

Patient-Centered Perspectives on Restoring Bladder Function via Spinal Cord-Machine Interface in Spinal Cord Injury

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Abstract

Background

Neurogenic lower urinary tract dysfunction is a frequent consequence of spinal cord injury (SCI), impairing bladder storage and voiding and reducing quality of life. Current management strategies focus on symptom control rather than restoration of voiding. In this study, we assessed patient acceptability of Spinal Cord-Machine Interface designed to restore bladder sensation and allow volitional bladder emptying in patients with SCI.

Methods

Thirteen adults with SCI and neurogenic lower urinary tract dysfunction participated in focus groups. Following a standardized video describing the investigational device, discussions were audio-recorded, transcribed, and analyzed using reflexive thematic analysis.

Results

Six themes emerged: (1) the importance of altered lower urinary tract sensation; (2) dissatisfaction with current bladder management; (3) dissatisfaction with current bladder management strategies and Burden of Dependency; (4) significant urinary tract infection burden; (5) social disruption from catheter use; (6) perceived benefits for autonomy and dignity; and (7) concerns over procedural invasiveness, surgical risks, device longevity, and long-term management.

Conclusions

While the potential for restored volitional bladder control was valued, concerns over safety and durability influence acceptability. Integrating patient perspectives early in development may ensure alignment with user priorities.

Introduction

Neurogenic lower urinary tract dysfunction (NLUTD) is a common and often life-altering consequence of spinal cord injury (SCI), affecting up to 80% of individuals with SCI within the first year [1]. NLUTD impairs both bladder storage and voiding function, leading to urinary incontinence, retention, and recurrent infections, significantly impacting patients' health and quality of life (QoL).

Current management strategies, such as clean intermittent catheterization (CIC) and pharmacotherapy, focus primarily on mitigating symptoms rather than restoring physiological bladder control [2,3]. These approaches often compromise patient autonomy and fail to restore QoL to baseline levels [4]. On the other hand, emerging technologies aimed at restoring bladder sensation and voluntary voiding offer new possibilities for individuals with NLUTD. Within the broader neurorestoration paradigm - which encompasses repair through regenerative medicine, replacement via neuroprosthetics, and optimization

through neuromodulation-enhanced learning - implantable devices are gaining interest for the potential of reestablishing LUT-central nervous system communication [5]. However, patients' perspective on the acceptability of such interventions remains unexplored. Since the 1970s, advances in neuroprosthetic technologies and neuromodulation have evolved from early electrical stimulation methods to sophisticated spinal cord stimulation and nerve stimulation devices aimed at restoring autonomic bladder control [6–8].

A promising approach to managing neurogenic bladder involves the development of a bidirectional Spinal Cord-Machine Interface (SCMI) [9]. Unlike traditional brain-machine interfaces, this system targets the white matter axonal bundles of the spinal cord to intercept and deliver signals. For bladder control, the SCMI functions by utilizing specialized microelectrode arrays to sense Axonal Compound Action Potentials that signal bladder fullness, while simultaneously providing modulated electrical stimulation to the efferent pathways (Fig. 1). By leveraging the compact and stable somatotopy of the spinal cord, the SCMI could theoretically restore the closed-loop communication between the bladder and the central nervous system that is severed in SCI [9]. The device aims to provide patients with a predictable and automated mechanism for bladder voiding and storage. For persons living with SCI, such a device represents a shift from manual management to a more autonomous, physiologically-aligned, and dignified neuroprosthetic solution.

Despite the advances in neuroprosthetic and neuromodulation techniques, little is known about how individuals living with SCI perceive emerging bladder restoration strategies in terms of benefits, concerns, and willingness to adopt implantable systems. Understanding patient perspectives is essential for the development of clinically relevant and acceptable neurorestorative interventions. Therefore, the objective of this study was to explore the perceptions, expectations, and acceptability of a novel bidirectional SCMI for restoration of bladder function among individuals with SCI and NLUTD through qualitative focus group analysis.

Methods

Patient selection and recruitment

This qualitative study was conducted using focus group interviews to explore participant perspectives of SCMI. This study received Institutional Review Board approval, and all participants provided informed consent prior to participation. Patients were recruited from the neuro-urology clinic at Rancho Los Amigos Rehabilitation Center using convenience sampling. Interviews were conducted in a private setting. Eligible participants were adults aged 18–80 years with a history of SCI at least one year prior to enrollment, American Spinal Injury Association (ASIA) Impairment Scale (AIS) classification A or B, English speaking, able and willing to comply with study procedures; and able and willing to provide informed consent. Participants were excluded if they were younger than 18, had a sacral or infra-sacral injury level, or had a cognitive or psychiatric illness preventing participation in a focus group. Eligible patients were approached via telephone call and subsequently contacted by email for scheduling and

study information. While efforts were made to recruit more female participants, relatively few within the clinic population met inclusion criteria.

Focus group design

The focus group sessions were moderated by clinicians with no involvement in device development or prior clinical relationships with participants. To minimize desirability bias, moderators used neutral, open-ended questions. A semi-structured focus group script (Appendix A) was developed by the study team for the moderators a priori to ensure consistency across sessions while allowing flexibility for participants to elaborate on their experiences and perspectives. Focus group sessions were conducted in a private meeting room, ranging in size from two to four patients and grouping based on participant availability. Upon arrival, each patient was given the option to utilize a pseudonym and given an informed consent information sheet and a device handout for later reference during the discussion (Appendix B). Following a brief introduction and verbal consent, audio recording began. Sessions lasted approximately one hour or until all discussion prompts had been addressed.

Initial questions explored participant understanding of implantable and “invasive” devices, current bladder management strategies, satisfaction with urinary incontinence management, quality-of-life impact, and major concerns related to urinary symptoms. Participants were then shown a brief video presentation (Appendix C ,<https://go.screenpal.com/watch/cOfubXnOm9k>) explaining the functionality of the device to ensure a shared understanding of the technology, followed by a discussion of three potential intervention models: a sensor-only system, a partially closed-loop system involving a novel bodily sensation paired with patient-controlled stimulation, and a fully closed-loop automated system.

Further discussion focused on perceived benefits, concerns, acceptable tradeoffs, willingness to undergo invasive spinal procedures, and interest in the device in the context of partial symptom improvement versus complete symptom resolution. Additional discussion explicitly addressed procedural risks and benefits, including whether restoration of bladder sensation would justify intraspinal surgery. Although all sessions followed the same general structure and script, participants were encouraged to ask questions and engage in free discussion.

Data Analysis

Audio recordings and auto-generated transcripts were obtained using the Apple Voice Memos application (Apple Inc., Cupertino, CA, USA). All identifying information was removed prior to analysis and pseudonyms were used in recorded transcripts. Each transcript subsequently underwent manual review by at least two investigators to verify transcription accuracy. Transcripts were then analyzed using reflexive thematic analysis as described by Braun and Clarke [10]. To this end, two investigators independently reviewed the transcripts and manually coded the data to identify meaningful segments of the text reflecting participant perspectives in the context of study objectives. Discrepancies were first resolved through discussion among the coders; a third senior investigator was consulted when

consensus could not be reached. Coded data were then collectively reviewed in a similar fashion to identify the emerging patterns, which were grouped into candidate themes alongside supporting transcript extracts. Themes were iteratively refined to ensure they accurately represented the breadth of participant views, and final themes were defined and named collaboratively by the study team. Thematic saturation was reached as recurring keywords and thematic patterns demonstrated repetition across later focus group sessions.

Results

Thirteen participants of varying injury level, severity, and ethnic backgrounds were enrolled across six focus group sessions. Participant demographics and clinical characteristics are outlined in Table 1. Analysis of the focus group transcripts revealed six primary themes regarding current lower urinary tract management after SCI and the acceptability of a SCMI. Thematic convergence began during the second session, and data saturation was achieved by the third session, with no novel themes emerging thereafter.

Table 1
Patient Demographics

Value	Number	Percentage
Sex		
Male	12	92.31%
Female	1	7.69%
Age		
18–30	0	0.00%
31–50	7	53.85%
50–65	6	46.15%
>65	0	0.00%
Race		
Black/ African American	3	23.08%
White	0	0.00%
Other/ Unknown	10	76.92%
Ethnicity		
Mexican	6	46.15%
Not Hispanic/ Latino	6	46.15%
Central American	1	7.69%
Injury characteristics		
Cervical	3	23.08%
Thoracic	9	69.23%
Lumbar	1	7.69%
Complete Injury	8	61.54%
Incomplete Injury	5	38.46%
Years since injury		
0–20	3	30.77%
20–40	9	69.23%
Bladder Management Method		
Clean Intermittent Catheterization	8	61.54%

Value	Number	Percentage
Suprapubic Tube	4	30.77%
Volitional	1	7.69%

Theme 1: Change in Lower Urinary Tract Sensation

Participants described a fundamental shift from normal urinary urgency experienced prior to their injury to a reliance on atypical, neurogenic surrogate markers to gauge bladder fullness. These new indicators often manifested as non-specific abdominal pressure, increased lower-limb spasticity, or symptoms of autonomic dysreflexia, including pounding headaches and diaphoresis.

Theme 2: Dissatisfaction with current bladder management strategies and Burden of Dependency

One participant described the experience of catheterizing as, “It’s very barbaric is what I call it ... afterwards it’s like I’m doing it again and it’s a bad feeling down there,” underscoring the emotional and physical toll of current methods. Similarly, those relying on indwelling catheters expressed frustration with incontinence during daily activities: “I leak during sports because of all the movement with the Foley.” The impact of bladder management on daily autonomy varied significantly by injury level. While participants with paraplegia largely maintained independence in self-catheterization, those with tetraplegia emphasized a profound reliance on assistive devices and family members. This dependency underscored a substantial caregiver burden, as daily routines had to be strictly synchronized with rigid voiding schedules. Consequently, patients with tetraplegia voiced the most profound frustration and dissatisfaction with current bladder management strategies.

Theme 3: The burden of recurrent urinary tract infections (UTIs)

As one participant expressed: “UTIs are horrible. I have to go every five minutes... it’s burning. So, right away when that happens I go to the emergency [room].” “Every time I get a UTI, it feels like I’m back to square one—not just physically, but mentally. I start planning my life around the next infection instead of living it.”

Theme 4: Social disruption related to catheter use

“Being able to control your bladder for an active person is priceless... having an accident can mess up your whole day.” Participants expressed the desire to reduce caregiver dependency, improve spontaneity, and re-enter the community without bladder-related limitations. “I don’t like the big bulky bag... it’s already embarrassing.”

Theme 5: Perceived benefits of the investigational device

Six patients said they would want to get the device themselves, four rejected the idea, two abstained from commenting and one was unsure. Reasons for rejecting the device included disliking of the remote-control format and the burden of adapting to a new routine. “Nobody wants a remote control for [their] bladder. Like, come on, there's so many things we can do, we [would] rather sacrifice it for something else”. On the other hand, a sense of normalcy and the elimination of catheter use were the main drivers of acceptability. “All of that is beneficial, you know, not having to be catheterized, not having to worry about medication or UTIs and stuff like that. Of course, that's beneficial.” “Just that sense of normalcy again with getting that sensation of being able to urinate on your own, I think that is such a plus.”

Theme 6: Acceptability of invasive procedures and long-term device reliability. During the focus group sessions, participants raised questions about the procedure and its potential implications. They were asked to reflect on their personal understanding of the term “invasive” and to consider their willingness to undergo such a procedure. A common theme was concern about surgical complications, particularly those involving the spine and nervous system. One frequently expressed question was, “Does this cause further injury to the spinal cord?”—a concern especially prominent among the individual who had regained the ability to walk. Additionally, participants expressed apprehension about the track record of similar procedures, with comments such as, “I would like to know how long this procedure has been done, and how well it bettered their lives.” Building on these concerns about surgical risk, participants also voiced significant apprehension regarding the device itself, particularly its reliability and long-term functionality. Questions arose about the need for ongoing maintenance, compatibility with MRI scans, expected lifespan, and whether additional surgeries might be necessary over time. For example, one participant asked, “Do you guys have to go in every so often to remove it? To check it?”.

Discussion

This study examined how individuals with SCI and NLUTD viewed a proposed SCMI. Participants expressed a clear desire to regain voluntary control over urination, but their readiness to accept an invasive procedure varied considerably.

Theme 1: Change in Lower Urinary Tract Sensation

New indicators of bladder fullness can include discomfort and symptoms of autonomic dysreflexia, potentially resulting in emergency care visits and reduced QoL [11]. Patients have expressed a desire for a reliable sensation signaling approaching bladder fullness, allowing them to manage bladder emptying before symptoms occur. Restoring or providing new somatic sensation for bladder fullness could reduce defensive catheterization or voiding and give patients sufficient time to access restroom facilities safely and comfortably. Along with improved QoL, reduced autonomic dysreflexia episodes could decrease emergent care needs and lighten healthcare costs [12].

Theme 2: Dissatisfaction with current bladder management strategies

Catheterization to maintain bladder emptying (whether indwelling or intermittent) remains the gold standard for many individuals with SCI [13], offering a means of regular drainage while preserving upper urinary tract function. Despite its benefits, catheterization can be burdensome and psychologically taxing. Patients frequently report discomfort, UTIs, and urethral trauma as ongoing concerns.

These challenges highlight the limitations of current symptom-management approaches and underscore the urgent need for innovative solutions. Technologies aimed at restoring natural bladder function, such as spinal cord stimulation combined with sensor-based feedback, offer a promising shift from symptom control to functional restoration.

Theme 3: The burden of recurrent UTIs

UTIs represent a significant and persistent complication for individuals living with SCI, substantially interfering with daily activities and social engagement. Over 50% of SCI patients experience at least one UTI requiring antibiotics annually, with 25.5% reporting three or more infections in the same period [14]. UTIs are particularly pronounced among individuals who rely on catheter-dependent bladder management, as they experience higher rates of infection compared to those with volitional voiding. The frequency of UTIs is correlated with increased risk of hospitalization, underscoring the serious health implications of recurrent infections [15].

Beyond their clinical burden, UTIs substantially impact QoL in SCI patients. Studies indicate that the frequency of patient-reported UTIs (PRUTIs) is inversely correlated with QoL. For example, individuals with SCI experiencing more than six UTIs per year are nine times more likely to avoid social outings due to UTIs compared to those without UTIs [15]. This restriction in social participation can contribute to increased feelings of isolation, frustration, and psychological distress.

UTIs also exacerbate physical symptoms commonly experienced by individuals with SCI. Patients frequently report increased muscle spasms and describe a persistent perception that UTIs “would not go away,” which intensifies both emotional and physical distress [15]. These symptoms are often unpredictable and disruptive, complicating daily management and requiring constant adaptation to their health condition. Over time, this can erode an individual’s sense of control and stability [16].

Crucially, the high incidence of UTIs in the SCI population is inextricably linked to the mechanical realities of current bladder management. Clinical data demonstrates a clear gradient in infection risk based on the presence of a foreign body in the urinary tract: UTI rates are consistently highest among patients utilizing indwelling catheters and CIC, whereas those relying on external condom catheters or volitional voiding experience significantly fewer infections [14]. Because the proposed SCMI facilitates volitional voiding without requiring any internal components to be in direct contact with urine or the urethral

mucosa, it fundamentally bypasses the primary vector for infection, offering the potential for a drastic reduction in UTI-related morbidity [11, 17].

Theme 4: Social disruption related to catheter use

The burden of CIC extends far beyond the physical act of emptying the bladder; it imposes a rigid logistical and temporal framework on an individual's daily life. Adherence to a strict catheterization schedule fundamentally strips away spontaneity. Patients frequently describe the cognitive load of living on a "bladder leash," where every social outing, travel itinerary, and daily commute must be meticulously calculated around bathroom accessibility and timing.

Furthermore, navigating the community introduces significant environmental and architectural barriers. While public spaces may technically offer Americans with Disabilities Act-accessible restrooms, these facilities frequently lack the necessary hygiene standards, privacy, or physical space required for a wheelchair user to safely lay out and utilize sterile catheterization supplies. In occupational settings, the requirement for prolonged and frequent bathroom breaks can severely disrupt workflow [18]. This logistical friction often leads to anxiety regarding job performance and perceived reliability, ultimately compromising work-life balance and career progression. As noted in recent qualitative evaluations, these compounding hurdles frequently compel individuals to preemptively withdraw from social and professional activities altogether [16].

The cumulative psychological toll of this continuous logistical planning, coupled with the persistent fear of public incontinence between catheterizations, frequently fosters profound feelings of isolation, stigma, and frustration [16]. In this context, the appeal of an implantable SCMI extends far beyond physiological health. By shifting bladder management from a supply-dependent, externally-scheduled physical task to an internalized, volitionally-controlled process, the SCMI has the potential to dismantle the primary logistical barriers that tether patients to their homes, thereby restoring a critical dimension of social and occupational autonomy [9, 19].

Theme 5: Perceived benefits of the investigational device

SCMI builds on the intricate neural pathways linking the spinal cord and bladder, pathways that are frequently disrupted in SCI [20]. Reflex micturition depends on coordinated input from pelvic nerve afferents, pudendal nerve fibers, and parasympathetic preganglionic neurons projecting to the vesical ganglia [20]. When this circuitry is damaged, as in NLUTD, bladder function becomes reliant on compensatory strategies such as catheterization—methods that, while clinically effective, often fail to restore the sensation or control that patients desire. Advances in neurotechnology now allow for more targeted interventions [21]. Stretchable electrode arrays can selectively trigger bladder contractions without co-activating surrounding pelvic organs, and microchannel neuroprostheses can detect fullness and deliver precise, low-noise stimulation to prevent unplanned voiding [22].

Theme 6: Acceptability of invasive procedures and long-term device reliability

Study participants weighed the potential benefits of urinary neurorestoration against concerns regarding procedural invasiveness, device longevity, and the long-term demands of living with an implanted system. These reflections highlighted broader anxieties not only about the initial procedure but also about the potential burden of long-term device management. Acceptability of this procedure also depended on how much the patient's daily routine would be altered. Many of the patients in this study with long-standing SCIs were wary of the burden of adjusting to a new routine, citing the frustrating unpredictability of their symptoms in the first few years of their injury. It would be unideal to undergo this procedure and essentially repeat their first two years of recovery, figuring out their body and new routine. On the other hand, the patients stated that their peers with more recent injuries may have a different threshold of tolerance for invasive interventions as their symptoms were still in the stabilization period. Individuals living with SCI often prioritize the stabilization of secondary complications and the enhancement of daily functional independence over the pursuit of 'curative' surgical interventions that carry high neurological risks [23].

Conclusion

This study highlights the complex and individualized perspectives of individuals with SCI and NLUTD toward a novel implantable bladder control device. While the promise of restored volitional voiding was viewed as a major advance, participants expressed reservations related to surgical risk, device longevity, and disruption to established coping routines. These findings emphasize the importance of incorporating patient perspectives early in device development and trial design. A user-centered approach may enhance clinical adoption and improve long-term outcomes.

Declarations

Data Availability Statement

The data that support the findings of this study are not publicly available due to the sensitive nature of qualitative data collected from individuals with spinal cord injury. De-identified data may be made available upon reasonable request to the corresponding author.

Funding Statement

Participant compensation was funded by Ecate LLC. The funder was represented among the study authors and was involved in manuscript preparation and the decision to submit for publication, but had no role in study design, data collection, or analysis.

Conflict of Interest Disclosure

Charles Liu and Alessandro Maggi are co-founders of Ecate LLC, a medical technology company developing neural interface technologies for spinal cord injury, which provided funding for participant compensation in this study. All other authors declare no competing interests.

Ethics Approval Statement

This study was approved by the Rancho Research Institute Institutional Review Board (Protocol #551). All procedures were conducted in accordance with the ethical standards of the Declaration of Helsinki.

Author	Credit roles	Contribution Description
Maria P. Molina	Conceptualization, data curation, formal analysis, investigation, writing original draft, review and editing	As first author, MPM led the design and execution of the focus group sessions, performed qualitative data analysis, and wrote the primary manuscript. She was responsible for coordinating all data collection activities.
Nhi Ha	Data curation, formal analysis, investigation, review and editing	NH served as a focus group moderator, facilitated participant discussions, and contributed to the qualitative coding and thematic analysis of the data. She critically reviewed and revised the manuscript for important intellectual content.
Aidin Abedi	Data curation, formal analysis, investigation, review and editing	AA co-moderated focus group sessions and participated in the systematic analysis and interpretation of qualitative data. He critically reviewed and revised the manuscript for important intellectual content.
Michael Reckers	Conceptualization, supervision, review and editing	MR contributed to the conceptual framework of the study and provided supervisory oversight throughout the research process. He reviewed the manuscript for important intellectual content.
Alessandro Maggi	Conceptualization, supervision, review and editing	AM contributed to the conceptualization of the study and provided expert guidance on neural interface technology relevant to the research questions. He reviewed and edited the manuscript critically for important intellectual content.
Charles Liu	Conceptualization, supervision, review and editing	CL contributed to study conceptualization and provided senior supervisory oversight of the project. He reviewed and edited the manuscript critically for important intellectual content.
Evgeniy I. Kreydin (Corresponding Author)	Conceptualization, funding acquisition, methodology, project administration, supervision, review and editing	EK conceived and designed the study, oversaw project administration, and provided overall supervisory direction. He contributed to manuscript preparation and made the decision to submit for publication.

References

1. Patel DP, Lenherr SM, Stoffel JT, et al. Study protocol: patient reported outcomes for bladder management strategies in spinal cord injury. *BMC Urol*. 2017;17(1):95. doi:10.1186/s12894-017-0286-3
2. Ginsberg D. The epidemiology and pathophysiology of neurogenic bladder. *Am J Manag Care*. 2013;19(10 Suppl):s191-196.
3. The AUA/SUFU Guideline on Adult Neurogenic Lower Urinary Tract Dysfunction: Treatment and Follow-up | Journal of Urology. *J Urol*. Accessed June 1, 2026.
<https://www.auajournals.org/doi/10.1097/JU.0000000000002239>
4. Gharbi M, Gazdovich S, Bazinet A, Cornu JN. Quality of life in neurogenic patients based on different bladder management methods: A review. *Prog En Urol*. 2022;32(11):784–808.
doi:10.1016/j.purol.2022.07.004
5. Liu C, Abedi A, L.W. Lam J, Yu Tung JL, Young CC. Neurorestoration – A New Synthesis: Repair, Replace, and Optimize. In: Hartley B, Stieg PE, Ramakrishna R, Apuzzo MLJ, eds. *Neurosurgery: Beyond the Cutting Edge*. Cambridge University Press; 2025:28–42
6. Collinger JL, Foldes S, Bruns TM, Wodlinger B, Gaunt R, Weber DJ. Neuroprosthetic technology for individuals with spinal cord injury. *J Spinal Cord Med*. 2013;36(4):258–272.
doi:10.1179/2045772313Y.00000000128
7. Steadman CJ, Grill WM. Spinal cord stimulation for the restoration of bladder function after spinal cord injury. *Healthc Technol Lett*. 2020;7(3):87–92. doi:10.1049/htl.2020.0026
8. Canagasingham A, Kovacic J, Popa I, Chung A. Sacral nerve neuromodulation: the past, present and future. *Trends Urol Mens Health*. 2023;14(5):30–33. doi:10.1002/tre.934
9. Lo YT, Maggi A, Wu K, et al. Exploring the Feasibility of Bidirectional Spinal Cord Machine Interface Through Sensing and Stimulation of Axonal Bundles. *IEEE Trans Neural Syst Rehabil Eng Publ IEEE Eng Med Biol Soc*. 2025;33:2004–2012. doi:10.1109/TNSRE.2025.3570324
10. Braun V, Clarke V. Reflecting on reflexive thematic analysis. *Qual Res Sport Exerc Health*. 2019;11(4):589–597. doi:10.1080/2159676X.2019.1628806
11. Weld KJ, Dmochowski RR. Effect of bladder management on urological complications in spinal cord injured patients. *J Urol*. 2000;163(3):768–772.
12. Squair JW, White BAB, Bravo GI, Martin Ginis KA, Krassioukov AV. The Economic Burden of Autonomic Dysreflexia during Hospitalization for Individuals with Spinal Cord Injury. *J Neurotrauma*. 2016;33(15):1422–1427. doi:10.1089/neu.2015.4370
13. Velaer KN, Welk B, Ginsberg D, Myers J, Shem K, Elliott C. Time Burden of Bladder Management in Individuals With Spinal Cord Injury. *Top Spinal Cord Inj Rehabil*. 2021;27(3):83–91.
doi:10.46292/sci20-00007
14. Elliott C, Kreydin E, Crew J, Shem K. The Current Epidemiology of Urinary Incontinence and Urinary Tract Infections After Spinal Cord Injury-A Model Systems Spinal Cord Injury Examination (2016–2021). *J Clin Med*. 2025;14(5):1434. doi:10.3390/jcm14051434

15. Theisen KM, Mann R, Roth JD, et al. Frequency of patient-reported UTIs is associated with poor quality of life after spinal cord injury: a prospective observational study. *Spinal Cord*. 2020;58(12):1274–1281. doi:10.1038/s41393-020-0481-z
16. Hearn JH, Selvarajah S, Kennedy P, Taylor J. Stigma and self-management: an Interpretative Phenomenological Analysis of the impact of chronic recurrent urinary tract infections after spinal cord injury. *Spinal Cord Ser Cases*. 2018;4(1):12. doi:10.1038/s41394-018-0042-2
17. Cameron AP, Wallner LP, Forchheimer MB, et al. Medical and psychosocial complications associated with method of bladder management after traumatic spinal cord injury. *Arch Phys Med Rehabil*. 2011;92(3):449–456. doi:10.1016/j.apmr.2010.06.028
18. Braaf S, Lennox A, Nunn A, Gabbe B. Social activity and relationship changes experienced by people with bowel and bladder dysfunction following spinal cord injury. *Spinal Cord*. 2017;55(7):679–686. doi:10.1038/sc.2017.19
19. Zhong S, Watkins E, Maggi A, et al. Intraspinal Microstimulation of Dorsolateral Funiculus for Coordinated Bladder Control. *IEEE Trans Neural Syst Rehabil Eng*. 2026;34:1650–1657. doi:10.1109/TNSRE.2026.3675572
20. de Groat WC, Griffiths D, Yoshimura N. Neural control of the lower urinary tract. *Compr Physiol*. 2015;5(1):327–396. doi:10.1002/cphy.c130056
21. D. Castro-Diaz, G. Del Popolo, J. Groen, et al. *EAU Guidelines on Neuro-Urology*. 2024. Accessed February 4, 2026. <https://uroweb.org/eau-guidelines>
22. Mickle AD, Won SM, Noh KN, et al. A Wireless Closed Loop System for Optogenetic Peripheral Neuromodulation. *Nature*. 2019;565(7739):361–365. doi:10.1038/s41586-018-0823-6
23. Anderson KD. Targeting Recovery: Priorities of the Spinal Cord-Injured Population. *J Neurotrauma*. 2004;21(10):1371–1383. doi:10.1089/neu.2004.21.1371

Figures

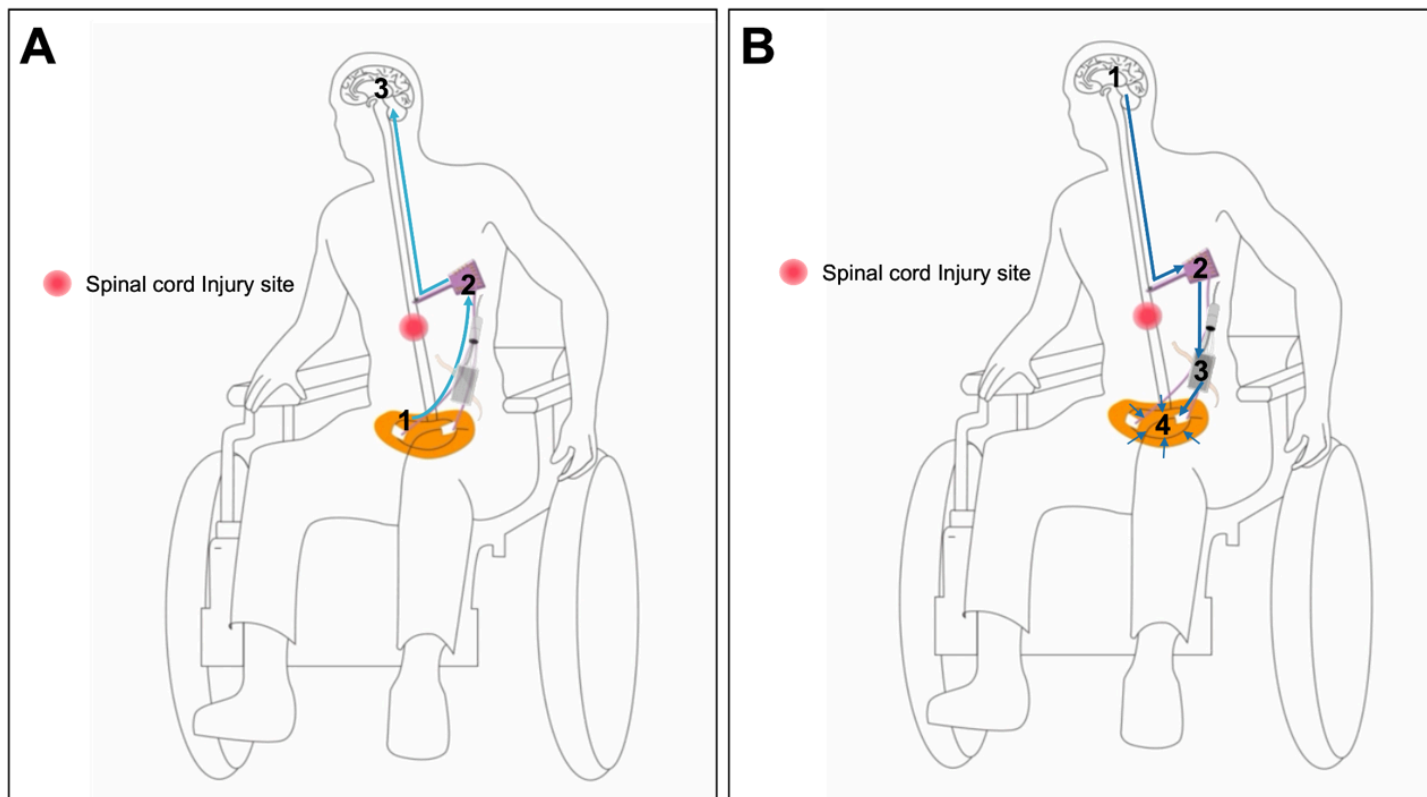


Figure 1

Bidirectional Spinal Cord- Machine Interface (SCMI).

A: When the bladder is full, sensors are activated and send an electrical signal to the intraspinal stimulator (A2), bypassing the spinal cord injury. The intraspinal stimulator stimulates the micturition afferent tracts, creating an artificial sensation of fullness. **B:** When the patient desires to micturate, their intention is sent from the central nervous system through the efferent micturation tracts above the level of injury. The signal is recorded by an intraspinal receiver (B2) electrode and relayed to a spinal cord stimulator (B3). The sacral stimulator causes bladder contraction. Although the urethral sphincter is stimulated at the same time, its striated muscle fatigues first, causing relaxation and expulsion of urine.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [COREQChecklist.pdf](#)