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Soft robotic shorts improve outdoor walking efficiency in older adults

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Enrica Tricomi[1], Francesco Missiroli[1,7], Michele Xiloyannis[2,7], Nicola Lotti[1], Xiaohui Zhang[1], Marios Stefanakis[3,4], Maximilian Theisen[5], Jürgen Bauer[3,4], Clemens Becker[3,4] & Lorenzo Masia[1,6]

Peoples' walking efficiency declines as they grow older, posing constraints on mobility, and affecting independence and quality of life. Although wearable assistive technologies are recognized as a potential solution for age-related movement challenges, few have proven effective for older adults, predominantly within controlled laboratory experiments. Here we present WalkON, a pair of soft robotic shorts designed to enhance walking efficiency for older individuals by assisting hip flexion. The system features a compact and lightweight tendon-driven design, using a controller based on natural leg movements to autonomously assist leg propagation. To assess WalkON's impact on daily walking, we initially conducted a technology assessment with young adults on a demanding outdoor uphill 500 m hiking trail. We then validated our findings with a group of older adults walking on a flat outdoor 400 m track. WalkON considerably reduced the metabolic cost of transport by 17.79% for young adults during uphill walking. At the same time, participants reported high perceived control over their voluntary movements (a self-reported mean score of 6.20 out of 7 on a Likert scale). Similarly, older adults reduced their metabolic cost by 10.48% when using WalkON during level ground walking, while retaining a strong sense of movement control (mean score of 6.09 out of 7). These findings emphasize the potential of wearable assistive devices to improve efficiency in outdoor walking, suggesting promising implications for promoting physical well-being and advancing mobility, particularly during the later stages of life.

Simple activities such as walking, ascending stairs or rising from a chair become more energetically demanding as people age, limiting mobility and independence[1,2].

As a reaction to these realities, the scientific community has intensified its efforts to design solutions that enhance mobility[3]. In the realm of robotics, this has led to the development of wearable assistive devices that support movement in various regions of the body. The first generation of these wearable robots featured rigid actuated links that produce large torques parallel to the human joints, best known as traditional exoskeletons[4–6]. Over time, a select few of these devices have been explicitly designed to strengthen the mobility of older adults, with a specific emphasis on walking, which is typically most affected as people age[3,7,8]. However, their use is confined mainly to laboratory-based experiments due to their weight and size[9]. Incorporation into daily life applications is also limited due to low social acceptance[10].

[1]Institut für Technische Informatik (ZITI), Heidelberg University, Heidelberg, Germany. [2]Akina AG, Zürich, Switzerland. [3]Digital Unit, Center for Geriatric Medicine, Heidelberg University Hospital, Heidelberg, Germany. [4]Network Aging Research, Heidelberg University, Heidelberg, Germany. [5]Psychological Institute, Heidelberg University, Heidelberg, Germany. [6]Department of Computer Engineering School of Computation, Information and Technology, Technical University of Munich (TUM), Munich, Germany. [7]These authors contributed equally: Francesco Missiroli, Michele Xiloyannis. e-mail: enrica.tricomi@ziti.uni-heidelberg.de

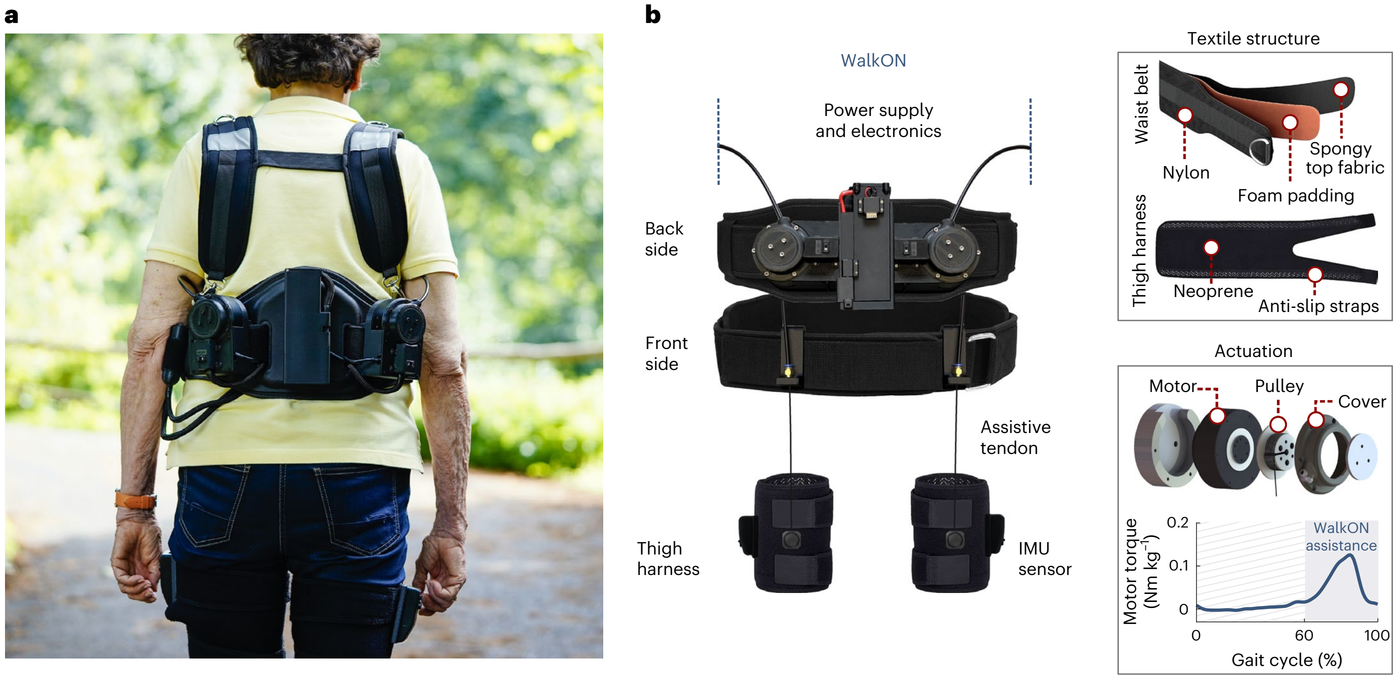

Fig. 1 | WalkON design. a, An older adult using WalkON for outdoor walking. Photography by Uwe Anspach. **b**, WalkON's design comprises a textile structure encompassing a waist belt and two thigh harnesses that can be comfortably worn over regular clothing. The actuation mechanism relies on a tendon-driven transmission, with artificial tendons linked to the front part of the user's legs. These tendons are actuated by motors in accordance with the user's gait cycle. Motor commands deliver assistive forces during the swing phase of each step according to the hip joint kinematics recorded through inertial measurement units (IMUs) in the sagittal plane.

In recent years there has been a notable shift towards soft, lightweight solutions. Commonly known as exosuits[9], these devices feature textile garments and active components working in parallel to the human muscles. They have proven efficacy both by alleviating muscle strain in upper body joints[11–13], and by reducing the metabolic expenditure associated with walking or running[14–16]. Exosuits have exhibited usability comparable with rigid exoskeletons, but with superior user satisfaction in terms of weight, effectiveness and safety[17].

Nonetheless, there are still substantial obstacles to the widespread adoption of such assistive technologies outside of controlled laboratory settings. With respect to walking support, foremost among the current limitations is the critical need for assistive devices to be self-contained and capable of adapting to the variable pace and modes of locomotion encountered in unstructured, real-world environments[18,19]. Furthermore, from the user's perspective, the sensation of precise control over voluntary movements, known as the sense of agency, holds paramount importance to enhancing the user experience[10,20]. Addressing these challenges has the potential to encourage a more extensive adoption of such technologies, ultimately lowering the mobility barriers imposed by aging.

In this study we present a pair of lightweight, soft robotic shorts, hereafter named WalkON, designed to be worn over regular clothing and to act as a walking aid for daily use. The primary goal of this technology is to enhance the autonomy and walking energy efficiency for its users, with a particular focus on providing support to older individuals.

By design, WalkON assists hip flexion during the swing phase of walking. The hip joint plays a vital role in ground clearance and limb advancement, demanding considerable power, especially up hills and stairs[21,22]. The role of the hip becomes more critical with advancing age. Compared with young adults, it exhibits more pronounced kinetics during the push-off phase, resulting in increased mechanical work required for locomotion and reduced energy efficiency[2,23,24]. Given these considerations, preserving hip function emerges as a fundamental strategy for maintaining walking ability[2,24].

WalkON aims to achieve this objective by supporting the propagation of upward leg movement through an actuation method that uses artificial tendons. It features a portable and lightweight design and employs a control strategy grounded in the user's natural leg movement pattern. This versatility makes it well-suited to facilitate prolonged walking sessions, accommodating both typical outdoor settings and more challenging hiking-like terrains.

We hypothesize that WalkON can reduce the metabolic cost of walking compared with unassisted walking. Furthermore, we posit that no restriction of the physiological kinematic patterns happens while using the system. We further expect that users maintain full control over their voluntary movements, thus reporting a strong sense of agency.

The contribution of this study is twofold. From a technical standpoint, we tested these hypotheses through a technology assessment involving young, healthy participants walking on a challenging outdoor uphill path to showcase the biomechanical effects of the system during demanding walking activities. We then conducted an efficacy study with our target population, involving participants aged 67 years and older on an outdoor walking track. These steps served to confirm the observed effects and provide a comprehensive understanding of WalkON's impact across different age groups.

Results

Technology assessment with young adults

Participants. Twelve young and physically fit individuals, comprising seven men and five women, were recruited for the technology assessment of WalkON (Fig. 1). Their average age was 25.42 ± 2.27 years, with a mean height of 173.50 ± 11.63 cm and weight of 66.25 ± 11.73 kg (refer to Extended Data Table 1 for individual demographics).

WalkON significantly reduced the metabolic cost of transport in uphill outdoor walking. The metabolic cost of transport, which measures the amount of metabolic energy required to cover a unit of

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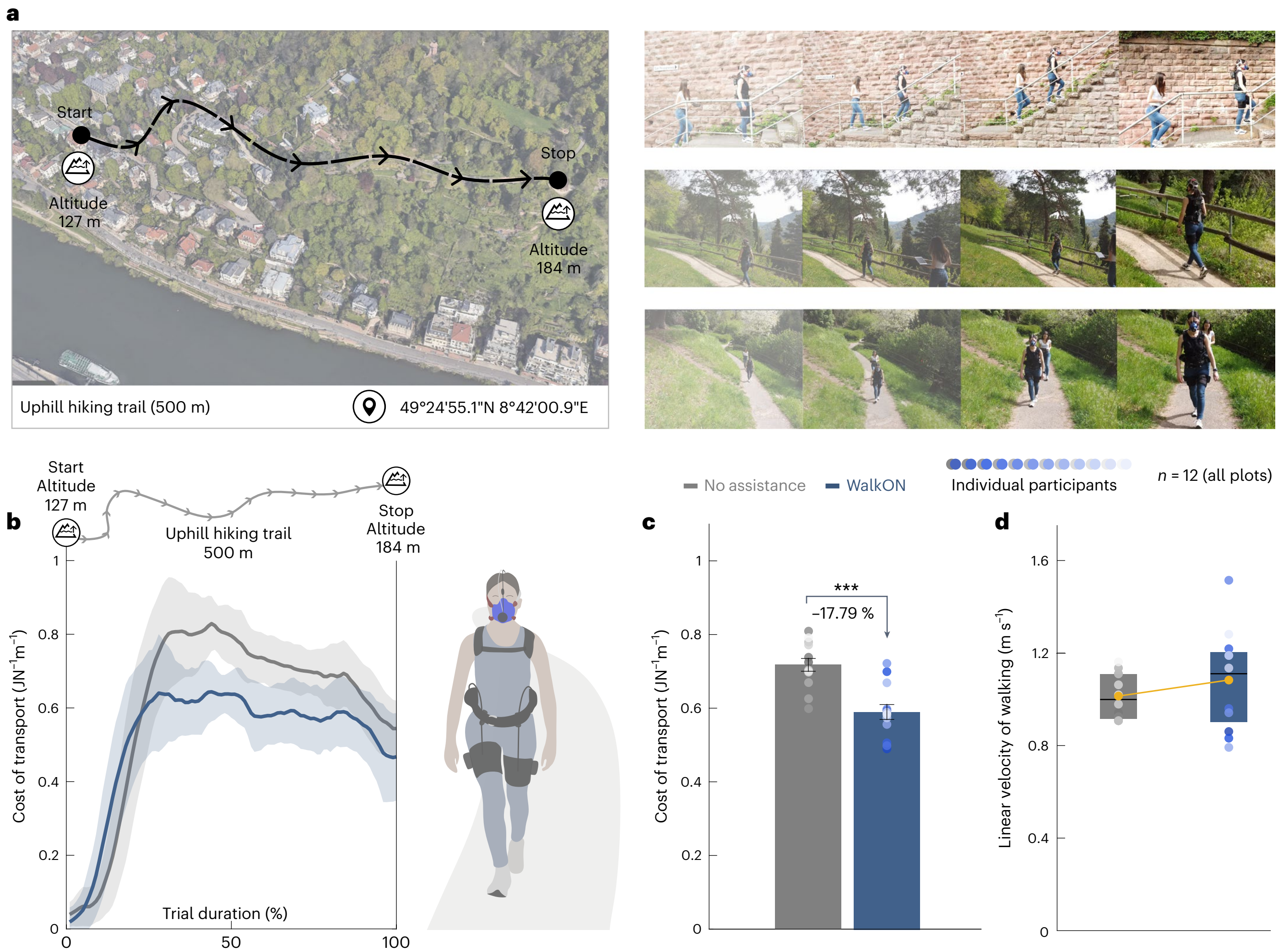

Fig. 2 | Uphill outdoor walking task and metabolic results for young adults. **a**, The task involved walking along a steep 500 m uphill trail presenting altitudes of 127 m and 184 m at the start and end points, respectively. Young adults walked at their preferred pace unassisted (grey) or while using WalkON (navy). Credit: Geobasis-DE/BKG (2009) (left panel). **b**,**c**, Metabolic results demonstrated a significant reduction in the cost of transport when using WalkON to perform the walking task. This is visible from the cost of transport time-series in **b** (in which the thick lines represent the average across subjects, and the shaded areas represent the s.d.) and the mean (± s.e.m.) cost of transport values in **c**. **d**, The preferred mean walking speed of participants along the trail was not significantly altered when using WalkON. The results are presented as box plots, where bounds of boxes represent the lower (25th percentile) and upper (75th percentile) quartiles, the horizontal lines are medians, and the orange circles represent means. Individual participants results are shown as dot plots. ***$P < 0.001$ (linear mixed-effects model).

distance[25], serves as a crucial indicator of the effectiveness of wearable robotic assistive devices. The twelve recruited young adults walked along a panoramic and winding 500 m uphill trail encompassing the surrounding hills of the city of Heidelberg (49°24′55.1″N 8°42′00.9″E, Philosophenweg, Heidelberg, Germany). The trail involved an altitude change of 57 m between the start (127 m altitude) and end (184 m altitude) points (Fig. 2a). Participants walked at their self-selected pace under two conditions: (1) no assistance, where they wore the robotic shorts in an unpowered mode, and (2) the WalkON condition, where they received assistance from the system.

Using WalkON, the metabolic demand of traversing the outdoor uphill trail was significantly reduced by 17.79 ± 2.03% (mean ± s.e.m., $n = 12$, $P < 0.001$) (Fig. 2b,c). There were no significant differences in the linear velocity of walking (Fig. 2d) between the two conditions ($P = 0.07$), although there was a trend towards an average increase of 6.34% with WalkON compared with no assistance. In particular, eight out of twelve participants increased their walking velocity with WalkON.

Natural hip joint movement was not restricted when using WalkON. Ensuring that the use of external assistive devices does not restrict or interfere with natural movement is essential, particularly for individuals without substantial movement impairments[9]. This principle underpins the use of the device, promoting health and energy optimization without sacrificing movement freedom.

During natural locomotion, the hip angle exhibits a periodic trajectory resembling a sinusoidal waveform, while the hip velocity is shifted by π/2 relative to the angle. These variables create a counterclockwise circular orbit in the hip phase portrait, representing the relationship between position and velocity in the gait cycle[26]. The angular separation between these two quantities indicates the leg's progression during walking. WalkON's control strategy is based on these principles (see Methods), which lay the basis for the delivery of assistive forces along the gait cycle.

Figure 3b shows the raw mean hip phase portrait for the twelve young adults walking along the uphill trail. It is noticeable that wearing WalkON did not restrict the natural progression of the hip angle and velocity along the gait cycle.

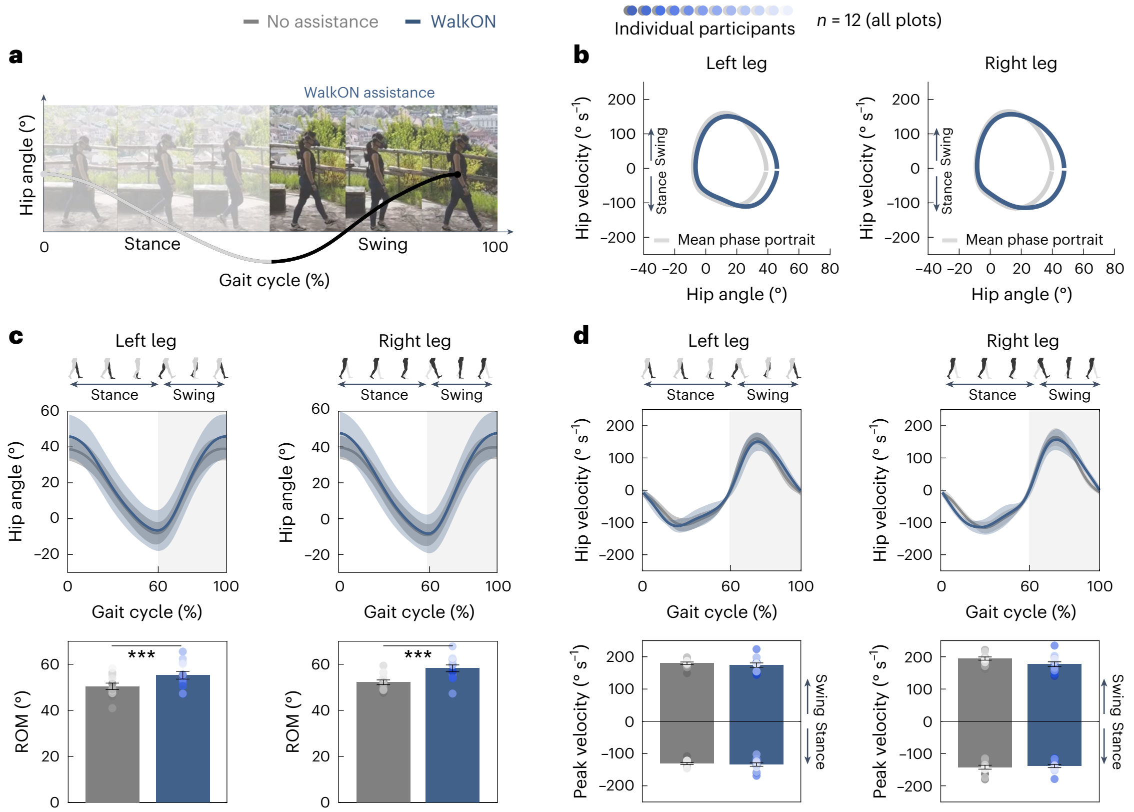

Fig. 3 | Hip joint motion results for young adults. a, WalkON actively assists the hip joint during swing. **b**, Raw hip phase portraits averaged across steps and subjects, combining hip angle and velocity measured on the sagittal plane. **c**, The hip range of motion (ROM) exhibited a significant increase with WalkON (navy) compared with the no assistance condition (grey). **d**, There were no significant variations in hip velocity peaks with WalkON compared with the no assistance condition. In **c** and **d**, the upper rows show the mean time-series across young adults and steps (where the shaded area is the s.d.), whereas the bar plots in the lower rows report the mean ± s.e.m hip ROM and peak velocity. ***$P < 0.001$ (linear mixed-effects model).

The range of motion of the hip joint exhibited a significant increase with the use of the assistive robotic shorts (Fig. 3c). In the no assistance condition, the range of motion was on average 51.42 ± 1.16° between the two legs and across subjects, which increased to 56.88 ± 1.51° with WalkON (+10.64 ± 1.76%, $n = 12$, $P < 0.001$). However, using the device did not result in a significant change in hip peak velocities throughout the gait cycle (Fig. 3d).

The sense of agency was preserved with WalkON. The perception of control over one's movements greatly influences the acceptance of wearable robotic technologies among potential users[20]. This concept is commonly referred to as sense of agency, which is typically defined as the feeling of being in control[27].

We administered a ten-item questionnaire to assess the sense of agency while using WalkON (Fig. 4). Each participant rated their level of agreement with the items on a Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree). After completing the walking task using WalkON, young adults consistently indicated high sense of agency, as can be seen by the distribution of answers in Fig. 4. On average, the mean self-reported score to the questionnaire was 6.20 ± 0.20 (mean ± s.e.m.) out of 7. Such scores were significantly higher than the midpoint of 4 on the Likert scale ($n = 12$, $t = 11.26$, $P < 0.001$), demonstrating that the users' perception of control over their movements was not altered when using WalkON.

Efficacy study with older adults

The primary objective of WalkON is to provide support for daily locomotion as individuals age, with the goal of elevating the autonomy, quality of life and overall well-being of its users in the long term. In line with this vision, an efficacy study was conducted to evaluate the effectiveness in improving the metabolic demands of outdoor walking specifically targeted at WalkON's intended users, that is, older adults.

Ten participants were recruited, whose ages spanned from 67 to 82 years (mean age = 74.10 ± 6.30 years), with a mean height of 176.10 ± 9.53 cm and weight of 73.10 ± 12.84 kg. The gender distribution was balanced, with an equal number of male and female participants. According to the LUCAS Functional Ability Index[28], nine out of the ten participants fell into the robust category, indicating that they are active individuals for whom health promotion and physical exercise are recommended. The remaining participant was classified as pre-frail, suggesting a higher likelihood of mobility issues (refer to Extended Data Table 2 for individual characteristics).

The outdoor walking path was intentionally less challenging to prevent overexertion among the older users and accommodate safety concerns of this population. Here, study participants undertook a 400 m walk on a flat athletic track (49°25′16.0″N 8°39′37.0″E, Heidelberg, Germany, Fig. 5a) at their preferred speed, both unassisted (no assistance) and with the support of WalkON.

Compared with the no assistance condition, the metabolic cost of transport required for the outdoor walking task was significantly reduced by an average of 10.48 ± 2.96% (mean ± s.e.m, $n = 10$, $P < 0.001$) while using WalkON (Fig. 5b). The linear velocity of walking increased for five out of ten participants, resulting in an overall slight average increasing trend of 5.31% ($P > 0.05$) (Fig. 5c).

The progression of the raw hip angle and velocity in the hip phase portrait was not altered by the assistive system (Fig. 5d). Neither the physiological range of motion of the hip joint (Fig. 5e), nor the peak velocities achieved at the joint during walking (Fig. 5f) were constrained when compared to the no assistance condition ($P > 0.05$).

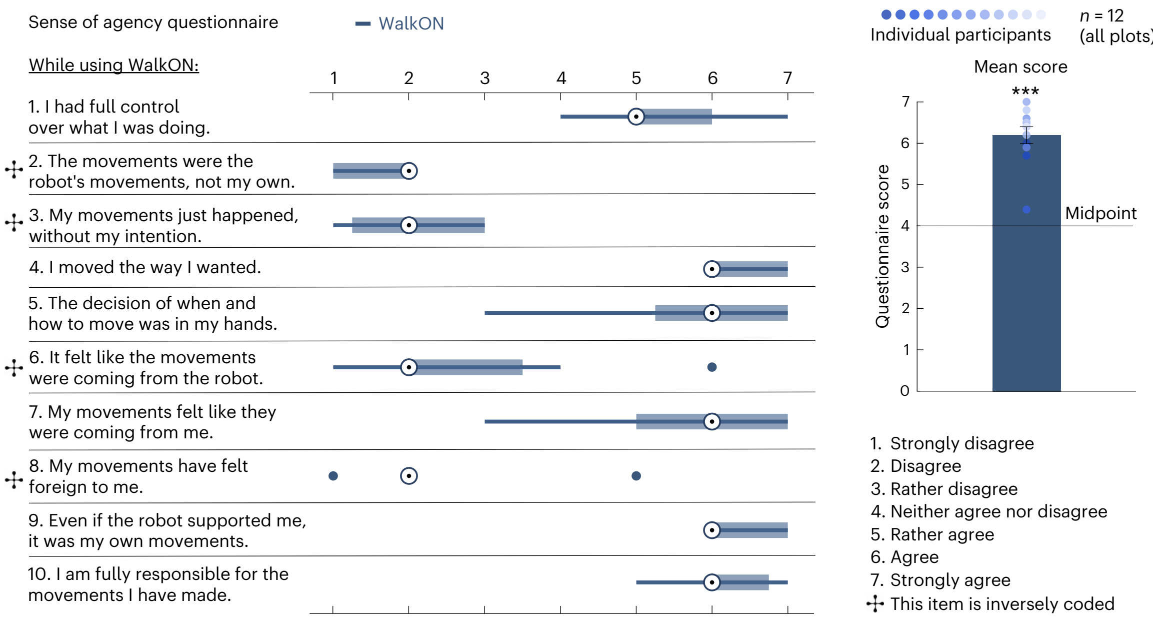

Fig. 4 | Sense of agency results for young adults. The sense of agency assessment for young adults using WalkON involved rating ten items about motor control on a Likert scale from 1 to 7, indicating their level of agreement with each statement. Items 2, 3, 6, and 8, which are inversely coded, were recoded before analysis. The distributions of answers are presented as box plots (where the white circles represent medians). The mean (±s.e.m.) across young adults demonstrates that participants significantly perceived themselves as having greater control over their movements than the device. This significant difference was tested in comparison with the midpoint value of 4 (neither agree nor disagree) on the Likert scale. ***$P < 0.001$ (two-tailed, one-sample t-test).

Older participants expressed strong sense of agency while using WalkON (Fig. 5g), with an overall mean self-reported evaluation of 6.09 ± 0.26, which was significantly above the scale midpoint of 4 ($n = 10$, $t = 8.34$, $P < 0.001$), signifying their high perception of control over their movements.

Discussion

As the world's population grows older, the issues surrounding the decline of mobility become more pressing, leading to a growing need for assistive mobility solutions. The challenge goes beyond merely extending physical activity; it is about addressing the constraints of aging and empowering individuals to thrive in their later years.

Back in 2009, Ferris envisioned[29] a promising future for wearable assistive technologies in everyday life, foreseeing that "by 2024, people will be walking down the street, in the malls, and to their homes wearing robotic exoskeletons". Yet, despite this visionary perspective, their actual use has remained largely experimental and primarily confined to laboratory settings[30].

We aspire to realize Ferris's vision with WalkON. We aim to offer an unobtrusive assistive tool for daily life to address the mobility challenges of aging by enhancing leg swing dynamics. Although it may seem theoretically unnecessary to expend substantial mechanical work to swing the legs due to the pendulum model[31], research has shown that leg swinging is, in fact, energetically costly[32]. Findings from past studies revealed that leg swinging can consume up to approximately one-third of the net energy required for walking[32]. This energy expenditure is primarily associated with the transition from one stance limb to the next and is linked to the work performed by the muscles to move the leg forward[22,32,33]. The effects of aging considerably compromise this function[24,34]. Investigations[35] have indicated that the strength of lower extremity muscles tends to decline at a rate of 1–4% per year, beginning around the age of 50. This decline is especially pronounced in the case of the hip flexors, which have been observed to be the first to deteriorate[24]. Due to loss in muscle strength, older adults adapt by incrementing the simultaneous co-activation of antagonistic muscles during walking[36]. However, this adjustment comes at notable increase in metabolic expenditure[34,36].

WalkON has demonstrated to improve the energy efficiency of walking in a technology assessment with young individuals and an efficacy study with older adults, contributing to enhanced mobility. In trials with young participants, WalkON facilitated energy savings of 17.79% on average compared with walking with no assistance (Fig. 2c), whereas in older adults we observed an average decrease in the cost of transport of 10.48% (Fig. 5b). In more practical terms, these savings are the equivalent of removing 10.3 kg and 6.3 kg from the waist for young and older adults, respectively[37].

Metabolic reductions of this magnitude are accomplished without necessitating high power outputs from the system (the mean peak motor power is 1.52 W kg^{-1} while walking). This underscores the high efficiency of the provided assistance. These findings align with past studies[38] that have demonstrated the superior efficiency of assisting hip flexion when compared with other lower-limb movements, such as hip extension[39] or ankle plantarflexion[40]. Even modest mechanical outputs from the assistive system are sufficient to achieve substantial reductions in metabolic costs[38].

Taking a broader perspective, optimizing energy efficiency in daily walking tasks can considerably reduce fatigue during extended walks. This enhancement enables individuals to cover greater distances or sustained activity, improving overall endurance[41]. Studies indicate that improving walking energy efficiency is pivotal for enhancing mobility, independence, and the overall quality of life for older adults. This is evidenced by positive effects on cardiovascular risk factors, decreased respiratory disease risk, and a general reduction in mortality from various causes[41]. Beyond physical health benefits, walking demonstrates a direct association with a reduced risk of depression, a positive influence on emotional well-being, and various aspects of health-related quality of life[42]. We therefore anticipate that prolonged usage of WalkON could yield numerous benefits over the long term. These benefits may encompass not only enhancements in physical condition but also improvements in secondary medical symptoms and other health outcomes; however, it is essential to acknowledge that potential risks associated with extended use—such as reduced reliance on natural muscle function—remain unknown and warrant evaluation.

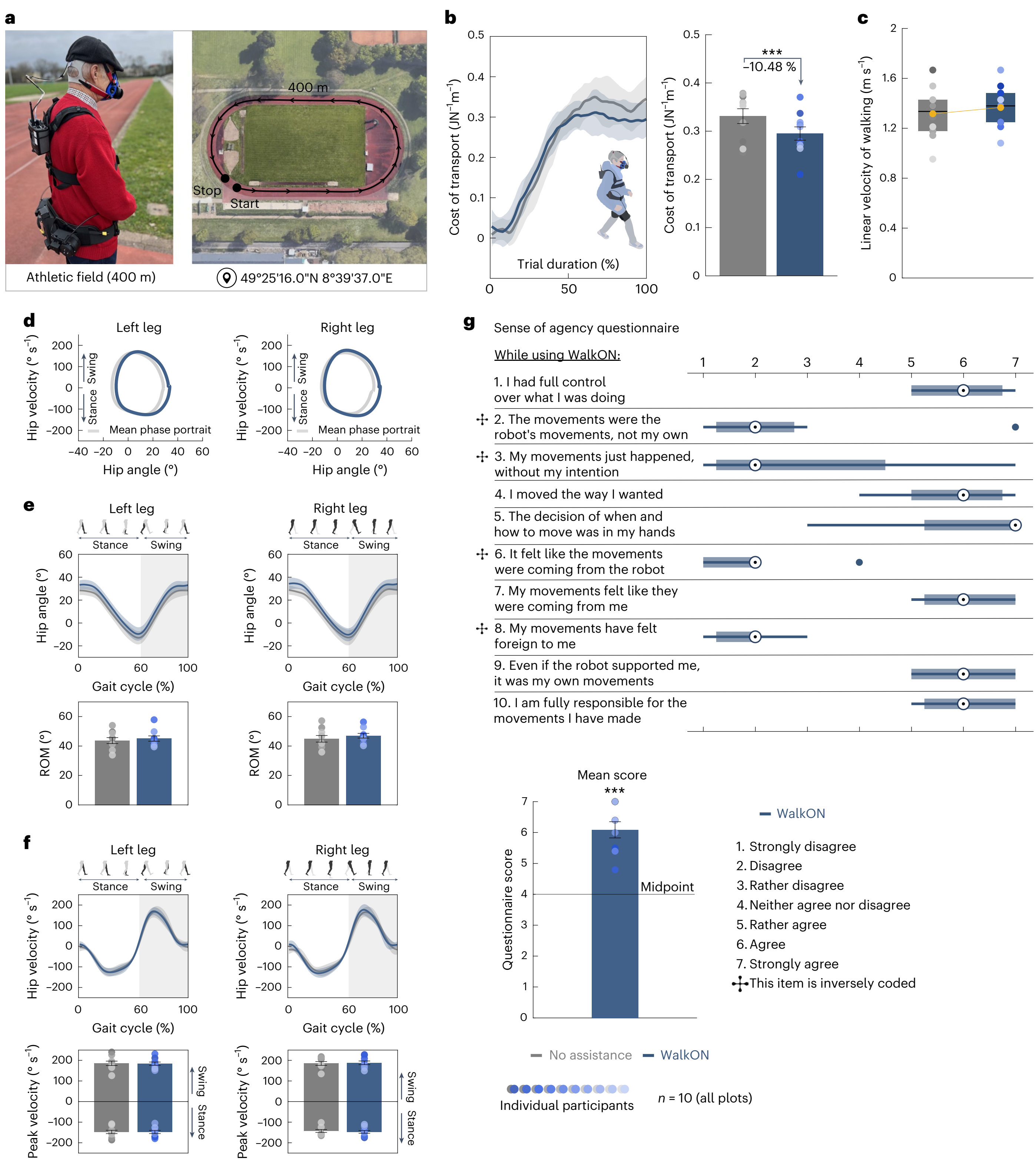

Fig. 5 | Efficacy study with older adults. a, Older participants completed a 400 m walk on a flat athletic track at their preferred speed unassisted (grey) or while using WalkON (navy). Credit: Geobasis-DE/BKG (2009) (right panel). **b**, Using WalkON significantly reduced the metabolic cost of transport (***$P < 0.001$, linear mixed-effects model). **c**, The linear velocity of walking was unaltered on average across participants. **d–f**, WalkON allowed for unrestricted hip motion, as visible from the raw hip phase portraits in (**d**), the hip range of motion (ROM) in (**e**) and the hip peak velocities in stance and swing in (**f**). **g**, Older adults reported strong perceived sense of control over voluntary movements while using WalkON (***$P < 0.001$, two-tailed one-sample t-test). The results for individual participants are shown as dot plots. The bar plots are presented as mean ± s.e.m, whereas time-series are presented as mean ± s.d. (shaded area). In box plots, bounds of boxes represent the lower (25th percentile) and upper (75th percentile) quartiles. In **c**, the black horizontal line is the median and the orange circle the mean; in **g** the white circle is the median.

Notably, studies demonstrating the effectiveness of wearable assistive technologies in comprehensive outdoor daily life scenarios are very sparse. Our ability to draw comparisons with existing literature is therefore quite limited. For instance, Haufe et al.[15] tested the Myosuit—a commercial wearable robot designed to assist hip and knee extension through a tendon-driven mechanism guided by a rigid joint at the knee level—in the context of a 400 m uphill gravel path with young participants. Their findings revealed an average metabolic saving of 10.6% compared with an unpowered condition. Instead, in a recent study, Slade et al.[18] introduced an ankle exoskeleton that reduced the cost of transport by an average of 17% in young, healthy subjects compared with not wearing the device. This outcome is particularly relevant considering the crucial role of the ankle, alongside the hip, as a primary power source for the forward propulsion during walking. This metabolic improvement was achieved on a 566 m flat path using a rigid system and a control algorithm that required specific adjustments and personalization for each user through data-driven approaches.

Although customization and personalization are important for optimizing individual assistance, they often compromise the device's ease of use and plug-and-play functionality. By contrast, WalkON's core strategy is to continuously analyze the user's movement pattern and derive the progression of their leg throughout the gait cycle. This is achieved by leveraging immediate feedback from real-time user measurements, thus eliminating the need for complex data processing or learning algorithms used in past research[18,43]. Such an approach ensures independence from pre-defined training examples. It also enhances responsiveness and efficiency while ensuring scalability (as detailed in Supplementary Fig. 2). These attributes collectively make WalkON a plug-and-play solution, allowing users to seamlessly integrate the system into their daily routines without the need for extensive set-up or customization. Furthermore, in both of the mentioned instances of the prior art, the outdoor tasks were comparatively less strenuous than our hiking activity, tests were conducted only on young and fit individuals, and the outcomes were achieved via systems featuring rigid links or joints. Such design elements typically simplify the characterization process, ensuring direct and predictable transmission of force, preserving component alignment and position, and facilitating ease of control. On the contrary, the core design of WalkON revolves around a soft structure that conforms to the body like regular clothing and lacks any rigid joints. This characteristic offers enhanced comfort, wearability and reduced intrusiveness. However, it does make the final force transmitted to the human body less predictable, necessitating greater attention to system modeling and control. Despite these challenges, our system showcased substantial metabolic advantages in a deliberately demanding and fatiguing task, all without impeding freedom of movement during use.

When evaluating hip joint movement during uphill hikes, young adults exhibited higher range of motion at the hip joint while using WalkON (Fig. 3c). From a physiological perspective, walking uphill requires an increase in the hip joint range of motion and a concurrent reduction in knee extension as the swing phase ends[21]. Using WalkON might have possibly accentuated this inherent adaptation; however, these enhancements did not result in any disruption of movement and, consequently, contributed to improved metabolic efficiency. Instead, for older individuals walking on level terrain, their natural hip joint motion remained unaltered, indicating the absence of any movement constraints (Fig. 5e,f).

So far we have not come across any research that delves into real-world applications of assistive technologies tailored specifically for older adults while quantifying the metabolic advantages and assessing the psychophysical impact. The latter aspect is undeniably of paramount importance and forms a cornerstone of any robotic assistive system. For the device to be considered valuable by potential users, it must provide an experience that unequivocally demonstrates its worth[44]. This aligns with the overarching objective of enhancing the user experience, ensuring that individuals feel in perfect synchronization with the system and retain complete autonomy over their movements. This concept is known in the literature as the sense of agency, and is often described as the sensation of being in control of a motor task[27]. It encompasses the experience of initiating one's voluntary actions and influencing the external world via these actions[45].

Our assessments regarding the sense of agency yielded promising outcomes (Figs. 4 and 5g). Participants reported a strong sense of agency on the administered questionnaire, with mean Likert scale ratings of 6.20 and 6.09 for young and older adults, respectively, out of a total score of 7. This indicates a notable alignment between their intentions and the system, emphasizing their perception of being the initiators and controllers of their motor plans. This result can be primarily attributed to the controller of WalkON, which synchronizes with the user's natural motion ensuring that no extraneous actions are imposed upon voluntary movements. The provided assistance harmonizes with the user's walking pattern and seamlessly adapts to variations in walking speed. This approach not only simplifies the user experience but also reduces usage barriers, making the technology more inclusive and akin to a pair of shorts for everyday use.

The primary limitation of our study lies in the absence of a control measurement of metabolic activity without wearing WalkON. We instead relied on a comparison based on gross metabolic changes, utilizing a condition in which the device was worn but turned off as a reference point. Although this approach may be less realistic in real-world terms, it was chosen for practical experimental reasons and it is the most widely adopted in the literature[9,15,46,47]. This decision allowed us to capture the user's movement during the no assistance condition for meaningful comparison, and to isolate the active biomechanical effect of assistance from the passive effects of wearing the suits. Only a subset of both young and older adults repeated the trial without the weight of the suit (results for this subgroup are included in Supplementary Figs. 8 and 9, and are representative of the minimal impact of the system's weight). In fact, due to the soft structure of the device, its limited weight (2.93 kg), and its positioning closer to the user's center of mass rather than on moving limbs, we do not anticipate any significant impact on the final outcomes, as demonstrated by biomechanical studies examining the effects of added mass on body segment[37].

The metabolic outcomes differed between the two participant groups, indicating distinct benefits from the system. We believe this was influenced by age-related factors, including a propensity for shorter walking sessions, and variations in experimental protocols. The primary distinction between the experiments comes from the dissimilarities in the walking tasks themselves. Specifically, young individuals were asked to walk in considerably more physically demanding conditions, particularly on steep uphill terrain. Ground incline plays a pivotal role in determining energy expenditure during walking, with costs escalating proportionally as the gradient increases[48]. In such scenarios, the phase of limb advancement becomes more demanding, necessitating greater effort from hip flexors to raise the swinging leg against gravity[2]. Consequently, the assistance offered by WalkON may deliver more pronounced benefits in these situations compared with walking on level ground.

Future research endeavors anticipate conducting a pilot randomized controlled trial involving our target population in an even more ecologically valid setting, such as stair climbing, with an enhanced assessment of the system's impact during everyday use. This will be complemented by a thorough analysis of usability and user acceptance to provide a more comprehensive understanding of the technology's potential and limitations. We envision that prolonged walking sessions with WalkON could yield even greater benefits for our target users and ultimately achieve our long-term objectives. An upcoming focus will involve evaluating the impact of repeated use of the device by individuals across multiple sessions. By conducting more extensive studies employing a longitudinal design, our objective is to offer a more profound insight into the effects of WalkON over time and its potential long-term advantages for users.

Looking to the future, we anticipate that the advantages of employing WalkON during extended walking sessions may become increasingly evident. Mitigating the metabolic requirements linked with daily tasks such as outdoor walks or indoor movement could not only enhance users' physical well-being but also potentially have a positive impact on their mental and emotional health[41]. As a result, older individuals could cover greater distances with reduced fatigue, thereby enhancing their autonomy and mobility. In doing so, we hope to move closer to realizing Ferris' vision—a future in which assistive technologies empower humans to achieve exceptional feats, even in old age.

Methods

WalkON hardware design

WalkON is a soft robotic assistive system featuring one motor per leg (AK60-6, 9 Nm peak torque, T-Motor, China), each wrapping up an artificial tendon on a spool (35 mm diameter). This design allows independence between assisted legs, enabling adjustments in the assistance profile to accommodate complex movements and a broad range of motion. The decision to adopt this design configuration resulted from a preliminary study involving young adults using WalkON in two distinct actuation set-ups during hiking. Further details and findings regarding this comparative study are reported in the 'WalkON design: a comparative study on two hardware configurations in young adults hiking' section in the Supplementary Information.

The weight of the device is 2.93 kg, most of which is located approximately at the level of the user's centre of mass to minimize the impact of the extra mass on the metabolic energy expenditure during walking[49].

WalkON is connected to the human body through a compliant textile structure. The textile interface consists of an adjustable waist belt (which is worn at the user's iliac crest level) and two thigh fabric harnesses. The belt and harnesses feature an inner layer of neoprene, offering good tensile strength and hardness while ensuring soft contact with the body. Velcro strips are used to provide a custom fit for a wide range of human body shapes and sizes. A blueprint of the textile components is provided in Extended Data Fig. 1. The textile interface serves as an anchor for the actuation stage and electronics and to guide the tendon-driven transmission.

The mentioned transmission uses artificial tendons made of black braided Kevlar fibre (KT5703-06, 2.2 kN max load, USA) to actively assist the user's hip flexion. These tendons run from the actuation stage—located at the back of the belt on a rigid plate—to a proximal anchor point on the front, guided by Bowden cables (Shimano SLR, 5 mm diameter, Sakai, Osaka, Japan). From here, the tendons run parallel to each leg and are anchored to a distal anchor point on the thigh textile harness. By shortening the distance between the proximal and distal anchor points on the suit, assistive forces delivered to the user generate a flexing moment around the hip joint.

The systems are powered by a portable lithium polymer battery (Tattu, 0.4 kg, 14.8 V, capacity of 3,700 mAh). Custom-designed housings for actuation, power and electronics, as well as anchor points, are fabricated using 3D printing technology with PLA (polylactic acid) material. Computer-aided design files for such elements are provided in the Supplementary Information.

The controller is executed on a microcontroller (Arduino MKR 1010 WiFi, Arduino, Italy) at a 100 Hz frequency, and it obtains information via the Bluetooth Low Energy (Feather nRF52832, Bluefruit, Adafruit) protocol from inertial measurement unit sensors (BNO055, Bosch, Germany) placed laterally on the thigh harness. These sensors stream the hip flexion angle of each leg as measured in the sagittal plane; these data are then converted by the control algorithm to an assistance profile according to the leg progression along the gait cycle.

A schematic of WalkON's components is provided in Extended Data Fig. 2.

WalkON controller

WalkON is operated using a control framework designed to actuate tendon displacement on the basis of the kinematics of the hip joint during human locomotion and its progression along the gait cycle. The entire architecture is built so that signals flow along a forward path from the sensing system to the control unit and finally to the actuation unit. This is achieved through a three-tiered approach: a high-level controller that estimates the gait phase in real-time from hip kinematic data; a mid-level controller that generates the actuator's reference motion on the basis of the user's gait phase; and a low-level controller that provides appropriate assistance to the user on the basis of the previous layer's outputs. The control framework is depicted in Extended Data Fig. 3. Detailed information on the algorithm and a pseudocode are provided in the 'Model for tendons displacement during walking' and 'WalkON controller pseudocode' sections in the Supplementary Information.

The high-level controller calculates a monotonically increasing gait phase variable from a single inertial sensor on each leg. The underlying approach incorporates the concepts from the general control theory of oscillating dynamical systems. Indeed, during natural locomotion, the angular position of the hip joint, $\theta(t)$, has a periodic trajectory that can be approximated as a sinusoidal waveform, similar to an undamped oscillator[26,50]. As such, the hip angular velocity, $\dot{\theta}(t)$, has a π/2 shift with respect to $\theta(t)$ and the two variables produce a circular orbit in the counterclockwise sense of rotation on the hip phase portrait, that is, position versus velocity phase plane. The gait phase, denoted $\phi(t) = f([\theta(t), \dot{\theta}(t)])$, is extracted in real-time by computing the polar angle between these two quantities. For each step, both variables are initially shifted about the origin of the hip phase portrait, and $\theta(t)$ is rescaled to match the amplitude of $\dot{\theta}(t)$ to produce a more circular orbit[51]. Information on the walking speed is intrinsically present in the gait phase extraction, allowing instant adaptation to changes in walking pattern. To comply with the sinusoidal nature of the hip flexion angular displacement measured on the sagittal plane, sinusoidal interpolation follows the gait phase estimation deriving a signal, $\theta_r(t)$, used as a basis for the motor reference trajectory.

As the gait phase extraction method shows sensitivity to noise captured from the inertial sensors on unstructured terrains, to filter out such noise from $\theta_r(t)$, a Kalman filter is implemented at the mid-level controller. Kalman filter parameters have been optimized in preliminary trials to strike a good balance between the noise in the real-time recorded data and the noise in the estimated data. The actuator's final position reference trajectory, $\theta_{ref}(t)$, is obtained using cubic spline interpolation on the Kalman-filtered $\theta_r(t)$. The magnitude of $\theta_{ref}(t)$ is established according to the user's hip range of motion, pulley diameter, and the positioning of anchor points on the user's body. This configuration is valid when the device is worn with the belt positioned on the iliac crest and the distal anchor point aligned with half the length of the thigh.

At the low-level controller, a feedback position loop compares the actual position of the motor $\theta_m(t)$ with the reference position $\theta_{ref}(t)$ extracted from the previous layer. A proportional-differential controller is used to convert the position error into motor angular velocity. To prevent disturbances or noise in the hip kinematics recordings from translating to unwanted motor commands when a subject stops walking, a stop detection condition is implemented based on the gait speed.

Study protocol

The first aim of the study is to evaluate WalkON's effectiveness in enhancing outdoor walking experiences. To achieve this objective, a technology assessment of the system was conducted on uphill hiking-like trails with young adults. The ultimate goal of the research is to propose this system as an effective support for walking in older individuals. To explore this possibility, an efficacy study was undertaken with participants aged over 67 years old.

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Before the study began, all participants provided informed written consent, as well as consent to publish identifiable images. Our research procedures were conducted in accordance with the principles of the Declaration of Helsinki and were approved by the Ethics Committee of Heidelberg University under resolution no. S-313/2020.

Recruited subjects, being first-time users of the device, were given sufficient time to become familiar with it prior to data collection, thus mitigating potential biases related to familiarization. This process foresaw walking with WalkON until they felt comfortable and confident in its usage. Additional details regarding the familiarization procedure can be found in the 'Experimental protocol and familiarization' section in the Supplementary Information.

During the study, each participant underwent evaluations in multiple conditions, acting as their own control for comparison.

Technology assessment with young adults. Inclusion criteria for young adults (n = 12) recruitment included an age between 18 and 35 years, no visual or auditory impairments, or any neurological, cardiovascular, metabolic or mental disorders that might interfere with the tasks at hand.

The chosen experimental path was a panoramic snake-like trail up the hills surrounding the city of Heidelberg, Germany, known as Philosophenweg (49°24′55.1"N 8°42′00.9"E). We selected the initial segment of the trail, which is a winding and quite steep 500 m track with a change of altitude from 127 m to 184 m between the starting and ending points (Fig. 2a). The trail began with 108 stairs made of sandstone irregular in shape, followed by an uphill section.

Study participants were instructed to walk at their preferred speed along the trail twice under different conditions: without assistance (no assistance) and with assistance from WalkON. In the no assistance condition, participants wore the system in the unpowered mode to allow for recordings of kinematic data. Given the physically demanding nature of the trial, we conducted the different conditions on separate days to minimize any fatigue-related effects.

After completing the uphill walking, a subgroup of participants (n = 7) walked the path downhill (total of 1 km). These results are presented in the Supplementary Fig. 6 due to the diminished importance of hip flexion assistance, as downhill walking necessitates less lift for ground clearance[52]. The main aim here was to show that the assistive system and its weight do not hinder motion or add metabolic burden downhill.

Moreover, another subgroup of young adults (n = 5) instead completed a third condition of uphill walking without donning the suit (no suit) to demonstrate the minimal metabolic impact of the device's extra weight. These results are outlined in Supplementary Fig. 8.

Efficacy study with older adults. Older adults enrolled for the efficacy study (n = 10) were selected on the basis of criteria that included being over 65 years of age, being categorized as either 'robust' or 'pre-frail' according to the LUCAS Functional Ability Index[28], and not having severe uncorrected visual or auditory impairments or notable neurological, cardiovascular, metabolic or mental conditions.

In consideration of the physical limitations and safety concerns of the frailer subjects in the study, we opted for a less demanding and more accessible path. This decision aimed to prevent any potential physical strain while ensuring an effective evaluation of the device's performance. As a result, we selected a shorter outdoor route with flat terrain. Participants were instructed to walk at their preferred speed on a 400 m athletic track on flat ground (located at 49°25′16.0"N 8°39′37.0"E, Heidelberg, Germany, Fig. 5a) under two different conditions: wearing the device in the unpowered mode (no assistance), and with assistance from WalkON. Both conditions were conducted on the same day, with a minimum 20 min rest period in between to prevent fatigue. The order of the conditions was randomized among participants to eliminate order effects.

A subset of older individuals (n = 4) participated in a third round of testing without wearing the suit (no suit). These findings are detailed in the Supplementary Fig. 9 accompanying this work.

Data analysis and statistics

To evaluate WalkON's effectiveness at improving walking efficiency, the principal outcome measure was the metabolic cost associated with walking. Oxygen and carbon dioxide consumption data were recorded using a portable respirometer (K5, COSMED, Italy), and the net metabolic cost was deduced using Péronnet's and Massicotte's formula[53]. To establish a baseline, participants were instructed to breathe normally for a 3 min period while standing at rest before each experiment began. The mean baseline metabolic cost from the final minute was then subtracted from the overall metabolic data to discern the cost of walking for each condition. To account for the different walking speeds across conditions, metabolic data were analyzed in terms of cost of transport[25]. This was computed by dividing the net metabolic cost by the product of the participant's weight, gravitational acceleration and average walking speed. The average walking speed was determined by the distance covered over the duration of the experiment. Considering that it takes approximately 2 min for metabolic data to stabilize after any notable changes in physical activity, for the technology assessments involving younger adults, we excluded the initial 2 min of recording and analyzed the remainder of the data. For the efficacy study with older adults, we examined the final 2 min of the trial, as the time taken by participants to traverse the walking track was approximately 4 min.

Kinematic evaluations were conducted on profiles of hip angle and velocity for both the left and right legs, using data recorded from inertial sensors integrated into the system. The raw motion data were divided into steps post low-pass filtering (fourth-order Butterworth, cut-off frequency 10 Hz). For each participant, we evaluated the range of motion, along with the average peak velocity during both stance and swing phases across all steps, under both unassisted and assisted conditions.

Results are presented as mean ± s.e.m, or box plots for the linear velocity of walking. Data were tested for normality using a Shapiro–Wilk test and resulted normally distributed. The significance level for all statistical tests was set to <0.05. A linear mixed-effects model was used for subsequent statistical analysis of the collected metabolic and motion data, employing the least-squares regression method (MATLAB, MathWorks Inc., Natick, MA, USA). The model accounted for the 'condition' ('no assistance', 'WalkON'), which was presented as dummy-encoded, categorical fixed-effect explanatory variables. A term 'participant' (either YA1 to YA12 for young adults or OA1 to OA10 for older adults) was included in the model as a random-effect variable.

In our analysis of the sense of agency, we asked study participants to answer to a questionnaire consisting of six positively framed items (items 1, 4, 5, 7, 9, 10 in Figs. 4 and 5g and four negatively framed items (items 2, 3, 6, 8) evaluating the sense of control they had while using WalkON. The items were derived from the theoretical literature on sense of agency and were fine-tuned to the context of wearable mobility aids[54]. The negatively framed items were recoded so that higher values indicate higher sense of agency. Internal consistency of the questionnaire scale after recoding was good ($\alpha = 0.84$, 95% CI [0.71; 0.92]). A mean score of the scale items was therefore calculated for further analyses. To test whether participants felt that their movements were more controlled by themselves or by the device, we tested whether the mean score significantly deviated from the scale midpoint of 4 (neither agree nor disagree) through a two-tailed, one-sample t-test. A mean above the scale midpoint suggested that the participants saw themselves more in control of their movements than the device.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data needed to evaluate the conclusions in the Article have been deposited in an online repository at https://doi.org/10.6084/m9.figshare.26125483 (ref. 55) and may be reused for ethical, scientific purposes.

Code availability

The exemplary scripts for data processing and analysis for this study have been deposited in an online repository at https://doi.org/10.6084/m9.figshare.26125483 (ref. 55).

References

1. Hortobágyi, T., Mizelle, C., Beam, S. & DeVita, P. Old adults perform activities of daily living near their maximal capabilities. *J. Gerontol. A* **58**, M453–M460 (2003).
2. Franz, J. R. & Kram, R. Advanced age and the mechanics of uphill walking: a joint-level, inverse dynamic analysis. *Gait Posture* **39**, 135–140 (2014).
3. Kapsalyamov, A., Jamwal, P. K., Hussain, S. & Ghayesh, M. H. State of the art lower limb robotic exoskeletons for elderly assistance. *IEEE Access* **7**, 95075–95086 (2019).
4. Ercolini, G., Trigili, E., Baldoni, A., Crea, S. & Vitiello, N. A novel generation of ergonomic upper-limb wearable robots: design challenges and solutions. *Robotica* **37**, 2056–2072 (2019).
5. Sawicki, G. S., Beck, O. N., Kang, I. & Young, A. J. The exoskeleton expansion: improving walking and running economy. *J. Neuroeng. Rehab.* **17**, 1–9 (2020).
6. Ishmael, M. K., Archangeli, D. & Lenzi, T. A powered hip exoskeleton with high torque density for walking, running, and stair ascent. *IEEE/ASME Trans. Mechatron.* **27**, 4561–4572 (2022).
7. Martini, E. et al. Gait training using a robotic hip exoskeleton improves metabolic gait efficiency in the elderly. *Sci. Rep.* **9**, 7157 (2019).
8. Lee, Hwang-Jae et al. A wearable hip assist robot can improve gait function and cardiopulmonary metabolic efficiency in elderly adults. *IEEE Trans. Neural Syst. Rehab. Eng.* **25**, 1549–1557 (2017).
9. Xiloyannis, M. et al. Soft robotic suits: state of the art, core technologies, and open challenges. *IEEE Trans. Robotics* **38**, 1343–1362 (2021).
10. Löloff, J., Theisen, M., Mertens, A. & Funke, J. Human-machine symbiosis: ambivalent intuitions regarding gain and loss of personal control explain acceptance of smart mobility aids. *Behav. Inform. Technol.* https://doi.org/10.1080/0144929X.2023.2276812 (2023).
11. Park, D. & Cho, K.-J. Development and evaluation of a soft wearable weight support device for reducing muscle fatigue on shoulder. *PloS One* **12**, e0173730 (2017).
12. Lotti, N. et al. Adaptive model-based myoelectric control for a soft wearable arm exosuit: a new generation of wearable robot control. *IEEE Robot. Autom. Mag.* **27**, 43–53 (2020).
13. Georgarakis, A.-M., Xiloyannis, M., Wolf, P. & Riener, R. A textile exomuscle that assists the shoulder during functional movements for everyday life. *Nat. Mach. Intell.* **4**, 574–582 (2022).
14. Kim, J. et al. Reducing the metabolic rate of walking and running with a versatile, portable exosuit. *Science* **365**, 668–672 (2019).
15. Haufe, F. L., Duroyon, E. G., Wolf, P., Riener, R. & Xiloyannis, M. Outside testing of wearable robots for gait assistance shows a higher metabolic benefit than testing on treadmills. *Sci. Rep.* **11**, 14833 (2021).
16. Zhang, X., Tricomi, E., Missiroli, F., Lotti, N. & Masia, L. Real-time assistive control via IMU locomotion mode detection in a soft exosuit: an effective approach to enhance walking metabolic efficiency. *IEEE/ASME Trans. Mechatron.* **29**, 1797–1808 (2023).
17. Basla, C. et al. Usability of an exosuit in domestic and community environments. *J. Neuroeng. Rehab.* **19**, 131 (2022).
18. Slade, P., Kochenderfer, M. J., Delp, S. L. & Collins, S. H. Personalizing exoskeleton assistance while walking in the real world. *Nature* **610**, 277–282 (2022).
19. Medrano, R. L., Thomas, G. C., Keais, C. G., Rouse, E. J. & Gregg, R. D. Real-time gait phase and task estimation for controlling a powered ankle exoskeleton on extremely uneven terrain. *IEEE Trans. Robot.* **39**, 2170–2182 (2023).
20. Torricelli, D. et al. Benchmarking wearable robots: challenges and recommendations from functional, user experience, and methodological perspectives. *Front. Robot. AI* https://doi.org/10.3389/frobt.2020.561774 (2020).
21. Leroux, A., Fung, J. & Barbeau, H. Postural adaptation to walking on inclined surfaces: I. Normal strategies. *Gait Posture* **15**, 64–74 (2002).
22. Donelan, J. M., Kram, R. & Kuo, A. D. Mechanical work for step-to-step transitions is a major determinant of the metabolic cost of human walking. *J. Exp. Biol.* **205**, 3717–3727 (2002).
23. Peterson, D. S. & Martin, P. E. Effects of age and walking speed on coactivation and cost of walking in healthy adults. *Gait Posture* **31**, 355–359 (2010).
24. Cheng, S.-J., Yang, Y.-R., Cheng, F.-Y., Chen, I.-Hsuan & Wang, R.-Y. The changes of muscle strength and functional activities during aging in male and female populations. *Intl J. Gerontol.* **8**, 197–202 (2014).
25. Ralston, H. J. Energy-speed relation and optimal speed during level walking. *Int. Z. Angew. Physiol.* **17**, 277–283 (1958).
26. Villarreal, D. J., Poonawala, H. A. & Gregg, R. D. A robust parameterization of human gait patterns across phase-shifting perturbations. *IEEE Trans. Neural Syst. Rehab. Eng.* **25**, 265–278 (2016).
27. Chambon, V., Sidarus, N. & Haggard, P. From action intentions to action effects: how does the sense of agency come about? *Front. Hum. Neurosci.* **8**, 320 (2014).
28. Dapp, U. et al. The inter-relationship between depressed mood, functional decline and disability over a 10-year observational period within the longitudinal urban cohort ageing study (lucas). *J. Epidemiol. Commun. Health* **75**, 450–457 (2021).
29. Ferris, D. P. The exoskeletons are here. *J. Neuroeng. Rehab.* **6**, 17 (2009).
30. Herr, H. Exoskeletons and orthoses: classification, design challenges and future directions. *J. Neuroeng. Rehab.* **6**, 21 (2009).
31. Rashevsky, N. A note on energy expenditure in walking on level ground and uphill. *Bull. Math. Biophys.* **24**, 217–227 (1962).
32. Marsh, R. L., Ellerby, D. J., Carr, J. A., Henry, H. T. & Buchanan, C. I. Partitioning the energetics of walking and running: swinging the limbs is expensive. *Science* **303**, 80–83 (2004).
33. Gottschall, J. S. & Kram, R. Energy cost and muscular activity required for leg swing during walking. *J. Appl. Physiol.* **99**, 23–30 (2005).
34. Ortega, J. D. & Farley, C. T. Effects of aging on mechanical efficiency and muscle activation during level and uphill walking. *J. Electromyogr. Kinesiol.* **25**, 193–198 (2015).
35. Goodpaster, B. H. et al. The loss of skeletal muscle strength, mass, and quality in older adults: the health, aging and body composition study. *J. Gerontol. A* **61**, 1059–1064 (2006).
36. Mian, O. S., Thom, J. M., Ardigo, L. P., Narici, M. V. & Minetti, A. E. Metabolic cost, mechanical work, and efficiency during walking in young and older men. *Acta Physiol.* **186**, 127–139 (2006).
37. Browning, R. C., Modica, J. R., Kram, R. & Goswami, A. The effects of adding mass to the legs on the energetics and biomechanics of walking. *Med. Sci. Sports Exercise* **39**, 515–525 (2007).
38. Kim, J. Reducing the energy cost of walking with low assistance levels through optimized hip flexion assistance from a soft exosuit. *Sci. Rep.* **12**, 11004 (2022).

39. Franks, P. W. Comparing optimized exoskeleton assistance of the hip, knee, and ankle in single and multi-joint configurations. *Wearable Technol.* **2**, e16 (2021).
40. Zhang, J. Human-in-the-loop optimization of exoskeleton assistance during walking. *Science* **356**, 1280–1284 (2017).
41. Ungvari, Z., Fazekas-Pongor, V., Csiszar, A. & Kunutsor, S. K. The multifaceted benefits of walking for healthy aging: from blue zones to molecular mechanisms. *Geroscience* **45**, 3211–3239 (2023).
42. Choi, K. W. Assessment of bidirectional relationships between physical activity and depression among adults: a 2-sample mendelian randomization study. *JAMA Psychiatry* **76**, 399–408 (2019).
43. Molinaro, D. D., Kang, I. & Young, A. J. Estimating human joint moments unifies exoskeleton control, reducing user effort. *Sci. Robotics* **9**, eadi8852 (2024).
44. Medrano, R. L., Thomas, G. C. & Rouse, E. J. Can humans perceive the metabolic benefit provided by augmentative exoskeletons? *J. Neuroeng. Rehab.* **19**, 26 (2022).
45. Beck, B., Di Costa, S. & Haggard, P. Having control over the external world increases the implicit sense of agency. *Cognition* **162**, 54–60 (2017).
46. Sawicki, G. S. & Ferris, D. P. Mechanics and energetics of level walking with powered ankle exoskeletons. *J. Exp. Biol.* **211**, 1402–1413 (2008).
47. Tricomi, E. Environment-based assistance modulation for a hip exosuit via computer vision. *IEEE Robot. Automation Lett.* **8**, 2550–2557 (2023).
48. Jessup, L. N., Kelly, L. A., Cresswell, A. G. & Lichtwark, G. A. It is not just the work you do, but how you do it: the metabolic cost of walking uphill and downhill with varying grades. *J. Appl. Physiol.* **135**, 1263–1267 (2023).
49. Myers, M. J. & Steudel, K. Effect of limb mass and its distribution on the energetic cost of running. *J. Exp. Biol.* **116**, 363–373 (1985).
50. Westervelt, E. R. et al. *Feedback Control of Dynamic Bipedal Robot Locomotion* (CRC, 2018).
51. Quintero, D., Lambert, D. J., Villarreal, D. J. & Gregg, R. D. Real-time continuous gait phase and speed estimation from a single sensor. In *2017 IEEE Conference on Control Technology and Applications* 847–852 (IEEE, 2017).
52. Kuster, M., Sakurai, S. & Wood, G. A. Kinematic and kinetic comparison of downhill and level walking. *Clin. Biomech.* **10**, 79–84 (1995).
53. Peronnet, F. & Massicotte, D. Table of nonprotein respiratory quotient: an update. *Can. J. Sport Sci.* **16**, 23–29 (1991).
54. Tapal, A., Oren, E., Dar, R. & Eitam, B. The sense of agency scale: a measure of consciously perceived control over one's mind, body, and the immediate environment. *Frontiers in psychology* **8**, 1552 (2017).
55. Tricomi, E. *Soft Robotic Shorts Improve Outdoor Walking Efficiency in Older Adults* (FigShare, 2024); https://doi.org/10.6084/m9.figshare.26125483

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Author contributions

E.T. designed and implemented the WalkON controller. N.L. and L.M. provided feedback to control implementation. E.T., F.M., X.Z. and L.M. led the design and implementation of the textile interface, actuator unit and electronics. E.T., F.M., N.L., M.X., J.B., C.B. and L.M. designed the study. E.T., F.M. and M.S. led the study conduct. M.T. provided the psychophysical evaluation questionnaire and analysed the related data. E.T. analyzed the data and prepared the manuscript, figures and related supplementary files. All authors reviewed the manuscript and provided critical feedback.

Competing interests

E.T., F.M., N.L. and L.M. are co-inventors of a patent application disclosing the walking assistive system described herein. The patent application is pending at the time of the submission of this paper. The remaining authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s42256-024-00894-8.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s42256-024-00894-8.

Correspondence and requests for materials should be addressed to Enrica Tricomi.

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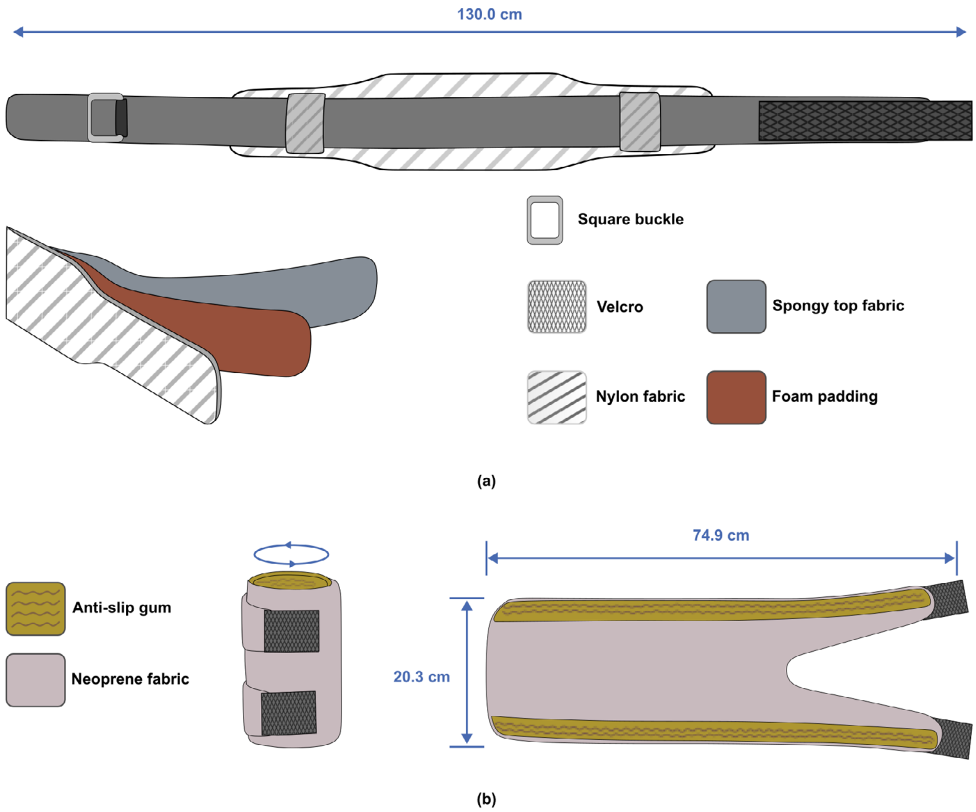

Extended Data Fig. 1 | Textile blueprint. (**a**) WalkON waist belt and layers composition. (**b**) Thigh textile harness inner view and closed configuration.

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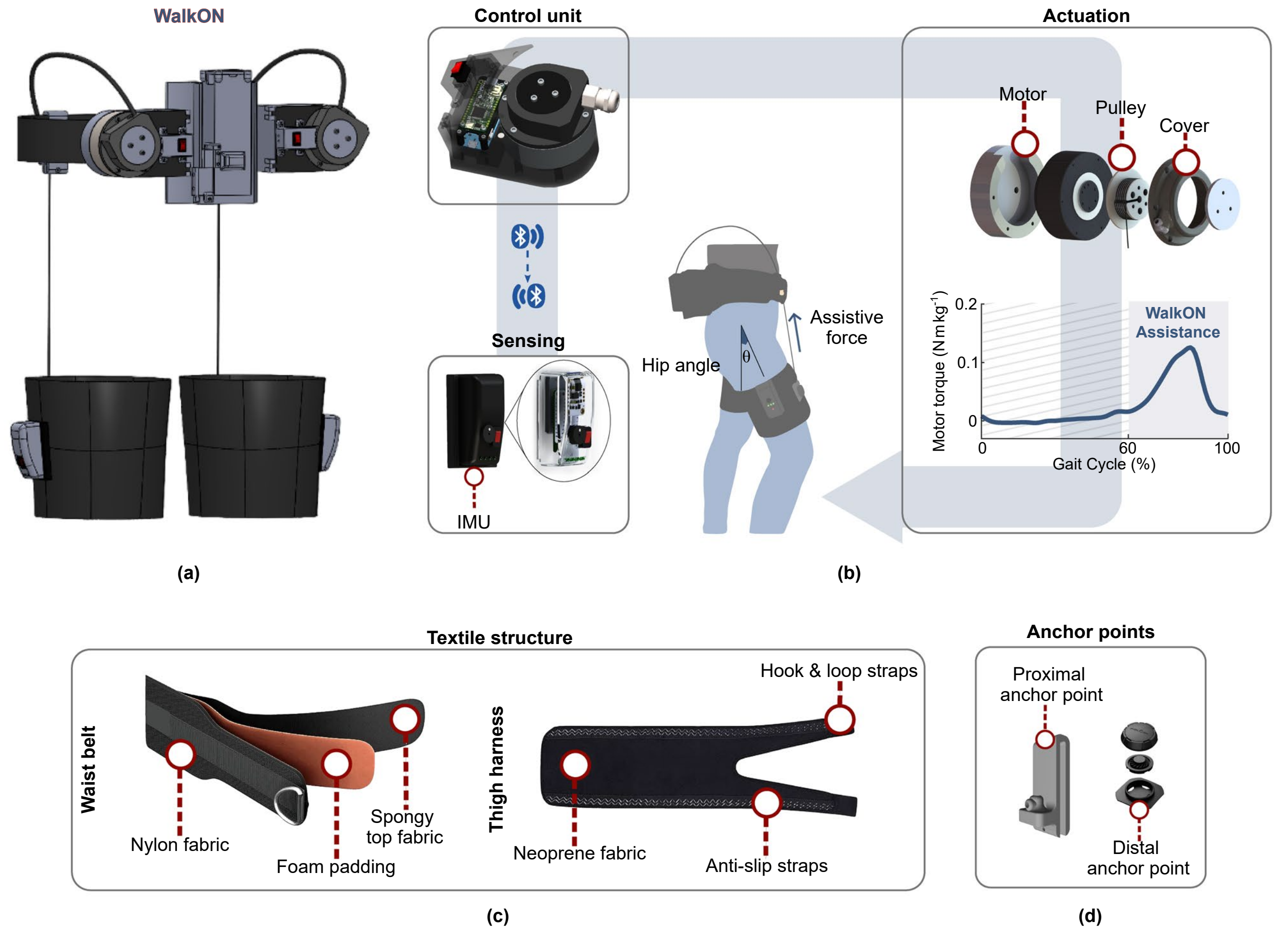

Extended Data Fig. 2 | WalkON hardware components. (**a**) Computer-aided design of WalkON (**b**) Inertial Measurement Unit (IMU) sensors stream hip motion data via Bluetooth Low Energy to the control unit. This unit runs the control algorithm on a microcontroller. The output is a velocity command sent to the actuators. The generated motor torque is transferred to the user's leg via the tendon-driven transmission. (**c**) The textile structure of WalkON is composed by a waist belt and two thigh harnesses. (**d**) Anchor points are placed on the belt and thigh harness to guide the artificial tendons.

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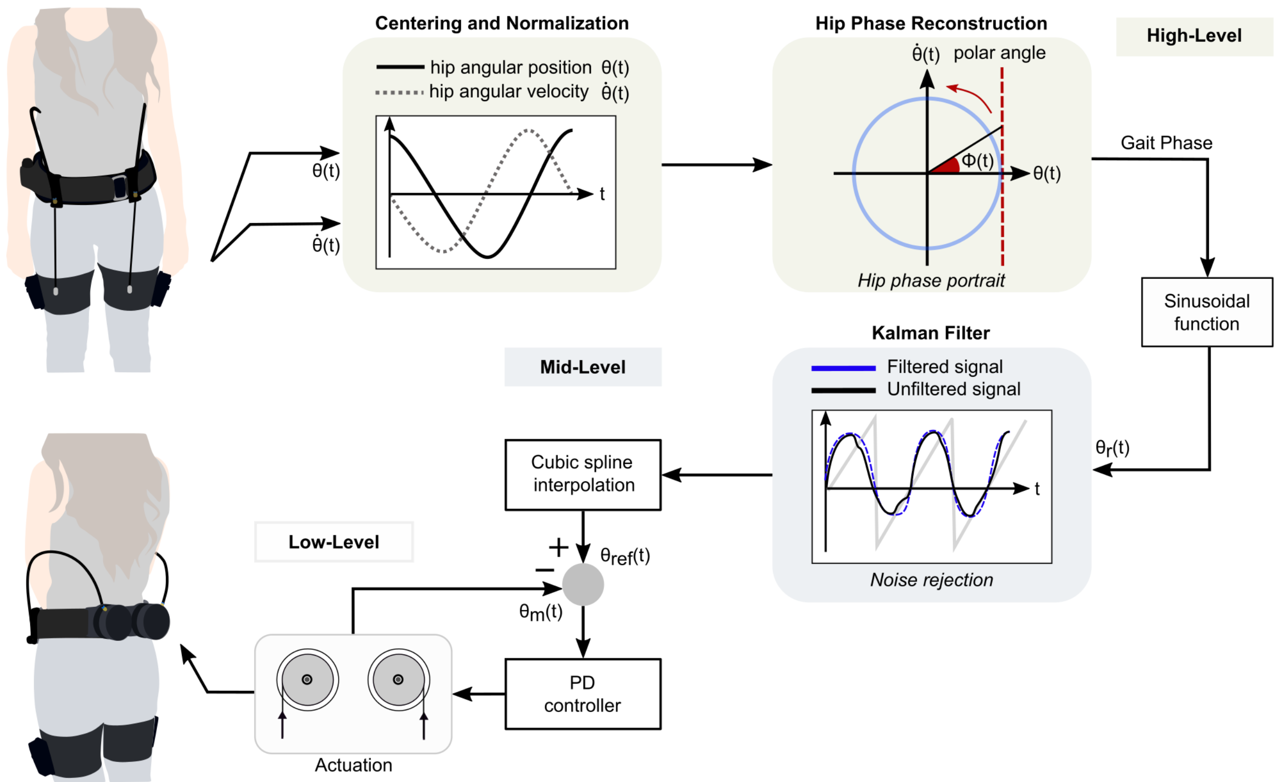

Extended Data Fig. 3 | WalkON Controller. The WalkON control system operates across three levels. The High-Level controller determines the gait phase by calculating the polar angle between the hip joint position, $\theta(t)$, and velocity, $\theta(t)$, during each gait cycle in real-time. It then uses sinusoidal interpolation to create a foundational trajectory for the reference motor position, $\theta_r(t)$. The Mid-Level controller applies a Kalman filter to $\theta_r(t)$ to eliminate noise emerging from the phase estimation method. Following this, it uses cubic spline interpolation to create the final trajectory for the final motor position reference, $\theta_{ref}(t)$. The Low-Level controller actuates tendon displacement based on the motor commands derived from the outputs of the previous levels and the current motor position $\theta_m(t)$.

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Extended Data Table 1 | Young adults demographic

Participant characteristics					
ID	Height (cm)	Weight (kg)	BMI (kg m^{-2})	Sex (-)	Age (years)
YA1	184	74	21.86	Male	24
YA2	156	60	24.65	Female	28
YA3	171	60	20.52	Male	23
YA4	193	93	24.97	Male	27
YA5	163	54	20.32	Female	28
YA6	171	70	23.94	Male	23
YA7	170	62	21.45	Female	25
YA8	158	48	19.23	Female	29
YA9	168	60	21.26	Female	27
YA10	185	73	21.33	Male	23
YA11	178	67	21.15	Male	25
YA12	185	74	21.62	Male	23

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Extended Data Table 2 | Older adults demographic

Participant characteristics						
ID	Height (cm)	Weight (kg)	BMI (kg m^{-2})	Sex	Age (years)	LUCAS Functional Ability Index
OA1	173	63	21.05	Female	69	Robust
OA2	186	90	26.01	Male	82	Robust
OA3	168	58	20.55	Female	78	Robust
OA4	165	70	25.71	Female	67	Robust
OA5	166	66	23.95	Female	69	Robust
OA6	179	65	20.29	Male	82	Pre-frail
OA7	187	90	25.74	Male	68	Robust
OA8	191	90	24.67	Male	69	Robust
OA9	168	61	21.61	Female	81	Robust
OA10	178	78	24.62	Male	76	Robust

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Corresponding author(s): Enrica Tricomi

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Reporting Summary

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Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☐	☒	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☐	☒	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☐	☒	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☒	☐	A description of all covariates tested
☐	☒	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☐	☒	For null hypothesis testing, the test statistic (e.g. F, t, r) with confidence intervals, effect sizes, degrees of freedom and P value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Data collection was performed using MATLAB Simulink (version 2022b) on a laptop communicating via Wi-Fi with an NVIDIA Jetson Nano board on the assistive device.
Data analysis	Data analysis was performed using MATLAB (version 2022b). Software scripts used for data analysis have been deposited in an online repository at https://doi.org/10.6084/m9.figshare.26125483

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

Data necessary to replicate this work have been deposited in an online repository at https://doi.org/10.6084/m9.figshare.26125483625

Research involving human participants, their data, or biological material

Policy information about studies with human participants or human data. See also policy information about sex, gender (identity/presentation), and sexual orientation and race, ethnicity and racism.

Reporting on sex and gender	Young adults (n = 12) recruited for the technology assessment study were seven men and five women. Older adults (n = 10) recruited for the efficacy study were five men and five women.
Reporting on race, ethnicity, or other socially relevant groupings	Grouping of participants was done by age difference. Other grouping factors were not relevant for the outcomes of this study.
Population characteristics	Young adults (n = 12) recruited for the technology assessment study were 25.42 ± 2.27 years old, with mean height 173.50 ± 11.63 cm, and weight 66.25 ± 11.73 kg. Older adults (n = 10) recruited for the efficacy study were 74.10 ± 6.30 years old, with mean height 176.10 ± 9.53 cm and weights 73.10 ± 12.84 kg.
Recruitment	Young adults were recruited among volunteers according to the following inclusion criteria: age between 18 and 35 years, no visual or auditory impairments or any neurological, cardiovascular, metabolic, or mental disorders that might interfere with the tasks at hand. Older adults, were recruited through the Center for Geriatric Medicine of the Heidelberg University Hospital. Older adults enrolled for the efficacy study were selected based on criteria that included being over 65 years of age, being categorized as either ”robust” or ”pre-frail” according to the LUCAS Functional Ability Index, and not having severe uncorrected visual or auditory impairments or significant neurological, cardiovascular, metabolic, or mental conditions. Recruited subjects, being first-time users of the device, were given sufficient time to become familiar with it prior to data collection, thus mitigating potential biases related to familiarization.
Ethics oversight	Research procedures were approved by the Ethics Committee of Heidelberg University under resolution No. S-313/2020.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☒ Life sciences ☐ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Life sciences study design

All studies must disclose on these points even when the disclosure is negative.

Sample size	We collected data from a total of twenty-two individuals: twelve young adults for the technology assessment and ten older adults for the efficacy study. According to a power analysis performed with metabolic data from outdoor walking experiments with an assistive wearable robotic suit (Haufe et al. 2021), we found that a sample size of at least six participants was necessary for our experiments. The analysis used the difference in metabolic rate between the assistive suit operated in zero-force mode (no assistance) and the active condition (with assistance) (difference is 10.6%) and the difference in standard deviation between the two conditions (6.9%). The test used a power of $1 - \beta = 0.8$ and $\alpha = 0.05$. For each group of participants (young and older adults) we recorded data from a higher number of individuals than the one suggested by the power analysis (12 and 10 respectively).
Data exclusions	No exclusions were made.
Replication	All experimental data and exemplary scripts for data analysis are available to replicate the results shown in the Figures of the manuscript.
Randomization	For the technology assessment with young adults, given the physically demanding nature of the trial, we conducted the different experimental conditions on separate days to minimize that fatigue-related effects influenced the outcomes of the comparison. The order of conditions was anyway randomized across participants. For the efficacy study with older adults, both experimental conditions were conducted on the same day, with a minimum 20-minute rest period in between to prevent fatigue. The order of the conditions was randomized among participants to eliminate order effects.
Blinding	Blinding was not relevant to this study because the participant could easily recognize whether they were walking unassisted or with assistance from the soft robotic shorts.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging