Development and Analysis of a Passive Ankle Exoskeleton for Reduction of Metabolic Costs in Gait

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ABSTRACT
Locomotion results from the combination of the nervous, muscular and skeletal systems, allowing humans to walk efficiently in the most diverse daily activities. A growing interest in enhancing human capacities using exoskeletons is clear, specifically in areas like defence or industry.
The main goal of this dissertation is the design and development of a passive exoskeleton to reduce metabolic costs during walking. The solution was developed based on an existing concept, addressing specific issues like the mobility of the ankle, maintaining the ergonomics of its users' shoe and the possibility of customization of the structure.
To evaluate the developed solution, a study was performed in the Lisbon Biomechanics Laboratory (LBL), using a spirometry monitoring system and a medical purpose treadmill. 14 subjects, belonging to the Portuguese Army were selected for this study. A quantitative analysis was conducted to 7 subjects, aiming to measure the metabolic costs during walking, with and without the exoskeleton, thought the evaluation of oxygen consumption. A qualitative analysis was also performed to all 14 subjects, targeting the mobility of the ankle, comfort and overall perception of the systems functionality.
Results show a reduction of the metabolic costs during walking in 4 of the 7 subjects. The average results suggest that the customization and tuning of the structure, force elements and control system play a key role in the efficiency of the developed solution, which materializes the future work focus of this dissertation.

Key words: passive exoskeleton, ankle, metabolic cost, gait, spirometry

INTRODUCTION

Locomotion is an essential task for human life, occurring due to the combined action of the nervous, muscular and skeletal systems, allowing us to walk efficiently in the most diverse daily activities. However, despite being at a very high efficiency level, the study of ways to minimize energy expenditure as well as joint wear is of great interest, in areas like defence, industry or rehabilitation [2]. Military activities, whether training or combat, depend on the mobility of the soldier, having to carry their individual equipment, which usually includes a backpack, personal protective equipment and their weapon. All this equipment culminates in a huge quantity of material transported, representing a great percentage of the corporal weight of a soldier. In addition to the factors already mentioned, the movements that a military does usually happen in irregular or inclined terrain, leading to a large expenditure of energy, and a high risk of injury [3-7].

Research into complex mechanical systems to amplify the movements of the human body has been increasing since the nineteenth century. However, the development of exoskeletons began in 1956 when Lent proposed the first technical concept, followed by Mizen in 1966, and then continued by General Electric in the late 1960s. The active exoskeleton, presented by Hardiman in 1971, was the first practical investigation that studied the use of exoskeletons for materials handling [8]. The two major areas where the use of exoskeletons is currently present are the enhancement of abilities in individuals without physical limitations and the support and/or correction of pathologies related to movement. The first comprises the exoskeleton systems normally used in the industrial, defence, public security and civil protection sectors. In this area of research, active devices have become the most studied type of exoskeletons, largely due to the technological evolution that has occurred during the last decades of control systems, sensors and actuators [9] and due to the large force capability, which they can provide in various functions.

Exoskeletons can be classified into three categories, according to whether they use or not an external power source, namely to as active, passive or quasi-passive. Passive exoskeletons are usually lighter, but due to the lack of power supply and electronic systems, they are not able to provide the mechanical power needed for more complex tasks. Active exoskeletons generally have integrated electronic control systems that can understand and learn the behaviour that the skeletal muscle system adopts for the different conditions that it is subjected to and use external power sources to actuate the human motion. A quasi-passive exoskeleton does not actively add power at the joints of the wearer but can integrate several other systems to control the device functioning [10, 11].

The main goal of this dissertation it to develop a passive ankle exoskeleton to support human locomotion focused on the degrees of freedom of the structure in the connection between the foot and leg modules that constitute it, and the development of a customized structure adapted to the physiognomy of the user and its footwear.

BACKGROUND

Ankle anatomy

The ankle joint is composed by three different joints: the tibio-tarsal joint, which controls the foot in the sagittal plane and is responsible for the propulsion and restraint required during gait; the subtalar joint that controls the foot in the frontal plane and is responsible for the inversion/eversion of the foot and the midtarsal joint. The tibio-tarsal joint is a hinged synovial joint, and presents only a degree of freedom, which allows only the execution of plantar flexion and dorsiflexion movements, commonly referred to as flexion and extension, respectively. The movement of the ankle foot is rarely performed singularly, resulting from a combination of other articulations, namely the subtalar and midtarsal, allowing plantar flexion to be associated with adduction and abduction of the foot, and dorsiflexion is associated with abduction and pronation of the foot.

These three ankle joints, supported by the axial rotation of the knee, form a single joint with three degrees of freedom, allowing the foot to move in any position in the space and that adapts to irregularities present in the ground [12].

Metabolic cost

The function that muscles exert as well as their energy source is described by Wasserman *et al* [13], i.e. the muscular system can be considered as a machine that is fed by the chemical energy that results from the food ingested and stored in the body in the form of carbohydrates or lipids. This energy source is usually termed as metabolic energy cost or metabolic costs and is believed to play an important role in locomotion.

Metabolic energy costs measure the effort that a person needs to make to perform an activity. This amount of energy can be estimated through gas analysis systems, which measure oxygen uptake and carbon dioxide production [14]. The energy cost of physical activities can then be classified by the ratio between the volume of oxygen required to perform a given task and the volume of oxygen used when an individual is at rest [15]. This ratio is called Metabolic Energy Task (MET), and through it we can quantify the intensity level of an activity. The reference value of this unit of measure represents the metabolic cost of an adult in the seated rest position [16], which corresponds to Equation 1.

$$1\,MET = 3.5\,ml\,O_2 \cdot kg^{-1} \cdot min^{-1} \quad (1)$$

Ankle exoskeletons

Chen *et al* [17] states that in addition to the exoskeletons for gait support, clinical rehabilitation and human enhancement, there are also devices to reduce the metabolic costs of the referred activity. Despite the efficiency that the human being presents in the gait cycle developed over centuries of human evolution, this task continues to generate a considerable expenditure of metabolic energy in daily life. Thus, systems that reduce fatigue in people, allowing walking for longer, are important to be studied. However, despite the difficulties in improving gait metabolic expenditure, a recent work, supported by an ankle exoskeleton, was able to achieve a significant reduction of the metabolic rate of 10% [18]. This autonomous exoskeleton is designed to assist the ankle joint during gait and consists of three main parts: a pair of fiberglass holders attached to each boot, one-way actuators mounted in front of the leg, a battery and controller in the waist [18].

Research into passive gait support elements is very recent. Passive elements, such as springs, began to appear in active exoskeletons to reduce dependence on external sources of energy for its operation [19]. From there, the idea of totally removing external sources of energy, making use of all the energy wasted by the man-machine system began to develop [1]. Here an example of passive exoskeleton is presented, which is included in the group of solutions whose objective is to reduce the metabolic cost of human movement. This experimental study [1] presents the development of a passive exoskeleton that reduces the metabolic rate when walking, assisting the locomotor systems in the task of pushing the ground, reducing the need to use biological force resulting from the system composed by the calf muscles and the Achilles tendon.

The device consists of an elastic system that acts in parallel with the calf muscles, removing load of the muscle and consequently reducing consumption of metabolic energy consumed in the contraction of the muscles. This system uses a mechanical gear that holds the spring that is stretched and relaxed by the movements of the ankle when the foot is in contact with the ground. This exoskeleton consumes neither electrical energy nor chemical energy and provides a positive mechanical workload, and it also reduces the metabolic cost of walking in 7.2% of a healthy person under natural conditions and can be equated with active devices [1].

Based on the exoskeleton developed by Collins *et al* [1] other investigations have been made on this subject, as is the case of the study developed by Dežman *et al* [20], in which uses the clutch system developed by Collins *et al* [1] with slight changes, and at the level of the support structure they have chosen to change the material used to aluminium. Dežman *et al* verified that the use of a spring with adequate stiffness leads to a reduction in the metabolic cost during walking. However, the optimal spring stiffness varies from person to person and the timing of the operation of the clutch must also be adequate.

CONCEPT DEVELOPMENT

Customer needs

At an early stage it was necessary to identify the needs of the users of a passive exoskeleton, a mandatory condition for the development of a user focused product.

In general, the requirements imposed by users of such a device relate primarily to safety, form, functionality, ergonomics and cost. The safety requirements are related to avoiding injury of the user, namely, to cause wounds

or falls due to the lack of stability. Here the geometry of the product plays an important role, since it underlies the volume and weight of the equipment. After this initial reflection on the possible requirements of the target audience for the product to be developed, it was necessary to interview people with experience in military ground operations, as well as to consult relevant studies in this field like North Atlantic Treaty Organization (NATO) working group, which studies the use of exoskeletons in the battlefield.
According to the requirements established by the workgroup [21], and the auditions made to individuals with experience in land-based military operations, it was possible to establish a list with the requirements, see Table 1, the exoskeleton which is being developed in this dissertation, must fulfil, in order to use it in the field of defence.

Table 1 - Requirements for exoskeleton development.

Requirements	
Do not compromise user safety/security - A	Simple maintenance - H
Quick and easy to assemble and disassemble – B	Ergonomics - I
Minimize user fatigue – C	Comfortable when using for long periods - J
Ease of use and operation learning – D	Robustness - K
Reduced weight – E	Noiseless - L
Do not have electromagnetic signature – F	Not be affected by adverse weather/environmental conditions - M
Minimize transportation requirements - G	

After that, it is necessary to define the degree of importance that each requirement presents. For that, it was used the diagram of Mudge, a tool that compares the requirements in pairs for all possible combinations, helping to determine the degree of importance each requirement represents for the user [22]. The requirements are arranged in the diagram and are compared through the notation of a designated letter, which is assigned to each of the requirements presented in the Table 1. To evaluate the impact of the requirements among the pairs, a numerical scale of 1 to 3 was used, with each value corresponding to the following situations: 1 - For a requirement as important as; 2 - For a more important requirement than; 3 - For a less important requirement than.
According to the Mudge diagram, see Table 2, it is possible to verify that the capacity of the exoskeleton to minimize the effects of fatigue on the user is the most important requirement, this is followed by minimization of transport requirements and third place of importance to the user is ergonomics of the device.

Table 2 - Mudge diagram.

A	B	C	D	E	F	G	H	I	J	K	L	M	Total	%	Rank
A	A2	C3	A1	E2	A1	A1	A1	A1	A1	K2	L2	M2	8	7	7
	B	C2	B2	B1	F2	G2	B1	I2	B1	B1	L2	B1	7	6	10
		C	C3	C1	C1	C2	C2	C1	C1	C1	C1	C1	19	16	1
			D	D2	D2	D1	D1	I2	J2	K2	L2	M2	6	5	11
				E	F1	E1	E1	I2	J2	K1	L2	M1	4	3	12
					F	G3	H1	I2	J1	K2	L2	M1	3	3	13
						G	G2	G1	G2	G1	G1	G1	13	11	2
							H	H3	H2	H1	L1	H1	8	7	8
								I	J1	I1	I2	I2	13	11	3
									J	J1	J2	M1	9	8	6
										K	K2	K2	11	9	4
											L	M1	11	9	5
												M	8	7	9
												Sum	120	100	

Concept generation

After identifying the requirements of potential users and establishing the target product specifications, it is necessary to determine the existing concepts and whether they can be applied. When generating new solutions for the various sets and subsets of the product, the norm is to divide a complex action into simple actions. This allows the process of concept generation and selection become easier. To meet user and product specifications, the concepts to be considered are the product structure, user adjustment, clutch arrangement and power elements, and the mechanism of connection between the segments of the structure.

Concept selection

After exposing the potentialities and vulnerabilities of the concepts, it is necessary to decide the most suitable concept for this project, through a decision matrix, in which for each concept under study a set of parameters is defined. Each parameter presents a degree of relative importance for each type of concept that is being analysed. Finally, the concept that has the highest total classification is the concept that will go to the next stage of development of the exoskeleton.
The concepts that are most important for the development of the exoskeleton are: the connection method between modules and the structure of the exoskeleton. After defining these concepts, the secondary concepts to be used are selected, being the adjustment system and the arrangement of the control system and the force elements.

PROTOTYPE MANUFACTURING

External structure

The external structure is one of the elements of the exoskeleton that is custom-made to the physiognomy and footwear of the user, so the first stage of the manufacturing consisted in the 3D scanning of the foot and user's leg. 3D modelling of the structure was designed around the cloud of points generated by the 3D. After the geometry of the Shank and Foot segment were defined, these two pieces were produced using additive manufacturing.

Force elements

The selection of spring elements was based on Collins *et al* [1] work.

For this purpose, 3 sets of different springs were purchased. The general characteristics of the springs, namely, the weight and their stiffness are set out in Table 3.

Table 3 - Springs mechanical characteristics.

Spring	Weight [kg]	Stiffness [kN/m]
F-1	0.065	8.422
A-1	0.015	7.058
A-2	0.020	4.801

Passive control

The control system of this exoskeleton is based on the clutch developed by Collins *et al* [1].

However, the general concept had to be adapted to the manufacturing techniques available and the materials available on the market. In addition, some of the components that compose the clutch had to be developed from scratch because the clutch is small and therefore requires elements that are not available in ordinary hardware stores, so it was necessary to order them abroad. This option was analysed, but since the delivery time was high and it was not possible to acquire small quantities of this element, the decision was to develop a mechanism that had the same behaviour and perform a correct positioning of the pawl.

The manufacturing process used in the production of the clutch was the chip-forming machining. For that purpose, we used the working facilities of Unidade de Apoio Geral de Material do Exército (UAGME), of the Portuguese Army. The clutch manufacturing process was mainly developed around the 3-axis CNC Mill, however due to the dimensions and geometry of some parts it was necessary to use conventional lathes and milling machines.

Assembling

The assembly sequence is the logical process of associating the various segments that constitute the exoskeleton, so it is proposed that the assembly proceed in the following order: 1) Clutch assembly; 2) Foot section assembly and 3) Shank section assembly.

Once the exoskeleton was assembled it was possible to compare the weight of the passive exoskeleton presented by Collins *et al* [1] and the exoskeleton developed in this dissertation. For this, considering that the mass of two exoskeletons with different sizes, US size 8 and US size 13, are presented in the article by Collins *et al* [1], it is possible to estimate by a linear interpolation the mass that an exoskeleton with the size US 9.5 (42.5 EU) would have, and subsequently compare it with the weight of the exoskeleton developed throughout this dissertation. It can be verified in Table 4, that the exoskeleton developed throughout this dissertation presents a decrease in the weight of some elements that constitute it. However, when analysing the exoskeleton, an increase of the total weight of the structure is verified.

Table 4 – Mass [g] comparison between exoskeletons.

Segment	Collins *et al* [1]	Prototype	Difference
Foot section	139	200	+44%
Ankle joint	40	10	-75%
Shank section	124.5	246	+98%
Frame mass	303.5	456	+50%
Average spring	76	33	-57%
Mechanical clutch	57	57	0%
Total Mass	**436.5**	**546**	**+25%**

EXPERIMENTAL ANALYSIS

The experimental acquisition of metabolic costs was done through the analysis of breathing gases during expiration in Lisbon Biomechanics Laboratory (LBL), in which the subjects under study are instructed to walk on a medical treadmill at a constant speed, as illustrated in Figure 1.

Experimental protocol

The experimental acquisition of metabolic costs was performed using the spirometry system ML206 Gas Analyzer - ADInstruments, with an acquisition frequency of 1000 Hz, and a WolfMedica Marathon Medical treadmill. This acquisition is based on the six-minute walking test (6MWT) [23]. However, since it is intended to have a comparison in terms of metabolic costs with the results available in the literature, namely in the compendium of physical activities [24], it was concluded that the speed of walking in the 6-minute walk test would not be the speed defined by the subject under study but rather at a standard velocity for which the metabolic cost has already been studied. In this way the subject under study will perform the 6MWT at the speed of 4km/h, which has a MET of 3 units.

Figure 1 - Subject during the experimental protocol at LBL.

For this study 14 individuals were selected according to the inclusion criteria: 1) not having any pathologies in the locomotive system; 2) practice physical activity regularly; 3) belong to the Armed Forces; 4) footsize and calf perimeter similar to the subject zero (foot size between 41 EU and 43 EU); and 5) present a Body Mass Index (BMI) between 18.5 and 29.9 (category of normal weight or pre-obesity). The biometric data regarding the study population, namely age, weight, height and BMI, are presented in Table 5.

Table 5 - Biometric data of the study population.

	Work group
Age	24.6 ± 3.4
Weight	75.2 ± 5.2 kg
Height	180.1 ± 4.3 cm
BMI	23.2 ± 1.3

Individuals who participated in this study were instructed to perform the adaptation prior to the acquisition of experimental data to become used with the fact that they had an external element attached to their legs. So, the exoskeleton was coupled to their legs and then walked freely for 25 minutes at the same speed that the acquisition of respiratory gas exchanges would be performed. According to Galle *et al* [25] this time is enough for the human body to adapt to the use of an exoskeleton. After the adaptation phase, the experimental data acquisition cycle started, for each of the situations under study, i.e.: 1) without exoskeleton; 2) with exoskeleton without springs; 3) with the exoskeleton operated by each of the 3 springs under study. At this stage the user is instructed to sit down and remain at rest for at least 6 minutes to estimate the individual's metabolic cost in the resting state, i.e. to ensure that the gait analysis was always started under the same conditions and would not be influenced by fatigue. After this, the volunteer is instructed to stand on the treadmill and perform the walking test for at least 7 minutes. Once the data has been collected, the user is instructed to sit down again and for at least 6 minutes does the recovery phase. The 5 situations for which the metabolic costs are acquired do not follow a predefined order, i.e. to guarantee the randomness of the values obtained, the order of execution of the acquisitions is different for each one of the individuals under study. In addition, the subjects were not informed about the relative stiffness between springs. Figure 2 illustrates the tasks and the sequence by which they occur during the experimental protocol.

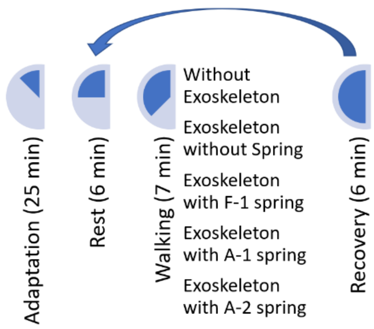

Figure 2 - Experimental protocol sequence.

At the end of the experimental protocol the individuals are instructed to respond to a questionnaire regarding the perceived exoskeleton functioning that they experienced during the experimental protocol. If there are mechanical failures in the operation of the clutch, or rupture of another element constituting the exoskeleton, the experimental protocol ends and is repeated.

Results
Regarding the acquisitions made to the work group, it is possible to compare the average metabolic cost that each one of the studied conditions presented. Results for the metabolic costs is showed in Figure 3, in which the values of the average metabolic costs as well as the standard deviation associated to each of the situations are presented.

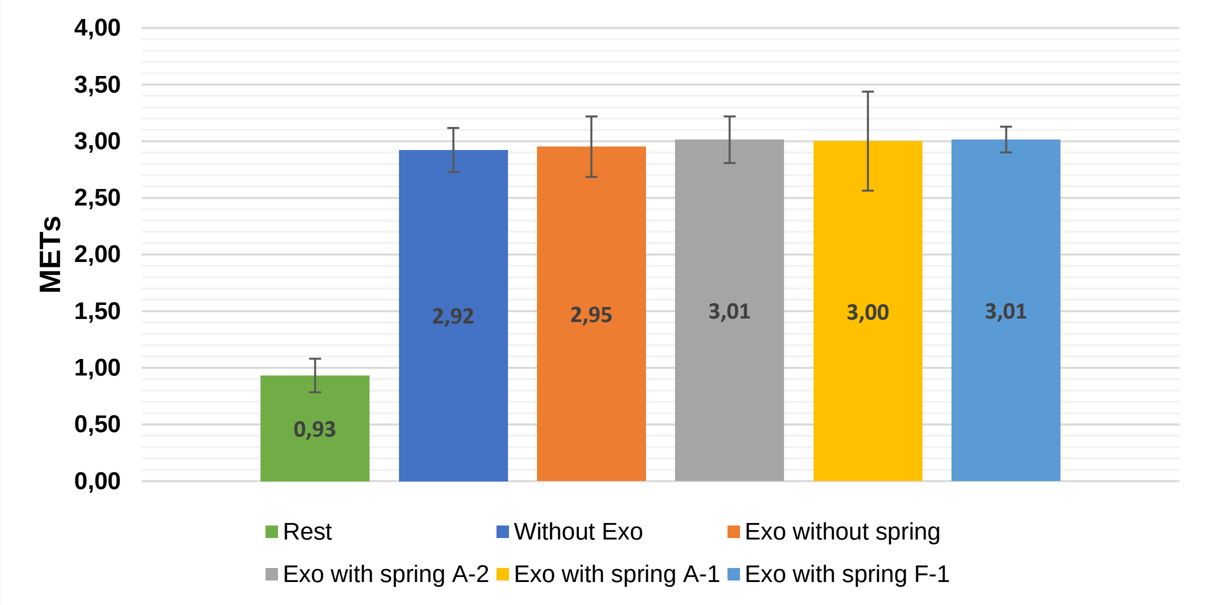

Figure 3 - METs comparison between the different conditions under study.

In this work group, the metabolic cost in the rest situation was 0.932 ± 0.148 METs, slightly lower than the reference value (1MET) that can be found in the literature [24]. As for the metabolic cost during the 6 minutes in which information was obtained regarding the volume of oxygen expired, after normalizing the results obtained with the weight of each individual, it was verified that on average the metabolic cost of the gait without exoskeleton was around 2.922 ± 0.195 METs, values that, as in the rest situation are slightly below the reference value for the walk at 4km/h. For the other conditions under study, it is not possible to compare the values obtained with some reference, because in this study we define a different experimental protocol. Beyond that the structure of the exoskeleton is different from the other researches, so it is not possible to establish a benchmark. Nevertheless, it was verified that the average metabolic cost of using the exoskeleton with or without the springs was higher than the metabolic cost without exoskeleton. The variation of the metabolic cost relative to the walk without exoskeleton was as follows +0.9%, +3.4%, +2.8% e +3.1%, respectively, for an exoskeleton walk with no spring action, with an exoskeleton actuated by spring A-2, with an exoskeleton actuated by spring A-1 and with exoskeleton actuated by spring F-1, respectively.
Figure 4 shows the results obtained by each individual in each situation under study. It is possible to verify that the global variation of the metabolic costs oscillated between -27.9% and 15.5%. It was also verified that for 4 of the 7 subjects who participated in this study, there was a reduction of metabolic costs in relation to walking without using the exoskeleton, and the results obtained ranged from -27.9% to -0.1%. In the same Figure, the results concerning the condition that each individual was able to extract the best efficiency by using the exoskeleton actuated by each one of the springs are also highlighted in red. Thus, the average of the results obtained with the most adequate spring for each user revealed an average reduction in metabolic costs of -3.1%, with overall values ranging from -27.9% to + 7.5%.
Concerning the qualitative analysis that each of the subjects performed at the end of the protocol, through a questionnaire of perception focused in exoskeleton functioning, for the adaptation time when walking with the exoskeleton, all the subjects answered that the adaptation time was enough. However, some elements added that at about half the time stipulated for adaptation they were comfortable to use the exoskeleton.
Regarding the questions in which the volunteers had to classify the perceived effort to cause displacement in the spring and if the spring aided in the phase of the Toe off, the level of effort perceived to cause strain of the three springs, on average, was classified as little. However, for the ability of the spring to aid in the gait cycle, there is no significant difference between the classification given to each of the springs. Although, according to the volunteers, the spring that most aided during gait cycle is the one with greater stiffness, i.e. the spring F-1. Also, the spring A-1 which has a stiffness lower than F-1 and greater than A-2 presents a lower value of aid perception. Finally, the spring with less stiffness, spring A-2, had the lower aid rating.
The subjects were also asked to order the tests in ascending order of force that they felt from the spring (this question aims to understand how the user can get a relative perception of the action that the springs had on the development of the gait cycle). The results indicate that most of the subjects noticed the rigidity that each of the springs had, since 69% rated the springs relative to their stiffness in the correct order.

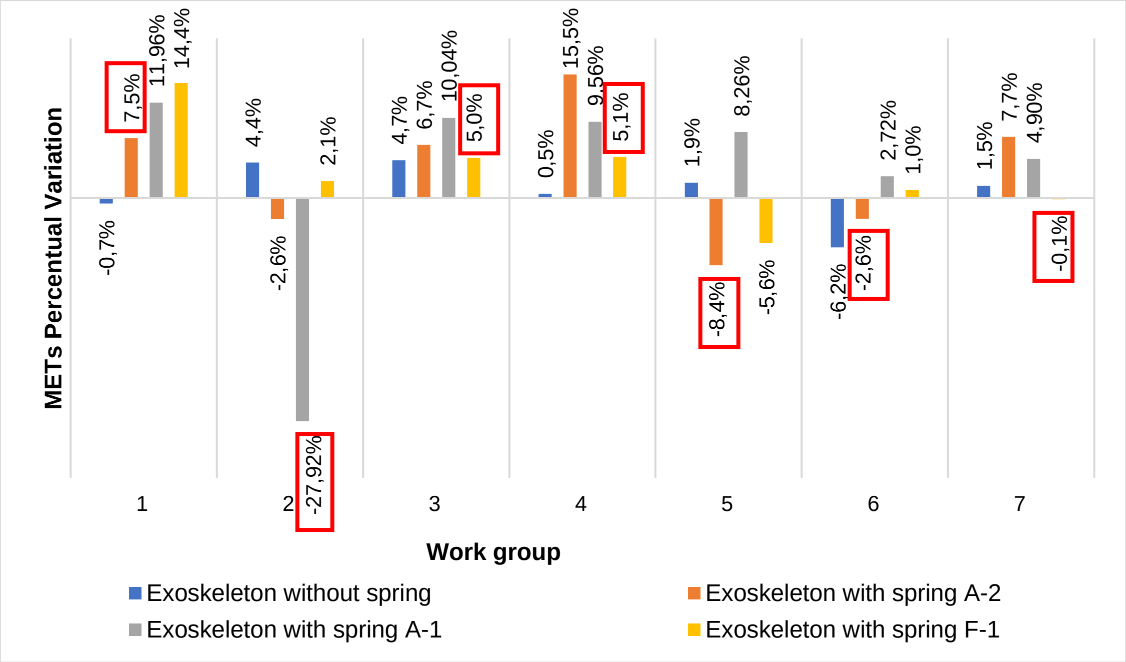

Figure 4 - Percentual variation in metabolic costs for each individual.

The range of motion that the exoskeleton allows to the user is one of the requirements presented by the customers. In this way, the subjects were asked to classify the mobility of movements that the structure allows. Based on the response, the exoskeleton has a moderate to a great mobility, regarding the ankle joint. Still, some of them have shown that it removes some mobility in the foot eversion movement.

Regarding comfort, the classification that the volunteers attributed to the structure was neutral, since some of the participants felt some discomfort in the frontal zone in which the shank segment contacts the leg, while others stated that they felt some discomfort since the calf perimeter of the structure was undersized for volunteers with a larger calf perimeter.

To refine the requirements defined in Table 1, the volunteers were asked to indicate possible changes with a view to a better performance of the exoskeleton in operational activities or even for day-to-day use. Most of the suggestions focused on reducing weight, reducing clutch noise, developing a more compact structure and using comfortable materials in the area where the exoskeleton contacts the leg.

Finally, regarding the possibility of volunteers using such devices to reduce the metabolic cost during activities that occur over long periods of time, most said that it was a possibility to consider.

Discussion

Analysing the graphic of Figure 3, (where the metabolic costs for each of the studied walking situations and resting stages are plotted), in average, the use of exoskeleton did not result in a reduction of the metabolic costs compared to not using the device. However, for some of the participants, a reduction of the metabolic cost was observed in relation to the use of the exoskeleton without springs, which shows that, for some individuals, when carrying the same amount of weight coupled to the legs, the use of the exoskeleton with springs allowed to reduce the energetic expenditure during gait.

As for the reduction of the metabolic costs compared to walking without the aid of the exoskeleton, that was intended to achieve, according to the research carried out by Collins *et al* [1], it was found that in average, this could not be achieved considering the springs selected for the study.

The results shown in Figure 4, obtained by each individual for each situation under analysis, support the idea that the actuating spring of the exoskeleton should be selected according to the characteristics of the individual in order to obtain a more efficient system. This conclusion is supported by the fact that, under the same conditions, some individuals showed a considerable reduction of the metabolic cost while others, in contrast, presented an increase of the same.

Also, in Figure 4, where the best results obtained by each subject are showed, an average reduction in metabolic costs of - 3.1% was obtained. The best result obtained by the subject 2, -27.9%, can be pointed as an outlier (atypical value against the sample). The acquisition procedure and the data processing process were verified and no reasons for an error were identified. If this value were withdrawn from the study, the average of the metabolic costs during gait would be 1.1%, regarding the non-use of the exoskeleton.

The values obtained for the best result of each subject in this study may highlight the importance that a customized structure to each user presents in terms of efficiency of this type of devices. That is, in the capacity to reduce the metabolic costs of the user during walking.

In addition to the fact that the spirometry analysis itself may have some influence on the results there are other factors that may have led to results similar to those of Collins *et al* [1], because although the exoskeleton has more degrees of freedom than that developed by this set of researchers, the device developed during the dissertation is

about 25% heavier. This can be verified in the Table 3, due to the process of construction of the adopted structure was different, presenting a much lower cost. However, the average increase in weight of the exoskeleton in the subjects in terms of percentages is 1.5%, and this variation is higher than the increase in average metabolic cost when the subject uses the non-spring exoskeleton, 0.9%. This may mean that the geometric shape of the exoskeleton structure may cause small displacements of the center of mass.
In addition, the exoskeleton used in the experimental acquisitions, for a matter of time available and budget was the same developed for subject zero. This may have influenced the results since the subjects who participated in the experimental acquisitions, despite having the same stature and physical constitution, had some differences at the level of the calf perimeter and the size of the foot. A smaller calf perimeter implies that the structure, although allowing some adjustment, will oscillate since it was not customized for each one of the volunteers. The same issue can occur, regarding the footwear and foot size, causing discomfort and increasing metabolic expenditure. Also, the relative position of the clutch in the leg of the user can influence the results obtained, since this can be in a place where the aid that the exoskeleton produces in the calf muscles is less effective.
Still, analysing the structure, it was verified that although heavier than the one developed by Collins *et al* [1], the option of developing an external structure to the footwear, as opposed to the internal structure developed by Collins *et al* [1] and Dežam *et al* [20], allows the ergonomics of the footwear not to be altered. Thus, it mitigates the discomfort that this device could cause in the sole of the foot due to the stiffness that an insole solution would have.
In addition, the increase in the metabolic costs, in most of the cases, may be due to the fact that the non-exoskeleton walking test was carried out with the footwear that the subject uses in his daily life, being adapted to the way of walking and positioning of the foot of the subject, while the exoskeleton tests were made with a footwear that is not adapted to the way of walking of the subjects.
Regarding the clutch operation itself, this may also influence the results, since its engagement, that then triggers the spring, should be adapted to the gait of each individual. Since each one presents slight variations in the gait patterns, and if the spring is actuated too early or late it may constrain the performance of the system. Moreover, with respect to operation, it should be added that although it did not influence the operation, the pulley recovery spring is not ideal for this purpose, since it is a one-way tensile spring, it should only work axially, which does not happen in this case. This results in a damaged spring, so adjustments should be made in the pulley to be able to engage another type of spring, for example a torsion spring.
From perception surveys, to which the volunteers were instructed to respond after the experimental acquisitions with the exoskeleton, helped verifying that for the influence of the springs with different stiffness coefficients the subjects, for the most part (about 69%) can make a clear distinction from the increase or decrease in stiffness of the springs with which they performed the tests. However, since four participants failed to make a clear distinction between the springs used it might be necessary to test a wider range of springs and could possibly achieve a decrease in the metabolic cost.
Regarding comfort and mobility, participants rated the exoskeleton as allowing moderate to large mobility. This is in part due to the use of the kneecap, allowing almost total mobility of the ankle joint in all directions, while the device developed by Collins *et al* [1] has only one axis of rotation. However, the exoskeleton developed during this dissertation still constrains some eversion movement of the foot when comparing the execution of this movement with the bare foot. This movement limitation may be beneficial as it may cause some stability of the foot and thus decrease the risk of injury when, for example, walking on rough terrain. Regarding perceived comfort, the classification was neutral. 78.6 % of the subjects found the use of the exoskeleton comfortable, and 21.4% of the study population classified as uncomfortable, this discomfort is in part due to the support structure that was not customized for each individual. In addition, cushioned elements should be added in contact surface, to reduce the abrasion of the skin.

CONCLUSIONS

This dissertation was focused on the design, manufacture and evaluation of the performance of a passive exoskeleton to actuate the ankle joint, with the aim of reducing the metabolic costs during walking.
From the experimental tests it was possible to obtain qualitative and quantitative results regarding the functionality and reliability of the exoskeleton.
Results obtained from the experimental acquisitions indicate that it is possible to obtain a reduction of the metabolic costs using a passive exoskeleton. This was verified for 4 of the 7 individuals whose experimental acquisitions were considered valid. In which it was observed a decrease of metabolic cost oscillating between −27.9% and −0.1%.
In addition, it was observed that there was a decrease in the metabolic cost when comparing the exoskeleton with spring and the exoskeleton without spring actuation. In this case, the reduction of the energy expenditure varied between −31.0% and −1.7%.
However, the springs that allowed to reduce the metabolic cost in some subjects did not present the same behaviour in all the subjects. Then it is perceived that it is necessary to estimate the stiffness of the spring suitable for each person.
Still, in the scope of the exoskeleton functioning, it should be noted that the moment of engagement of the clutch may vary from person to person as each person presents slight variations in the gait patterns.
Beyond that, the system that attach the spring to the clutch cable may generate slight misalignments in the functioning of the exoskeleton.

The results are also influenced by the fact that the absence of customized structure for each one of the subjects that participated in the experimental acquisitions may have created situations of discomfort or diminished functionality of the exoskeleton.
The structure, although presenting a greater weight than the developed by Collins *et al* [1] did not produce a significant increase in the metabolic cost in the individuals who used it. In addition, it presents functionalities that the second one does not have, namely, in terms of the range of motion at the ankle.
The use of additive manufacturing to build the exoskeleton structure allows a custom-made structure with a low acquisition cost.

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