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Development and Functional Evaluation of a Passive Ankle Exoskeleton to Support Military Locomotion

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Abstract:

This work aims to develop an exoskeleton structure that complies with a set of military requirements in line with the current operational environment demands. A design process was implemented so that these requirements could be identified and embedded in the development of a functional prototype suited for laboratory trials. The prototype was manufactured using 3D scanning and additive manufacturing technologies, and a functional evaluation of the developed solution was performed by 30 subjects to assess its suitability for military applications. Results show that the developed design is suitable for military activities, incorporating requirements addressing ergonomics, range of motion and comfort. Also, additive manufacturing is suitable for developing tailor-made exoskeleton structures, allowing for the prompt production of affordable personalized parts.

Keywords:

additive manufacturing, ankle augmentation, ergonomic design, military requirements, passive exoskeleton

1 Introduction

Although military specifications limit soldiers loads to values between 30 % and 45 % of their body weight (BW) [1-3], the current environment of military operations often leads to excessive loading of soldiers, with values topping 57 % of BW in assault load conditions and up to 73 % of BW in approach march situations. These load levels, during both training and operations, can decrease soldiers' overall capability by reducing agility and mobility due to the higher fatigue levels and increased injury risks, which results in significant operational, economic and social costs [4, 5]. Exoskeletons emerge as a potential solution for these concerns since these devices can assist the user, avoiding

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possible injuries, or can augment the user's performance and reduce the energy expenditure [4, 6].

Exoskeletons can generally be described as wearable robotics with a kinematic structure that replicates human motion and are usually applied to enhance or restore the user's capability to perform specific tasks [7, 8]. These solutions are typically composed of a rigid structure, force-generating elements and control systems. The structural components are essential to provide the functionality of the system, since these elements interact directly with the user, supporting the loads and transmitting forces. Exosuits are a particular group of exoskeletons that integrate a compliant structure instead of a rigid one, relying on the user's musculoskeletal apparatus to work [9]. The structural components are usually actuated by force-generating elements, which are managed by the control system that includes sensors and processing units to provide assistance when needed [10].

According to their actuation, exoskeletons can be divided into three major groups: active, passive and quasi-passive [11, 12]. In the active solutions, the actuation is made by way of an external power source, which is usually applied to feed the electrical motors [13], hydraulic [10] or pneumatic [14] systems. In contrast, passive solutions do not use external power sources, relying only on passive force elements, like springs and dampers, to store, release or dissipate energy [15, 16]. Quasi-passive exoskeletons consider the use of external power sources for control purposes only, being the actuation provided by passive elements [12].

The application of exoskeletons in military operations is an emerging topic that is currently being encouraged and supported by military alliances, such as the North Atlantic Treaty Organization (NATO) [17] or the European Defence Agency (EDA) [18]. In keeping with this trend, this work aims to develop an exoskeleton structure that meets the military requirements identified during the study, which are, in effect, common to any potential user of these solutions. Moreover, since 80 % to 85 % of the energy expenditure in gait – one of the key movements performed during a military operation – occurs at the ankle level [19], this work will focus on the development of a dual-use passive solution for this joint that allows for the reduction of metabolic costs while walking. The choice of a passive solution arises from the advantages of not requiring external power sources, being lighter and having a low electromagnetic profile.

To accomplish this objective, a concept development process was implemented, consisting of the identification and sorting of the exoskeleton requirements and the design and development of a physical prototype, which considered the use of novel 3D technologies, such as 3D scanning and additive manufacturing (AM) alongside with computer-aided design (CAD). The reliability, comfort and functionality of the developed solution were tested by a group of 30 male subjects from the Portuguese Armed Forces.

2 Materials and Methods

A concept development process, based on the model presented by Ulrich and Eppinger [20, 21] and with adaptations relative to the specificity of the developed product, was implemented to develop an ankle exoskeleton prototype that can be used in military operations. To reach a final product, the proposed methodology features six major steps: opportunity identification, needs analysis, product specifications, concept generation, prototyping and testing, and results analysis, all of which are detailed below.

2.1 Opportunity Identification

To identify the exoskeletons available in the literature, a state-of-art analysis was conducted considering solutions for lower limbs in medical, industrial and military fields [11]. Focusing on human augmentation exoskeletons, several solutions were identified that included systems developed for industrial, defense, public security and civil protection sectors [10, 13, 15, 22, 23]. Since then, other works have been published presenting novel or validating previous concepts, which showed promising results regarding the reduction of metabolic costs [9, 24-26]. Solutions based on complacent structures have also been proposed, achieving a decrease in the energy expended during gait. In particular, Quinlivan et al. tested different levels of active assistance in an exosuit, obtaining a reduction of approximately 22 % for the best tested case [9]. Similarly, Lee et al. presented an active exosuit for load-carrying that achieved a reduction of the metabolic costs of approximately 15 % when compared to walking without any assistive device [25].

Among the current challenges of exoskeleton solutions for military purposes, the development of long-lasting and lightweight batteries stands out since the resolution of this problem would allow for the increase of the exoskeletons' autonomy while simultaneously reducing their weight. Other issues that need to be taken into consideration are the prevention of misalignments during long term use and the development of control methodologies for better interaction between the exoskeleton and the user. Passive and quasi-passive systems emerge as possible solutions to address the issue of energy needs [15, 24]. However, these approaches tend to be less efficient and, in some cases, fail to achieve a clear reduction of the metabolic costs [16].

Specifically addressing ankle exoskeletons, several studies achieved the reduction of the metabolic costs during walking [9, 13, 15, 26]. In one of these projects, Collins et al. [15], followed later by other researchers [23], were able to develop a passive and autonomous system capable of reducing metabolic costs during walking by 7.2 % ± 2.6 %. The working principle of this device is based on an elastic system that actuates the ankle joint in parallel with the calf muscles and Achilles tendon, storing elastic energy during the initial and midstance phases of the gait cycle and releasing it during the push-off phase of the gait cycle. The system is controlled by a mechanical clutch that locks the elastic system during the initial and midstance phase and unlocks it during the swing phase to allow the free movement of the foot [15]. Although with promising results in terms of metabolic cost reduction during walking, this system presents limitations for potential military use since it restrains the range of motion (ROM) of the ankle joint allowing only 1° of freedom (DOF). Moreover, the use of a carbon fiber insole could compromise the user's comfort during long term use, as the insertion of one more element in the interior of the shoe can interfere, in some cases, with footwear ergonomics, requiring an adaptation in the existent insole or a larger shoe size.

2.2 Needs Analysis

The identification of product requirements [21] was determined based on three main vectors: specific requirements from previous and ongoing studies in this field [4, 6, 22]; non-structured interviews with military personnel with significant operational experience (10 in total); and focus groups meetings with specialists from military, physical training, medicine, biomechanics, and engineering areas. The initial analysis allowed for the identification of a list of requirements that should be considered in the development of an exoskeleton for military purposes (Tab. 1). Essentially, the identified

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requirements were mainly associated with safety, functionality, geometry, ergonomics, and cost, while being reliable and easy to use and maintain.

Tab. 1 List of the principal requirements identified in the first steps of the needs analysis for a military exoskeleton

Requirements	Designation	Requirements	Designation
Do not compromise users' safety	A	Ergonomics	I
Quick and easy donning/doffing	B	Not being affected by adverse Weather/environmental conditions	J
Minimize users' fatigue	C		
Ease of use	D	Comfortable during long term use	K
Lightweight	E	Robustness	L
Not having an electromagnetic signature	F	Noiseless	M
Portable	G	Range of motion	N
Simple maintenance	H	Autonomy	O

To better assess the impact of each requirement in the development process and its importance for its users, a Mudge diagram was applied [21] (Tab. 2). This tool allows for the assessment of different characteristics by evaluating the relative importance of one with respect to the others, allowing to understand what requirements are considered the most relevant for the users. Based on the previous method, the most significant requirements were: (A) not compromising user safety, (I) having good ergonomics, (K) being comfortable during long term use, (C) minimize user fatigue, (E) being lightweight, (N) maintaining user range of motion, and (O) having good autonomy.

A Kano model was also implemented to assess user perspectives on this kind of product [20]. Fig. 1 shows the results for the Kano model implementation for user satisfaction relative to the use of exoskeletons in military operations. The following were identified as essential features: being safe to use, robust, being comfortable during long term use, good ergonomics, minimizing user fatigue and being functional under adverse conditions. The features of maintaining joint ROM, being lightweight, having good autonomy and requiring low maintenance were identified as performance needs. Finally: low noise emission, having different modes of use and allowing feedback were identified as excitement or delighters.

2.3 Product Specifications

After identifying user requirements and understanding their effect on customer satisfaction, these were converted into technical specifications to feed the design process (Tab. 3). The selected specifications are mainly related to the physical characteristics of the exoskeleton, such as volume, weight, and functionality (e.g., ROM, metabolic costs reduction, noise, reliability and ease in dressing (donning) and undressing (doffing) the system). The limits for each technical specification were defined according to its applicability in military operations.

Tab. 2 Mudge diagram assessing the relevance of each product requirement

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	Total	%	Rank
A	A3	A1	A3	A3	A5	A3	A3	A1	A3	A3	A3	A5	A3	A3	42	19	1
	B	C3	0	E1	B3	G3	B1	I3	J1	K3	L1	M1	N1	O1	4	2	12
		C	C3	C3	C3	C3	C3	I1	C3	K1	C1	C1	C3	C1	27	12	4
			D	0	D1	G3	D1	I3	J1	K3	D1	D1	N1	O3	4	2	11
				E	E3	E3	E3	I3	E3	K3	L1	K1	N1	O3	19	9	5
					F	G1	0	I3	J1	K3	L3	M3	N3	O1	0	0	15
						G	G3	I3	G1	K3	G1	G1	N3	O1	13	6	8
							H	I3	H1	K3	L3	M3	N3	O1	1	0	14
								I	I3	I1	I3	I3	I1	I1	31	14	2
									J	K3	L1	M1	N1	O1	3	1	13
										K	K1	K3	K1	K1	28	13	3
											L	L1	L1	O1	11	5	9
												M	N1	O3	8	4	10
													N	O1	14	6	7
														O	16	7	6
													Sum		221	100	

Relationship	**Value**
Much more important	5
More important	3
Somewhat more important	1
Equal value	0

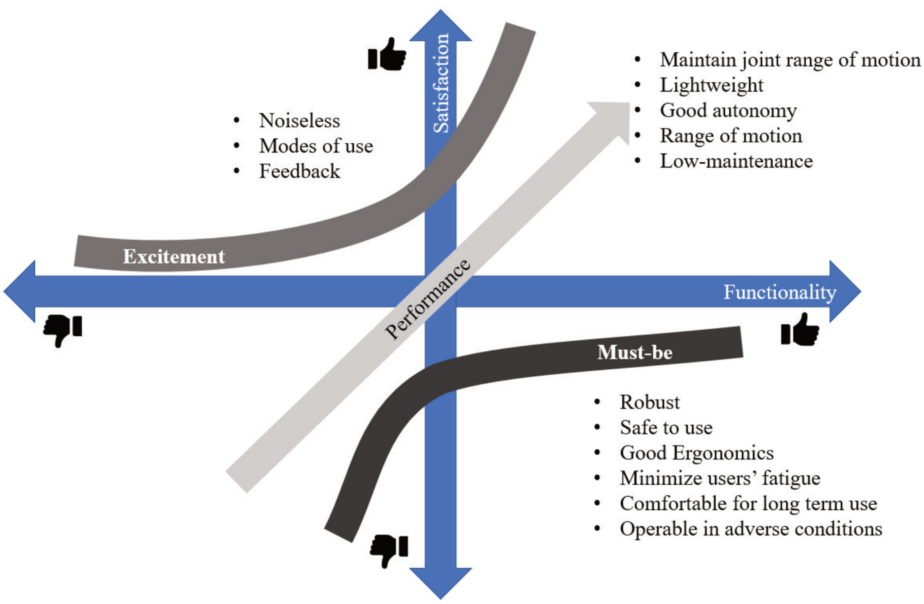

Fig. 1 Kano model implementation for customer satisfaction

Tab. 3 Exoskeleton technical specifications

Requirements	Description	Limits	Units
A, B, E, G, I	Maximum length	< 400	mm
C, G, I, K	Weight	< 0.65	kg
B, D, G, H	Number of breakdowns	< 1 every 10 h	unitary
A, I, K	Mechanical Properties (Von Mises stress)	60 % of the yield strength of AM material	MPa
A, I, K	Body contact area	> 50 × 50	mm^2
A, I	Degrees of freedom	3DOF	unitary
A	Minimum radius of edges	>1	mm
B, D, H	Donning/doffing	< 300 (5 min)	s
C, I, K	Metabolic costs	> 5 %	MET
D	Training time	> 10	min
G, I	Volume	< 400 × 200 × 200	mm^3
A, F, J, M	Noise	< 20	dB

As a result, the structure should be simultaneously comfortable and robust to sustain the efforts related to walking with heavy loads on uneven terrain. It should result in the reduction of metabolic costs without requiring a long training period. Due to the nature of the missions, the system should be noiseless and should not require long donning and doffing times.

2.4 Concept Generation

The generation of the exoskeleton concept was divided into two main stages: *i*) selection and development of the actuation unit (clutch and force elements); and *ii*) design and development of the exoskeleton structural elements.

For the actuation unit, the selected concept followed the passive system presented by Collins et al. [15]. The clutch components were modelled in the SolidWorks™ 2017 CAD software (Dassault Systèmes®, France) following the specifications presented in the original work and then produced recurring to a Leadwell V-40 CNC milling machine (Leadwell®, Taiwan). A set of three coil springs with different stiffnesses (8.42 kN/m, 7.06 kN/m, and 4.80 kN/m) were used to test different levels of assistance. The stiffness values were selected according to the values presented in the original work. The connection between the spring element and the exoskeleton structure was achieved using a steel cable to minimize its influence on the force transmission between the actuation unit and the structural elements.

The exoskeleton structure was developed to meet the requirements and specifications identified in the preceding stages. The development of the new structure focused on two major tasks, namely: *i*) redesign of the exoskeleton structure; and *ii*) emulation of the joint ankle.

The exoskeleton structure is responsible for supporting the control and actuation systems and for the interaction with its user. Both parts were designed with attention to the anthropometry of the user, ensuring the comfort of the solution during long periods of use. The selected concept consists of a modular product composed of two main sections, one connected to the leg (upper structure) and the other fixed to the footwear (lower structure). The two elements were designed to be produced using AM since these techniques allow for quickly obtaining an affordable and lightweight solution optimized for each user. The upper structure was designed to include only one vertical beam, located in the lateral aspect of the leg that, when combined with a proper mechanical joint, ensures 3 DOF at the ankle, enabling walking on uneven terrain, topped by a semicircular part that supports the clutch system and attaches to the leg. This latter element makes use of a VELCRO® strap to secure the structure to the limb, allowing for fast and easy donning and doffing.

The lower element was designed to be exteriorly attached to the footwear sole. Despite, at this stage, requiring the drilling of the footwear, this solution preserves the ergonomics and comfort of the shoe, avoiding the use of rigid insoles while being easily adapted to different footwear options.

To emulate the ankle joint range of motion, the proposed concept considers a solution that preserves the movement of the talocrural and subtalar joints (3 DOF), resorting to a radial spherical plain bearing, allowing for free ROM in the sagittal plane (plantar and dorsiflexion) and in the coronal plane (unconstrained eversion and inversion movements up until 15°) [27].

A qualitative analysis of the clutch position on the exoskeleton was also performed, resulting in it being placed in a position identical to the original concept [15]; i.e., the clutch was integrated in the posterior part of the upper structure and the force transmission elements were aligned with the action line of the Triceps Surae muscle. This way, the clutch is placed in a proximal part of the body, which reduces the inertia of the system, and the force elements directly promote the movement of the ankle in the sagittal plane without the need for more structural elements and mechanisms, reducing the exoskeleton overall weight.

2.5 Protocol for the Design and Development of a Customized Ankle Exoskeleton Structure

The design procedure considered the application of different methodologies to achieve a fully customized structure, comprising three design steps: *i*) 3D scanning; *ii*) modelling and simulation; *iii*) 3D printing. To obtain the geometries for developing the two exoskeleton structures, the scanning procedure was divided into two steps: footwear and lower limb imaging. Both procedures were performed resorting to an EinScan Pro™ scanner (SHINNING 3D Tech. Co. Ltd., China) with the EinScan Software™ V2.6 software. The processing of the points cloud and geometry mesh was also performed in the EinScan™ acquisition software. 3D modelling was performed in CAD software SolidWorks™ 2017 (Dassault Systèmes®, France). The reference geometry was created by combining both the scanned geometries of the leg and shoe and used both in the design and analysis of the structural components of the exoskeleton. Fig. 2 illustrates the concept development sequence, from the mesh obtained using 3D scanning to the final version.

Since the intended goal for this phase of the project was the development of a Technology Readiness Level (TRL) 4 solution, which would allow for the validation and laboratory analysis of the concept, a Fused Filament Fabrication (FFF) printer with polylactic acid (PLA) [28] was used to produce the physical prototype. This material was selected considering its ease of use and setup, significant mechanical properties, low cost, and wide availability. The software used to convert the 3D mesh to a G-code file was the Ultimaker Cura™ (Ultimaker B.V., Netherlands). The printer used to build both elements was the Sharebot™ XXL (Sharebot S.r.l., Italy).

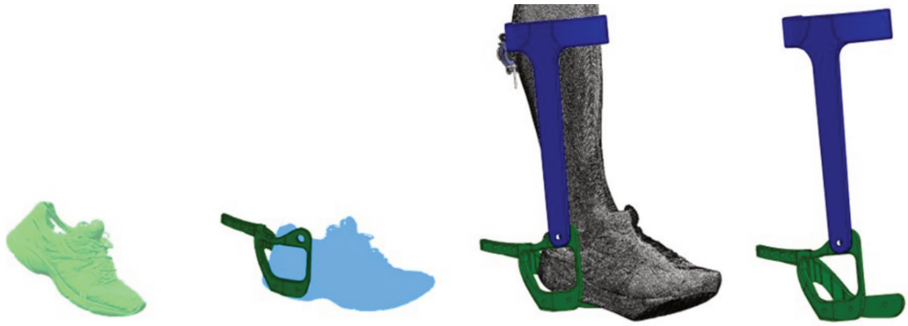

Fig. 2 Foot segment modelling sequence.

2.6 Proof of Concept

To determine if the structure performed as expected, the exoskeleton was assembled using the following sequence: 1) Two holes were drilled into the footwear sole, in a rear mid-position, so that neither the comfort nor the ergonomics of the shoe were significantly affected; 2) The lower structure of the exoskeleton was fixed to the footwear using two steel threaded rods; 3) The radial spherical plain bearing was assembled in the lower structure using epoxy glue; 4) The clutch was fixed in the posterior part of the upper structure, using bolts and nuts; 5) A non-abrasive protection material (Lightweight polyethylene foam – Pelite®) was applied in the interior of the structure, where it contacts with the shin; 6) Both parts were connected using a nylon screw; 7) The steel cable and spring were connected. After the assembly, the exoskeleton was tested, replicating the gait cycle (Fig. 3). The full assembly of the exoskeleton can be seen in Fig. 4.

Fig. 3 Exoskeleton motion sequence during the gait cycle

Following the guidelines presented in [6], a set of controlled tasks was also performed with the exoskeleton to assess its mechanical behavior and the interaction between the structural components and the user (Fig. 5).

The performed tasks included analysis of the ankle ROM, levelled ground and uneven terrain walking, movement between operational tasks (prone, crouched, seated, standing upright), change between firing positions (prone to taking-a-knee to upright), crawling and stepping over obstacles. The geometry of the rear spring support was identified as a limitation when progressing in uneven terrain, locations with dense vegetation or while passing through tight sections. Nevertheless, the exoskeleton showed no significant limitations regarding the safety of its potential users, ROM, comfort, or its working principle; therefore, it was considered suitable for experimental trials.

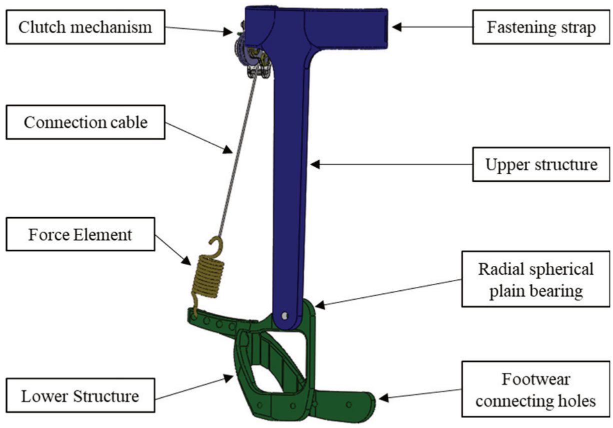

Fig. 4 Exoskeleton full assembly

Fig. 5 Functional movements: firing positions (prone; taking-a-knee; upright), crawling and stepping over obstacles

2.7 Concept Experimental Trials

The evaluation of the exoskeleton functionality and comfort was performed in the Lisbon Biomechanics Laboratory, using a WolfMedica Marathon Medical treadmill (WolfMedica Hellas – Medical Technology SA, Greece). Following the literature and the stage A guidelines for military exoskeletons, a protocol based on the 6 Minute Walk Test (6 MWT) with a fixed speed of 4 km/h was implemented [4, 6, 15, 29].

To minimize the overall costs of the project, all trials were performed with one structure that was developed based on the limb geometry of one volunteer – subject zero. This arrangement also made it possible to provide more load (working time) to the prototype to evaluate its performance on a long-term basis.

Thirty subjects participated in the study and were selected according to the following inclusion criteria: 1) no history of musculoskeletal and neuromuscular disorders; 2) regular physical training; 3) belonging to the Portuguese Armed Forces; 4) Foot size between 41 EU and 43 EU; 5) Body mass index (BMI) between 18.5 kg/m^2 and 29.9 kg/m^2 (normal or pre-obesity categories). In order to allow for the use of the same exoskeleton structure during all the trials, the volunteers were selected so that their anthropometric values, namely weight, height, BMI and calf circumference, would be similar to subject zero.

The study was submitted to the ethics committee of Instituto Superior Técnico (Universidade de Lisboa) and was approved in July 2020 (Ref. nr. 16/2020 (CE-IST)). The trials included an adaptation period of 25 minutes [30], followed by another period of 10 minutes wearing the exoskeleton to allow for a progressive adaptation to the structure. The main test was divided into five steps, each one with 7 minutes in length, to ensure 6 minutes at a stable speed, according to the following conditions: 1) walking with no exoskeleton; 2) walking with exoskeleton without actuation; 3), 4) and 5) walking with the exoskeleton actuated with three springs with different stiffnesses. After performing the walking trials, the volunteers were asked to fill in a short questionnaire concerning the performance of the exoskeleton.

3 Results

The experimental analysis of the developed prototype suggests that the application of additive manufacturing techniques supported by 3D scanning can be used to achieve an affordable and customized exoskeleton solution with possible applications in military operations.

Results associated with product specifications were obtained for all the analyzed topics (Tab. 4). Regarding the exoskeleton structure, the maximum length is 0.32 m (referring to subject zero with 1.77 m), when disassembled. In the same mode, once disassembled from the footwear and with both structures disconnected, one pair of exoskeletons can be packed into a container of (160 × 330 × 150) mm, being easily transported during military operations. The total weight of each exoskeleton structure with the actuation unit is 0.52 kg and can be attached to and removed from the footwear in less than 5 minutes, half of the product specifications limit. It is important to note that in case of emergency, the system can be removed together with the footwear in less than 10 seconds. Regarding ankle mobility, the results indicate that the structure does not severely restrain ankle ROM, even when walking in uneven terrain, since the 3 DOFs approach, achieved with the inclusion of the radial spherical plain bearing combined with one lateral beam upper structure, allows to preserve the mobility of both the talocrural and subtalar joints (inversion/eversion – 15°; plantarflexion/dorsiflexion – 360° (without the actuation system)). In fact, the constraints introduced by the bearing in the coronal and axial planes are consistent with the ROM of the ankle joint, avoiding excessive movements in these planes, preventing ankle sprains.

During the performed trials, the exoskeleton structure did not present breakdowns, delivering consistently for over 19 hours. No lesions related to skin abrasion were detected in the volunteers, indicating that the shin contact area (40 mm^2 × 90 mm^2), with the protective material, was enough to decrease the pressure to non-injury levels. Finally, the training period for the treadmill and exoskeleton was superior to the time defined in the product specifications, being in line with the values reported in the literature [4, 6].

A preliminary structural analysis of the upper and lower elements, carried out with the finite elements analysis (FEA) toolbox available in SolidWorks™ 2017, showed stresses lower than 12 MPa, under 60 % of PLA yield strength [28]. The exoskeleton was not tested for noise levels since no sound was detected from the structural components. However, when actuated, it is possible to hear some noise related to the clutch operation.

Tab. 4 Product specifications results

Description	Limits	Results	Units
Maximum length	< 400	321	mm
Weight	< 0.65	0.525	kg
Number of breakdowns	< 1 every 10 h	0	unitary
Mechanical Properties (Von Mises stress)	(PLA) 20	<12 (FEA)	MPa
Body contact area	> 50 × 50	40 × 90	mm^2
Degrees of freedom	3 DOF	3 DOF (15º, 360º)	unitary/degree
Minimum radius of fillets	> 1	2	mm
Donning/Doffing	< 600	< ~300	s
Metabolic costs	< 5 %	Not tested	MET
Training time	> 10	25 + 10	min
Volume	< 400 × 200 × 200	6.22×10^{-3} (0.321 × 0.155 × 0.125)	m^3
Noise	< 20	Not tested	dB

Results referring to the questionnaire confirmed the good mobility and comfort of the developed solution (Tab. 5). In question 1, all volunteers answered that the training time was enough to get used to the exoskeleton, indicating good adaptability to the developed structure. Question 2, which evaluated the ROM of the ankle joint, indicated moderate to great mobility, not referring to significant limitations on the movement while using the exoskeleton. The comfort assessment described the apparatus as neutral to comfortable. Two users mentioned a slight discomfort in the ankle (contact with the structure) and five mentioned discomfort on the shin, suggesting a larger contact area. Only one of the volunteers indicated feeling the connecting rod in the footwear while walking. As for question 4, 90 % of the subjects stated that they would consider using an exoskeleton with similar characteristics over extended periods in their military activities and daily life. The last question, which focused on recommendations, pointed to the reduction of weight and clutch noise and the development of a compact structure as possible improvements. Three of the subjects indicated the limitation in the ROM provided by the use of a spherical bearing as an advantage since it could prevent an ankle sprain. It was also recommended that the actuation system should have a more progressive action, and the attachment site of the attachment lower part should be redesigned to avoid possible limitations while progressing on uneven terrain.

4 Discussion

Results suggest that additive manufacturing techniques can be used to develop an exoskeleton structure, with 90 % of the volunteers indicating that they would consider using a similar system during military operations. The use of additive manufacturing allows for the development of an affordable customized solution with a significant impact on comfort and overall performance. When implemented and tuned, the protocol for the design and development of the customized structure can lead to the delivery of the exoskeleton in under 24 hours.

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Tab. 5 Result of the qualitative analysis of the exoskeleton performance

Question	Scale	Answer
1. Did you consider the adaptation period adequate to get used to the exoskeleton?	Yes or No (if the answer is no, please suggest a different period)	91 % [Yes]
2. Please evaluate the exoskeleton in terms of the range of motion of the ankle, considering the following scale:	Likert Scale: 1 – Strongly Limited; 2 – Limited; 3 – Moderate; 4 – Free Mobility	3.1 ± 0.63
3. Please evaluate the exoskeleton in terms of comfort, considering the following scale:	Likert Scale: 1 – Very uncomfortable; 2 – Uncomfortable; 3 – Neutral; 4 – Comfortable	3.1 ± 0.51
4. Would you consider using this structure for long periods?	Yes or No (if the answer is no, please support your answer)	90 % [Yes]
5. Based on your experience, please give us some insights about what you would improve or change.	Not Applicable (N.A.)	Noise; weight reduction; bulkiness;

The developed solution was able to complete 30 trials without structural failure. If a failure occurs, each part can be substituted for a pre-printed part or repaired using specific glue in less than 20 minutes, a key feature in military operations.

All the technical specifications defined for the solution were achieved. Nevertheless, the weight and volume items can be further improved if a structural optimization approach is followed.

Timing is a critical issue in military operations. With the proposed system, it is possible to put on the exoskeleton in less than 5 minutes. Moreover, and in case of emergency, the removal time can be less than 10 seconds if the user removes the exoskeleton together with the footwear. Noise and metabolic costs during walking were not addressed in this study.

An important aspect identified during the needs analysis stage was the mobility of the ankle joint. The ROM, provided by the use of one lateral beam together with a radial spherical plain bearing, enables its application in missions that require walking on uneven terrain, stepping over obstacles, among other tasks. The adopted solution also allows for improved comfort and performance while executing crawling and prone shooting tasks. Moreover, the constrained joint prevents excessive movements, minimizing possible ankle lesions. Questionnaire results validate this idea grading the mobility of the ankle joint as moderate to great.

Each user was asked to evaluate the exoskeleton in terms of comfort, based on his perception during the trials, rating it as neutral to comfortable. These results are promising as the prototype was not fully optimized for each subject. Only one volunteer indicated a slight discomfort at the foot level caused by attaching the structure to the shoe. This result supports the design purpose of preserving the ergonomics of the insole and footwear. Nevertheless, it is expected that the comfort and overall performance would be improved with a fully customized exoskeleton, as it would permit mitigating some problems reported during the trials. In particular, the unwanted contact at the ankle level reported by two of the volunteers and a high-pressure contact in some regions of the shin mentioned by five users.

During the laboratory trials, some noise was produced by the control mechanism (clutch) and the relative motion of the force element (spring). This issue will be considered in future versions since it is out of the scope of this work, as the actuation solution was based on a previous study. As for the developed structure, it presents a low noise emission since the only movement apparatus is the radial bearing applied to emulate the ankle joint.

When compared with the Collins et al. structure [15], the proposed solution made it possible to achieve three constrained DOFs, contrasting with the 1 DOF approach followed by Collins et al. [15], which is essential for balance and progression on uneven terrain. The choice for using an external connection with the foot made it possible to maintain shoe ergonomics, avoiding, in some cases, the need for larger-size footwear or the adaptation of the original insole to sustain the internal structure. Furthermore, the duration of the missions can extend for several hours, thus using a shoe that is ergonomically similar to the one the soldier uses regularly is important to ensure his comfort during long-term operations.

Fully customized solutions are certainly an added value for the orthotics and exoskeleton industry, as they enable the development of a product that fits the user's needs. The use of 3D scanning and modelling alongside with AM techniques could bring about this objective since, besides having an important role during the first TRL stages of product development, these can also be used in later stages to manufacture products in which customization is either essential or an added value.

It is important to note that the ideal solution often requires the acquisition of the user's limbs geometry to obtain a fully customized model, which is expected to be more comfortable during long term use. The idea of a customized solution is clearly supported by the product requirement analysis, which indicated that ergonomics and comfort during long term use were relevant characteristics for the final solution. Given the current manufacturing procedures, the AM stands out as one of the most promising methodologies as it makes it possible to produce a unique product that fulfils the user's needs in a reasonable time and at a low cost.

As limitations of the current work, it is important to note that no structural optimizations were carried out in the development of the structures. Moreover, this study did not evaluate the changes in metabolic costs. Also, the studied sample was composed of young, healthy adults in good physical condition, which does not allow to extrapolate the results to a broader population. Regarding the additive manufacturing techniques, the present work considered the use of PLA for the development of the prototype, which is known to have characteristics that limit its use outdoors. Therefore, another material should be considered when stepping up to a TRL 5 stage.

Future work will consider the use of structural optimization methodologies to achieve a lighter solution. The design of the structure will also be addressed to reduce the overall volume and bulky shape, focusing specifically on the attachment site of the lower structure. Other materials, with better mechanical and outdoor performances, should also be tested to enable the assessment of the structure in operational environments. Although the developed structure preserves ankle mobility, when the clutch is locked, the spring restrains the dorsiflexion movement. This behavior could reduce users' comfort while performing specific tasks. Consequently, the next steps should consider the development of a control system that allows for the unlocking of the actuation unit when it's not being used. The evaluation of the metabolic costs during gait, as well as functional testing in an operational environment, should also be addressed in future work.

5 Conclusions

This work had as main objective the development of an exoskeleton structure fitted for military operations. A concept development process was implemented to identify and define the major product specifications aiming at the reduction of the metabolic costs associated with walking. A modular structure was designed, consisting of two parts connected at the ankle level with a radial spherical plain bearing, to preserve the talocrural and subtalar movement. To avoid limitations during the performance of the most common military tasks, the upper structure was designed using only one lateral supporting beam. This way, using the exoskeleton while performing military movements, such as crawling, stepping over obstacles and fast variations between different firing positions, will not be uncomfortable for the user. Moreover, the external connection adopted for the lower part allows for the easy adaptation to different footwear types and the maintenance of their ergonomics. The prototype was subsequently produced using FFF technology, and a functional evaluation was performed by 30 volunteers belonging to the Portuguese Armed Forces.

The laboratory evaluation suggests that the adopted design is suitable for military activities, namely regarding ergonomics, range of motion and comfort. The prototype achieved satisfying scores in terms of comfort and mobility, with 90 % of users referring that they would consider using a similar system in the future. Moreover, additive manufacturing techniques proved to be a suitable solution to develop affordable and reliable exoskeleton structures, customized for the users' needs, not presenting any failure during all the walking trials.

The main outcomes of this study are the identification of a set of military requirements for the development of exoskeletons, and the development of an exoskeleton structure in line with such requirements, specifically addressing ergonomics and comfort.

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