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Computational Design of an Adaptable Harness-Based Carrying System for Patients with Dementia Symptoms

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Abstract
Patients with dementia often encounter difficulties in carrying essential items such as health cards, IDs, keys, and money. Traditional bags and pockets can be inadequate; bags are often misplaced, and pockets may not be suitable. This thesis presents the development of an ergonomic harness-based carrying system using body geometry analysis based on the scan data of elderly patients suffering from dementia symptoms, and virtual garment simulation, allowing for optimal adjustment to the body even in motion while ensuring a high level of adaptability, comfort, and functionality. The resulting harness-belt system effectively addresses the needs of carrying essential items and promotes autonomy for patients.

Keywords
dementia patients, adaptive clothing, carrying system, pattern design, 3D modelling.

1. Introduction

We are living in a world with a permanent aging population. According to the World Health Organisation, by 2030, 1 in 6 people in the world will be aged 60 years or over [1]. At this time, the share of the population aged 60 years and over will have increased from 1 billion in 2020 to 1.4 billion. Older age is characterized by the emergence of several complex health states, and dementia belongs to the common group of them.

Dementia is a broad category of brain diseases that cause a long-term and often gradual decrease in the ability to think and remember. As the disease progresses, people living with dementia experience, in addition to impaired cognitive functions, gradual dysfunction and loss of individual autonomies. This decline significantly impacts daily functioning, requiring patients to depend heavily on caregivers for support [2]. The progressive nature of dementia exacerbates the difficulties faced by patients, as they struggle with memory loss, disorientation, and reduced mobility. For caregivers, managing these challenges can be physically demanding and emotionally exhausting, underscoring the need for innovative solutions that can alleviate some of the burdens associated with caregiving [3]. Therefore, developing supportive devices for patients with dementia is crucial in enhancing their quality of life and providing relief to their caregivers. Such devices can assist in daily tasks, promote independence, and ensure safety, thereby improving overall well-being.

One promising option for such devices is carrying systems which are designed to offer a practical and ergonomic solution for carrying personal items without compromising mobility. Patients with dementia, in addition to the numerous other daily challenges, need to carry essential items such as health cards, identification cards, keys, and money when leaving the house. Moreover, if a person gets lost in the street, having their documents with them at all times is essential for their safety. Traditional carrying solutions, like pockets in clothing or bags, often fall short of meeting their needs. Pockets may not always be available in their clothing, and all possessions should be transferred to the new attitude by changing clothing. Carrying bags can be easily forgotten or can limit the freedom of movement, adding this to the daily struggles of patients with dementia syndromes.

The existing solutions for hands-free carrying items are presented on the market in the form of hip bags, waist packs, and carry belts [4]. Hands-free carrying systems have been effectively used in various fields where carrying items is an important part of the daily work routine (for example, the care sector, military missions, and building construction). Particularly for industrial workers, who need to carry tools and equipment while keeping their hands free and maintaining ease of movement, is the load-carrying system the right decision as a form of protection from low-back injury [5, 6]. Thanks to the above benefits, belt systems have migrated from the functional field to everyday use, finding applications in baby-carrying, traveling, and sports [7–9]. They are designed with different features, allowing users to carry items efficiently and not disturbing their movements. The choice of a hip bag often depends on the specific activity. For instance, minimalist designs with smaller capacities are suitable for sports activities, where only essential items are carried [10]. Some models, like the Ergon BA Hip Pack, include features such as hydration bladder compatibility and protector holders, enhancing their versatility for various outdoor pursuits [11].

Hip bags typically consist of a main compartment secured to the body with

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an adjustable belt. Since a high level of adaptability is not required for this application, these solutions are not specifically designed to fit individual body geometry or provide advanced ergonomic support. However, when carrying heavier loads, ergonomics plays a crucial role in distributing pressure across the contact surface. In such cases, carrying solutions are often harness-based, incorporating an adjustable belt for improved weight distribution and stability [12].

Selecting appropriate hands-free carrying systems involves assessing individual needs, considering factors such as activity type, required capacity, and desired features. Adapting the carrying system concept for dementia patients, we aim to create a system that not only serves for unloading when carrying weights but primarily provides a lot of functionality, a high comfort level, and ease of use.

To realize this, we tried to transform the needs into design points, using all the advantages of modern digital design approaches. The spreading of three-dimensional (3D) modelling in garment design has revolutionized the way products are developed and customized. By utilizing 3D analysis and modelling software, designers can create highly accurate and detailed digital representations of products, check the fit properties, make changes, and follow them in real time [13]. Virtual simulation technology allows for precise adjustments and pattern optimization, ensuring the final product is functional and comfortable for the user. In the case of the harness-based carrying system, 3D modelling enables the creation of a multi-layered belt that matches the body's geometry around the hip, providing a stable and ergonomic fit.

Since garment design always refers to body geometry, it is necessary to generate the correct input data in the form of body measurements. Modern scan technologies allow us to obtain body surface characteristics easily and precisely. The application area of 3D scans in the apparel industry varies from made-to-measure apparel [14] to integrating in Augmented Reality to create immersive and interactive shopping experiences [15]. The advent of conventional 3D body scanners introduced new methods for capturing body shapes; however, their application often remained limited to measurement extraction, without fully leveraging their potential for comprehensive body shape analysis [16]. Recent studies have expanded the scope of anthropometric research by exploring body measurements in dynamic and extreme postures to enhance the fit and performance of protective and sports clothing.

The emergence of 4D scanning technology, capable of capturing the human body surface in motion, offers the potential to collect more realistic and complex anthropometric data. This advancement allows for the application of such data in computer-aided design (CAD) environments to simulate human-product interactions [17]. Integrating dynamic anthropometric data into the design process is essential for creating balanced and better-fitting garments, enhancing both comfort and functionality [18].

This study reports on the development of an ergonomic harness-based carrying system for dementia patients, focusing on the use of 3D modelling techniques. The objectives of the study were to design a system that improves patient comfort and caregiver ease, to evaluate the effectiveness of the system through virtual testing, and to explore the potential impact of the system on the quality of life for dementia patients and their caregivers. By combining an ergonomic design approach with advanced three-dimensional modelling, this research significantly advanced assistive technology for dementia care.

2. Methods and materials

The development process was focused on creating a harness-based carrying system that meets the requirements of individuals with dementia for carrying necessary items in their daily mobility. In this study we employed a multi-phase design approach, beginning with an extensive needs analysis, followed by the iterative design and development of the harness system. The final phase involved comprehensively evaluating the system's ergonomics, comfort, and functionality.

2.1. Materials used

Modern lightweight fabrics were selected for the belt-harness prototype to ensure comfort and durability. Elastic materials were proposed in strategic areas to provide flexibility and support. Fall protection was achieved through 3D knitted fabric-based padding.

To make the approaching virtual simulation realistic, we digitized the fabrics that we were using for the prototype manufacturing. The physical properties of the fabric were tested with a Browzwear's fabric analyzer FAB 2.0. The testing set translates the data into material parameters, including mass, thickness, bend, stretch, linearity, and shear. The parameter values obtained are connected to the testing method and are only valid for the selected CAD system [19]. Even a correlation between standardized and Browzwear's measurements was observed. To evaluate them correctly, a converting algorithm for the standardized measurement system, like KES-f (Kawabata Evaluation System for fabrics) and FAST, is required [20].

Advanced 3D modelling and scanning technologies were employed to create a precise and adaptable design. Specific tools and software included Move4D scanning equipment, Lectra Design Concept, and Clo3D software.

2.2. Digital reconstruction of the body geometry

A 4D scan was conducted to capture the body geometry of elderly patients in static or dynamic conditions. The scanning was performed utilizing the MOVE4D scanner, installed in the scan lab of the Chair of Development and Assembly of Textile Products, ITM, TU Dresden, Germany. The woman was scanned in the starting A-Position, followed by

Material	Fabric weight (g/m²)	Fabric thickness (mm)	Resistance to stretch, warp/weft (N/m)	Resistance to bend, warp/weft (dyn*cm)	Resistance to shear (N/m)
330D CORDURA® Classic, 100 PA 6.6	185	0.52	3468.76/3186.43	1463.89/2180.72	56.035
3D knitted fabric, 100 PE	300	3.57	403.81/296.45	2802.8/2701.55	212.38

Table 1. Values of material characteristics measured by a Browzwear's fabric analyzer FAB 2.0

typical movements, namely walking, reaching, and bending. The scans were processed in Move4D software. As output, an animated digital avatar of the person scanned was obtained, and the body shapes were measured in static and dynamic condition in real-time. This technology provides a comprehensive dataset for the following garment design and virtual simulation process.

2.3. 3D pattern design

A model was generated from body scan data and converted from triangulated surfaces into spline surfaces for CAD applications (NURBS). Using the model, we designed belt patterns directly in 3D with Lectra Design Concept software. The belt geometry was derived from waist and hip circumferences, ensuring precise alignment with body contours. The 3D model was then unfolded into 2D patterns using the software's built-in algorithm. This unfolding process ensured that the final product would conform closely to the patient's body geometry and adapt to their movements.

The main feature of the models computed in Lectra Design Concept software 3D is that by linking the CAD data with an Excel sheet where the point information has been stored, it is thus possible to generate a different size at the touch of a key in a computer-aided operation [21]. Therefore, using this parameterized human model eliminates the need to create a new figurine with every new body model. Moreover, if any parameters of the figurine are changed, all subsequent further steps will automatically inherit those changes. As a result, the pattern design is dynamically adapted to the new body geometry.

This approach allows for an easy transition between personalized design and mass customization. The methodology developed allows to scale the patterns obtained for different figure types and sizes, accommodating the full variability of target groups.

In one of our previous studies, we demonstrated how to optimize pattern design for mass production using this automated process [22]. Belt pattern outlines—obtained through the flattening of the parametric model surface—were analyzed and clustered based on curvature and length. Curves were parameterized, discretized, and smoothed using the Balanced Discrete Curve (BDC) approximation method. Curvature values were calculated using Discrete Differential Geometry (DDG) methods. A cluster analysis based on normalized curvature and length identified six optimal size groups. The resulting 2D patterns were then exported in DXF format.

2.4. Garment virtual simulation

To assess the fit and apply necessary adjustments, we utilized three-dimensional modeling with Clo3D virtual simulation software. The finalized 2D patterns, created in Lectra Design Concept, were imported into Clo3D, enabling the creation of an initial digital prototype of the harness. This prototype was applied to a 3D avatar, replicating the body shape and movement patterns of an elderly individual. That allows for a detailed visualization and initial adjustments. Simulations were conducted across all pattern layers, using fabrics specified for each layer. These patterns were digitally stitched and fitted onto the avatar's torso.

The fit quality was evaluated with Clo3D's built-in analysis tools, which generated stress, strain, and tightness maps to allow general fit analysis. As the design included dynamic elements such as straps and accessory pouches for carrying items, it was also essential to assess their behavior in motion to ensure they did not impede typical movements. To achieve this, the avatar was animated based on scanned motion sequences, allowing close observation of any changes that arose during simulated movement.

3. Results

Adaptive clothing for dementia refers to functional clothing designed to address the unique challenges faced by individuals with dementia. These types of garments are specifically created with features that make self-care easier for people who struggle with motor skills or cognitive impairment. Additionally, adaptive clothing can help to maintain a person's dignity and independence, which is also very important for older adults [23]. Overall, adaptive clothing can significantly improve the quality of life for people with dementia or Alzheimer's by reducing stress and promoting independence in daily activities [24].

Clothing for patients with dementia symptoms should prioritize some key requirements and considerations [25,26]. They are summarised in Table 2 below.

Based on the requirements studied, we developed a new prototype of a harness-belt system for individuals with dementia. The prototype incorporates several key features and properties to ensure the required functionality and comfort. The main features of the concept developed are secure placement on the body, back support elements, pouches for necessary items, adaptability, and fall injury protection.

Requirements	Features	Functions
Enhanced comfort	Soft fabrics	Using soft, hypoallergenic fabrics such as cotton or bamboo minimizes discomfort and alleviates skin irritation.
	Elastic waistbands	Elastic waistbands on pants enhance comfort and facilitate the dressing process.
	Layering	Lightweight layers allow for effective temperature regulation throughout the day.
Ease of use	Simple fastenings	Use of Velcro, magnetic closures, or large, easy-to-use buttons in place of traditional buttons and zippers
	Loose fit	Garments should fit loosely, with large openings for easy and comfortable dressing.
Safety	Non-slip footwear	Non-slip socks or shoes can reduce the risk of falls
	Bright colors	Brightly colored or patterned clothing can help patients recognize their clothing more easily and may enhance their mood or prevent depressive symptoms.
Dignity	Stylish designs	Attire that is both stylish and comfortable plays a vital role in preserving the dignity and self-esteem of patients.
	Adaptive underwear	Consideration of options that facilitate restroom use is important in maintaining dignity during daily activities.
Functionality	Pockets	Built-in pockets provide patients with the ability to carry personal items, ensuring effective storage solutions and minimizing the risk of loss.
	Elastic and adjustable features	Adjustable waistbands, cuffs, and similar features should be designed for easy modification, ensuring a snug yet comfortable fit.
Ease of care	Machine washable	The durability of clothing to withstand frequent laundering is essential for practicality.
	Stain-resistant fabrics	Selecting fabrics that exhibit stain-resistant properties is recommended for maintaining a clean appearance with minimal effort.
Lightening the caregiver's load	Adaptive clothing features	Adaptive design can streamline dressing routines, making them less time-consuming and stressful for caregivers.
Additional considerations	Sensory issues	Patients with dementia may have heightened sensitivity to textures and tags; tagless options are preferred.
	Weather appropriateness	The clothing provided should be suitable for different weather conditions, ensuring warmth in the winter and coolness in the summer.

Table 2. Key requirements and considerations for clothing designed for individuals with dementia symptoms

The carrying belt system is designed to be securely positioned around the hips and does not restrict freedom of movement. The placement focuses on areas of the body that experience minimal movement restriction. It also includes a back support feature to help maintain proper posture and reduce strain on the lower back, which is particularly important for dementia patients who may have weakened musculature.

The design includes multiple pouches to facilitate the carrying of essential items such as health cards, IDs, keys, and money.

A 3D-knitted fabric lining is incorporated into the belt padding in the lateral hip area, providing cushioning and protection in the event of a fall. This material was selected for its durability and impact-absorbing properties. Adjustable straps allow quick and easy modifications to the fit, and for individuals in the early stages of dementia, these straps can be removed.

The pouches are modular and feature secure yet easy-to-use attachment points, ensuring flexibility and adaptability to the user's needs.

The design process involved drawing the belt on a digital avatar in Lectra Design Concept software (Fig. 1a). The 3D pattern was generated through free-form surfaces. The pattern can inherit all the changes applied to the digital figurine. This approach ensured that the belt conformed closely to the body's contours.

Once the digital design was finalized, the model was unfolded into 2D patterns (Fig. 1b). The different colors in the belt image indicate the curvature analysis of that region and, ultimately, the different levels of stretch applied to the fabric. This mapping allows us to identify areas where body curvature is pronounced, which requires adding design elements, such as darts or elastic inserts, to reduce excessive stress on these regions. The important benefit of this workflow is that by changing the digital figurine's form, the belt pattern's geometry adjusts automatically. Using this approach, we can quickly recalculate the pattern geometry and redesign the garment for several sizes, covering a whole range of typical ladies' figures.

To move from an individual design to mass production, it is necessary to modify the patterns according to the requirements of the manufacturing process. To perform this, the belt pattern was imported into Grafis CAD software. Using the software's tools, several changes were applied to the pattern. The contours of the pattern were smoothed out. The pattern was divided into front, back, and side insert parts. The dimensions of

each part were calculated based on the dimensions of the integrated pockets, which should allow for holding certain items, such as keys, cards, and mobile phones. The Molle (Modular Lightweight Load-Carrying Equipment) system was designed to provide the possibility of attaching additional pouches on the garment's front and back (Fig. 2). The parametric pattern design in Grafis CAD allows us to extend the principle of automated inheritance of changes, which was set up at the previous research stage.

A comprehensive simulation was conducted in Clo3D to check the fit and ergonomics of the harness system. The virtual fitting process involved matching the pattern with a digital avatar surface that replicated the body shape of the scanned older woman. The simulation tested various movements, such as walking, bending, and reaching, to ensure that the harness remained stable and comfortable throughout these actions (Fig. 3).

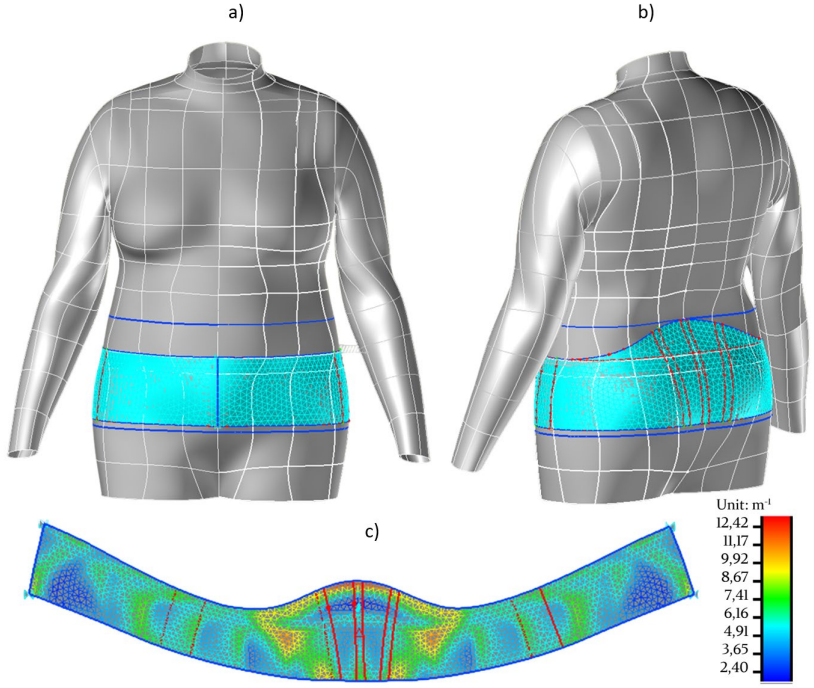

Fig. 1. Digital design in Lectra Design Concept: adjustment of the belt pattern to a typical figure of an elderly woman front (a) and back (b). the belt pattern unfolded with scala (c)

The color map in Fig. 3 shows the degree of material strain. The zone considered critical is the one in which the red colors predominate. In our case, this zone is dedicated to the lateral area where the elastic inserts are located. As already mentioned, the simulation considers the properties of the materials according to their specification. It is, therefore, logical that the material of the elastic insert has a high stress level as it is used to compensate for the dynamic load caused by the movement-induced elongation.

Based on the simulation outcomes, the design was iteratively refined to optimize ergonomic efficiency and functionality. Namely, a cross strap over the chest was added to prevent the strap from slipping off the shoulders while moving. The exact location of the straps was determined to allow them to avoid the chest area, as passing through the breast center can cause discomfort due to high

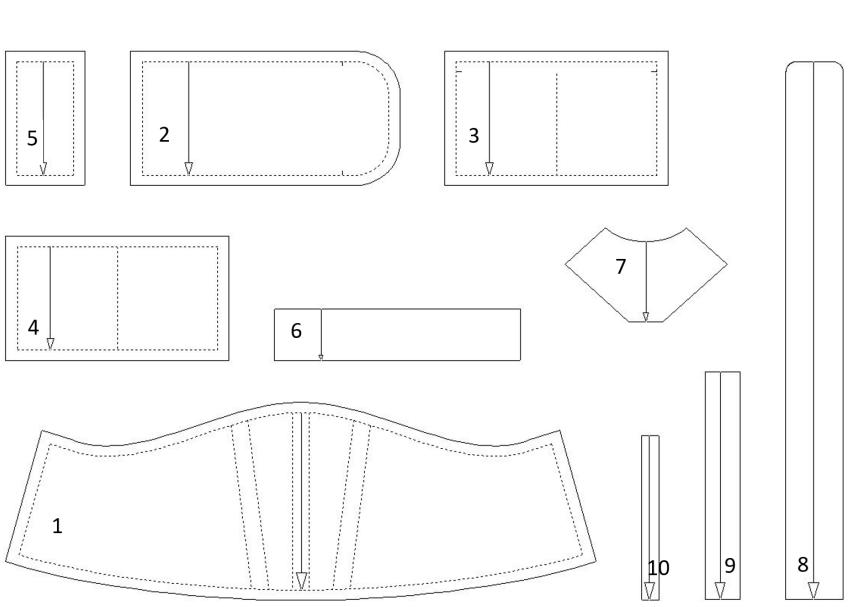

Fig. 2. Basic pattern design in Grafis CAD Software

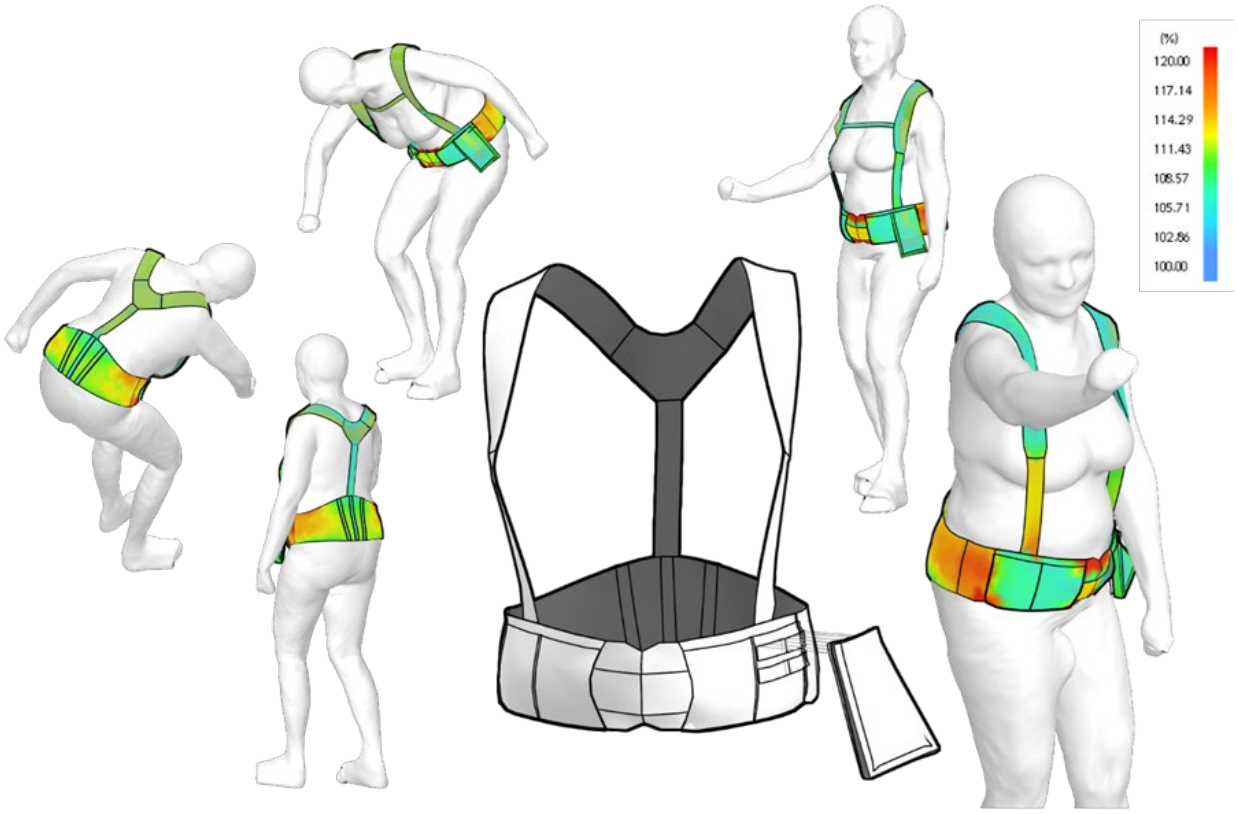

Fig. 3. Quality evaluation of the carrying belt design in the motions with Clo3D's Strain Map

pressure and deformation of soft tissue. The location and size of the pockets were also clarified in terms of their interaction with the leg surface when bending and lifting it. Each iteration was tested until the optimal design was achieved.

Wear trials were conducted to evaluate user satisfaction of the harness-based carrying system prototype developed. Two female individuals were recruited to test the prototype, focusing on key areas such as fit, comfort, ease of use, and modularity (Fig. 4). The wear trials were conducted over three days. Each participant was assigned to wear the belt during daily activity.

Throughout the trial, participants assessed their experiences daily by rating their emotions on a scale of 1 to 5, incorporating the key factors previously discussed. At the end of the study, a structured interview and evaluation of the main criteria were conducted to gather both numerical data and open-ended feedback.

According to the qualitative feedback obtained, the harness fits well, and the testers described it as sufficiently comfortable throughout the testing period. Mobility was not affected, allowing the tester to carry necessary items without any restrictions on movement. The testers praised the comfortable fit, easy adjustment of the harness, and the modularity achieved through the different pockets' availability. They also extra noted the effectiveness of the back support elements.

The following quantitative data supported these findings (Table 2). Table 2 shows a primarily positive trend, with comfort, ease of use, and functionality growth rates. Comfort was rated as 4, highlighting the user-centric design; but getting used to wearing the belt takes some time. The testers reported having no mobility restrictions and gave the product ergonomics a score of 5. Ease of use was noted as 4. One testing person observed that the first-time harness setup, including adjusting all the straps for a perfect fit, took considerable time and could feel overwhelming for unfamiliar users. The harness received a score of 5 for its functionality, which demonstrates the effectiveness of the solution through its primary function, namely the transfer of necessary items. However, some features need to be improved.

4. Discussion

Traditional carrying solutions, such as bags and pockets, often fall short of meeting the needs of individuals suffering from dementia symptoms. Bags can be easily forgotten or lost, and pockets in clothing are not always available or convenient. The harness-based system addresses these issues and offers a secure, hands-free solution to keep essential items within easy reach.

The development of the harness-based carrying system was driven by the need to address the specific challenges faced by dementia patients. Comfort and

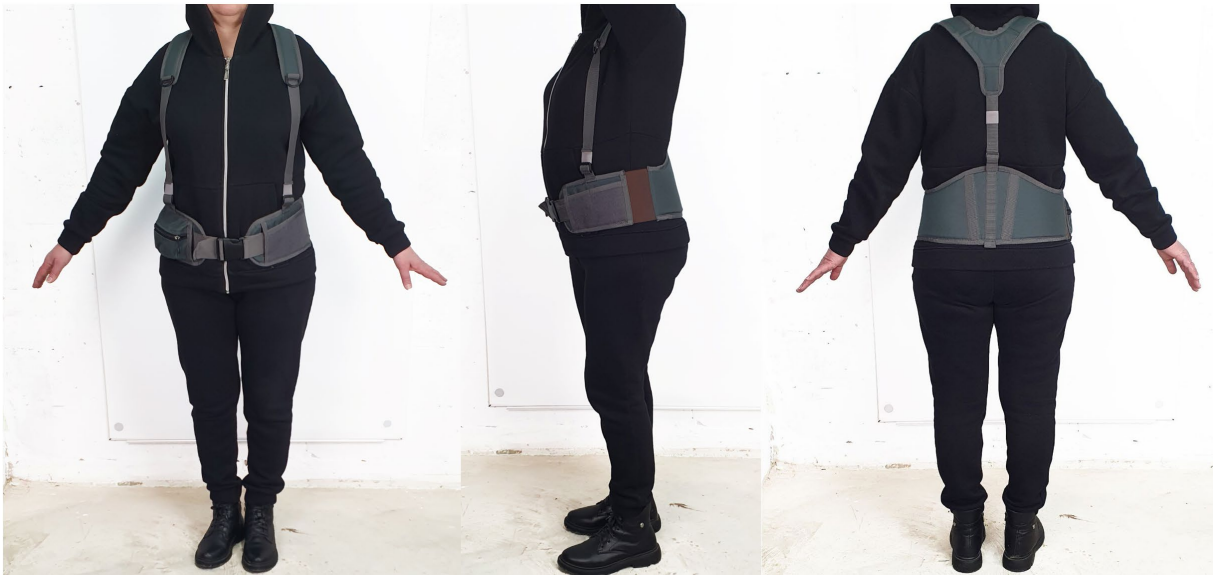

Fig. 4. Testing of the physical prototype of the carrying system

Function	Tester 1			Tester 2			Average score
	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3	
Comfort	4	4	4	4	4	5	4
Ergonomics	5	5	4	5	5	5	5
Ease of Use	3	4	4	3	4	4	4
Functionality	5	5	4	4	5	5	5

Table 2. Average results for the harness-based carrying system wear trials

ergonomics were essential in the design of the harness, while functionality was a primary consideration. By capturing detailed body geometry and typical movement data from an older adult and combining it with typical women's figures, the design process ensured that the belt would fit well not only the figure being tested but also a particular spectrum of body shapes and sizes. The customized components included in the belt design, namely elastic parts, adjustable straps, and removable harnesses, ensured a comfortable fit. The strategic placement of the belt elements on the hips allowed unrestricted movement. Incorporating back support elements and fall protection through a 3D knitted fabric-based lining added to the overall well-being and safety of dementia patients. Through the comprehensive development and testing process, the final harness-based carrying system was optimized to meet the established requirements while fulfilling tasks, providing a practical and ergonomic solution for carrying essential items.

Based on the practical issue involved in performing the study, we developed a solution with high potential to enhance the quality of life for patients suffering from dementia symptoms by improving their self-reliance and dignity while easing the burden on their caregivers. This system allows patients to carry their belongings independently, which benefits everyone involved in the care process. For dementia patients, it promotes a sense of autonomy by helping them organize daily routines and go out without worrying about losing their way or misplacing important items. For nursing staff, the system simplifies the management of patients' belongings and provides confidence that their needs are being effectively met.

However, the harness-based carrying system had some drawbacks. The tested patients reported that the initial setup was somewhat complex and suggested that the adjustment mechanisms could be simplified. Another challenge identified is the overlapping of the harness straps with the bra straps. This could result in additional stress on the shoulder area, potentially causing discomfort, which individuals with dementia may be susceptible to. A potential solution to this issue is utilizing a sports bra with wide soft straps or operating the system without straps, as the harness is designed to be easily detachable.

Additionally, the system's adaptability has its limitations. While it was developed to accommodate a wide range of body sizes and shapes, certain body types may still require further customization to achieve an optimal fit. Addressing these challenges in future iterations will enhance the system's usability and broaden its applicability.

Future iterations of the design should address these limitations. Additionally, further research is recommended to evaluate the long-term effects of the belt-harness system on patients' mobility and self-reliance. Moreover, expanding the

system's flexibility by integrating smart technologies could provide significant benefits. Incorporating GPS tracking or health-monitoring sensors could significantly enhance the harness's functionality. Extending the use of such technologies may improve the harness's performance and broaden its application field to patients with similar needs.

5. Conclusion

The harness-based carrying system introduced in this study enhances and expands existing assistive technologies for patients experiencing dementia symptoms. Through a customized approach, we incorporated all features identified in the study to effectively address patients' needs. By utilizing advanced 4D scanning and 3D modelling technologies during the design process, we achieved high levels of adaptability, comfort, and functionality.

The pattern design workflow can be easily automated, as the digital technologies used in this project allow for the inheritance of changes. This capability enables us to scale the size range and application areas of the product developed. The harness-belt system not only fulfils the practical need for carrying essential items but also promotes patient autonomy and supports caregivers, making it a valuable addition to dementia care solutions.

While there are areas for improvement, this research provides a strong foundation for future innovations in the field.

Ethics and consent

No personal data within the meaning of the General Data Protection Regulation will be processed. Optical, commercially available scanning systems based on the photogrammetry principle with several photo cameras are used for the non-contact recording of the test subjects' surface data. Therefore, the necessary scanning processes are identical to the simultaneous taking of photos. The scans are carried out with clothing. The conducting of surface scans is independent of gender or diversity and does not result in any restrictions or additional requirements, as the necessary process steps and software solutions are already designed for various anatomical differences. The participants involved are entirely voluntary. They give their consent to participate by signing a consent form in writing. The data collected is stored anonymously with the consent of the test subjects. The scanning procedure is, therefore, ethically acceptable overall.

Declaration of Conflicting Interests

The authors declare that they have no competing interests.

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Disclosure Statements

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