Int J Interact Des Manuf (2017) 11:263–277
DOI 10.1007/s12008-015-0282-3

ORIGINAL PAPER

Implementation of ergonomic aspects throughout the engineering design process: Human-Artefact-Context analysis

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Received: 20 May 2015 / Accepted: 25 June 2015 / Published online: 23 July 2015

Abstract The design process of an object, system or space must consider the physical, mental and psychological traits of its intended users. Moreover, the results of the design process are also defined by the attributes related to the context. However, current product design approaches does not offer a proper balance among the "human", "artefact" and "context" dimensions. Consequently, a product design methodology that covers the overall Human-Artefact-Context system, from a cognitive and physical ergonomics point of view, is proposed. The generalization of the proposal is based on a synergic structure of User-Centered Design methodologies and ergonomic criteria that prevails throughout the product development stages. The latter ensures a better adaptation to specific context and user needs in a way that improves efficiency, security and consumer well-being.

Keywords Human-Artefact-Context System · Ergonomics · Human factor · Product design methodology · User Centered Design · User experience · Usability

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1 Introduction

In different product design methodologies the importance of the user within the ideation and embodiment of the product is a matter that has always been relevant; even trying to project the image of the final consumer over the product. Besides, the final user requires more sophisticated attributes and seeks to fulfil his/her needs by connecting with the object at functional, aesthetical and emotional levels [1,2]. Paradoxically, designers often disregard or simply ignore the end user, by either means of omission, comfort, inadequate planning times or an inadequate use of available design tools. Therefore, there is a latent challenge to develop products adapting mental models of a broad range of people, since these are built through a lifetime experience, education, as well as both cultural and social aspects of each user [3]. The conceptual model of the product is related with the principles of configuration laid out by the designer (form, material, colour, texture) and it is the representation that individuals make when using it, enabling to predict, in terms of the user, the effects of interacting with the finished product. The end user will not easily interpret the conceptual model if the information transmitted through this image is far from ideal [4].

Some authors consider that during the development of the product there has to be focus on the product itself, and not on the end user. However, they highlight that there is a myriad of products upon which apparently, there was less than little consideration with the ergonomic relationship amongst human, object and spatial factors, throughout the product design process [1–4]. According to Flores [2] and Rubín [4], when an end user, an object, and a physical space exist to perform any given activity, the designer should encompass an integrated vision of ergonomics in the design process, in order to avoid segmentation between these three factors.

Karwowski [5] states that by applying human factors and ergonomics (HF/E) within the design process, the risk of malfunctions, potential mishaps, and high total costs within the product life cycle can be diminished. Besides, this facilitates the usage of the product, as well as the capability of transmitting its formal/functional language, efficiency, satisfaction and adaptability.

The study of *ergonomic factors* within design, seeks to create products and elements of daily use adapted to the traits presented by end users. In some cases, a vision of ergonomics is implemented on early stages of the design process, considering elements and variables that can affect the product-user interaction, such as movement, sound, lighting, though, etc. In this way, designers evade the need to include the user in the physical and cognitive dimensions within all stages of design and development of the product. However, this generates late changes in the design process that in the long term will represent additional hidden costs within projects.

Some authors [6–10] have mentioned approaches related to the consideration of the user in the design process, but they lack providing a balance between the different methodologies addressing Human-Artefact-Context (HAC)system's elements during all the stages of the design process.

Therefore, a design methodology that adheres implicitly to ergonomic *triad*, in other words the system *HAC*, at a physical and a cognitive level at all stages of the design process was developed. This guarantees a higher level of adaptation to the context as well as user needs and capabilities, and improves the efficiency, safety, well-being, and user experience of consumers. Also, the proposed approach considers explicit procedures including activities, tasks, tools, inputs and outputs throughout the design process, derived from a Design Inclusive Research approach.

The bases of the ideas proposed by this article are not the result of a mere anthology of different points of view proposed by recognized authors in the field, along with information that supports the notion of the limited adaptability that some products have in terms of complying with user needs and expectations. In contrast, it actually originates from experiences faced by assuming the role of designer, comparing and validating tangible results from a conventional design process undertaken within the electrical-industrial sector in the city of Medellin, Colombia. Employing a research methodology, adapted from “Design Inclusive Research” [11], featuring explorative, creative, and confirmative stages, a specific product was redesigned in order to enhance the system's interaction. Quantitative and qualitative indexes were employed with the aim of directing user satisfaction towards an enhanced user-experience, efficiency, language and emotional connection with the product. The initial question prompted towards redesigning the product was How to design a technical system fitted to a user within a specific context taking into account human factors in every stage of its development?

The proposed methodology, with its activities, tasks and explicit tools, represents an interactive design process, considering different factors in the execution of the product. These are related to cognitive, sensory and physical analysis between the human, the artefact and the context, in order to create a balance between them [12].

The creative process was implemented to strength the cognitive users perception in the use situations between the the human, the artefact and the context, taking into account experts knowledge, end users satisfaction and realizations of ergonomic functions in early stages of the design process. The design problem is solved using creativity methods, numerical techniques, sensorial approaches and knowledge engineering tools [13].

This interactive design supports decision making in the usage and adaptations of visual techniques, ergonomic integrations of the product-end-user in the design process, implementations of Human-centered design techniques, realization of a real multi-disciplinary engineering approach, modelling and simulation of the product behaviour [12].

The document presents guidelines that allow inclusion of ergonomics throughout the product design process, aiming not for an ideal structure intended for all design cases, but instead a guide that allows the designer to generate answers and particular methodological approaches [3].

Next chapter presents some current ergonomic considerations and applications related to the product design process. Section 3 explains the development process of the proposed methodology based on the Design Inclusive Research approach, followed, in Sect. 4, by the results of the methodology and the case study. At the end, some conclusions and further developments are presented in Sects. 5 and 6, respectively.

2 Literature review

2.1 Ergonomic considerations and applications

Murrell [14] and Grandjean [15] propose ergonomics as the study of the human beings within their working environment, focusing their vision in the design of office workstation, temporal and environmental analysis, as well as mental and physical efforts of the worker. Singleton [16] defines ergonomics as the interaction between man and surrounding environmental conditions, setting his vision towards the Human–Machine system; relating the information emitted by the object towards the coding of man. Wisner [17] conceptualises ergonomics as a set of scientific knowledge, relative to man, necessary to conceive machines and devices that can be utilized with maximum effectiveness, safety and comfort.

Likewise, ergonomics has been related with design variables and criteria of functional effectiveness or of well-being for people [18], and with the application of scientific methods to obtain scientific information about the user applicable in design problems [19].

Currently, there is a set of ergonomics specifically destined for health care related with the prevention of labour and psychosocial risks, safety hazards and management of prevention, entailing aspects taken from judiciary ergonomics by analysing work, and the criteria of disability, accidental event reconstruction, and professional ailments originated from ergonomic risk factors and injury causes [20,21]. Ergonomics in organizational design and management allows the allocation of human resources and organizational competences within the operational unit [22]. In industrial design, ergonomics comprises market and user research and requirements applied to anthropometrics and biomechanics in order to more accurately adapt the form of the product to the user needs [23,24]. Related to ergonomics, the User Centered Design (UCD) is the philosophy that strives to optimize efficiency and effectiveness in the use of products or systems on behalf of users [25]. A large number of authors consider this term as a synonym of ergonomics and human factors, but they are not necessarily related.

Many authors use terms like "Human factors", "ergonomics" and similar ones unequivocally as synonyms, with reference to dual visions and defined fields of study: *ergonomics for the design of consumer products* and *industrial ergonomics*. For interaction to exist it is necessary to have two elements: the subject and the object. In ergonomics for the design of consumer products, the subject is the end user and the object is any product used by the subject. In turn, for industrial ergonomics the subject is the worker whom operates the tool or entire workstation. Within this subject–object relationship the physical intervention of humans is manifested through anatomic-physiologic and anthropometric factors [2,26–31].

To enhance the study and systematisation of ergonomics, all of the key aspects discussed through this article have been framed and related to the scope encompassed by the HAC triad. All of the information and the data related with the human have been defined as *human factors* (Anatomic-physiological, anthropometric, psychological, societal and cultural). In turn, all data relative to the context is named *environmental factors* (Temperature, humidity, ventilation, illumination, colour, noise/sound, vibration and pollution) while the traits and data intrinsic to the artefact are defined by industrial design as *objectual factors* (Shape, volume, weight, size, material, surface finish, colour, texture, technology, controls, indicators, symbols and signs) [2]. In this context, this approach is related to "ergonomics for the design of products under and interaction between man, product and environment", considering the branch of ergonomics as a body of knowledge that speaks of human abilities, limitations, and traits that are relevant for a design. Communication is another fundamental part within the relationship, since, by indicators, the object emits information received by the sensorial body parts, then codified and responded by attitudes or movements get to the object back, through its controls.

Regardless of the differences between ergonomic considerations and applications, ergonomics always strives to attain a higher degree of equilibrium between the needs and possibilities of the user and the performance and requirements of the products. However, the analysis of the relationships established, through sensorial body parts, with the objects has been supported by UCD. Woodson and Selby affirm that this is a new way of team-designing and as such not limited to just a set of individual techniques applied to design [32]. Other authors, propose three principles that present relevance regarding the implementation of a new philosophy of work for the field of product design: a) focus on users and the tasks they will be performing with the product, from the very beginning, b) use of test prototypes for the collection of field-data, c) design in an iterative way that allows cyclical repetitions within the phases of design, allowing the alteration of parameters and product usability tests from the very beginning, in other to attain a fulfilling result [4,33–36]. Sagot performs analysis around the contribution that ergonomics has over the design process of new products, referencing a cooperative and retro-active methodology [37].

2.2 Ergonomics in the design process

Ergonomics and design over time have had three different aims relative to the user needs, resources and the designer's objectives. The first scope is based on ergonomics as an instrumental discipline that supplies data to the designer through the design process, especially on the stages of proposals and concept generation, as well as its final evaluation. The second scope is based on ergonomics as a discipline of support that allows the understanding of human beings from his/her physical and cognitive processes; from the initial stages of the design process (UCD–usability). The third scope is based on ergonomics as an integrating discipline that seeks to involve people throughout the design process (participative ergonomics and participative design), intending to comprehend people far beyond their physical and cognitive processes (emotional design) [3].

Ergonomics within the design process can be identified through two points of view: (a) the "ergonomics police" where the ergonomics specialist evaluates the work performed by designers, establishing both the right and bad decisions in terms of the product, space or system. Despite this, frustration arises for both of the relevant participants because the feedback given through ergonomics can rarely be fully applied on the fundamental aspects of the project, that due to its level of execution are in many cases unmodifiable [38], (b) the second possibility is considering ergonomics conceptually embedded from the initial stages of the design process, something that enables a higher level of feedback and mutual construction along the project development [39].

Some authors have created methodologies aimed to involve in a more active manner the topic of ergonomics within design stages, although they are not developed in an explicit manner and, therefore, they do not optimize the process of product development. In reference to human factors, de León established that incompatibilities among user and product must be addressed and corrected during the design process, considering activities that user must accomplish with the product, the physical, sensorial, and associated mental demands to fulfil, and the context factors [40]. López proposed an approach for ergonomics learning, from its relationship with the design process, optimizing the contexts where the user performs his/her activities [41].

The USAP model of participatory design (Usability, Safety, Attractiveness, Participatory), can be applied to the development of products based on user-centric design [42]. Marshall uses the tool "personas" and/or user data sets to obtain end user proper information [43]. These methodologies provide concrete, stable and focused information to designers in order to define aspects of human behaviour and motivations. For authors like Suri and Marsh a methodology of scenario building can be useful since the descriptions of natural, constructed or imagined contexts can foresee the users interactions with a determinate product [38].

Other general design approaches, from authors like Beitz [44] and Eppinger [45], include an authentication of ergonomic criteria within the phases of user analysis that does not venture further from a literary search based on guides and qualitative analysis of the targeted end user. The norm VDI 2221 is a systematic design method for technical product generation and problem solving, contacting the client and comparing the new product with the competence [46].

The Kansei engineering analyzes the users and understands their feelings to know how they can be reflected in the product. It uses a psycho-physiological research with measurement techniques and semantic reviews [6].

The approaches suggested by Dore [7], Yannou [8] and Petiot [9] are focused in the semantic definition of the user needs to find links between sensory and functional characterization of the product.

The proposed approach differs from the Kansei engineering and the latter approaches by the data collection techniques used with the user and the decentralization of the human element in the system, since it implements explicit activities focusing in the physical and cognitive ergonomics in each stages of the design process. Additionally, the HAC system is analyzed like a full package, considering the users in order to understand and associate what they say, do and feel. Also, it integrates the usage situation with the artefact and the context, transforming this information into inputs, outputs and constant and cyclic requirements of the design.

With this prospect of design methodologies, it is essential to define an approach that explicitly considers features such as functional, bio mechanics, anthropometric and cognitive aspects, in order to diminish iteration cycles; optimizing the relationship between human, artefact and context.

3 Development of the methodology through Design Inclusive Research

The Design Inclusive Research (DIR) [11] was adapted in order to developed the proposed approach. The design process of an upper body protective system for the manipulation of electric poles in mountainous terrain has been used as a case study for the creation and validation of the design methodology implementing ergonomic aspects. This specific exercise of design has been selected since it is a development with a high content of user requirements that arise from specific anthropometric traits, body positions that respond to load manipulation and musculoskeletal injury arising from short and long-term sustained strains that diminish safety and conditions for activity performance. This research comprises three stages: explorative, creative and confirmative, as it is presented in Fig. 1.

3.1 Explorative

The first stage of exploration starts with the evaluation of an initial upper body protective system called *Carrier Vest A*, where different aspects and considerations of human interaction were overlooked. This design is presented in Fig. 2. The design is poorly adapted to the actual necessities of the end-user, built with costly parts that did not adequately fulfil its function, thus generating a design that inhibits the manipulation movements of the user, decreasing performance by improper load distribution and not being able to absorb collisions.

At this stage the objective was to observe the use of a design prescriptive method adapted from Ulrich and Eppinger [45], presented in Fig. 3, considering the user in the stages of system testing, perception of usability and in the comprehension of the user manual. The reverse engineering and redesign methodology proposed by Otto and Wood [47] was applied in the manner of a guide, rather than a particular set of obliging and constraining a set of rules, since this method lacks a stage of functional model development, prototypes or any additional documentation eventually required by the project.

Therefore, new stages of analysis and synthesis of the problem before the development of concepts, and ergonomic

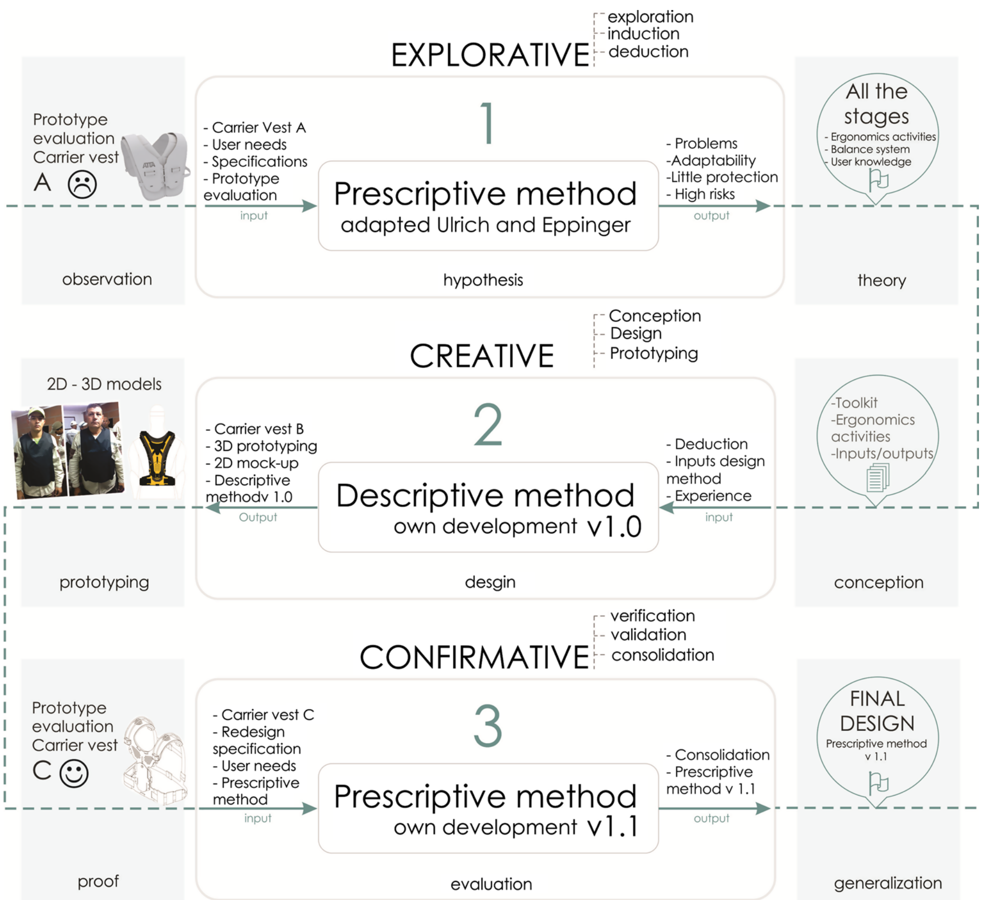

Fig. 1 Development approach based on Design Inclusive Research. Adapted from Horvath [11]

Fig. 2 Carrier Vest A

design criteria (human and objectual factors) in all of the stages of design process were implemented in an initial methodology (version 1.0), as it is presented in Fig. 4. In this way, both priorities and the methodological distribution that was used in the design of the Carrier Vest A were modified. With this purpose, the next stage was devoted to the establishment of a first design approach considering ergonomic aspects in HAC systems and its validation in the case study of a preliminary conceptual redesign.

3.2 Creative

At this point, a redesign process of the *Carrier Vest A* was undertaken as a design exercise in order to analyse bio mechanical and ergonomics standpoints stated previously, to fine-tune the design approach integrating ergonomic aspects in HAC systems and to create new opportunities for generating new knowledge. In this way, the evolving product contributes to theory building in context [11].

Analysing variables such as the mass and positioning of the centre of gravity, which varies each time the operator modifies his/her position due to the irregularity of the hilly terrain, and the elements used during the activity in order to augment the area of contact with the load in order to distribute

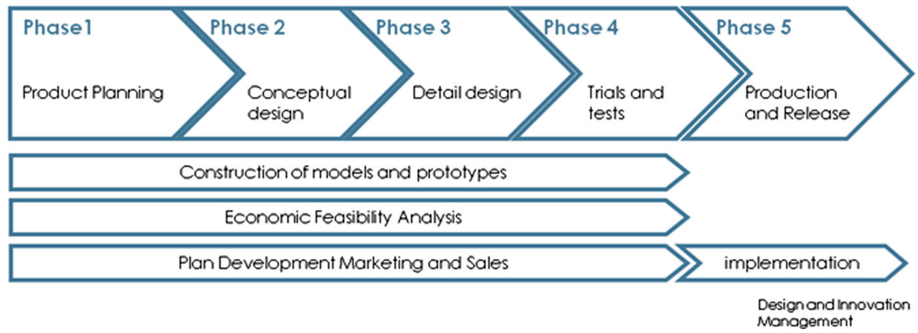

Fig. 3 Prescriptive design method used to analyse Carrier Vest A

strain and generate greater comfort, this redesign process results in a new *Carrier Vest B1*, presented in Fig. 5.

In order to determine the form of the *Carrier Vest B1* the specific traits of the human body were considered at conceptual level. Especially those of the upper body, generating both soft and rigid re-enforcements intended to protect the parts involved in the process of manipulating heavy loads. Anthropometric measurements were identified through a literary and qualitative research, directed to a specific sample of 150 workers of the national electric sector, in order to determine the necessary distances and measurements demanded by the frame and the protective vest.

In order to validate the effectiveness of the proposed methodology (Fig. 4), the efficiency of the shape of *Carrier Vest B1* was calculated concerning the mobility of upper body limbs and the adaptability to the measurements of the studied sample. Dimensional and user perception tests were designed and carried out, developing a prototype of *Carrier Vest B1* from a resilient material, resistant to weathering, and comparing its proportions in relationship to current user bodies within a specific manipulation context, as it is shown in Fig. 6. Here, different critical points in relationship with the design were analysed concerning both anatomic and anthropometric factors of the observed users.

3.3 Confirmative

3.3.1 Proof and verification

From the adaptability test of the prototype of the *Carrier Vest B1*, in relationship with the user and context, the methodology was reconsidered, augmenting the number of activities and tools employed in the gathering of anthropometric data and the perceptual analysis in accordance to user characterization. By increasing the number of activities focused on the detailed analysis of context and user interaction, considerable aspects were identified in relationship to the concepts redesign. In this way, a third design, called *Carrier Vest B2* (see Fig. 7), was generated with the intention of improving limitations on the users movements and augmenting adaptability in relationship with his/her anatomy and anthropometric. The manipulation of loads and the way of making better use of body segments able to cope better with higher loads and levels of strain were considered, all with the purpose of adequately distribute them and generate a higher degree of comfort.

The methodology suggested that, in order to obtain a design better suited for all possible scenarios, it was necessary to analyse other contexts of use within scopes such as manufacture, assembly, dis assembly, transportation, etc. Complicated and obtrusive shapes were avoided for *Carrier Vest B2* and the overall parts susceptible to breakage or misplacing was reduced. If the vest is too big and voluminous, there is a risk that users avoid its use during stages of load manipulation, leading to commercialization fail.

The feasibility of the design represented by the *Carrier Vest B2* was evaluated, analysing 12 systems and 2 patents with similar traits in relationship with the protective vest, thus determining requirements, advantages and relative disadvantages. The contexts of each system were focused towards different users and needs. After the 3D parametrization and analysis of strain and load distribution of the *Carrier Vest B2*, it was evident that the initial methodology (Fig. 4) lacked of balance within the HAC system and there was not an explicit proportion of the activities, tools, input and outputs of each of the design stages, allowing product adaptation in terms of its shape, use and user experience.

Next, final methodology is proposed, applied and validated in terms of the final redesign of *Carrier Vest B2*. It was fundamental to examine the functionality and the level of importance of some of the parts composing the design, in order to take advantage of the resistance of back muscles and vertebrae ligaments for the adequate distribution of localized loads.

3.3.2 Evaluation and validation

At this point, considering evaluating tools and activities in relationship to the HAC system, the product has been redesigned and a fourth prototype is obtained, called *Carrier Vest C* (see Fig. 8), thus ensuring an appropriate balance among the final results as well as enhanced adaptability. The solution embodied by the final design allows the proper distribution of weight along the upper body, improving endurance

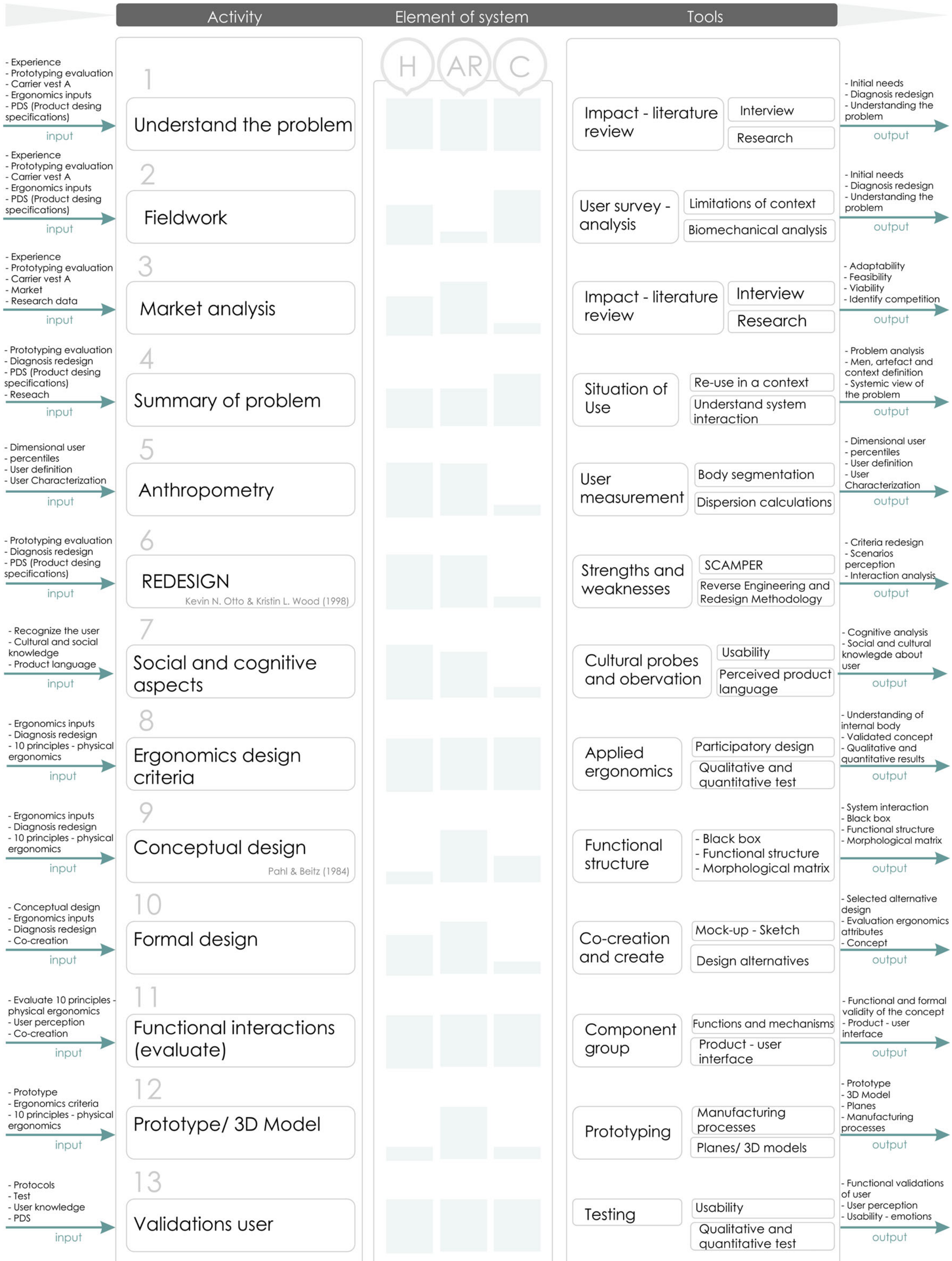

Fig. 4 Initial proposed methodology—Descriptive method V1.0

and comfort for the user when handling heavy loads. Positioning the back in the right position, improper turning and twisting of the spinal column is prevented during transport. Walking is possible by aligning movement over the body's central line, since deviations from that posture generate an imbalance of forces that generate torque (balancing when walking), which is nothing more than the body's attempt to reduce said imbalance of forces. When a person is standing up-right, the spinal column transfers to the lower body the weight of the head, mid-section and upper body, or any

Fig. 5 Carrier Vest B1

Fig. 6 Usage situations for prototype Carrier Vest B1. **a** Appropriate Silhouette, **b** inappropriate Silhouette

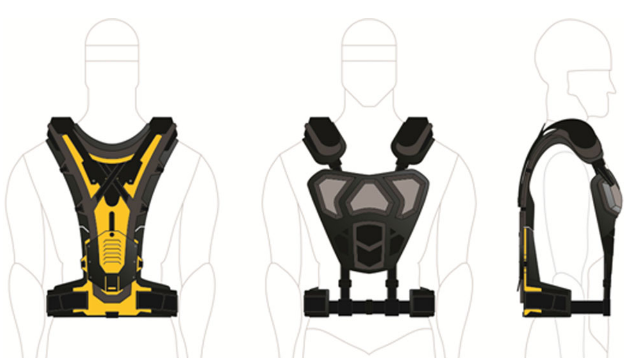

Fig. 7 Carrier Vest B2

other load. For that matter, the lumbar vertebrae located in the lower spine support the totality of the load. Therefore, loads must be carried frontally and the closest possible to the body, distributing weight symmetrically between both arms.

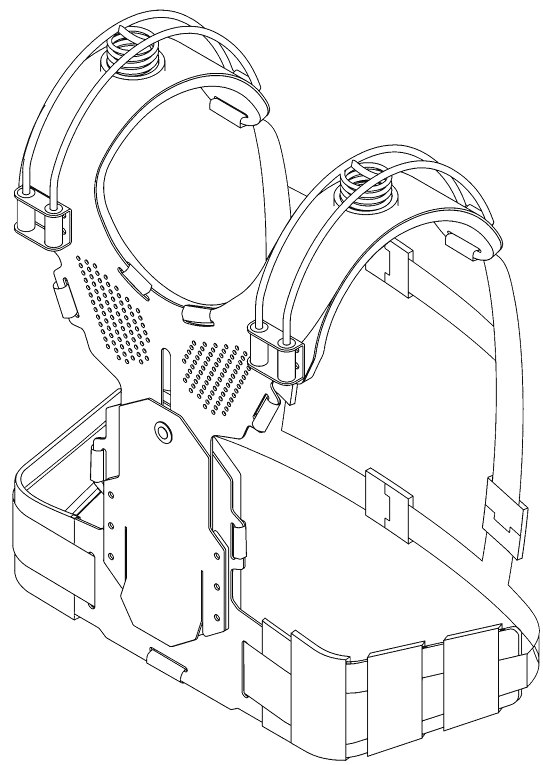

Fig. 8 Carrier Vest C

The final design adjusts and adapts to the lumbar and stabilizes the posture of the user, allowing the efforts to be transmitted by inter vertebral discs. When handling a load with improper posture, the core does not stay in the centre of the inter vertebral disc, but moves by the impingement of the vertebral platforms. Repeated efforts and abnormal movements (large amplitude deflections, rotations, etc.) cause a progressive deterioration of the inter vertebral disc.

3.3.3 Generalization and consolidation

Rothwell [48] proposes different iterations for the group of tools associated in a sequential manner throughout the design process, employing a logical paradigm for problem solving mentioned by Roozenburg [46]. The evolution of the models presents two premises, the first being based on the product's lifecycle [48] and the second is based upon the functions carried out by the different departments that typically conform a company (marketing, design, and/or production) [49]. Although Eekels [50] stems from a concept of operational design carried out through actions and activities specific for each stage of the design process, all human activity requires task patterns in order to achieve set objectives, through human capabilities (physical and cognitive) and available means (objects and spatial conditions) [51].

Generally, design processes have a limited evolution in relationship with human factors, since they are based on the

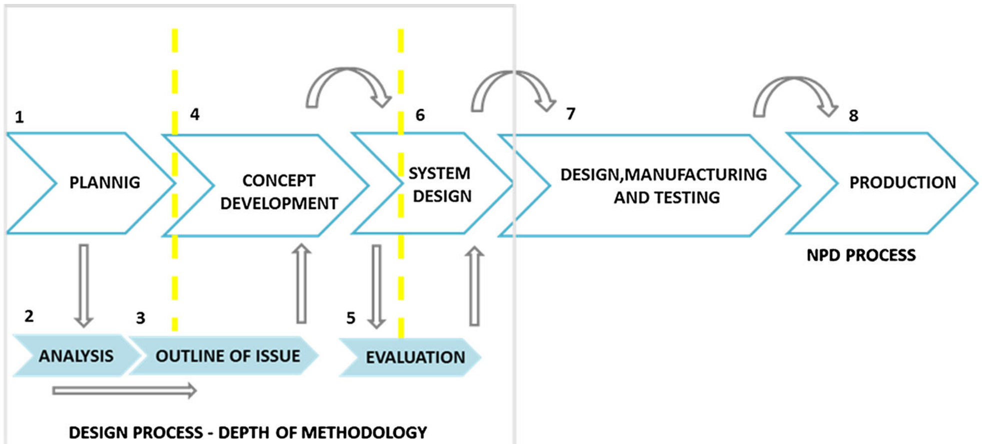

Fig. 9 Design process—depth of methodology

system that identifies human characteristics (capabilities and limitations) in order to generate design principles, evaluated at the very end of the process; applying changes only of future designs [3,42].

For the development of the participative design and ergonomics methodology, some conventional stages of product design and development proposed by several authors were correlated, as well as tools and integration methods; making the methodology an explicit and adaptable approach in both design and redesign cases, as it is shown in Fig. 9.

In order to layout the methodology, processes of *Analysis* and *Outline of issue* were added before *Concept development*, in order to identify more accurately the problem at hand and to analyse user requirements and context limitations. Likewise, the process of *Evaluation* was positioned before the *System design* stage, in order to determine prototypes and models, user perception, functionality and product language.

Design processes have evolved towards work flows that are cyclic rather than lineal, where leveraging complexity and uncertainty is vital. These must be capable of integrating the necessary information in order to be able to grasp said complexity and result in products and services coherent with the dynamics of daily operation. For such reasons, the methodology and the conceptual structure of the design process must be edited in accordance to each individual project, since there will never exist a method that is universal and infallible. The proposed methodology involves, at each individual stage, considerations within the HAC relationship, implementing criteria based on both physical (anthropometric and bio mechanics) and cognitive ergonomics (societal, cultural and emotional aspects). Therefore, this approach aims to guarantee a higher degree of adaptation from technical artefacts within contexts where they perform, as well as its capabilities. These are needs that people have in order to obtain improvements on efficiency, safety and well-being.

The final methodology (version 1.1), presented in Fig. 10, incorporates design methods in different stages, adding aspects related to ergonomics and participative design with the users [52]. Interaction among the main pillars of HAC and adaptation to the requirements are balanced through a feedback synergy among processes of planning, user analysis, and selection criteria based on human factors, concept development, evaluation, systematic design, final design and production. Besides, aspects related to user motivation, accuracy, and efficiency are considered during the usage of the product.

During the *Analysis* phase it is fundamental to take into account a degree of relevance amongst the three elements of the HAC system and the impact that user has during the use scenario. It is necessary to collect information of the state of the art and identify substitute products. In addition, the context must be understood as a factor that adds its own variables independently of the use activity and the product design.

In the *Outline of issue* phase, there are three milestones; at the beginning, the context is an element that has the most relevance in order to be able to recognize the design problem and the limitations set on the inputs and outputs of the system. The second moment centres on the user, analysing his/her needs, personal experiences and ways (s)he can adapt to a certain task. Finally, the third moment is defined by the interaction between the user and the context in order to enable the adaptation of findings into the design or redesign approach.

The design requirements are analysed in the *Concept development* phase, with bio mechanics, anthropometrics and cognitive aspects. In the next phases, 2D and 3D models are created, adapting the design according to the context conditions, user characteristics and product requirements. Finally, in the System design phase the prototype is validated with different users in real contexts. The product is evaluated with indicators of usability and participatory design.

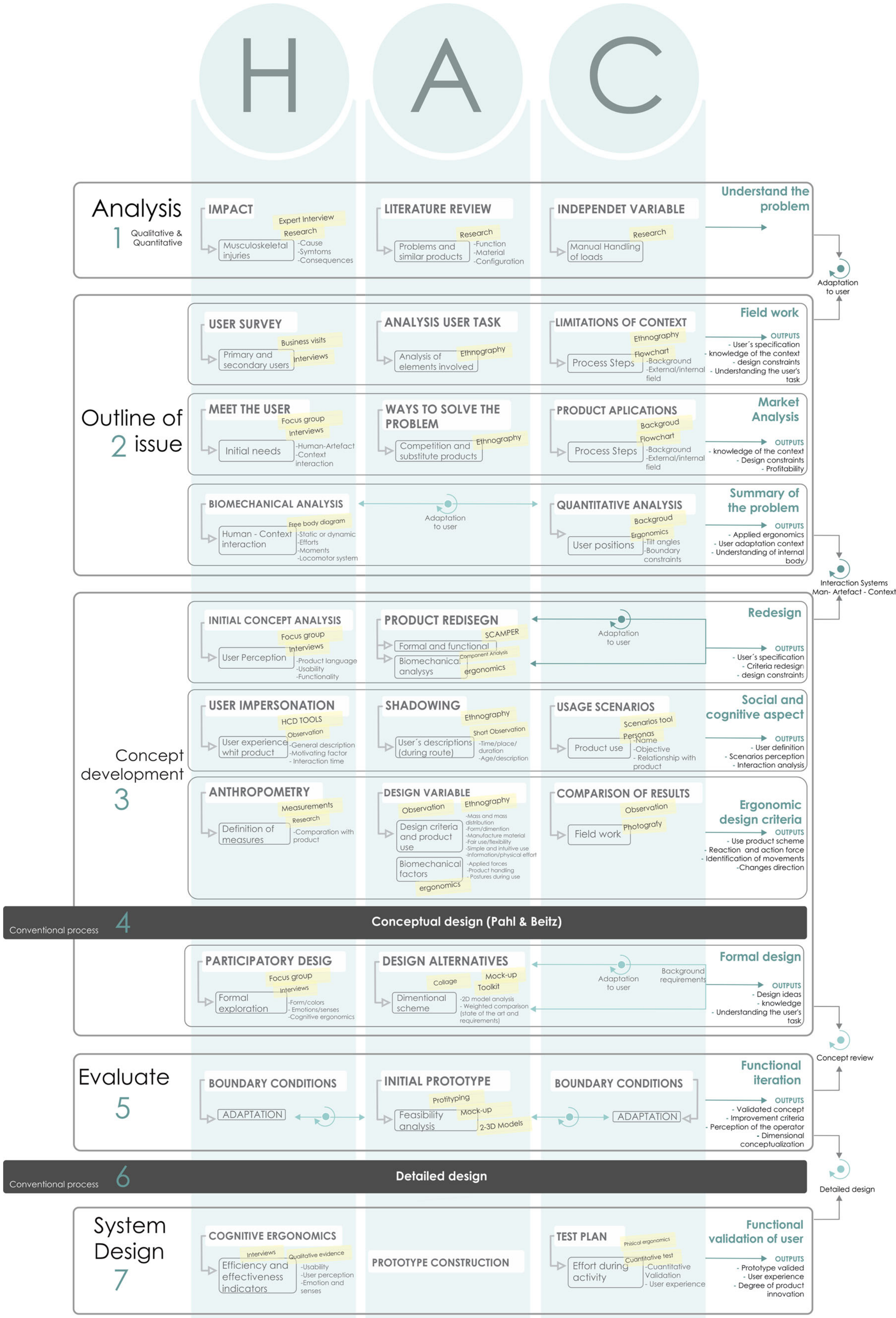

Fig. 10 Methodological framework for design and redesign products—Prescriptive method V1.1

4 Results and analysis

4.1 Methodology analysis

To settle the reliability of the three presented approaches, the data gathered by authors were analyzed in relation with the whole data provided by the methods. As it is observed in Table 1, the final version of the methodology (version 1.1) was 34.44 % more reliable in comparison with the methodology adapted from Ulrich and Eppinger (M1) and 23.78 % more in regards to the version 1.0.

To analyze the balance between the elements of HAC system, additional activities used by the designer were identified in relation with the activities provided by the method. In the final version 1.1 additional activities were not needed in 65.23 % of the times compared with the demand of the initial method. Also each output for every method was analyzed, and for the final version 1.1 the percentage of balance in the HAC system increased in 54.47 % compared with the initial method (M1). In the version 1.0 the percentage of balance is 4.47 % lower in relation with the final version, a predictable aspect taking into account that this research is an evolution of the methodological process in which knowledge is being developed and applied through time.

It was identified that the initial version (M1) does not have the tools suggested for each output, so the coming versions were improved in this regards, going from 45 to 57.14 % until the last version.

In order to ensure adaptability, a percentage of utility for each method was tested in regards with some extra activities done by the designer. When comparing the initial version with the last version, it allowed reducing the need for extra activities in 56.11 %. To test performance, the final version 1.1 had an increase in objectives achieved in 35.46 % in comparison with the initial version and 20 % with the version 1.0. The percentage of tools used to achieve the objectives proposed for the final version 1.1 increases in 60.04 % in comparison with the initial version and in 50.47 % in comparison with the version 1.0.

4.2 Prototype analysis

Table 2 compares different aspects between the initial and the final prototypes of the carrier vest.

The result of this research suggests that when considering the bio mechanics and ergonomic principles for cargo handling (design requirements of the final concept *Carrier Vest C*):

- The energy cost decreased by 26.66 % Carrier Vest C vs no protection, and decreased by 8.97 % Carrier Vest C vs Carrier Vest A.
- The percentage of deformation generated in the shoulder decreased by 32.97 % and at the back by 74.48 % Carrier Vest C vs Carrier Vest A on flat land.
- The percentage of difference between the shoulder and the back strain when using Carrier Vest C (final concept) is 93.57 %, being higher in the back.

5 Conclusions

Ergonomics considerations can contribute to the solution of a great number of issues related to health, security, comfort and efficiency. If products are developed taking into account ergonomic criteria within a determined environment, it could be a very promising topic in a social, economic and human level, improving user experience as well as performance and adaptability for target users.

Currently, there is a variety of methodologies, tools and design methods for the development of products. Some of them incorporate, within the user analysis phases, a verification of ergonomics criteria that is limited to literature research and qualitative analysis of the user. In many cases the mental models of designers are not the same as the users, for this reason, the designers seldom take into account the human model of activity (product operability) during the drafting of a design; thus minimizing task quality and satisfaction. Therefore, a method or explicit tool was defined within systemic processes of design, in order to involve functional considerations, bio mechanical, anthropometric, and cognitive aspects, amongst others. This diminishes iteration cycles and optimizes the relationship between product and user.

The methodology provide more adapted products to users, minimizing the risk of failure, improving usability and comfort during use. This will only become relevant, if the element of ergonomic design is to be upheld as mandatory for the development of any product as a user requirement.

This is when the conscience of primary and secondary users is necessary in order to demand products with the aforementioned traits, marking a significant difference within the mainstream market. In the end, this will contribute to change perspective towards ergonomic design under the notion of the HAC system.

For the case study of the carrier vest, even though there was an increase of 40 % for processes of design and activities incorporated in Carrier vest C, the result was more efficient comparing it with the initial design, because the requirements were not corrected in the advanced stages. The results are not about how many times the users is involved in the design process, because in both cases it was about 53.33 % proportionally, but it is about the way in which ergonomic design criteria is integrated in the design process and the equilibrium that exists between the components of the HAC system.

Table 1 Methodological comparison—indicators

Item			M1 Initial version	M2 Version 1.0	M3 Version 1.1
Reliability of initial guide	1	%, which the guide provides information to improve the design process (from the point of view of a designer)	56 %	66.66 %	90.44 %
Balance between system elements	2	% additional activities that were implemented in the project	72.50 %	58 %	7.27 %
	3	% balance between the elements H-A-C	25 %	85 %	89.47 %
	4	% suggested tools for each agent process	0 %	45 %	57.14 %
Acceptability [53]	5	% Profit = extra activities	72.50 %	55.26 %	16.39 %
	6	Level Reliability = The probability of a guide to perform a required function under stated conditions for a specified period of time	66.66 %	20 %	33.33 %
Effectiveness (which achieves the ultimate goals of the system with maximum precision)	7	%, objectives achieved with the methodology	54.54 %	70 %	90 %
	8	% Tools used by the method to achieve the objectives	30.43 %	40 %	90.47 %
	9	Human efficiency level	3/5	3/4	5/3
Efficiency (Use the least amount of resources and/or efforts to achieve the objectives) ISO 9241 – ISO 9241-11	10	Activities included successfully	81.81 %	90.47 %	92.15 %
	11	Scheduled activities	35 %	19.04 %	5.88 %
	12	Activities undertaken	100 %	100 %	98.03 %
	13	Reported errors	10 %	10 %	4.16 %

Table 2 Comparison of prototypes (Carrier Vest A vs Carrier Vest C)

Type of validation		Analysis criteria			Measuring unit	Carrier Vest A	Carrier Vest C	YES	NO
Qual.	Quant.					Initial prototype	Final prototype		
	X	Deformation	Shoulders	Flat land (0°)	µm/m	38.4	11.69	X	
	X			Downhill sloping ground (170.5°)	µm/m	56.68	23.44	X	
	X		Back		µm/m	712.67	18.85	X	
	X	Average time			seg	16.7	16.21	X	
	X	Average speed			Km/h	4.938	4.82	X	
X		Arduous nature of the task	Proper posture		%	25	75	X	
X			Mild facial expressions comfort (visual analog scale 0–10)		%	37.5	75		X
X			Verbal expressions of comfort		%	25	62.5	X	
X			Negligible signals forced breath after each test		%	37.5	87.5		X
X		Physiological characteristics	Direct (oxygen consumption): variation metabolic consumption		W/m^2	max. 204.1 min. 120.9	max 174.7 min 136.7	X	
X			Indirect aspects (resilience fatigue in relation to heart rate)		beats per minute	105	112.87		X
X		Psychophysical characteristics—Borg scale	Moment greater effort		%	100 at beginning	75 final	N/A	
X			Favoring final terms during the test		%	100	75		X
X			Post-effort		37 % fatigue after 24 h of the test 25 % decreased their daily activities by fatigue 100 % did not sleep disturbance				

When the methodology v1.1 was applied in the design of Carrier Vest C, the development time decreased 33.33 %. This is proof of the increased effectiveness of the process. Although this results could be related with the level of expertise acquired in the design of Carrier Vest A.

6 Future studies

The current state of development of the methodology requires additional cycles of testing in order to validate its applicability and importance within New Product Development (NDP) processes, quantifying results through usability, product experience and perception indicators.

It is essential to reassess the methodology in a controlled group with similar conditions, using a conventional methodology vs the one presented. The aim of this is to decrease uncontrollable factors and quantify usability and effectiveness indicators

It is necessary to create conscience amongst the partaking entities within the design process, who are concept creators and end users. It is important that designers acquire relevant knowledge about users' needs taking into account ergonomic taxonomy from a preventive perspective within the design and conception of products, avoiding corrective phases where the errors must be corrected and the artefact has to be redesigned.

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