HUMAN FACTORS AND ERGONOMICS IN DESIGNING WEARABLES TO ENHANCE WALKING STABILITY

David W. ROSEN[1]**, Christina Youngmi CHOI**[2]
[1]Agency for Science, Technology and Research, Singapore
[2]Royal College of Art, United Kingdom

ABSTRACT
Walking is an important component in many activities of daily living. Particularly for older adults, the ability to maintain balance and walk without falls contributes to the likelihood of remaining independently mobile. There are many classes of mobility aids from canes and walkers to wheelchairs to robotics. While walking has been studied for centuries, the factors that contribute to successful locomotion are many, complex and can be difficult to properly incorporate into a successful device intervention. In this paper we propose an approach for designing assistive wearables that aid walking stability with the consideration of human factors and ergonomics (HFE). The approach is derived from a more general configuration design process from engineering. It integrates the HFE into the engineering design process to augment biomechanical models of human gait, maneuverability, trunk control during walking, and intervention strategies that improve stability with requirements for comfort, ease of use, and wearer confidence. A proposed design method is presented briefly along with concepts of solution configuration using elements from a design library. We explore a sample exoskeleton concept that passively provides restoring forces to the torso and sketch out its components. This approach is informed from a wide range of studies that investigated active and passive exoskeletons for the torso, pelvis, leg, and ankle regions. Two variations of the concept are proposed that comfortably conform to the wearer's size and shape, do not interfere with desired activities, are easy to don and doff, and improve walking stability.

Keywords: Design method, Walking stability, Wearables, Exoskeleton

1 INTRODUCTION

Instability during walking is a key contributing factor to falls particularly among the elderly and those with musculoskeletal or neurological impairments [1]. Mobility aids such as canes and walkers are commonly used but are generally applicable devices that are not tailored to the specific needs of the user. Wearables that enhance walking stability have the potential to be personalized to address instabilities due to age, impairments, rehabilitation of stroke and Parkinson's patients, as well as for occupational safety, sports training, and military purposes.

Walking stability wearables are a rapidly developing field that combines biomechanics, robotics, and rehabilitation engineering. As such, these wearables can be considered cyber-physical-human systems (CPHS) [2]. Broadly, they can be classified into two categories, monitoring and feedback devices that do not actively adjust gait or posture [3], and exoskeletons and orthotics that actively enhance stability by making adjustments to gait or posture [4]. Monitoring and feedback devices typically have sensors that continuously monitor a person's gait patterns and stability such as step symmetry, stride length, and center-of-mass irregularities. When gait deviations occur, these devices can alert the wearer, notify a caregiver, or take other action. In some cases, feedback to the wearer is provided, for example through vibratory or auditory signals, so that wearers can learn to compensate or correct for the deviations.

Active exoskeletons and orthotics take actions to correct gaits or compensate for instabilities. They can take the form of lower-limb exoskeletons (hips or legs), exoskeletons that extend to the torso, or orthotics such as insoles, or smart shoes. Exoskeletons typically have actuators for hip, knee, or ankle joint regions to provide the active corrections. In contrast, the orthotics solutions make smaller corrections to foot placement or step mechanics in ankle-foot orthoses.

Walking instability characteristics can be related broadly to strategies to correct or compensate for them. Spatiotemporal instabilities related to coordination issues between limbs can be corrected by rhythmic auditory cues from smart orthoses that help patients improve gait timing [3] or by exoskeletons that apply torque assistance to hip, knee, or ankle joints [4]. Balance issues caused by impaired control of the trunk (center-of-mass) can be addressed through vibrotactile feedback belts or similar devices that provide directional cues when the trunk tilts too much [5]. Some novel soft exosuits have been developed as well [6]. Hip or ankle exoskeletons can also be used to provide corrective torques. For abnormal joint trajectories (e.g., drop foot) or irregular or weakness in gaits, a variety of ankle-foot orthoses and exoskeletons have been developed [7-10]. An alternative approach is functional electrical stimulation to stimulate weak muscles which can help restore joint motion [11]. Some patients exhibit cognitive or perceptual issues that manifest as freezing of gait in Parkinson's patients or have difficulty navigating uneven terrain. In these cases, visual cueing systems (e.g. augmented reality glasses) [12] or rhythmic sensory stimulation wearables (auditory or vibration signals, as mentioned) have been tested [13].

The larger context for this paper relates to our interest in developing an assistive devices design methodology based on CPHS design approaches. A very wide variety of literature exists that is relevant, from inclusive and human-centered design methods [14] to design principles for wearables [15] and for specific types of rehabilitation devices [16]. In this paper, we discuss human factors and ergonomics and their importance to the design of wearables and walking stability aids, specifically. We briefly introduce a design method for the physical configuration design of wearables and later apply it to the walking stability design problem. For this method, a design problem statement should be specified and a design concept already identified. Then, physical principles and components, modules, and subassemblies should be selected and system solutions configured. Each configured solution should then be evaluated against the requirements.

2. HUMAN FACTORS AND ERGONOMICS

Human Factors and Ergonomics (HFE) is a critical consideration in the design and evaluation of wearables, and in particular for assistive devices [17]. HFE is concerned with understanding and optimizing the interactions between humans and elements of a system, including physical, cognitive and organizational factors [18].

Physical ergonomics are related to anatomic, anthropometric and biomechanical factors which contribute directly to factors such as comfort, fit, adjustability, and freedom of movement. Wearables must be adjustable across a range of shapes and sizes to accommodate user variability and impairments. Adjustments must be easy to perform and accurate to appropriate body landmarks to avoid discomfort or restrictions to range of motion needed to perform intended tasks. It is important to consider overall weight and distribution to control center-of-gravity to promote ease of use, acceptance, and long-term usage.

Cognitive ergonomics are related to the mental process involved with using and controlling a device, including perception, information processing/feedback and decision making. These aspects of human-machine interaction directly impact usability. The richness of feedback and required controls must be balanced for their specific users. Individuals with neurological impairments may require different approaches than others with physical impairments, choosing to employ for example vibrotactile, auditory, or visual feedback. Interfaces should be intuitive and enable appropriate corrective actions without being cognitively overwhelming or difficult to use.

Together HFE provides frameworks for examining a system's fit for purpose to aid a human in completing a task and methods for identifying and addressing issues. Relevant examples for wearables include assessing the process and required mechanisms for putting on and taking off the device ("don and doff") and making appropriate adjustments; evaluating the cognitive load, accuracy and efficiency of control interfaces; or determining the type, level of control and sensitivity required for automated features that intervene without deliberate input.

HFE considerations, measurement and evaluation techniques and methods, with related examples are summarized in Table 1. Selected pre-prototyping evaluation methods are included; however, user testing remains critical in fully evaluating assistive technologies and devices.

Table 1. HFE considerations, measures, evaluations methods, and examples

HFE Consideration	How It Can Be Measured / Evaluated	Pre-Prototyping Evaluation Methods	Example
Fit & Adjustability	• Anthropometric coverage (fit tests) • Subjective comfort ratings	• Digital Human Modeling with anthropometric databases (e.g., CAESAR) • Virtual strap placement simulations	textile-based straps conform to body, adjustable [6]
Range of Motion (ROM) & Kinematic Compatibility	• Motion capture • % reduction in ROM vs. baseline	• Biomechanical simulations (OpenSim, AnyBody) • Virtual joint alignment checks in CAD models	*Honda Walking Assist Device* [9]: hip actuators aligned with anatomy
Load & Pressure Distribution	• Pressure mapping • Peak pressure <30 kPa threshold	• FEA of strap and pad forces • Virtual pressure distribution models	*BalanceBelt* [19]: lightweight belt with distributed load
Weight & Mass Distribution	• Device mass • Center of gravity shift • Energy expenditure	• Digital human balance simulations • Static/dynamic load distribution in virtual mannequins	*EksoGT*: [20]: modular design, distributes weight through rigid frame
Donning & Doffing Ease	• Task analysis (time, errors) • Usability heuristics	• Virtual assembly/disassembly simulations • VR mock-up of donning sequence	*Ottobock C-Brace* [21]: buckle system allows independent donning
Cognitive Workload & Feedback Usability	• NASA-TLX surveys • Dual-task gait studies • Cue response accuracy	• VR/AR prototypes for testing haptic, audio, or visual feedback • Cognitive task simulations	*Vibrotactile belts* [5]: intuitive directional cues, low demand
Social Acceptability & Aesthetics	• User surveys • Observational studies	• VR avatars or digital renders for user feedback • Participatory design workshops	Discreet smart insoles with hidden sensors [22]
Safety & Reliability	• Failure mode analysis • Fall/perturbation simulations	• Digital fault injection in control system simulations • Virtual perturbation tests with biomechanical models	*ReWalk® exoskeleton* [23]: safety interlocks, FDA clearance

Acronyms: AR=augmented reality, FEA = finite element analysis, VR = virtual reality

3 PROPOSED CONFIGURATION DESIGN METHODOLOGY

The proposed configuration design method will be described, followed by further discussion on the problem formulation, design library, and the configuration process.

3.1 Configuration design method

The configuration design method proposed here builds on the method presented in [24] for configuring assistive devices and is shown in Figure 1. Given a problem definition and an initial concept, two nested loops are used to iterate through each design requirements and then identify components and modules for each requirement. A design library is assumed that consists of components and modules often found in smart and assistive products. With the library, the design method matches each requirement to elements in the library to identify candidate components and modules. With a set of candidate components and modules, complete product configurations can be generated. It is expected that some requirements will address problem aspects that do not facilitate matching with physical components, such as requirements on safety, acceptability, usability, etc. and will be ignored. Steps are numbered for easy reference.

The design method starts in Step 1 by selecting a subset of design requirements that refers to functional or structural aspects of the problem. Since some design library components may correspond to more than one design requirement, groups of one or more requirements are used for subsequent steps. The outer loop (Steps 1-5) considers all combinations of the selected design requirements. Then, the inner loop tries to match each requirement combination (Step 2) with design library elements that satisfy requirements in that combination (Step 3). When all requirement subsets have been processed, the inner loop ends.

From all of the matched components and modules from the design library, candidate device designs are configured (Step 4). They are then evaluated against all design requirements, particularly on human factors (Step 5) since product evaluation requires more than just ensuring one component satisfies one requirement. Product evaluation involves analyses of virtual device models for technical feasibility, including detailed technical analyses if detailed models can be developed. However, for usability, acceptance, and other HFE requirements, assessments will likely be limited to designer evaluations of configuration device models using task analysis, risk assessments, anthropomorphic analyses, and similar approaches. If a device design appears promising, the designer should choose to store it for further consideration (Step 6). If not, the solution should be discarded. The designer can decide to continue solution generation (execute the outer loop again) or stop the configuration design process to further develop device designs.
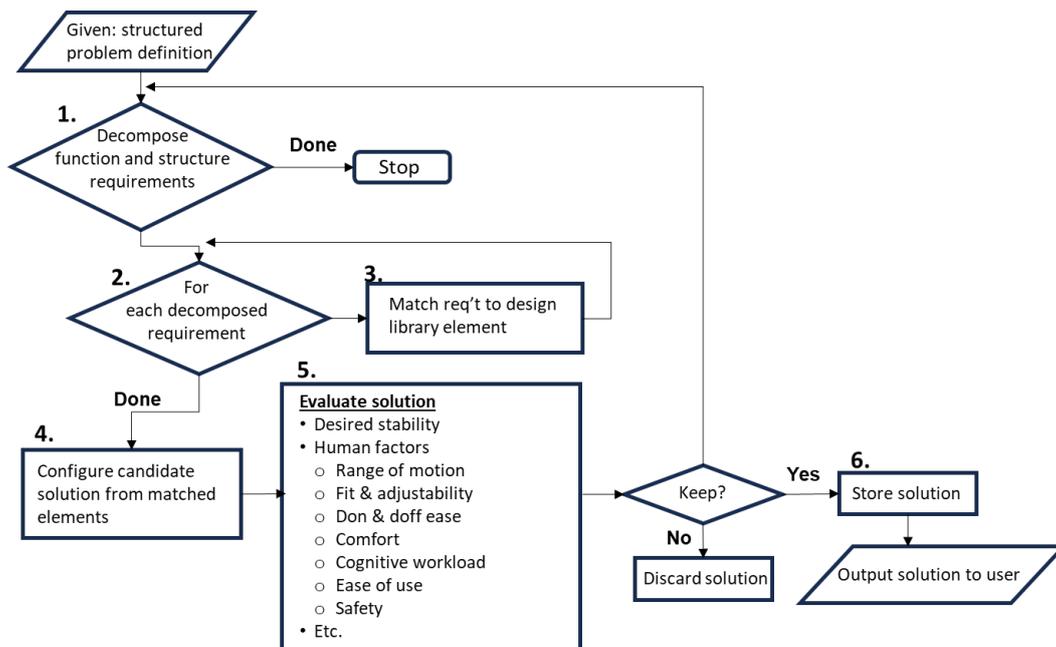

Figure 1. Proposed configuration design method

3.2 Design library

Assistive walking devices, as with most smart products, consist of many standard types of components, including actuators, sensors, motion systems, energy sources, feedback devices, closures, etc. To facilitate device design, we are developing a design library of these standard component types. An initial listing of device types is given in Table 2, along with the types of information to be associated with each library entry (i.e., the left-most column lists the information types, while all other columns list different types of devices). The component lists are not meant to be comprehensive, but include those commonly used. Information included about each entry is its classification in a type-of hierarchy, function or purpose, a description of its behavior, relevant physical principles(s), geometry and size parameters, and important properties.

As presented in Table 2, the design library contains abstract entries with attributes that are representative of broad classes of devices. In the future, we envision that the design library will be a hierarchy of increasingly detailed device descriptions. At the lowest level, library entries will refer to specific items available in vendor catalogs. During conceptual design, the higher level (more abstract) entries will be sufficient to support design, as indicated in Section 4, while later design stages will take advantage of the lower hierarchy levels.

Structural components of assistive walking devices are typically designed specifically for each device. Although some parts of these structures may be standard, it is difficult to provide a general design library entry for these parts such that the entry would be useful. That said, we do plan to include lists of standard materials along with their mechanical and physical properties.

Table 2. Design library representation and examples

Information	Sensors	Actuators	Motion System	Energy Source	Feedback Device
Class of component	Pressure	Servomotor	Cable driven	Battery	Sound
Function	Motion - resistive	Stepper motor	Geared transmission	Wall AC	Lights
Behavior/motion/action	Motion - capacitive	Hydraulics	Hydraulics	Hydraulic pressure	Piezoelectric
Physical principles	Motion - strain	Pneumatics	Pneumatics	Pneumatic pressure	Electroactive polymer
Shape/geometry	Photodetector	Shape memory alloy	Shape memory		
Material	Inertial Measurement Unit	Piezoelectric			
Mechanical properties	Gyroscope				
Physical properties					
Connection features					

3.3 Walking stability aid design problem definition

A design problem template is proposed for designing walking stability aids to provide guidance on structuring the design problem. Standard terminology is proposed for defining design problems and design library elements. Accordingly, designers can formulate problems and ensure that all relevant types of requirements are included. Furthermore, having consistent terminology enables design requirements on functional, behavioural, or structural aspects to be matched to elements of the design library.

Table 3 presents the walking stability aid design problem template. The template is structured according to requirement categories such as functional, behavior, structural, HFE, etc. The subtypes column provides specializations of the overall categories. Note that not all HFE considerations are included in the table since they were listed in Table 1. Also note that other requirements on regulatory compliance, privacy, security, etc. may be important but are outside the scope of this paper. Functionality should include aspects of providing support and stability, sensing, and communications. We suggest that the terminology specified by the functional basis should be used as much as possible for functions and behaviours [24]. The third column includes sources of information for completing the design requirements and some examples to provide guidance.

3.4 Configuration of devices

The objective of configuration design is to generate promising concepts and layouts that are worth further development. Since designs are not fully developed, they must be reviewed using a heuristic, qualitative or other assessment to identify promising solutions, that is, are likely to reasonably satisfy each requirement.

Device configuration includes matching each requirement, or part of a requirement, to an element from the design library, adjusting the shape and size of each element to the corresponding body part, then assembling all selected elements into a candidate solution. The walking aid's spatial layout should be proposed and interfaces and connections between the main components should be specified. Additionally, multiple spatial layouts and configuration should be generated from the same set of library elements.

4 EXOSUIT DESIGN

A passive exosuit example will be explored. The specific problem statement is: A walking stability device should aid mobility limited people in maintaining balance. If the wearer starts tilting sideways, forward or backward, the device should passively provide restoring forces and moments to the torso. No actuators should be incorporated into the device. A fall sensor should trigger an alert to a caregiver if the wearer does fall. The device should be easy to don and doff. It should require at most one simple user action to initiate its operation.

The device will be referred to as a (passive) exosuit since it is intended to replace conventional exoskeletons that could provide similar functionality. Functional and HFE requirements are listed in Table 4, as well as two candidate design solutions. Sketches of the solutions are shown in Figure 2 and a comparison with HFE considerations is offered in Table 5.

Table 3. Walking stability aid design problem template

Requirement Categories	Subtypes	Sources, Examples
Functional	Provide support and stability	Prevent side-to-side sway
	Sensing	
	Communications	
		use functional basis for specific purpose
Behavior		motions, dynamics, functional basis
Structural	Shape, geometry	
	Product architecture	
	Components, modules	Design library
Human factors and ergonomics	Fit, comfort, adjustability	Ranges of sizes and adjustability; anthropomorphic considerations
	Range of motion allowed	Limits on side-to-side sway
	Load and pressure distribution	Peak pressure, center of gravity shift allowed
	Cognitive workload	Usability
	(see Table 1)	
Customization needed		none, choose from range of models, customize per patient
Manufacturability		
Cost		
etc.		

4.1 Solution 1

Two candidate solutions will be presented, where both are based on the physical principle of compression-based support of the torso using an inflated garment. The concept is that such compression aids stability by preventing torso rotation. Fore-aft bending is resisted due to compressive forces. Additionally, solution 1 utilizes rigid struts to restrict side-to-side sway. Further, intended wearers are assumed to have sufficient balance stability to respond to warnings about excessive tilt. As such, a vibrotactile belt will be integrated that provides a vibration signal in the direction of tilt so that the wearer can correct his/her posture. Accordingly, the exosuit extends only to the hips, but does not cover the hips or incorporate the upper legs.

Regarding HFE, the user can don the exosuit similarly to a vest. Velcro straps along the front of the exosuit ensure a secure fit and provide some adjustability. Removal of the exosuit is straightforward, as with a vest. Regarding operation, inflation of the exosuit will be accomplished using a CO_2 cartridge in the garment that is activated by a force sensor under a Velcro strap, such that inflation is a natural consequence of donning the exosuit. A wall-mounted fixture will be designed on which to hang the garment when not being worn. As part of this concept, the CO_2 cartridge should engage a device that recharges the cartridge when the exosuit is in the fixture.

To add another layer of functionality, the exosuit will be able to detect falls and communicate with caregivers. A sensor will be incorporated into the exosuit, as well as Bluetooth communications in this regard. In Solution 1, an accelerometer is selected as the fall detection sensor. A rechargeable battery will be used to power the sensor, communication system, vibrotactile belt, and CO_2 cartridge trigger. A wireless recharger will be incorporated into the fixture.

Table 4. Exosuit functional design requirements and candidate solutions

| Functional Requirements	Solution 1	Solution 2
Provide restoring forces and moments		
Sideways disturbances	Inflatable compression, rigid struts	Inflatable compression
Front/back disturbances	Inflatable compression	Inflatable compression
Attach to body	Velcro straps	Velcro straps
Operation	Straps: manual Inflation: force sensor, CO2 cartridge	Straps: manual Inflation: force sensor, CO2 cartridge
Warn excess tilt	Vibrotactile belt	--
Detect fall	Accelerometer	IMU
Communicate with caregiver	Bluetooth	Bluetooth
Provide power	Wireless rechargeable battery	Wireless rechargeable battery
Recharge power source	Wireless recharger in fixture for storing garment	Wireless recharger for removable battery pack
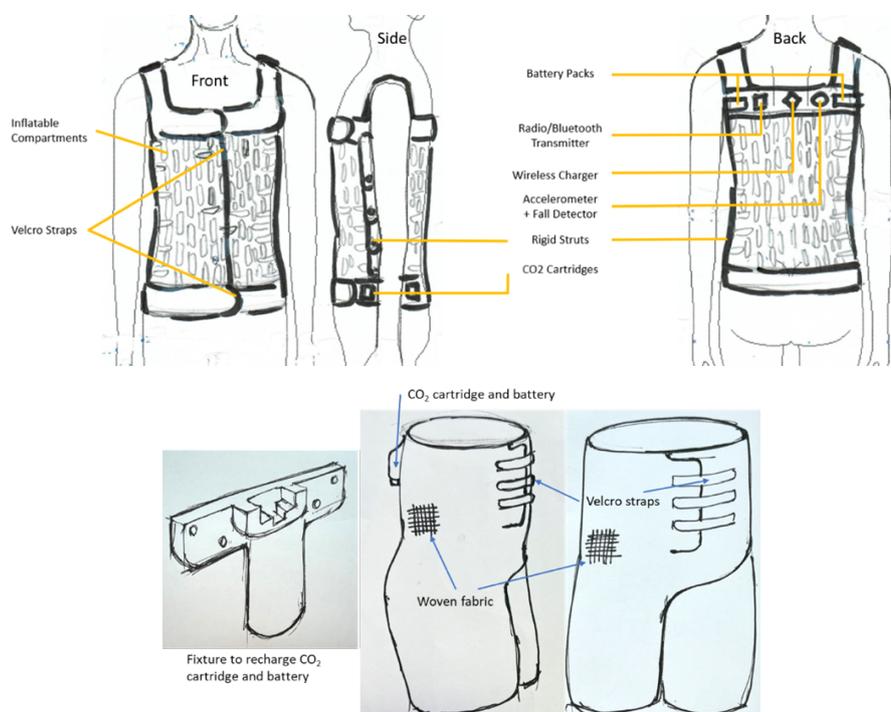
Figure 2. Two candidate solutions: (top) exosuit with rigid struts and (bottom) exosuit that covers hips and upper thighs

4.2 Solution 2

Solution 2 has many similarities with Solution 1 but is meant for patients with less balance stability. Hence, the exosuit covers the hips and extend to the upper thighs to provide greater resistive forces. The suit will be inflatable, similar to Solution 1, but will not require rigid struts on the sides. The other significant difference is that vibrotactile signals will not be used to warn the wearer of excess tilt since they are assumed to have less balance stability.

From the HFE perspective, the wearer should don the exosuit as they would with a bodysuit with shorts (as opposed to long pants). Front closures secured with Velcro straps will be used to achieve a secure, adjustable fit in the torso area. Modifications to the lower part of this exosuit concept can be made to enable more adjustments if necessary. An inertial measurement unit (IMU) is selected as the fall detection sensor for this solution.

Table 5. Evaluation of solutions with respect to HFE considerations

HFE Consideration	Solution 1	Solution 2
Fit and adjustability	Velcro straps ensure secure fit and adjustability. Inflatable garment should minimize stress concentrations.	
Range of Motion	Compression controllable by inflation pressure	
	side-to-side tilt constrained by struts	no additional restraints
Weight Distribution	inflatable garment ensures even distribution	
Don and Doff Ease	as a vest with Velcro straps	as a bodysuit-vest combination
Cognitive Workload	one-step operation, attention to vibrotactile signals for tilt correction	one-step operation
Aesthetics/Acceptance	low profile garment, can be worn under or over clothing	
Safety	inflatable garment with no off-center mass. low inflation pressures reduce impact of burst.	

5. CONCLUSIONS

Walking stability wearables can aid older adults and impaired people to maintain balance and walk without falls. In this paper, we analyzed human factors and ergonomics (HFE) of relevance to walking stability wearables and proposed a method for designing assistive wearables for walking stability that included HFE considerations. These HFE considerations play three important roles in the design method. First, they should be part of the design problem formulation in terms of requirements. Second, they can inform the selection of components that are included in the design library to ensure that these components contribute to positive HFE characteristics of the overall product. Third, they should be used as evaluation criteria when evaluating design alternatives.

We explored an inflatable exoskeleton concept that passively provides restoring forces to the torso and sketched out its components. Two variations of the concept were proposed that respond to different levels of walking assistance needs. HFE evaluations of the concepts show that they appear to comfortably conform to the wearer's size and shape, do not interfere with desired activities, are easy to don and doff, and improve walking stability. HFE requirements related to more subjective or individual perception-based considerations, such as safety and aesthetics/acceptance, were included in the solution evaluation process but should be further assessed by user testing with physical prototypes.

Future work should explore additional design concepts for a wider range of walking assistance needs. A much larger design library of HFE-suitable components is needed, particularly for exoskeletons with active components. The presented design method provides overall guidance but should be more specific about configuration design and the incorporation of HFE considerations. We hope that this paper encourages other researchers to contribute to the design of walking wearables and other assistive mobility devices.

ACKNOWLEDGMENTS

REFERENCES

[1] Frank, J. S., and Patla, A. E. Balance and mobility challenges in older adults: implications for preserving community mobility. *American Journal of Preventive Medicine*, 2003, 25(3), 157–163.

[2] Rosen, D. W., and Choi, C. Research issues in the generative design of cyber-physical-human systems. *Journal of Computing and Information Science in Engineering*, 2023, 23, 060810.

[3] Biswas, N., Chakrabarti, S., Jones, L. D., and Ashili, S. Smart wearables addressing gait disorders: a review. *Materials Today Communications*, 2023, 35, 106250.

[4] Sterke, B., Jabeen, S., Baines, P., Vallery, H., Ribbers, G., and Heijenbrok-Kal, M. Direct biomechanical manipulation of human gait stability: a systematic review. *Plos One*, 2024, 19(7), e0305564.

[5]   van Erp, J. B., van Veen, H. A., Jansen, C., and Dobbins, T. Waypoint navigation with a vibrotactile waist belt. *ACM Transactions on Applied Perception*, 2005, 2(2), 106–117.

[6]   Awad, L. N., Bae, J., O'Donnell, K., De Rossi, S. M., Hendron, K., Sloot, L. H., *et al.* A soft robotic exosuit improves walking in patients after stroke. *Science Translational Medicine*, 2017, 9(400), eaai9084.

[7]   Moltedo, M., Godi, M., Arcolin, I., Giardini, M., Pisano, F., and Artoni, F. Gait stability in stroke survivors walking with a powered ankle exoskeleton. *Frontiers in Human Neuroscience*, 2018, 12, 119.

[8]   Serrao, M., Casali, C., Ranavolo, A., Mari, S., Conte, C., Chini, G., *et al.* Use of dynamic movement orthoses to improve gait stability and trunk control in ataxic patients. *European Journal of Physical and Rehabilitation Medicine*, 2017, 53(5), 735–743.

[9]   Satoh, Y., Yamada, T., Arai, Y., Shimamura, R., Hirosawa, M., Yamakawa, R., and Takagi, S. The immediate effect of the Honda Walking Assist Device on foot and ankle function in hemiplegic stroke patients. *Journal of Physical Therapy Science*, 2020, 32(6), 405–409.

[10] Kwon, J., Park, J. H., Ku, S., Jeong, Y., Paik, N. J., and Park, Y. L. A soft wearable robotic ankle-foot orthosis for post-stroke patients. *IEEE Robotics and Automation Letters*, 2019, 4(3), 2547–2552.

[11] Kesar, T. M., Perumal, R., Reisman, D. S., Jancosko, A., Rudolph, K. S., Higginson, J. S., and Binder-Macleod, S. A. Functional electrical stimulation of ankle plantarflexor and dorsiflexor muscles: effects on post-stroke gait. *Stroke*, 2009, 40(12), 3821–3827.

[12] Hollands, K. L., Pelton, T. A., Wimperis, A., Whitham, D., Tan, W., Jowett, S., *et al.* Feasibility and preliminary efficacy of visual cue training to improve adaptability of walking after stroke: a multicentre, single-blind randomised controlled pilot trial. *Plos One*, 2015, 10(10), e0139261.

[13] Sejdić, E., Fu, Y., Pak, A., Fairley, J. A., and Chau, T. The effects of rhythmic sensory cues on the temporal dynamics of human gait. *Plos One*, 2012, 7(8), e43104.

[14] Clarkson, J., Coleman, R., Keates, S., and Lebbon, C. *Inclusive Design: Design for the Whole Population*. 1st ed. London: Springer, 2003.

[15] Salisbury, L. J., McGinley, C., and Yenigun, E. O. Applying people-centred design methods to enhance the development of wearable technology for everyday use. In *Smart Clothes and Wearable Technology*, 2023, pp. 447–483. Woodhead Publishing.

[16] Castellini, C. Design principles of a light, wearable upper limb interface for prosthetics and teleoperation. In *Wearable Robotics*, 2020, pp. 377–391. Academic Press.

[17] Salvendy, G. (ed.). *Handbook of Human Factors and Ergonomics*. John Wiley & Sons, 2012.

[18] Stefana, E., Marciano, F., Rossi, D., Cocca, P., and Tomasoni, G. Wearable devices for ergonomics: a systematic literature review. *Sensors*, 2021, 21(3), 777.

[19] Kingma, H., Hougaard, D. D., and Van de Berg, R. Subconscious vibrotactile stimulation improves mobility and balance in patients with bilateral vestibulopathy: adherence over 2 years. *Frontiers in Neurology*, 2024, 15, 1491195.

[20] Bach Baunsgaard, C., Vig Nissen, U., Katrin Brust, A., Frotzler, A., Ribeill, C., Kalke, Y. B., *et al.* Gait training after spinal cord injury: safety, feasibility and gait function following 8 weeks of training with the exoskeletons from Ekso Bionics. *Spinal Cord*, 2018, 56(2), 106–116.

[21] Pröbsting, E., Kannenberg, A., and Zacharias, B. Safety and walking ability of KAFO users with the C-Brace® Orthotronic Mobility System, a microprocessor stance and swing control orthosis. *Prosthetics and Orthotics International*, 2016, 41(1), 65–77.

[22] Wang, Q., Guan, H., Wang, C., Lei, P., Sheng, H., Bi, H., *et al.* A wireless, self-powered smart insole for gait monitoring and recognition via nonlinear synergistic pressure sensing. *Science Advances*, 2025, 11(16), eadu1598.

[23] Awad, L. N., Esquenazi, A., Francisco, G. E., Nolan, K. J., and Jayaraman, A. The ReWalk ReStore™ soft robotic exosuit: a multi-site clinical trial of the safety, reliability, and feasibility of exosuit-augmented post-stroke gait rehabilitation. *Journal of NeuroEngineering and Rehabilitation*, 2020, 17(1), 80.

[24] Rosen, D. W., Choi, C. Y., and Sinha, A. K. Toward a design methodology for configuring assistive wearables. In *Proceedings of the Design Conference*, Dubrovnik, Croatia, May 20–23, 2024.