

Functionality and comfort of use of various types of medical exoskeletons in the patients' subjective judgment

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Published online: April 30, 2026

Accepted for publication: April 15, 2026

DOI:10.7752/jpes.2026.04078

Abstract:

Background: Impaired mobility is an increasing global health challenge associated with population aging and the rising prevalence of chronic diseases, leading to lower-limb dysfunction and long-term disability. Wearable lower-limb exoskeleton robots (ERs) have emerged as promising tools for gait rehabilitation; however, evidence regarding user-perceived comfort, safety, and functionality remains limited, particularly from the perspective of experienced users. **Materials and methods:** A cross-sectional survey was conducted among 59 adult users of medical lower-limb ERs in Poland. A purpose-developed structured questionnaire assessed the subjective perceptions of comfort, functionality, stability, and usability across different ER configurations, including variations in actuation systems, structural design, and human–robot interfaces. Descriptive statistics and non-parametric comparative analyses were applied. **Results:** The ERs equipped with four actuators were generally perceived as sufficiently functional, with overall ratings ranging from moderate to good. Strap-based interface systems were preferred over in-shoe fastening due to shorter fitting times and improved usability. The ability to abduct the lower limbs in the seated position was identified as a particularly valuable feature. Key limitations included insufficient stability during standing and walking, discomfort related to body-device contact, and restricted adaptability. Users emphasised the need for enhanced motion modes, broader velocity ranges, and improved adjustability. Importantly, a strong demand was expressed for increased safety while maintaining independence from external assistive devices. **Conclusions:** The user-centred evaluation highlighted critical design priorities for future ER development, particularly in terms of stability, adaptability, and ease of use. Incorporating patient-reported experiences into the design and clinical implementation of ERs may improve comfort, functional outcomes, and user acceptance, thereby enhancing the effectiveness of rehabilitation interventions.

Key words: wearable robotic exoskeletons, human-robot interface, assistive technology usability, gait assistive devices, patient-reported outcomes, device ergonomics

Introduction

Impaired mobility is a major and growing global health problem and a significant challenge for modern healthcare systems. Population aging and the increasing prevalence of chronic non-communicable diseases, such as stroke, diabetes, and cardiovascular disorders, have led to a substantial rise in individuals with lower-limb weakness, paresis, or long-term mobility limitations (Prynn & Kuper, 2019; Katzarzyk et al., 2022; Safiri et al., 2023). These conditions reduce independence, decrease quality of life, and increase the demand for long-term care and rehabilitation, generating a considerable socioeconomic burden.

In response, wearable lower-limb exoskeleton robots (ERs) have emerged as promising assistive and rehabilitation technologies that support or restore locomotor function through external mechanical assistance. Over the past decade, significant progress has been made in ER development, including advances in actuation, control strategies, and rehabilitation applications (Rodríguez-Fernández et al., 2021; Tang et al., 2022; Rakhmatillaev et al., 2024; Mashud et al., 2025; Hasan & Alam, 2025). Systematic reviews indicate that ER-assisted gait training can improve walking ability, gait symmetry, and energy efficiency, particularly in individuals with neurological impairments (Tefertiller et al., 2018; Leow et al., 2023; Daliri et al., 2024). At the same time, increasing attention has been directed toward optimising human–robot interaction. Factors such as biomechanical alignment, force transmission, and adaptability of assistance are critical for both therapeutic effectiveness and user comfort (Sanchez-Villamañan et al., 2019; Di Natali et al., 2020; Bettella et al., 2025; Wu et al., 2025). Recent developments in compliant actuators, soft exosuits, and human-in-the-loop control strategies further emphasise the importance of personalisation and adaptability in ER design (Guo et al., 2025). Despite these advances, a significant gap remains. Most studies focused on objective clinical outcomes or technical performance, while subjective user experience, particularly among long-term users, remains underexplored.

Available evidence suggests that the ease of donning and doffing, perceived safety, stability, interface comfort, and usability are key factors influencing user acceptance and real-world applicability (Wolff et al., 2014; Muijzer-Witteveen et al., 2018; Poritz et al., 2020). However, comparative data on how different design configurations are perceived by users are scarce. This gap is particularly relevant in clinical practice where multiple ER systems with diverse structural and functional characteristics are available. Differences in actuation, structure, and interface design may substantially influence comfort, safety, and functional performance; yet evidence identifying the most relevant features from the users' perspective is limited. Therefore, collecting and analysing subjective user feedback is essential for understanding real-world needs. Such data may support clinicians in device selection and guide engineers in designing next-generation ER systems that better meet user expectations. The aim of the present study was to present subjective opinions obtained directly from ER users regarding which construction elements and functional features they consider most important for comfortable use. Such information remains scarce in the existing literature despite its clear relevance to engineers, healthcare professionals, and patients. To address this gap, the study adopted a cross-sectional, user-centred research approach based on a structured survey administered to adult users of medical lower-limb exoskeletons. The survey collected subjective evaluations of key aspects of device use, including comfort, functionality, stability, and usability, across different structural and interface configurations. The data were analysed to identify patterns in user preferences and priorities. This approach enables the identification of the design features that are most critical for ER use from the users' perspective and provides practical insights for the future development and clinical application of exoskeleton technologies. Importantly, the objective of this study was not to compare specific ER models in a marketing sense but rather to treat them as distinct constellations of features and functionalities.

Material & methods

Design

This was a one-time assessment of the subjective opinions of a cohort of volunteers (medical ER users) on the functionality and comfort of using these devices, conducted by means of a structured survey created by an expert group. It was part of a larger project that received approval from the Bioethics Committee (no. 72/KBL/OIL/2024).

Recruitment

Recruitment was carried out via e-mail correspondence addressed to the medical ER users registered in the databases of institutions offering the possibility of ER-based therapy. It contained a request to take part in the survey, information about its purpose and on how the data would be processed, information on maintaining the full anonymity of respondents, and a link to the survey itself. Participation was voluntary; participants were not offered any financial or other benefits.

Eligibility criteria

Participant eligibility was defined a priori to ensure a homogeneous study population and minimise potential confounding factors related to health status and experience with ERs. The inclusion criteria were as follows: 1) Age between 18 and 60 years. The lower limit ensured legal adulthood and capacity to provide informed consent, while the upper limit was selected to reduce the likelihood of age-related comorbidities that could interfere with the interpretation of subjective assessments; 2) Presence of neurological or musculoskeletal dysfunction constituting a clinical indication for the medical use of ERs; 3) Duration of the underlying dysfunction exceeding 5 years, to ensure a stable clinical condition; 4) Prior experience with ER use of at least 5 hours, ensuring that participants had sufficient exposure to the device to provide informed and experience-based subjective evaluations; 5) Absence of severe comorbidities that could substantially affect physical functioning or confound the assessment of ER functionality and comfort. The exclusion criteria were limited to methodological considerations and included: 1) incorrect completion of the questionnaire (e.g., missing responses), incorrect number of answers to a given question, or internally contradictory responses that precluded reliable interpretation. All the inclusion and exclusion criteria were applied consistently during data screening prior to analysis.

Participants

A total of 149 recruitment messages were distributed, resulting in 82 responses (response rate: 55%). Following the application of the predefined eligibility criteria, 61 respondents were deemed eligible for inclusion in the study. Of the 21 respondents excluded at this stage, 7 reported comorbidities that could substantially influence perceived comfort during ER use, 6 had insufficient experience with ERs to reliably assess their functionality and comfort, and 10 questionnaires were excluded due to internally contradictory responses. In several cases, more than one exclusion criterion applied to the same respondent. Preliminary analysis of the eligible responses indicated that the participants primarily used three types of medical ERs: Ekso NR (Ekso Bionics, USA), Indego (Parker Hannifin, USA), and ReWalk (ReWalk Robotics, Israel). Only two respondents reported using a different device (FreeWalk, Free Bionics, Taiwan). Due to the very limited representation of this latter system, it was excluded from the comparative analyses. Consequently, the final dataset used for the analysis comprised responses from 59 participants using 3 types of medical ERs. A detailed breakdown of the study sample is presented in Table 1.

Table 1. Basic characteristics of the study group (mean [median] $\pm$ standard deviation (min-max) or N (%)). Presented are the *P*-values for the comparisons between the 3 types of exoskeleton robots.

	Total		Ekso NR		Indego		ReWalk		P-value
Number	59 (100)		33 (55.9)		12 (20.3)		14 (23.7)		-----
Sex	F: 28 (47.5) M: 31 (52.5)		F: 14 (42.4) M: 19 (57.6)		F: 4 (33.3) M: 8 (67.7)		F: 10 (71.4) M: 4 (28.6)		0.10 [^]
Age (y)	33.93 [32] $\pm$ 9.32 (20-54)		35.79 [34] $\pm$ 9.10 (20-54)		29.75 [31] $\pm$ 5.89 (20-37)		33.14 [31] $\pm$ 11.35 (20-52)		0.15 [#]
Body mass (kg)	74.75 [75] $\pm$ 8.19 (59-89)		75.81 [75] $\pm$ 6.50 (65-88)		76.83 [80] $\pm$ 7.91 (65-89)		70.43 [66] $\pm$ 10.75 (59-88)		0.09 [†]
Body height (cm)	172.17 [171] $\pm$ 7.44 (160-185)		173.03 [171] $\pm$ 5.94 (162-184)		174.50 [175] $\pm$ 8.41 (162-185)		168.14 [165] $\pm$ 8.71 (160-182)		0.06 [†]
Dysfunction	NG	6 (10.2)	NG	3 (9.1)	NG	0 (0.0)	NG	3 (21.4)	0.05 [^]
	NT	26 (44.1)	NT	15 (45.4)	NT	5 (41.7)	NT	6 (42.9)	
	NC	15 (25.4)	NC	9 (27.3)	NC	6 (50.0)	NC	0 (0.0)	
	ND	7 (8.5)	ND	2 (6.1)	ND	1 (8.3)	ND	4 (28.6)	
	MS	5 (11.8)	MS	4 (12.1)	MS	0 (0.0)	MS	1 (7.1)	
Dysfunction time (y)	5	12 (20.3)	5	7 (21.2)	5	0 (0.0)	5	5 (35.7)	0.006 ^{**}
	6-10	28 (47.5)	6-10	15 (45.5)	6-10	4 (33.3)	6-10	9 (64.3)	
	>10	19 (32.2)	>10	11 (33.3)	>10	8 (67.7)	>10	0 (0.0)	
Exoskeleton robot usage time (h)	<5	7 (11.9)	5	7 (21.2)	5	0 (0.0)	5	0 (0.0)	0.005 ^{**}
	6-25	37 (62.7)	5-25	15 (45.5)	5-25	8 (67.7)	5-25	14 (100.0)	
	>25	15 (25.4)	>25	11 (33.3)	>25	4 (33.3)	>25	0 (0.0)	

*Statistically significant; [#]one-way analysis of variance (normal distribution present); [†]Kruskal–Wallis test (deviations from normal distribution present); [^]Chi square test (nominal-scale variables); NG, neurogenetic; NT, neurotraumatic; NC, neurocongenital; ND, neural disease; MS, musculoskeletal

Exoskeleton robots

The most important characteristics of the compared ERs are presented in Table 2.

Table 2. Mechanical characteristics of the 3 types of exoskeleton robots.

	Ekso NR	Indego	ReWalk
Motion modes (N)	5	2	3
Actuators (N)	4	4	4
Gait velocity range (m/s)	0.5-1.5	0.6-0.8	0.4-0.8
Numerical scale on adjustable sections	Yes	Yes	Yes
Adjustment system	Screws, pins	Screws	Screws, pins
Mounting system	Feet: ski-binding-like thigh, shin: straps trunk: strap, suspenders	Feet: inside the shoe thigh, shin: straps trunk: strap, suspenders	Feet: inside the shoe thigh, shin: straps trunk: strap, suspenders
Hip abduction	Yes	No	No
Assistance	Needed	Not needed at home in mild disabilities, otherwise - needed	Needed
Assistive gear	Crutch, cane, walker	Crutch, cane, walker	Crutch
Mass (kg)	27	12-17	27-30
Disassemble option	Yes	Yes	No
Patient height range (cm)	152-194	150-190	160-190
Patient's maximum mass (kg)	100	113	100
Battery time (h)	3	4	3

Survey

Information on respondents' subjective opinions regarding the functionality and comfort of use of medical ERs was collected using a purpose-developed online questionnaire. The survey was open, anonymous, individual, one-time, and structured, and was administered in the native language of the respondents to ensure adequate comprehension and minimise language-related response bias.

The questionnaire consisted of a metric section and a substantive section composed primarily of closed-ended items (N = 18), supplemented by a limited number of open-ended questions (N = 2). The instrument was designed as a descriptive diagnostic survey commonly used in psychology and the social sciences to collect subjective assessments at a single time point.

The questionnaire was not intended to operationalise latent constructs, support hypothesis testing, or enable inter- or intra-group comparisons. Consequently, formal psychometric validation procedures were not

undertaken. Instead, methodological rigor was ensured through systematic procedures aimed at establishing content validity and face validity, which are appropriate for exploratory and descriptive survey research.

Questionnaire development was conducted by a multidisciplinary expert panel consisting of five members. The panel included 2 bioengineering specialists with 10 and 15 years of professional experience in developing biomedical assistive devices; both had been directly involved in the present ER project for approximately 5 years. Two physiotherapists with 15 and 18 years of clinical experience working with neurological patients using various assistive and rehabilitation devices also participated. In addition, the panel included a patient representative with approximately 8 years of experience using ERs, who had been actively engaged in multiple projects as a tester of different ERs systems. The inclusion of both professional experts and an experienced end user was intended to enhance the relevance and completeness of the questionnaire content.

Following the definition of the research objectives and a review of relevant literature on ER usability, functionality, and comfort, each panel member independently proposed candidate items. A modified Delphi technique was then applied in two iterative rounds, during which the items were reviewed for relevance, clarity, and representativeness of the target domains. The items were revised, merged, or eliminated based on expert consensus, supporting the content validity of the final questionnaire.

No explicit separation between items related to functionality and comfort of use was introduced, as these domains were considered inherently interrelated. In many cases, specific functional features directly influence perceived comfort. Treating these aspects jointly was therefore considered conceptually justified.

To support face validity and comprehensibility, the preliminary questionnaire was pilot-tested with five volunteers representative of the target population. Minor linguistic and formatting adjustments were introduced based on participant feedback prior to the implementation of the final electronic version. The questionnaire was subsequently distributed to respondents together with standardised instructions.

Procedure

The survey, along with appropriate comments and instructions, was sent in an electronic form to a group of potential respondents registered in electronic databases of people using medical ERs. After obtaining voluntary responses, the respondents were sent a note of thanks. In the absence of a response, a reminder was sent after 2 weeks. Again, if a response did not come within the subsequent 2 weeks, no further attempts were made. All responses were collected in an electronic database, to which the researchers did not have access until data collection was completed. After that, they verified the correctness of the responses and proceeded to statistical analysis of the data. Incorrectly completed surveys were not returned to the respondents for correction; they were excluded from further procedures.

Statistical analysis

In the statistical analysis, deviations from normality of the ratio-scale characteristics of the study group (age, body mass, and height) were assessed using the Shapiro–Wilk test. Inter-ER differences were analysed using one-way analysis of variance in one case (age). In the remaining two cases (body mass and height), the Kruskal–Wallis test was applied due to deviations from the normal distribution (see Table 1).

For the outcome measures, normality was not assessed as their nominal or ordinal measurement level necessitated the use of non-parametric statistical methods. Initially, basic descriptive statistics were calculated for ordinal-scale variables, and frequency tables were constructed for nominal-scale variables. Comparisons between different types of ERs were performed using the Kruskal–Wallis test, followed by a dedicated post-hoc test (only for ordinal-scale variables). Effect sizes for post-hoc analyses were calculated using the non-parametric effect size coefficient r , defined as $r = Z / N^{1/2}$, where Z represents the standardised test statistic and N , the total sample size. The absolute value of r indicates the magnitude of the effect, with values of 0.1, 0.3, and 0.5, conventionally interpreted as small, medium, and large effects, respectively, while the sign reflects the direction of the difference between the groups. All analyses were conducted using Statistica 13.0 (StatSoft, Tulsa, USA).

Results

In the analysis of factors affecting the comfort of ER use, it was found that the most obvious comfort-limiting problems associated with the contact of the device components with the body included various types of abrasions (44% of the total group) and, with the highest frequency, they appeared in the case of the ReWalk construction (71%). Pressure and discomfort most often occurred in Ekso NR (58%). Relatively often, users did not report any problems (32% of the total group), and such a situation was typical for ER Indego (67%) (Figure 1). As for the lower limbs, problems of pressure and discomfort occurred most often in the thigh area (22% of the total group), less often in the ankle joint area (7% of the total group). Interestingly, in the case of all designs, they also affected the upper part of the body, i.e. the shoulder area (31% of the total group) and torso (8% of the total group; Figure 2).

Among the main limitations of ER user comfort, the respondents most often mentioned a lack of appropriate education (31% of the total group), and this opinion applied to all the tested ER designs. In addition, significant limitations were unnatural gait (27% of the total group), as well as problems with maintaining balance (16% of the total group), which appeared particularly often in the case of ReWalk (43%). Indego ER users critically assessed the need for assistance (33%); and Ekso NR users, the number of actuators (24%; Figure 3),

although it was the same in each design (Table 2). The range of possible adjustments was the primary comfort-promoting factor (19% of the total group) among the users of all ER designs. In addition, respondents mentioned also the speed adjustment feature in the case of Ekso NR, (23%); the size of the device in the case of Indego (33%); and education and in the case of ReWalk (30%; Figure 4). As a possible “to-be-added” option, Ekso NR users indicated the possibility of non-assisted usage (67%). For Indego and ReWalk users, it was the number of motion modes, 67% and 64%, respectively (Figure 5).

In terms of the functionality of the tested ERs, the Ekso NR design was the leader in terms of the fitting time, with results of less than 5 minutes (36%) and from 5 to 15 minutes (64%). In general, the fitting time was most often in the range of 5 to 15 minutes (31% of the total group; Figure 6). The negatively assessed functionalities of the individual designs were primarily the gait quality (Ekso NR, 25%; Indego, 75%; ReWalk, 48%; Figure 7). The functionality assessed positively was primarily the possibility of data analysis (29% of the total group), appearing in the responses of users of all designs (Figure 8). In addition, all participants valued the ease of use (22% of the total group). Ekso NR users placed particular emphasis on battery life (36%); however, this did not differ significantly from the other models (Table 2). The functionality that the respondents indicated as possible “to-be-added” was primarily the possibility of non-assisted usage (46% of the total group). In the case of Ekso NR, the disassemble option was also indicated (34%), and in the Indego and ReWalk constructions, the number of motion modes (33% and 31%, respectively; Figure 9).

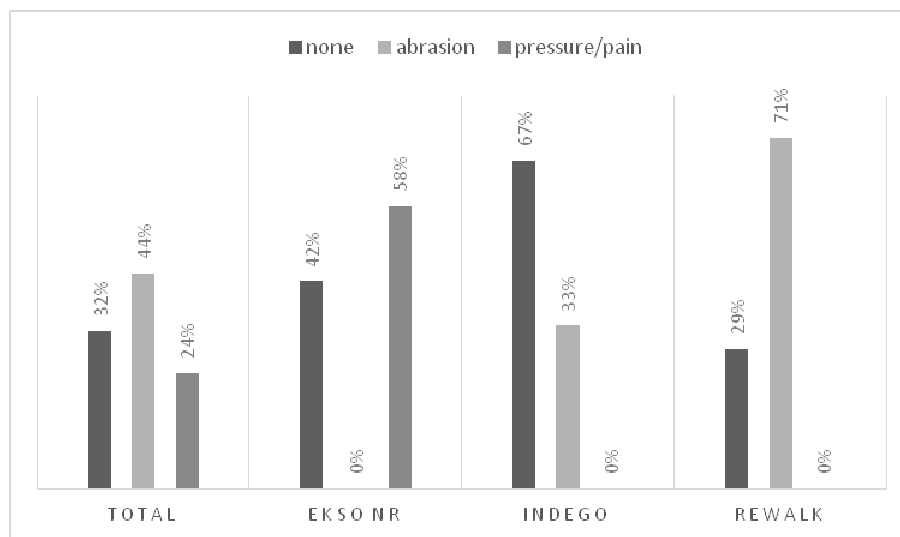


Figure 1. Major “contact-with-the-body” comfort-limiting problems for the total group of respondents and users of the individual exoskeleton robot types.

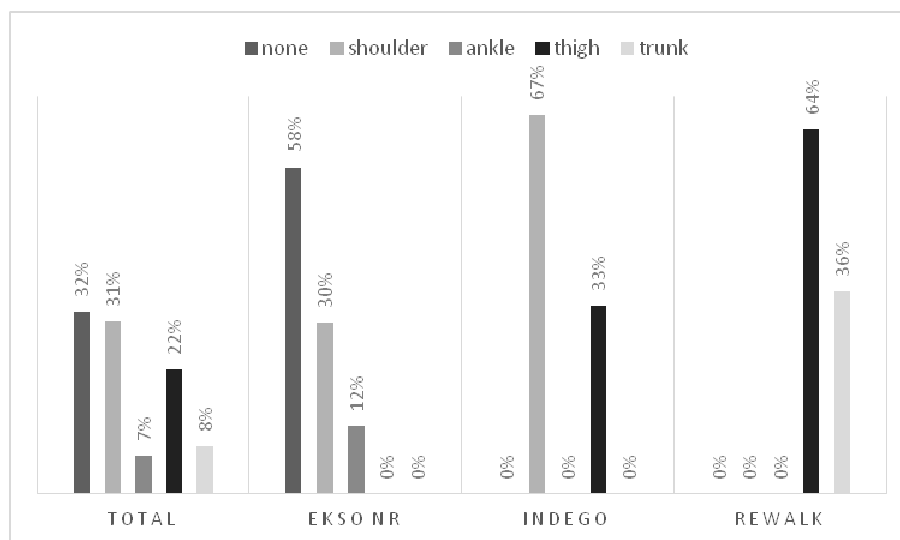


Figure 2. Localisation of the “contact-with-the-body” comfort-limiting problems for the total group of respondents and users of the individual exoskeleton robot types.

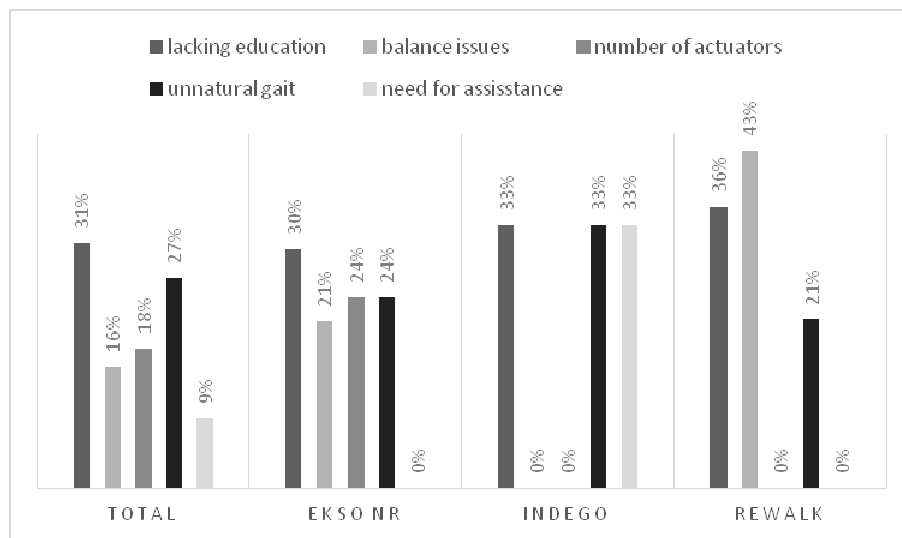


Figure 3. Major comfort-limiting factors identified in the total group of respondents and users of the individual exoskeleton robot types.

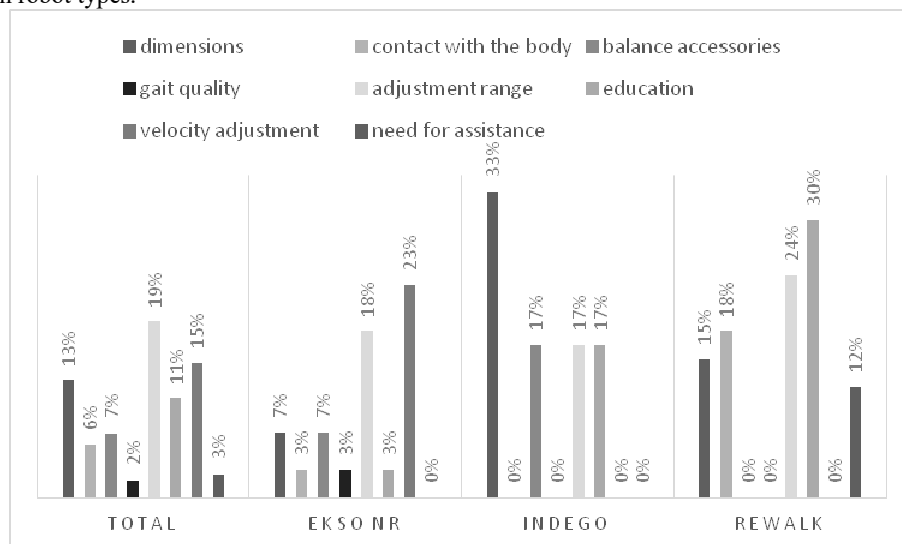


Figure 4. Major comfort-promoting factors identified in the total group of respondents and users of the individual exoskeleton robot types.

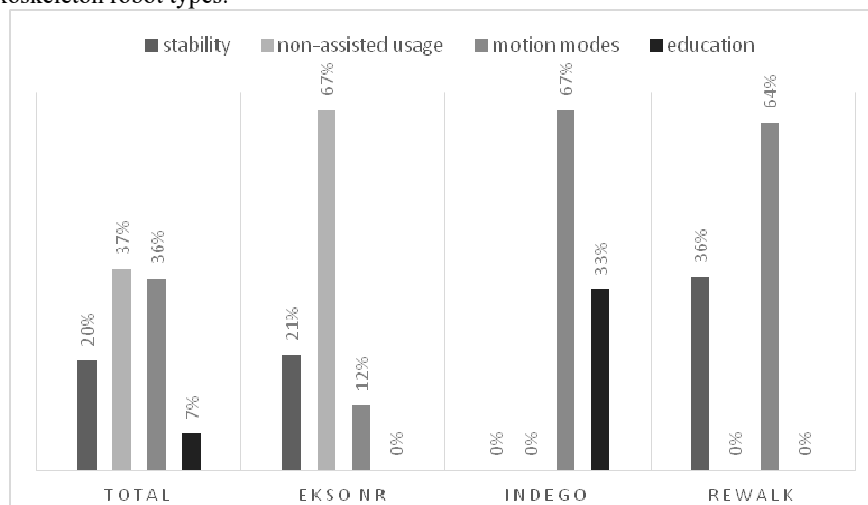


Figure 5. Comfort-promoting options "to-be-added" identified in the total group of respondents and users of the individual exoskeleton robot types.

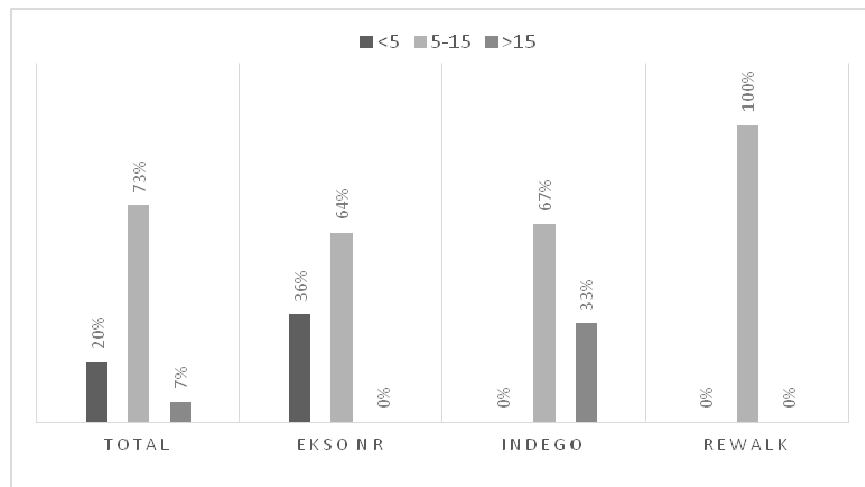


Figure 6. Fitting time in the total group of respondents and users of the individual exoskeleton robot types.

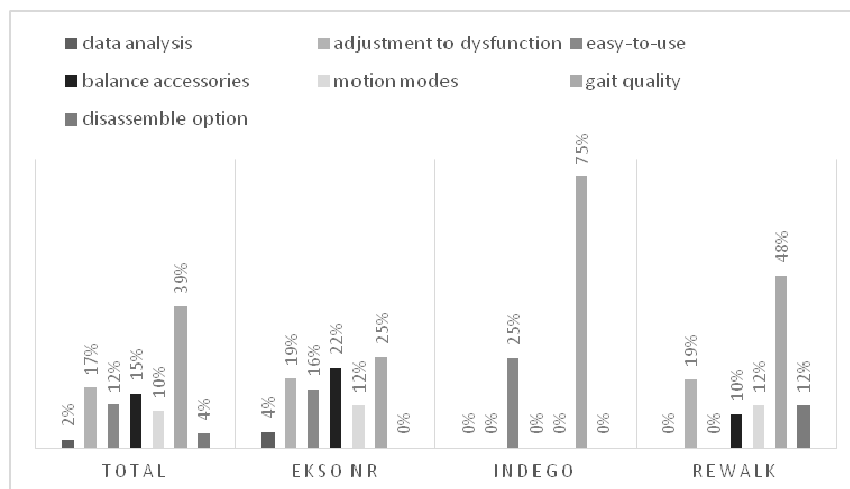


Figure 7. Negatively perceived functionalities of the exoskeleton robots identified in the total group of respondents and users of the individual exoskeleton robot types.

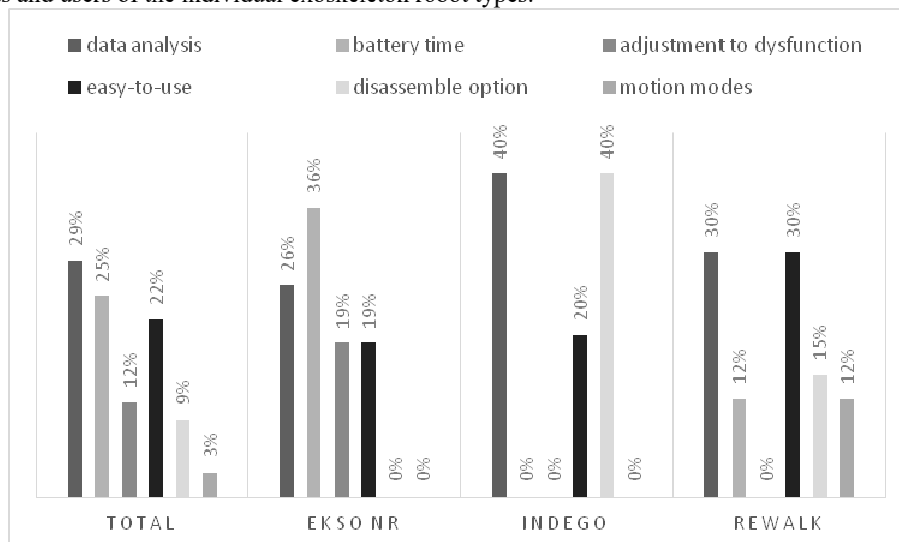


Figure 8. Positively perceived functionalities of the exoskeleton robots identified in the total group of respondents and users of the individual exoskeleton robot types.

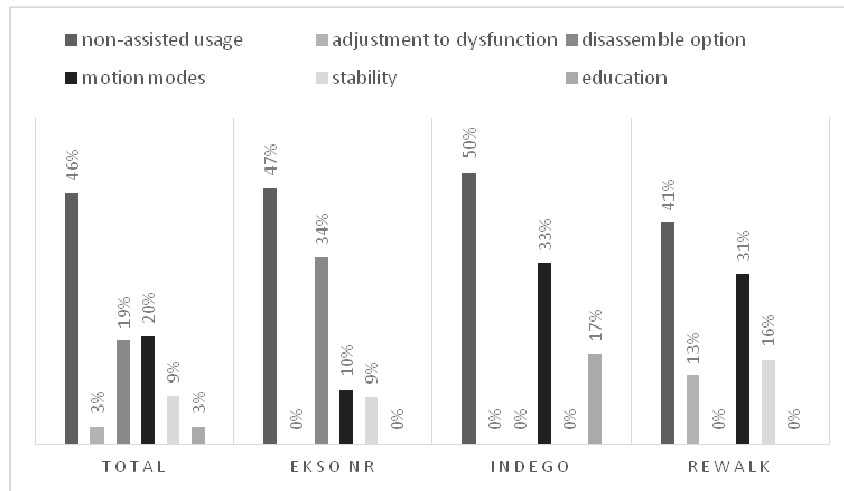


Figure 9. Functionality options “to-be-added” identified in the total group of respondents and users of the individual exoskeleton robot types.

In the Table 3, presented are the ratings (ordinal scale) of the selected features of the tested ERs, as well as the overall comfort ratings and global comfort ratings. All these ratings were moderate to good (2.50-4.33 on the 5-point scale [5 = highest rating]). In the majority of cases (excluding balance in standing position, $P=0.154$), significant differences between the 3 types of tested ER were shown. Most often, the Ekso NR construction received the highest notes. The comfort rating for this construction was also the highest (3.88 points), while the overall rating was comparable to that of ReWalk (3.97 vs. 4.00 points, respectively).

Table 3. Descriptive statistics for the variables measured with the use of the ordinal rating scales. Presented are mean values $\pm$ standard deviations (median, minimum-maximum), P -values and H statistics of the Kruskal–Wallis test for comparisons between the 3 types of exoskeleton robots, and P -values, Z statistics, and effect sizes (the r coefficient) for the post-hoc analysis.

	Total	Ekso NR (1)	Indego (2)	ReWalk (3)	P -value H	P -value post-hoc, Z statistic (effect size r)
Fitting	3.54 $\pm$ 0.50 (4; 3-4)	3.67 $\pm$ 0.48 (4; 3-4)	3.00 $\pm$ 0.00 (3; 3-3)	3.71 $\pm$ 0.47 (4; 3-4)	<0.001* 17.64	1-2 <0.01*, 3.40 (0.50) 1-3 >0.05, 0.26 (0.04) 2-3 <0.01*, 3.12 (0.61)
Balance standing	2.90 $\pm$ 0.80 (3; 1-5)	3.06 $\pm$ 0.83 (3; 2-5)	2.50 $\pm$ 0.80 (3; 1-4)	2.86 $\pm$ 0.66 (3; 2-4)	>0.05 H=3.74	-----
Balance gait	3.47 $\pm$ 0.70 (4; 2-5)	3.70 $\pm$ 0.64 (4; 2-5)	2.92 $\pm$ 0.79 (3; 2-4)	3.43 $\pm$ 0.51 (3; 3-4)	<0.01* H=9.57	1-2 <0.05*, 2.77 (0.41) 1-3 >0.05, 1.22 (0.20) 2-3 >0.05, 1.38 (0.27)
Range of motion adjustment	3.42 $\pm$ 0.77 (3; 2-5)	3.76 $\pm$ 0.66 (4; 3-5)	2.92 $\pm$ 0.67 (3; 2-4)	3.07 $\pm$ 0.73 (3; 2-4)	0.001* H=13.76	1-2 <0.01*, 2.96 (0.44) 1-3 <0.05*, 2.49 (0.41) 2-3 >0.05, 0.52 (0.10)
Muscle engagement	3.66 $\pm$ 0.99 (4; 2-5)	4.33 $\pm$ 0.54 (4; 3-5)	2.67 $\pm$ 0.78 (3; 2-4)	2.93 $\pm$ 0.73 (3; 2-4)	<0.001* H=35.33	1-2 <0.001*, 4.68 (0.70) 1-3 <0.001*, 4.35 (0.71) 2-3 >0.05, 0.48 (0.09)
Velocity range	3.88 $\pm$ 0.95 (4; 2-5)	4.33 $\pm$ 0.65 (4; 3-5)	2.92 $\pm$ 0.90 (3; 2-4)	3.64 $\pm$ 0.93 (4; 2-5)	<0.001* H=19.10	1-2 <0.001*, 3.94 (0.59) 1-3 >0.05, 2.19 (0.36) 2-3 >0.05, 1.60 (0.31)
Gait quality	3.08 $\pm$ 0.77 (3; 2-4)	3.42 $\pm$ 0.61 (3; 2-4)	2.50 $\pm$ 0.67 (2; 2-4)	2.79 $\pm$ 0.80 (3; 2-4)	0.001* H=14.98	1-2 <0.01*, 3.29 (0.49) 1-3 <0.05*, 2.40 (0.39) 2-3 >0.05, 0.87 (0.17)
Skin contact comfort	3.63 $\pm$ 0.85 (4; 2-5)	4.12 $\pm$ 0.65 (4; 3-5)	2.58 $\pm$ 0.51 (3; 2-3)	3.36 $\pm$ 0.50 (3; 3-4)	<0.001* H=30.91	1-2 <0.001*, 5.01 (0.75) 1-3 <0.05*, 2.84 (0.47) 2-3 >0.05, 1.99 (0.39)
Comfort rating	3.56 $\pm$ 0.60 (4; 3-5)	3.88 $\pm$ 0.55 (4; 3-5)	3.33 $\pm$ 0.49 (3; 3-4)	3.00 $\pm$ 0.00 (3; 3-3)	<0.001* H=25.36	1-2 <0.05*, 2.43 (0.36) 1-3 <0.001*, 4.28 (0.70) 2-3 >0.05, 1.38 (0.27)
Overall rating	3.85 $\pm$ 0.48 (3; 4-5)	3.97 $\pm$ 0.47 (4; 3-5)	3.33 $\pm$ 0.49 (3; 3-4)	4.00 $\pm$ 0.00 (4; 4-4)	<0.001* H=17.86	1-2 <0.01*, 3.01 (0.45) 1-3 >0.05, 0.23 (0.04) 2-3 <0.01*, 2.76 (0.54)

*Statistically significant

Discussion

To date, there is limited evidence addressing the subjective user opinions of ERs. Only a few studies have incorporated user-reported experiences, satisfaction, or broader stakeholder perspectives. For example, Poritz et al. (2020) used a structured questionnaire to compare two lower-limb ERs (REX vs. Ekso) and identified transportability and ease of transfer as the key determinants of user satisfaction. Similarly, stakeholder surveys involving wheelchair users and clinicians have identified priorities, such as ease of donning and doffing, perceived safety and stability, interface comfort, and usability (Wolff et al., 2014). Additional important factors include reliability, simplicity of operation, and suitability for everyday use. This pattern aligns with the present findings, where users prioritised comfort, ease of fitting, stability, and usability over purely technical features. Subjective evaluations have also been used to assess preferences for sensory feedback following ER training (Muijzer-Witteveen et al., 2018).

Despite these contributions, comparative studies based on structured subjective evaluations across multiple ERs remain scarce. Therefore, the present study focused on interpreting user-centred findings while highlighting the originality of a multi-device approach. The study provides a systematic comparison of three medical ERs from the perspective of long-term users with neurological or musculoskeletal dysfunction using a purpose-developed questionnaire combining quantitative ratings and targeted open-ended responses. Compared to previous research, which typically focused on single devices or isolated aspects, this approach evaluates functionality, comfort, interface ergonomics, stability, and adjustability across devices, offering a more comprehensive understanding of user priorities. From a functional perspective, ER joint configuration and actuator distribution vary across devices (Qiu et al., 2023; Foroutannia & Mohammadian, 2026; Herrera-Valenzuela et al., 2023). In the present study, all ERs were equipped with four actuators, which were rated as sufficient by the users (Table 3). Although some differences between the devices were statistically significant, their magnitude was small, suggesting comparable functional support. Clinically, this indicates that additional actuators may not substantially improve the perceived functionality in typical rehabilitation settings. The interface design plays a critical role in usability. The components responsible for force transmission and fixation influence both comfort and fitting time (Foroutannia & Mohammadian, 2026; Herrera-Valenzuela et al., 2023). In this study, strap-based solutions (e.g. Ekso NR) were rated more favourably than in-shoe fastening systems, particularly in terms of the fitting time. Even small reductions in fitting time may improve clinical workflow and user independence.

The ability to abduct the legs in the sitting position, available only in Ekso NR, was identified as particularly important. This device was also associated with fewer and less severe skin-related issues (Figure 1; Table 3), suggesting that interface design can meaningfully influence comfort, reduce the risk of skin injury, and potentially improve adherence. These findings highlight the importance of optimising the fastening systems and contact regions. Users also reported the need for greater functionality, including more motion modes, wider velocity adjustments, and increased structural adjustability (Figures 4 and 9; Table 3).

Despite the use of fall-prevention technologies, users reported instability and a lack of balance during both standing and walking (Figure 3-4; Table 3). These findings indicate that the current solutions do not fully address user-perceived stability, particularly under static conditions. Users expressed a preference for improved stability with reduced reliance on assistive devices, such as crutches. Only a limited number of ERs provide full-body stabilisation, typically through walker-based designs (Hasan & Alam, 2025). These systems allow the free use of the upper limbs and may better address user expectations. In addition, adaptive control strategies, including neural network-based approaches, have been shown to improve stabilisation and resistance to disturbances (Liu et al., 2021). Together, these findings suggest that future ER designs should integrate both mechanical support and adaptive control strategies to enhance stability and independence (Woźniak et al., 2025). Consistent with previous research, the ease of donning, modularity, and transportability remain important design requirements (Laffranchi et al., 2021).

Finally, user comfort is influenced not only by device design but also by non-technical factors. Insufficient user education was identified as a barrier to comfort, while access to performance feedback (e.g. data analysis) was positively evaluated. These findings suggest that integrating educational support and feedback mechanisms may improve adherence and functional outcomes.

Conclusions

The findings of this study provide a comprehensive user-centred perspective on the functionality and comfort of use of contemporary lower-limb medical exoskeletons. Overall, devices equipped with four actuators were perceived as sufficiently functional, with global ratings ranging from moderate to good, indicating that the current actuation configurations are generally adequate to meet users' basic functional needs. Importantly, differences between devices were observed not so much in core functionality but rather in usability-related aspects, particularly those associated with the human-robot interface and device ergonomics.

Among the evaluated features, strap-based body-exoskeleton interfaces were consistently rated more favourably than in-shoe fastening systems, primarily due to the reduced fitting time and greater ease of use. The ability to abduct the lower limbs while seated emerged as a particularly valuable functional characteristic, highlighting the importance of accommodating everyday user needs beyond gait assistance alone. At the same

time, a number of limitations were identified, including discomfort related to skin contact, insufficient stability during both standing and walking, and restricted adaptability of the device parameters.

From a functional perspective, users expressed a clear need for enhanced device versatility, including a greater number of motion modes, wider range of velocity adjustment, and more flexible structural adaptation to individual anthropometric and clinical characteristics. Notably, one of the most prominent expectations concerned the simultaneous improvement of stability and reduction of reliance on external assistive devices, reflecting a broader demand for increased independence and safety during use.

The results of this study have important practical implications. First, they underline the critical role of human–robot interface design in shaping user experience and suggest that improvements in ergonomics and fitting procedures may significantly enhance device acceptance and usability. Second, they indicate that further development of adaptive control systems and stabilisation strategies is necessary to address user-reported balance deficits. Third, they highlight the relevance of non-technical factors, such as user education and access to performance feedback (e.g. data analysis), which may indirectly influence comfort, confidence, and long-term adherence to rehabilitation programs.

From a theoretical perspective, the present findings contribute to the growing body of knowledge, emphasising the importance of integrating subjective user experience into the evaluation and design of assistive technologies. They support a shift from purely technology-driven development toward a more holistic, user-centred approach, in which functionality, comfort, and usability are treated as interdependent dimensions of device performance.

Despite certain limitations, including a relatively small and unevenly distributed sample across device types, the study provides valuable insights into user priorities and expectations. Future research should focus on larger and more balanced cohorts, longitudinal assessments of user adaptation, and integration of objective biomechanical measures with subjective evaluations. Such approaches may further support the development of next-generation exoskeletons that better align with real-world user needs.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT (OpenAI) in order to improve the clarity, language quality, and academic style of the manuscript. After using this tool, the authors carefully reviewed and edited the content as needed and take full responsibility for the content of the publication.

Conflicts of interest

The authors declare no conflicts of interest with respect to the research, authorship, and/or publication of this article.

Limitations

Several limitations of this study should be acknowledged. First, the generalisability of the results is limited to adult participants up to 60 years of age, predominantly with neurological conditions, relatively short prior exposure to exoskeleton use (mostly <25 hours), and a dysfunction duration of up to 10 years. Therefore, the findings may not be directly applicable to other populations, such as older adults or individuals with different clinical characteristics.

Second, there was an uneven distribution of participants across ER types, with most participants using Ekso NR (n = 33), compared with Indego (n = 12) and ReWalk (n = 14). This imbalance reduces the statistical power of the between-device comparisons and should be taken into account when interpreting the observed differences. The unequal representation likely reflects the availability and distribution of specific exoskeleton systems in clinical practice.

Third, the study relied exclusively on self-reported data obtained through a structured questionnaire without incorporating objective biomechanical or clinical outcome measures. Although this approach is appropriate for capturing user perspectives, it may introduce response bias and limit the ability to directly relate subjective perceptions to functional performance.

Finally, the cross-sectional design did not allow for the assessment of changes in user perceptions over time, including adaptation to the device or long-term usability.

Despite these limitations, the study provides valuable user-centred insights that may inform both clinical decision-making and future exoskeleton design.

Funding source

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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