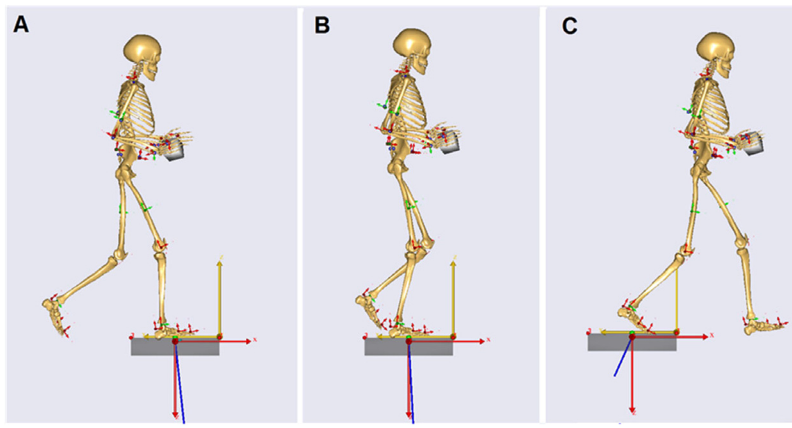


Fig. 1. Walking at usual speed while carrying a payload task kinematic simulation. (A) loading response, (B) mid-stance, (C) terminal stance.

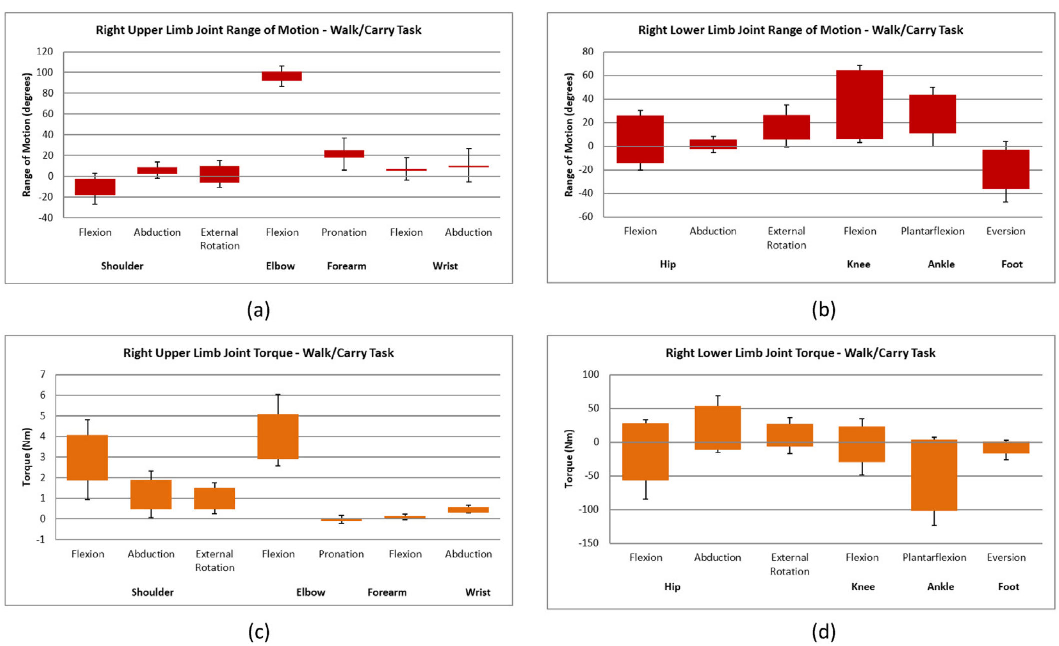
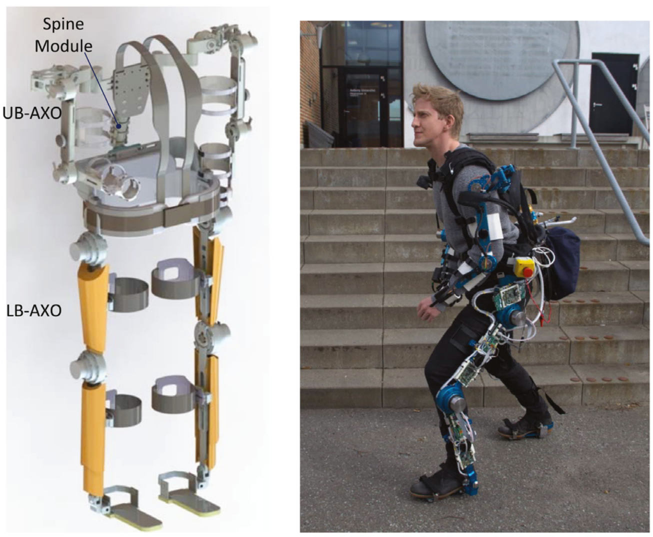


Fig. 2. Motion study of load carrying while walking. (a & b) Range of motion during the walking and carrying task at the major joints of the right upper and lower limbs. (c & d) Joint torques during the walking and carrying task at the major joints of the right upper and lower limbs. The boxes indicate the mean range (i.e. mean maximum joint position to mean minimum joint position) observed across all participants (n = 8).

Table 3
Laboratory motion study of activities.

No.	ADL	Description
1	Sit to stand/Stand to sit	Getting up/sitting down from chair without using hands for assistance
2	Walking	Walking without a load to carry
3	Standing	Standing quietly e.g. at a table/kitchen sink
4	Lifting/dropping	Lifting/lowering an item from floor to table
5	Reaching to side	overhead/opposite shoulder Opening/closing a curtain
6	Push/pull in standing	Pushing/pulling an item (2 kg approx.) across a table surface
7	Holding object in front (2 hands)	Standing while holding a 4 kg item
8	Getting up from kneeling	Both knees on floor, step forward with one foot, rise to standing (without leaning on external object for support)
9	Getting up from a squat	Squat with thighs parallel to floor (or as close as possible to this) and rise without support
10	Carrying small objects (1 hand)	Carrying a 0.5 kg item to front and side e.g. a cup/mug



(a) (b)

Fig. 3. AXO-SUIT exoskeleton, (a) CAD model, (b) a prototype worn on the human body.

Table 4
Range of Motions (RoM) and actuation of AXO-SUIT.

Module	Joint	RoM	Actuation/motion
Spine	lumbar flex./ext.	30°/−30°	Rubber disks
	axial rot.	30°/−30°	Rubber disks
	lateral flex.	30°/−30°	Rubber disks
Shoulder	protraction/retraction	122°/−122°	Passive
	abd./add.	120°/−80°	EC-i40 and LCS-17-100
	int./ext. rot.	90°/−50°	Passive joint
	flex./ext.	170°/−10°	EC-i40 and LCS-17-100
Elbow	flex./ext.	145°/0°	EC-i40 and LCS-17-50
Hip	flex./ext.	122°/−122°	EC-60, 100 W
	medial/lateral rot.	45°/−45°	Passive joint
	abd./add.	80°/−80°	Passive joint
Knee	flex./ext	122°/0°	EC-60, 100 W
Ankle	dorsi/plantar flex.	25°/−30°	Passive joint
	inversion/eversion	35°/−35°	Passive joint

3.1. The upper-body subsystem UB-AXO

The UB-AXO subsystem, shown in Fig. 4(a), has 15 degrees of freedom, 3 at a spine module, 5 at each shoulder module and 1 at each elbow module. The shoulder module was designed to match the 3 degrees of freedom of human glenohumeral joint movement. Shoulder abduction/adduction and flexion/extension joints are powered, while shoulder internal/external rotation joint is passively supported by a double parallelogram linkage [19]. The elbow mechanism is a single powered joint that supports flexion/extension.

Each active joint in the UB-AXO is powered by a brushless DC-motor with harmonic gear. The harmonic gear was selected for its back-drivability, which allows the user to move even if the motors are powered off. Force sensors designed at the AAU laboratory were used at the wrist of the UB-AXO to detect the arm motion.

3.2. The lower-body subsystem LB-AXO

The LB-AXO subsystem is designed to support the weight of the wearer and provide supplementary assistance to perform a range of basic motions for activities of daily living. These motions include walking on flat ground, standing stably in free space, sit-to-stand transfers (and vice versa), and traversing up/down stairs. A lightweight design giving up to 50% physical assistance was developed so that it complies with the low-risk physical assistant robot as defined in EN ISO 13482.

The structure of the LB-AXO, illustrated in Fig. 4(b), is adaptable to wearers of different weights and heights. The adjustment was designed to allow good fit at the waist, thighs, shanks and feet, and can be easily adjusted for the wearers′ stature (1.55–1.8 m tall) and weight (70–110 kg). A maximum of 50% assistance can be provided at each joint (of maximum torque for walking, sit-to-stand and balance motion in sagittal plane).

There are 12 degrees of freedom (8 passive and 4 active); the active joints are the hip and knee in the sagittal plane. The hip joint has a passive rotation and abduction/adduction dof. The ankle is fully passive and has 1 flexion and 1 inversion/aversion passive dof. The specifications of the hip, knee and ankle joints in terms of their actuation and the range of movements are detailed in Table 4, where the motors are EC series DC motor from Maxon Motor.

3.3. Spine module

The spine module connects the UB-AXO to the LB-AXO modules and transfers the load from the UB-AXO to the LB-AXO and finally to the ground. The module was designed with three degrees of freedom to match the motion of the human lumbar spine, i.e. the lumbar flexion/extension (LFE), axial rotation (LAR) and lateral flexion (LLR). As shown in Fig. 5, the spine module adopts a biomimetic design and resembles the human lumbar spine, with a vertebral body of aluminum and intervertebral disk of rubber. This makes our design novel over other designs which connect lower and upper bodies rigidly. The compliance of the rubber disks allows all degrees of freedom to have spring-back support. Moreover, by selecting different rubber disks of varying stiffness, the spine module can provide varying levels of stiffness of the mechanism, which is essential to support users.

4. Performance assessment and analysis

4.1. Assistance control strategies

The full body exoskeleton system comprises separate UB-AXO and LB-AXO modules. Sensors and controllers were developed for motion detection and control.

The assistance control strategy is implemented in two levels; a high level and a low level control. The high-level control is based on human intention detection [20], which recognizes the users intention of motion and delivers a desirable assistance τ_d. The low-level control is a joint level control to implement the torque at the actuated joints of the exoskeleton. The low-level control is an admittance based control of assistance torque τ_{act}, referring to Fig. 6. The control uses feedback from the force/torque sensors to measure the contract force/torque between the user and exoskeleton (τ_{con}) and the motors Hall sensors to measure the velocity of the exoskeleton joint (denoted as ω_{joint}). For the UB-AXO, the interaction force is measured through force sensors embedded in the forearm cuffs (Fig. 4a). For the LB-AXO system, the interaction force-based control strategy is implemented through multiple force/torque sensors mounted at the interfaces with the wearer (the thigh, shank and foot attachments), as indicated in Fig. 4b, which detect the intentions of the human and communicate this to the control system of the LB-AXO.

It is noted that the control implementation is slightly different for the UB-AXO and LB-AXO. Further details of control for the two module can be found in [18].

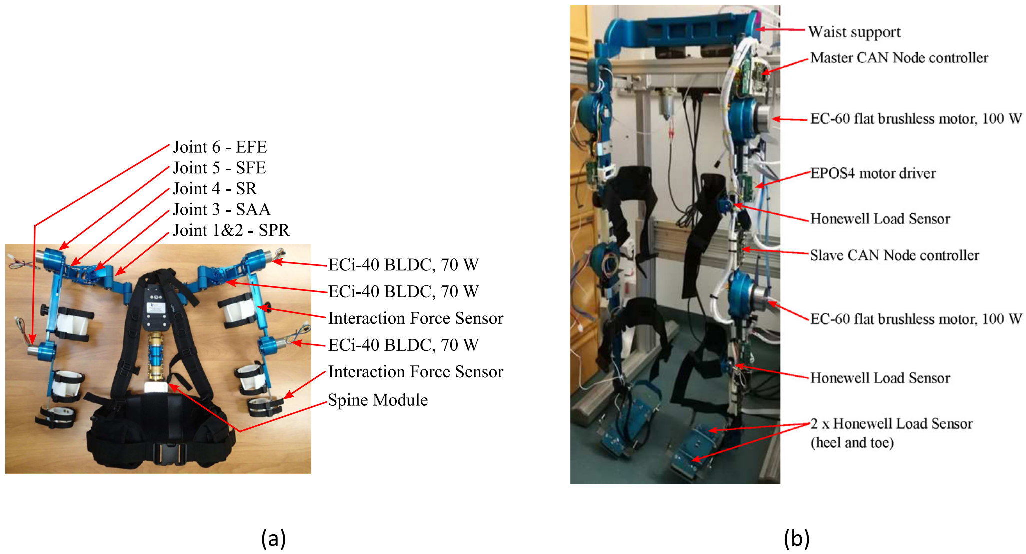


Fig. 4. AXO-SUIT subsystems, (a) UB-AXO, where SPR, SAA, SFE and SR stand for shoulder protraction/retraction, abduction/adduction, flexion/extension, and shoulder internal/external rotation respectively, (b) LB-AXO.

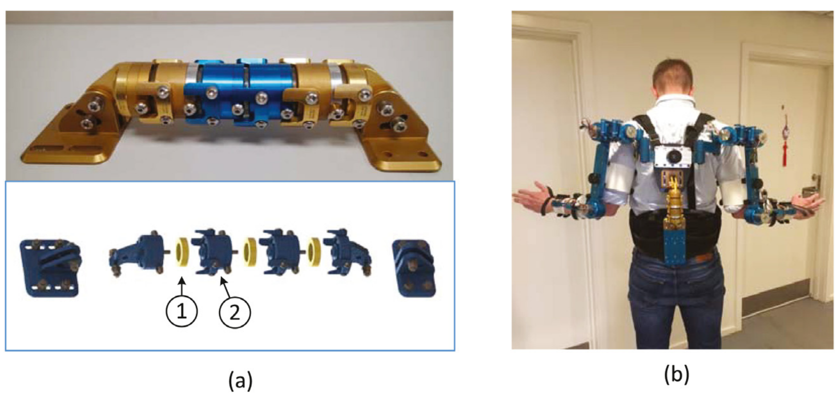


Fig. 5. Spine module, (a) an assembly and an exploded view showing (1) intervertebral disk and (2) vertebral body, (b) module mounted in UB-AXO.

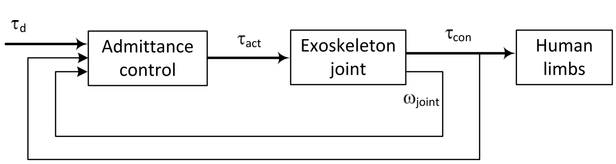


Fig. 6. Control diagram of AXO-SUIT.

4.2. Assistance performance tests

The final AXO-SUIT subsystems and the combined full-body AXO-SUIT were tested with a selection of end-users. Approval for testing was granted by the Ethics Committee for Region Nordjylland, Denmark, and all participants provided written informed consent prior to participation.

The aim of our testing was to evaluate the usability of AXO-SUIT in terms of effectiveness, efficiency and user satisfaction [21]. To test the system in a feasible, safe and ethical manner, physical testing of AXO-SUIT was split into two distinct levels:

- Level 1: Participants were healthy adults aged 18 years and over. The test protocol included performance of tasks with and without wearing AXO-SUIT. Effectiveness was recorded via objective and subjective measures of task performance e.g. task completeness, time to complete task. Efficiency was objectively measured using surface electromyography (EMG) of selected muscles, and subjectively via participant′s Rating of Perceived Exertion (RPE) for each task. User′s perceived pressure/discomfort due to the exoskeleton at specific body areas [22,23], and via open questions were recorded. Testing duration was approximately 1 h.
- Level 2: Participants were healthy adults aged 50 years and over. A simplified physical testing protocol was used, which included performance of tasks with and without wearing AXO-SUIT. Measures of effectiveness and satisfaction were recorded, as per Level 1 testing. For efficiency, EMG data were not recorded, only participant′s RPE for each task. Testing duration was approximately 0.5 h.

The UB-AXO, LB-AXO, and FB-AXO subsystems were subject to Level 1 testing, as shown in Fig. 7. Level 2 testing was performed with a limited number of participants and conditions on safety and feasibility grounds, as the participants were older adults. The tasks included in the test protocols were selected to represent activities of daily living based on the user surveys in Section 2 above. The tasks include lifting and lowering a load (6 kg) from the floor to a table ('Lift' and 'Lower'), picking up and pouring out a 1 liter container of water ('Pour'), carrying a load (6 kg) while walking ('Carry').

Our tests were focused on lifting and carrying assistance. EMG procedures were carried out to collect data for the relevant tasks with

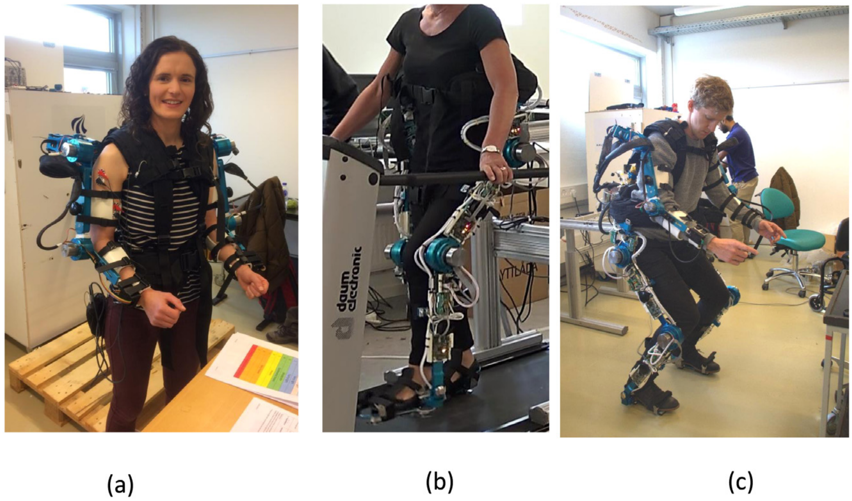


Fig. 7. Tests of AXO-SUIT modules, (a) UB-AXO, (b) LB-AXO, (c) FB-AXO.

and without wearing the UB-AXO prototype. EMG electrode locations for the biceps brachii — short head and long head, deltoid — middle, erector spinae — longissimus were selected based on SENIAM recommendations [22]. Markings were made while the participant stood in the mounted UB-AXO prototype, and if significant interference of the exoskeleton cuffs/straps with electrodes was foreseen, electrode locations were adjusted to minimize interference, while remaining on the belly of the relevant muscle, in line with the muscle fiber direction. Disposable, pre-gelled, adhesive surface electrodes (Covidien H124SG, Ag/AgCl, circular, 24 mm diameter) were placed on the belly of each muscle, in line with the muscle fiber direction, with an inter-electrode distance of 20 mm. Before electrode placement, the area was shaved and cleaned with single-use 70% isopropyl alcohol wipes to reduce skin impedance. A reference electrode was placed on the spinous process of the C7 vertebra. Surface EMG data for all tasks were recorded using the four-channel NeXus-10 MKII hardware and BioTrace+ V2017 A software (Mind Media B.V., Netherlands).

Sample test results are displayed in Tables 5 and 6, which present root mean square (RMS) muscle activities for the biceps brachii and middle deltoid muscles obtained during Level 1 testing, with and without the UB-AXO ($n = 8$; 4 male, 4 female; height 175 ± 10.53 cm, body mass 71.75 ± 10.08 kg). Table 5 presents results of assistance of carrying for 1 minute (Carry_M1), 2 minutes (Carry_M2), and 3 minutes (Carry_M3). Assistance effect can be observed, as indicated from EMG measurement of the biceps brachii in task Carry_M3. For tasks Carry_M1 and Carry_M2, the assistance is not very obvious. One reason for this might be the mutual adaptation of human and exoskeletons — the human needs time to learn how to utilize the assistance from the exoskeletons.

Table 6 lists results of other tasks. For this group of tasks, the results indicate that using the UB-AXO produced highly variable effects on muscle activity. It is notable that testing was performed wearing the UB-AXO only, as shown in Fig. 7a. Therefore, the participants had to carry the weight of the UB-AXO. This additional mass would be expected to increase supporting muscle activities overall, as shown in literature [24]. It is also noticeable that the muscle activities have a high SD variation among participants. This might be due to the differences of subjects muscle strength, compatibility with the exoskeletons, with all these affecting their muscle activities. In addition, cognitive activities may also have influenced the readings, as some subjects indicated a certain level of nervousness on wearing the exoskeleton. Our preliminary tests involved eight subjects. Tests with increase numbers of subjects would be necessary to perform statistical analysis. Table 7 details the RPE scores for the testing which indicates marginally higher RPE scores for some body regions, reflecting the weight of the exoskeleton.

4.3. User Satisfaction Questionnaire (USQ)

In combination with testing, satisfaction was measured using a modified version of the User Satisfaction Questionnaire (USQ), based on the questionnaire described in Section 2.

Overall user satisfaction reported during UB-AXO Level 1 testing was moderate, with a median total USQ score of 80 (min. = 58; max.= 87), out of a maximum possible score of 120. To identify the main positive and negative points in terms of usability, each item on the USQ was scored on a five-point Likert scale, from a score of 1 for ‘Strongly Disagree’ to a score of 5 for ‘Strongly Agree’. With 12 participants included, the maximum item score was 60. The highest and lowest rated items were then compiled to determine the most positive and negative features of UB-AXO Level 1 user satisfaction. The items with which participants agreed most were:

- Overall, I find the AXO-SUIT exoskeleton is silent. (51/60)
- It is easy for me to remember how to perform tasks using the AXO-SUIT exoskeleton. (50/60)
- When performing a task using the AXO-SUIT exoskeleton, it stops when desired. (50/60)
- Learning to use the AXO-SUIT exoskeleton is easy for me. (48/60)
- When performing a task using the AXO-SUIT exoskeleton, it moves at the desired speed. (48/60)
- When performing a task using the AXO-SUIT exoskeleton, it moves in the desired direction. (47/60)
- When performing a task using the AXO-SUIT exoskeleton, it moves when desired. (46/60)

The items with which participants disagreed most were:

- Overall, I find the AXO-SUIT exoskeleton easy to put on. (22/60)
- When performing the assessment tasks, the AXO-SUIT exoskeleton did not restrict my range of movement. (29/60)
- Overall, I find the AXO-SUIT exoskeleton easy to adjust. (31/60)
- Interacting with the AXO-SUIT exoskeleton requires a lot of mental effort. (31/60)
- I find it takes a lot of effort to become skillful at using the AXO-SUIT exoskeleton. (31/60)

It is clear that while participants were largely positive in relation to the responsiveness of the UB-AXO prototype to their movements during the performance of the selected tasks, a number of issues relating to usability were identified. The main issues relate to the wearability of the UB-AXO, specifically difficulties encountered in putting on the device, issues with adjusting the UB-AXO to fit, and as a result of

Table 5
Normalized muscle activity of biceps brachii and middle deltoid muscles in carrying task. % MVC = Percentage of participant's Maximal Voluntary Contraction; SD = Standard Deviation.

Muscle	Task	Without UB-AXO (%MVC, Mean ± SD)	With UB-AXO (%MVC, Mean ± SD)	Mean difference (%MVC, Mean ± SD)
Bicep	Carry-M1	11.78 ± 5.75	15.04 ± 6.15	2.01 ± 1.47
	Carry-M2	13.48 ± 6.83	16.00 ± 8.72	2.52 ± 1.09
	Carry-M3	14.17 ± 8.02	10.79 ± 6.81	−3.38 ± 1.21
Deltoid	Carry-M1	2.15 ± 1.05	4.65 ± 2.86	1.67 ± 0.64
	Carry-M2	2.03 ± 1.11	3.37 ± 2.08	1.34 ± 0.93
	Carry-M3	2.11 ± 1.32	2.35 ± 2.47	0.24 ± 1.08

Table 6
Normalized muscle activity of biceps brachii and middle deltoid muscles on other tasks % MVC = Percentage of participant's Maximal Voluntary Contraction; SD = Standard Deviation.

Muscle	task	Without UB-AXO (%MVC, Mean ± SD)	With UB-AXO (%MVC, Mean ± SD)	Mean difference (%MVC, Mean ± SD)
Bicep	Lift	8.99 ± 6.84	14.28 ± 23.83	5.29 ± 6.57
	Lower	11.71 ± 9.72	13.91 ± 18.17	2.20 ± 6.50
	Pour	2.79 ± 2.11	2.21 ± 1.27	−0.58 ± 0.54
Deltoid	Lift	6.21 ± 2.69	6.58 ± 4.37	0.37 ± 3.10
	Lower	5.88 ± 3.59	7.97 ± 5.03	2.10 ± 1.58
	Pour	3.09 ± 1.94	5.15 ± 2.11	2.06 ± 1.48

Table 7
Ratings of Perceived Exertion (RPE) for all tasks with and without the UB-AXO.

	No Exo	UB-AXO	
Task	Median (Min–Max)	Median (Min–Max)	Mean Diff.
Lift	3.0 (1.0–3.0)	2.0 (1.0–4.0)	−0.2
Lower	2.0 (1.0–3.0)	2.0 (1.0–4.0)	+0.2
LiftLower x5	4.0 (2.0–4.0)	4.0 (1.0–7.0)	+0.8
Pour	0.5 (0.5–1.0)	1.0 (0.5–3.0)	+1.1
Outstretched Hold	2.0 (0.5–3.0)	2.0 (0.5–5.0)	+0.8
Pour Hold	2.0 (0.5–4.0)	1.0 (0.5–3.0)	−0.9
Carry	4.0 (1.0–5.0)	3.0 (3.0–7.0)	+0.6

Note: Mean diff. is the mean of the within-participant differences for each task performed with the UB-AXO and without the exoskeleton.

poor fitting, problems with restricted range of motion. From a positive perspective, participants reported that the UB-AXO was not taxing to use, or to learn to use.

User feedback was helpful in determining short-term design improvements to be implemented in the UB-AXO and LB-AXO, and planning for future longer-term improvements. For example, user feedback from Level 1 testing of the UB-AXO resulted in the addition of extra shoulder strap padding and a layer of soft fabric to line the wrist cuffs to improve user comfort. A longer-term design revision recommended by participants to improve user comfort for both the UB-AXO and the LB-AXO was to reduce the weight of the systems.

5. Discussion and conclusions

In this paper, the design of a modular full-body assistive exoskeleton AXO-SUIT is presented. The AXO-SUIT exoskeleton enables flexible physical assistance in such a way that it can be used as a whole body system, or as either upper-body or lower body subsystem to assist persons with different needs. This is achieved through a user-centered design approach. To this end, a closed and intensive involvement of end-users was included in the system development, covering from design requirement specification to system evaluations.

The results of the end-user involvement are the two AXO-SUIT subsystem prototypes; the lower-body subsystem (LB-AXO), and upper-body subsystem (UB-AXO). The LB-AXO consists of 2 legs which each have 6 degrees of freedom, of which 2 are active and 4 are passive. Moreover, the LB-AXO is able to adjust for users with a height of 1.55–1.8 m and weight of 70–110 kg. The UB-AXO consists of a spine module with 3 passive degrees of freedom and two arms, each having 3 active and 3 passive degrees of freedom. Similar to the LB-AXO, the UB-AXO can adjust its links to fit different user sizes.

A major part of this work is dedicated to the end-user testing, which is important for human–robotic system development. The testing was conducted with selected subjects. Two levels of tests were conducted based on ethical consideration and also physical capability of different age groups. In the testing, not only objective measures (electromyography of relevant muscle groups) but also subjective measures (ratings of user exertion, comfort and overall user experience) were collected, the latter providing very valuable information reflecting the usability of the system and the user acceptance, which is quite often ignored in other exoskeleton testing. The comprehensive assessment of the exoskeleton for human motion assistance is a major contribution of this work. In general, the results show effective assistance with some users. It has to be noted the assistance effect is affected by many factors, such as the control strategy, system compatibility, and also users learning capability [25].

It is noted that the tests were focused on the upper-body exoskeleton, with the interest to learn what level of assistance on load carrying and other manipulating tasks can be achieved. For the lower-body exoskeleton, objective measures in terms of EMG were not collected, as we were unable to measure EMG reliably in the lower limb due to movement of the electrodes relative to the muscles being studied, which was not the case for the upper body. An overall assessment at the whole body level will be considered in future research.

The testing reveals also some limitations of the system, from which some lessons have been learned. One is that the system weight matters for assistive applications, particularly for the elderly user group. As the actuators account for more than half of the total weight, high power intensity actuators or cable-driven mechanisms are desirable. Another issue is the possible misalignment of human joints and the counterparts of the exoskeleton. The misalignment, when coupled with the stiff structure, can lead to motion resistance by the exoskeleton, rather than assistance, in some worst case scenarios. Moreover, a compact exoskeleton design has to be considered and achieved from a user acceptance perspective. Further improvements in compliant structure and actuation, human intention sensing, and interaction control have been considered, along with continuing performance testing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.birob.2021.100032.

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