

Supplementary Material to:

Active knee-ankle-foot orthosis with personalized knee trajectory compared with locked orthosis and multi-joint exoskeleton

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Survey questionnaire, scoring, and development notes

Purpose and scope

This Persian, self-administered electronic survey was developed as a needs-assessment tool for individuals with spinal cord injury (SCI) who had experience with conventional lower-limb orthoses and lower-limb exoskeleton walking. The survey was designed to identify and rank the device problems reported by users and to inform the design rationale for an assistive walking device. The questionnaire included 25 problem-specific items: 11 items related to conventional orthoses/locked KAFO use and 14 items related to lower-limb exoskeleton use. The items were intended to capture distinct device-related barriers; therefore, the survey was analyzed and interpreted at the item level rather than as a total questionnaire score.

Scoring and descriptive reporting

Participants rated the extent to which each problem affected device use using an 11-point numeric rating scale from 0 to 10, where 0 indicated no effect/not problematic and 10 indicated extreme effect/extremely problematic. For reporting in the manuscript, raw scores were linearly converted to a 0–100 scale:

Converted score = raw 0–10 score $\times$ 10

The mean converted score was calculated for each item and used to rank reported problems. For the response-distribution bars in Fig. 4 of the manuscript, raw 0–10 responses were grouped into five ordered descriptive categories:

0–2 = Not at all problematic; 3–4 = Slightly problematic; 5–6 = Moderately problematic; 7–8 = Considerably problematic; 9–10 = Extremely problematic.

The original questionnaire was developed and administered in Persian. The English version provided below is a translation of the Persian data-collection instrument and is included for transparency and reader reference. It was not used for data collection and has not been independently validated.

The full Persian questionnaire, its English translation, and the short labels used in Fig. 4 of the manuscript are provided in Supplementary Table S1. Additional notes on item development, content review, clarity and relevance feedback, item-level interpretation, and the scope of the survey data are summarized in Supplementary Table S2.

Table S1. Full Persian questionnaire, English translation, and short labels used in Fig. 4

Device	Category	Short label used in Fig. 4	Original Persian item	English translation
Locked KAFO	Gait pattern and performance	Unnatural gait	الگوی راه رفتنم طبیعی نیست و حس می‌کنم جلب توجه می‌کند.	My gait is not natural, and I feel that it attracts attention.
Locked KAFO	Gait pattern and performance	Slow walking speed	سرعت راه رفتنم پایین است و باعث می‌شود از همراهان عقب بمانم.	My walking speed is low, and this causes me to fall behind people walking with me.
Locked KAFO	Gait pattern and performance	Non-adjustable knee lock	دوست دارم میزان قفل بودن مفصل زانوی ارتزم، به‌صورت انتخابی و امن قابل تنظیم باشد، نه اینکه همیشه در حالت قفل کامل راه بروم.	I would like the degree of knee locking in my orthosis to be selectively and safely adjustable, rather than always walking with the knee fully locked.
Locked KAFO	Gait pattern and performance	Lack of gait metrics feedback	ترجیح می‌دهم ویژگی‌های راه رفتن مثل تعداد گام، سرعت یا مسافت را بتوانم بعد از راه رفتنم ببینم تا معیاری از پیشرفت خود داشته باشم.	I would prefer to see gait-related information, such as step count, speed, or distance, after walking so that I have a measure of my progress.
Locked KAFO	Usability and practical use	Balance / falling	در حین راه رفتن، گاهی تعادل را از دست می‌دهم و نگران افتادن هستم.	While walking, I sometimes lose my balance and worry about falling.
Locked KAFO	Usability and practical use	Foot clearance effort	برای اینکه نوک پایم به زمین گیر نکند، مجبورم انرژی زیادی، به‌خصوص در بالاتنه، مصرف کنم.	To prevent my toe from catching on the ground, I have to use a lot of effort, especially in my upper body.
Locked KAFO	Usability and practical use	Secondary joint risk	نگرانم استفاده طولانی‌مدت از بریس باعث آسیب ثانویه به سایر مفاصل، از جمله شانه‌ها یا لگنم، شود.	I am concerned that long-term use of the brace may cause secondary injury to other joints, including my shoulders or hips.
Locked KAFO	Usability and practical use	Uneven surfaces	در راه رفتن روی سطح غیرصاف، مثلاً در حضور لبه در، شیب یا پله، مشکل زیادی دارم و این کار برایم سخت است.	I have considerable difficulty walking on uneven surfaces, such as door thresholds, slopes, or stairs.
Locked KAFO	Usability and practical use	Early fatigue	بعد از مدت کوتاهی راه رفتن با بریس خسته می‌شوم و نیاز دارم بنشینم.	After walking with the brace for a short time, I become tired and need to sit down.

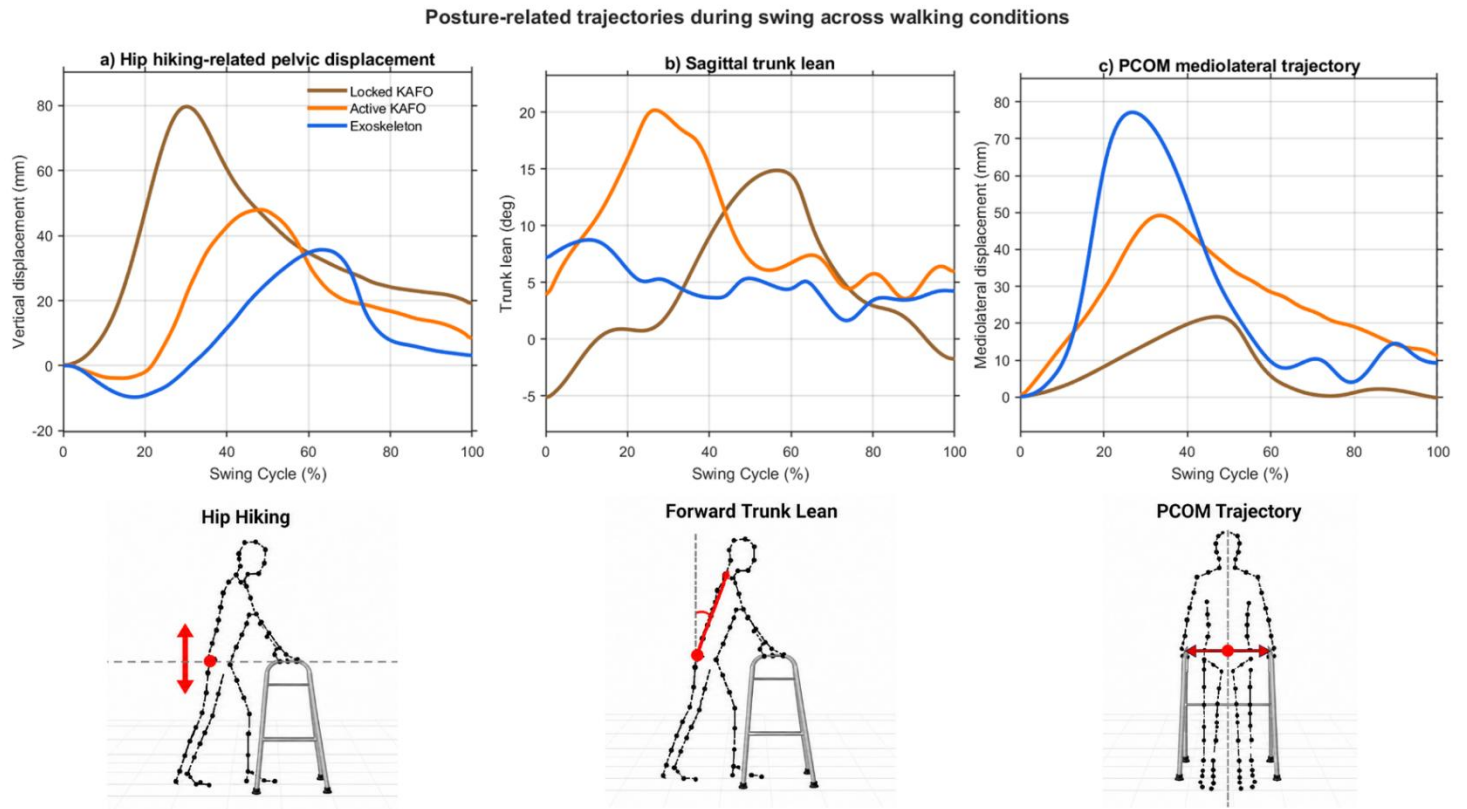
Device	Category	Short label used in Fig. 4	Original Persian item	English translation
Locked KAFO	Usability and practical use	Standing up help	بلند شدن از روی صندلی یا مبل برایم سخت است و گاهی نیاز به کمک دارم.	Standing up from a chair or sofa is difficult for me, and I sometimes need assistance.
Locked KAFO	Usability and practical use	Unstable sitting	هنگام نشستن، احساس پرت‌شدگی و ناپایداری دارم.	When sitting down, I feel unstable and as if I may lose my balance.
Lower limb exoskeleton	Cost, maintenance, and reliability	High overall cost	قیمت دستگاه خیلی بالاست و هزینه‌های نگهداری آن نیز سنگین است.	The device is very expensive, and its maintenance costs are also high.
Lower limb exoskeleton	Cost, maintenance, and reliability	Frequent repairs	دستگاه به‌طور مکرر به تعمیر و نگهداری نیاز دارد و گاهی ممکن است بدون هشدار قبلی دچار مشکل یا خرابی شود.	The device frequently requires repair and maintenance, and it may sometimes develop problems or fail without prior warning.
Lower limb exoskeleton	Cost, maintenance, and reliability	Charging burden	بعد از هر بار استفاده، باید ربات را به شارژر بزنم و این موضوع برایم آزاردهنده است.	After each use, I have to charge the robot, and this is bothersome for me.
Lower limb exoskeleton	Usability and practical use	Mobility aid, not rehab	دستگاه بیشتر شبیه وسیله جابه‌جایی است تا ابزار تمرینی/توان‌بخشی.	The device feels more like a mobility aid than a training or rehabilitation tool.
Lower limb exoskeleton	Usability and practical use	High training demand	یادگیری کار با دستگاه سخت است و به آموزش و تمرین زیادی نیاز دارد.	Learning to use the device is difficult and requires extensive training and practice.
Lower limb exoskeleton	Usability and practical use	Poor body fit	دستگاه پاها و تنه را به‌طور کامل و پایدار دربر نمی‌گیرد و برخی اتصالات آن شل یا ناپایدار احساس می‌شود.	The device does not fully and securely support the legs and trunk, and some of its attachments feel loose or unstable.
Lower limb exoskeleton	Usability and practical use	Backward fall and seating limits	جعبه پشتی دستگاه سنگین است، مرا به عقب می‌کشد و باعث می‌شود نتوانم راحت روی صندلی یا مبل بنشینم.	The back-mounted module of the device is heavy, pulls me backward, and makes it difficult to sit comfortably on a chair or sofa.
Lower limb exoskeleton	Usability and practical use	Donning/doffing difficulty	پوشیدن و درآوردن دستگاه سخت و زمان‌بر است و معمولاً به کمک فرد دیگر نیاز دارم.	Donning and doffing the device is difficult and time-consuming, and I usually need help from another person.

Device	Category	Short label used in Fig. 4	Original Persian item	English translation
Lower limb exoskeleton	Gait pattern and performance	Generic gait pattern	الگوی گام دستگاه برای همه یکسان است، در حالی که ترجیح می‌دادم برای هر فرد، متناسب با بدن و شرایط همان فرد، الگوی گام تعریف شود.	The device uses the same gait pattern for everyone, whereas I would prefer the gait pattern to be defined for each person according to their body and condition.
Lower limb exoskeleton	Gait pattern and performance	Manual gait trigger	دستگاه حرکت لگن یا آمادگی بدن من برای شروع گام را به‌خوبی در نظر نمی‌گیرد و حرکت بیشتر با دکمه شروع می‌شود؛ دوست دارم حرکت ربات به‌صورت خودکار یا بر اساس حرکت بدن/لگن شروع شود و مجبور نباشم همه چیز را با دکمه کنترل کنم.	The device does not adequately account for my hip movement or body readiness to initiate a step, and movement is mostly initiated by pressing a button; I would prefer the robot to start moving automatically or based on body/hip movement, rather than requiring everything to be controlled by a button.
Lower limb exoskeleton	Gait pattern and performance	Non-adjustable assistive torque	توان پاهای من در دو سمت متفاوت است و قدرت یا میزان کمک دستگاه باید متناسب با توان واقعی هر پا قابل تنظیم باشد.	The strength of my legs differs between sides, and the device power or assistance level should be adjustable according to the actual ability of each leg.
Lower limb exoskeleton	Physical and aesthetic design	Device weight/bulk	وزن و حجم زیاد دستگاه، حمل آن، استفاده در خانه و نشستن در خودرو را دشوار کرده است.	The high weight and bulk of the device make it difficult to carry, use at home, and sit in a car.
Lower limb exoskeleton	Physical and aesthetic design	Attention grabbing look	ظاهر دستگاه در بیرون از منزل خیلی جلب توجه می‌کند.	The appearance of the device attracts a lot of attention outside the home.
Lower limb exoskeleton	Physical and aesthetic design	Non-customizable appearance	ظاهر دستگاه خشک و صنعتی است و دوست دارم رنگ و طرح آن قابل انتخاب و شخصی‌سازی باشد، مثل بریس یا حتی قاب موبایل.	The device has a rigid, industrial look, and I would like its color and design to be selectable and customizable, similar to a brace or even a mobile phone case.

Table S2. Survey development and interpretation notes.

Aspect	Information
Item generation and content review	Items were informed by prior literature, semi-structured interviews with individuals with SCI, and clinician feedback. The draft item pool was reviewed by domain experts with experience in rehabilitation and assistive walking technologies to assess its relevance to the target device-use context, clinical and rehabilitation relevance, and coverage of the main user-perceived problem areas.
Clarity and relevance feedback	During item development, feedback from individuals with SCI was used to check whether the candidate items were understandable, relevant to their device-use experience, and free of major ambiguity. Minor wording revisions were made before distribution.
Item-level interpretation	The survey was interpreted at the item level. Individual items were intended to represent distinct device-related barriers rather than interchangeable indicators of a single latent construct. Therefore, no total questionnaire score was used.
Internal consistency	Internal consistency was not used as a primary basis for interpretation because the items were designed to capture distinct, non-redundant device-related barriers rather than interchangeable indicators of a single latent construct. Accordingly, a total internal-consistency estimate was not considered conceptually appropriate.
Test–retest and inter-rater reliability	Test–retest reliability was not assessed because the survey was used as a cross-sectional needs-assessment tool in this feasibility study. Inter-rater reliability was not applicable because the questionnaire was self-administered and did not involve external raters.
Construct, criterion, and diagnostic validity	Formal construct validity, criterion validity, and diagnostic validity were not assessed because the survey was not intended as a diagnostic instrument, standardized outcome measure, or psychometric scale.
Interpretation of survey data	The survey should be interpreted as an item-level needs-assessment and problem-prioritization tool used to inform the design rationale. The reported results should therefore be interpreted as descriptive user-priority information rather than as evidence of a fully validated questionnaire.

Additional posture-related biomechanical analysis



Supplementary Figure 1. Panels show ensemble mean trajectories over the normalized swing phase. (a) Hip-hiking-related pelvic displacement, estimated from the vertical displacement of the swing-side pelvic marker and expressed relative to the beginning of swing. (b) Sagittal trunk lean, computed from the T10–C7 marker line in the sagittal plane. (c) PCOM mediolateral trajectory, estimated from pelvis-center displacement in the mediolateral direction and expressed relative to the beginning of swing. Curves show the ensemble mean across analyzed steps over the normalized swing phase for the locked KAFO, active KAFO, and exoskeleton conditions. The locked-KAFO condition showed the largest peak hip-hiking-related displacement (~8 cm), followed by the active KAFO (~4.5 cm) and the exoskeleton (~3.5 cm). Peak forward trunk lean was greatest in the active-KAFO condition (~20°), while the locked-KAFO condition started at approximately 5° posterior lean and later reached a peak forward lean of ~15°; the exoskeleton condition showed a smaller peak forward lean (~8°). Peak PCOM mediolateral excursion was greatest in the exoskeleton condition (~8 cm), followed by the active KAFO (~5 cm) and the locked KAFO (~2 cm).

Descriptive interpretation of posture-related measures

These supplementary posture-related trajectories provide descriptive context for the walker-support and compensation-related findings in the main text. The larger early hip-hiking-related pelvic displacement in the locked-KAFO condition is consistent with greater vertical compensatory motion to achieve toe-off and swing clearance when knee flexion is unavailable. In the active-KAFO and exoskeleton conditions, this displacement was smaller, consistent with

reduced need for hip-hiking-related compensation. Sagittal trunk lean was greatest in the active-KAFO condition, which may reflect cautious visual monitoring of foot placement and limited familiarization with the active device. The exoskeleton condition showed a smaller and more stable forward trunk-lean profile. In contrast, mediolateral PCOM excursion was greatest in the exoskeleton condition, which may reflect a larger weight-shifting requirement during swing, whereas the locked-KAFO condition showed the smallest lateral excursion. These supplementary measures are descriptive and are included only to provide additional context for the primary gait and walker-support outcomes.