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A multifaceted hybrid ES-robotic device for gait training in individuals with neurological disorders

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The integration of robotics and Electrical Stimulation (ES) in neurorehabilitation leverages robotics' precise task execution alongside ES-induced motor learning, muscle conditioning, and cardiovascular benefits. We propose a hybrid system for overground gait training, combining neuromuscular ES and a motorized exoskeleton. Different combination modalities are proposed: ES-motor cooperation for the swinging knee, synchronized but independent ES and motor assistance for hip movements and for the knee during stance, and ES-only for the non-actuated ankle. Twelve non-disabled subjects and eleven participants with neurological disorders tested the system under two conditions: exoskeleton-only and hybrid. The hybrid condition reduced knee motor torque by 48% during swing without compromising tracking accuracy, showing that ES can effectively drive limb motion. Neurological participants rated the hybrid system as more usable than the exoskeleton alone (median 5-point improvement of System Usability Scale). These findings support the feasibility of hybrid ES-motorized exoskeletons in clinical settings. Future studies should investigate their potential to enhance therapeutic outcomes.

Spinal Cord Injury (SCI) and stroke are leading causes of long-term disability[1], altering muscle function, provoking secondary health issues[2], and negatively impacting individuals' independence[3]. Several technologies have been developed to assist neurologically impaired subjects and support their motor recovery. Among these, rehabilitation robots play a key role in promoting motor relearning[4,5] by enabling multi-joint, repetitive, and task-oriented training[6,7]. Complementary to robotic approaches, Electrical Stimulation (ES) offers additional benefits by inducing peripheral physiological effects[8], increasing metabolic demand[9,10], and enhancing neural plasticity at the central level[11–14]. ES can provide afferent sensory feedback when delivered below the motor threshold (Sensory Afferent Electrical Stimulation - SAES) or induce functional movements when delivered above the motor threshold (Functional Electrical Stimulation - FES). Nevertheless, this is hindered by the non-linear relation between injected currents and induced muscle contractions[15,16], and the early onset of muscle fatigue[17,18] due to the spatially fixed and synchronous recruitment of motor units[15,19,20].

A promising opportunity lies in combining the two approaches into a single hybrid device[16,21–25]. On one hand, robotic assistance facilitates controlled and accurate movement execution, enabling task-specific training with real-time feedback, even in individuals with

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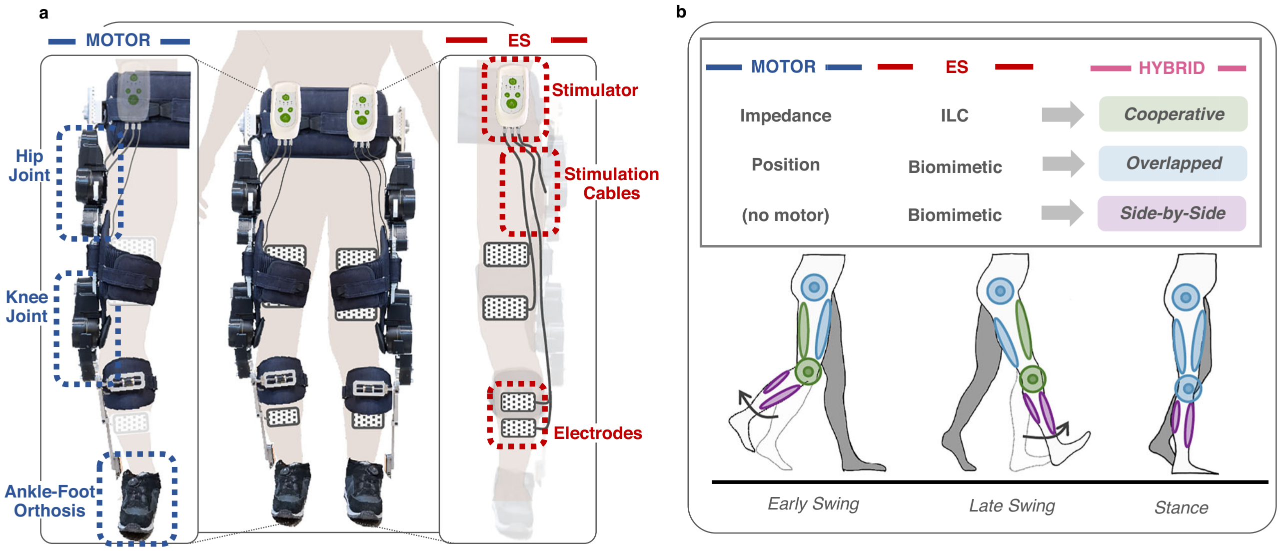

Fig. 1 | Hybrid lower-limb exoskeleton for gait training. a Hardware components of the hybrid device: Twin exoskeleton and two RehaMove3 stimulators with their cables. **b** Details of the motor control (either position or impedance) and ES control (either Biomimetic or ILC) employed by the three hybrid modalities (*Cooperative*, *Overlapped* and *Side-by-Side*). The scheme below illustrates which joint/muscle implement the different modalities throughout the gait cycle. ES Electrical Stimulation, ILC Iterative Learning Control.

minimal residual motor function. Additionally, it can compensate for the variability of FES-induced movements and decrease the required stimulation intensity, potentially delaying the onset of muscle fatigue. On the other hand, ES provides task-associated muscular contraction feedback, relevant to brain plasticity[11–14] and the healthiness of muscular and cardiovascular systems[26]. When possible, the inclusion of users' voluntary contributions would be highly valuable, as it has shown to further enhance neuroplasticity[11–14].

Different ES-motor hybrid modalities have been proposed in the last 15 years: i) the *Side-by-Side* modality, where motors and electrical stimulation, either below or above the functional motor level (i.e., SAES or FES), act on different joints but each contributes to an overall multi-joint complex motor task[27,28]; ii) the *Overlapped* modality, in which motor assistance and electrical stimulation are both active on the same joint, working in a coordinated and synchronous manner to achieve the same function, but controlled by two independent control loops; ES can operate either below or above motor threshold; when ES operates below the motor threshold, it enhances the sensorimotor feedback associated with the task without directly driving the motor action, which is performed solely by the motor[29]; and iii) the *Cooperative* modality, which involves both the motors and ES acting on the same joint, integrated within a single control loop. They share a common control signal, enabling coordinated collaboration that optimizes movement performance by leveraging the complementary strengths of each actuator[21,30–32]. In this scenario, ES is typically applied above motor threshold, actively contributing to the movement through a combination of FES-induced muscle contractions and compliant motor control. This approach reduces motor torque demands thanks to FES assistance but poses significant challenges due to the actuation redundancy and the nonlinear, time-varying dynamics of FES-induced movements[33,34].

These various approaches used in hybrid solutions are not primarily intended to compete with each other but rather to serve as complementary alternatives. They can be combined to optimize treatment strategies, taking into account the limitations of each technology, while ensuring the safety of task execution, particularly in applications related to walking.

In this work, we propose a hybrid device integrating the four-degrees-of-freedom (DOFs) Twin exoskeleton (developed by the Italian Institute of Technology - IIT) with an 8-channel neuroprosthesis (Fig. 1a), intended to support overground locomotion in individuals with neurological disorders. Our goal was to develop a device that meets the following key requirements: i) Clinical suitability, with minimal setup time and a fast calibration process, ideally required only during the first training session; ii) Safety, ensuring secure overground gait training even for non-ambulatory subjects with minimal effort required from the therapist; iii) Maximization of ES-induced effects, incorporating FES through a *Cooperative modality* when appropriate, in order to enable prolonged training sessions and promote user participation in task execution. We believe that such a device holds the potential to improve therapeutic outcomes of gait training for neurological patients.

To achieve this goal, the integration of electrical stimulation and robotics leverages all three modalities described above into a unique, multifaced hybrid solution, depending on the achievable muscle performance and the technical constraints of the exoskeleton (Fig. 1b):

- The hip employs the *Overlapped* modality, where the motors operate under rigid position control, and ES is applied below the motor threshold. The stimulation timing follows biomimetic patterns, mimicking natural muscle activity during walking. This approach is necessary because mono-articular hip flexors are deep muscles, making them difficult to induce functional movements using surface electrodes.
- The knee employs the *Cooperative* modality during the swing phase, where motor assistance and FES applied to the knee-actuating muscles (Quadriceps and Hamstrings) work together to generate the movement. This cooperation is guided by trajectory tracking errors, with slow, iterative updates of the stimulation current (Iterative Learning Control - ILC) combined with rapid motor corrections using impedance control. During the stance phase, instead, the *Overlapped* modality is used to guarantee knee stability and user safety.
- The ankle joint was not actuated by the Twin exoskeleton, therefore a *Side-by-Side* modality was implemented. In this approach, the stimulation timing follows the biomimetic pattern, with amplitude adjusted either below or above the movement threshold based on the user's needs and safety requirements.

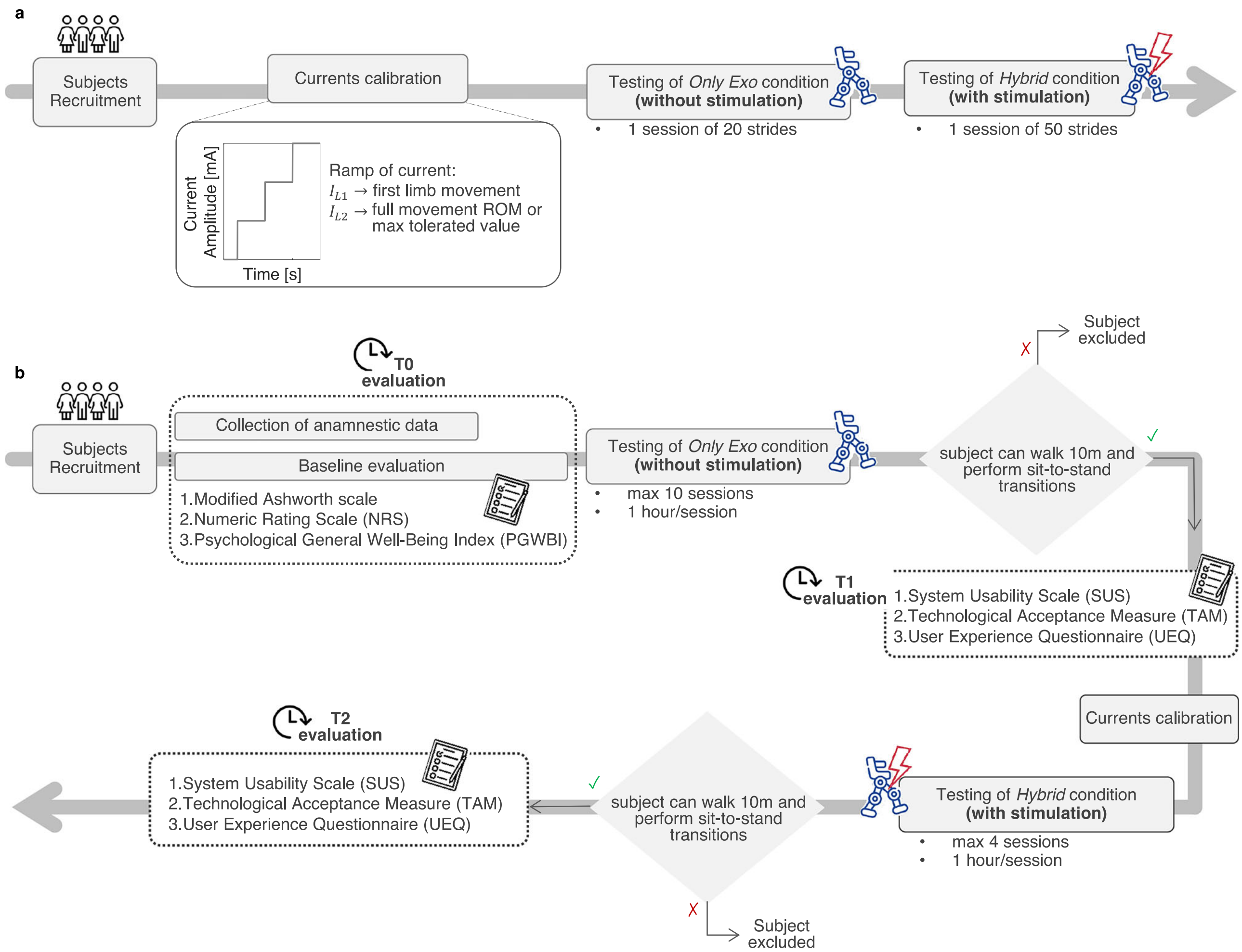

Fig. 2 | Experimental protocol. a Protocol of Study 1, involving non-disabled participants. **b** Protocol of Study 2, involving participants with neurological disorders. The exoskeleton icon was designed by Freepik from Flaticon. Other icons were taken from Microsoft PowerPoint.

The main research questions addressed in this work were: i) is the solution feasible and compatible with clinical constraints?; ii) is the *Cooperative* control modality capable of effectively exploiting FES to induce limb movement, thereby reducing motor power while ensuring successful task execution?; iii) how do end-users perceive the usability of this solution? To answer these questions, an extensive experimental procedure was conducted, involving twelve non-disabled participants(Study 1) and eleven subjects with neurological disorders (Study 2). The results demonstrated the clinical feasibility of the proposed approach and showed that, when integrated cooperatively, ES can reduce motor power demands in both able-bodied individuals and neurological patients, including those with complete SCI. Furthermore, target users found the hybrid system to be more usable compared to the exoskeleton alone.

Results

Study 1

Twelve non-disabled participants (2 M and 10 F, mean age 25.3 ± 4.9 years, average height 166 cm, and weight 57 kg) were recruited for this study. Their demographic characteristics are reported in Supplementary Table 2. The *Hybrid* condition was verified against the *Only Exo* condition, where full motor support was exploited and stimulation was turned off (Fig. 2a). The calibration phase lasted on average 15 min, including the adjustment of the exoskeleton to match the subject's anthropometry and the setting of the current amplitude for all stimulated muscles. The values of current amplitude set during calibration are reported in Supplementary Table 3.

The temporal profiles of angular position, motor current, motor torque, and stimulation current are reported in Supplementary Fig. 2 for one exemplary subject (ID S1) in the *Hybrid* condition, both at an initial strike (stride 7) and a late strike (stride 45). An update of the stimulation current profile can be noticed by comparing the initial and late stride, with an improvement in the tracking performance at the knee joint, as well as a reduction in motor torque.

Figure 3 reports the metrics recorded across all subjects. The position RMSE for those joints under the *Overlapped* modality (light blue panels) was comparable between the *Only Exo* and the *Hybrid* condition. Since both cases share the same motor control, this result proves that the trajectory tracking is consistent and is not affected by stimulation at sensory level. Moreover, the negligible RMSE values indicate accurate trajectory tracking, attributable to the rigid position control of the motor implemented in this modality. Similarly, the motor current displayed a comparable trend for both conditions. However, one significant difference ($p = 0.046$, Wilcoxon signed-rank test) was detected in the RMSE of the hip joint during the swing phase, with values of 0.703° in the *Only Exo* condition and 0.704° in the *Hybrid* one. Despite the statistical significance, the nearly identical absolute values render this difference negligible.

In the *Cooperative* modality (green panels), no significant differences in angular trajectories were observed between conditions with

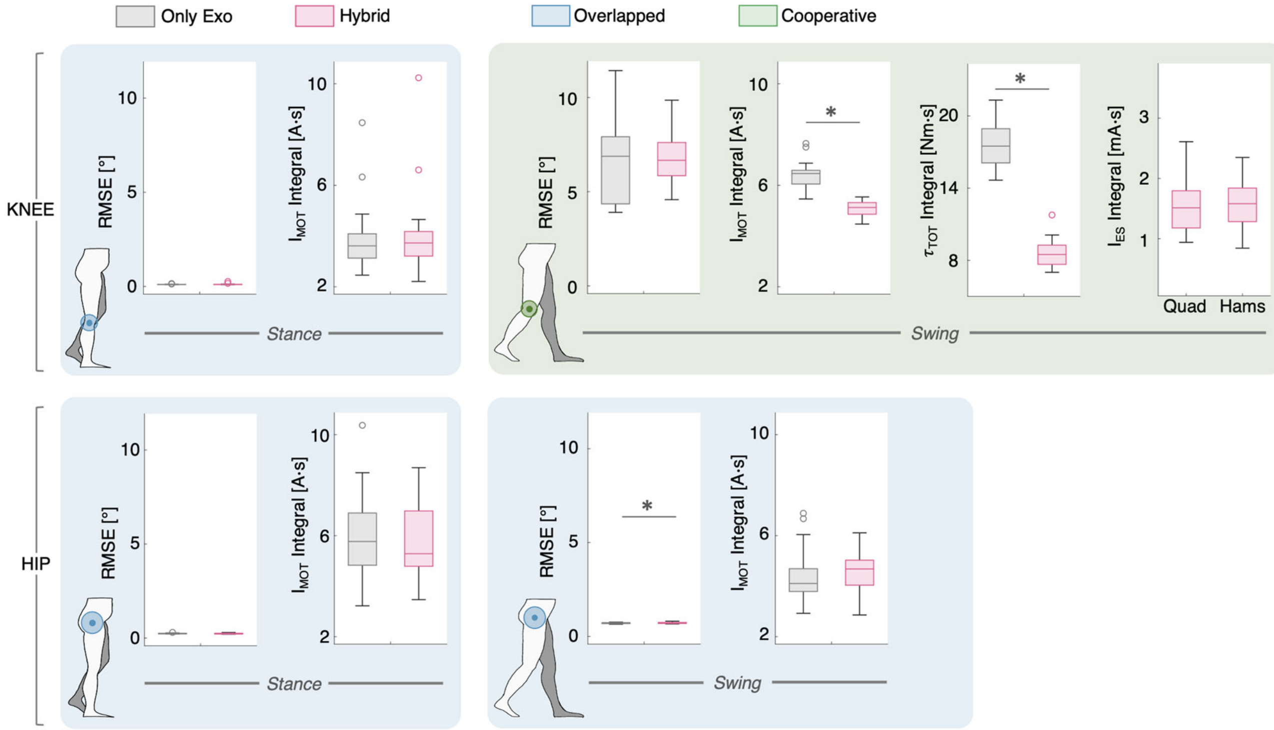

Fig. 3 | Metrics computed during walking experiments for Study 1 considering all tested subjects ($n = 12$). For each subject, the average metric of all strides, considering both sides, was computed and included in the statistical analysis. Both the *Only Exo* (gray) and *Hybrid* (pink) condition are reported and a different background-color is used for joints implementing the *Overlapped* (light blue) and the *Cooperative* (green) modality. Boxplots report position RMSE (*RMSE* [°]) and integral of the motor current (I_{MOT} Integral [A · s]) for both joints (knee and hip) and phases (stance and swing). For the sole knee joint during swing, also the estimated motor torque integral (τ_{MOT} Integral [N · m · s]) is reported, along with the stimulation current integral (I_{ES} Integral [mA · s]) delivered to Quadriceps and Hamstrings. The center line of the box represents the median, the edges of the box indicate the lower (Q1) and upper (Q3) quartiles, and the whiskers extend to the minimum and maximum values that are not considered outliers. Differences were considered statistically significant when p-value < 0.05 (Wilcoxon signed-rank test, two-sided). Significant differences were found for I_{MOT} and τ_{MOT} Integral of the knee joint during swing ($p < 0.001$) and RMSE of the hip joint during swing ($p = 0.045$). RMSE: Root Mean Squared Error.

and without FES, with median RMSE values of 6.7° and 6.9°, respectively. As expected, RMSE values in both conditions were higher in the *Cooperative* modality compared to the *Overlapped* modality. This increase resulted from the compliant control strategy applied to the robot in the *Cooperative* modality. Regarding motor current and estimated motor torque integrals, a significant reduction ($p < 0.001$, Wilcoxon signed-rank test) was observed in the *Hybrid* condition compared to the *Only Exo* condition. Specifically, the motor current integral was reduced by about ≈21% in the *Hybrid* condition, while the estimated motor torque integral decreased by about ≈51%. This reduction occurs because, in the *Only Exo* condition, the robot fully supports the movement of both the exoskeleton and the subject's legs. In contrast, in the *Hybrid* condition, FES drives the leg movements, and the motors primarily compensate for the exoskeleton's weight and correct deviations from the target trajectory. The successful completion of the task, despite reduced motor power, demonstrates the ability of FES-induced movements to compensate for the decrease in robotic assistance.

For the swing knee, metrics were also analyzed in windows of 5 consecutive swings (Supplementary Fig. 3a). No clear trends of increasing RMSE, motor current or motor torque demand were observed, indicating that muscle fatigue did not become apparent within the first 50 strides. However, for a single subject (ID S1), a longer test involving 75 strides was conducted. In this test, all metrics showed an increase at the end of the trial (Supplementary Fig. 4), suggesting a potential onset of muscle fatigue after 50 strides.

Study 2

Thirteen subjects (12 M and 1 F, mean age 40.7 ± 8.3 years) were recruited at Villa Beretta rehabilitation center (Costa Masnaga, Lecco): four suffered from a complete SCI (cSCI), four from an incomplete SCI (iSCI) and five were stroke survivors. Their demographic and clinical characteristics are reported in Tables 1 and 2. Two subjects (one cSCI and one iSCI) did not complete the protocol since they were not able to walk and perform sit-to-stand transitions in the *Only Exo* condition. Results are therefore reported for eleven subjects.

Overall, the participants' general psychological condition was good, as assessed using the Psychological General Well-Being Index[35] (Supplementary Fig. 5) prior to the start of the testing procedure (T0).

Before testing the *Hybrid* condition, a calibration procedure was carried out to adjust the exoskeleton to the subject's anthropometry and to set the current amplitude for all stimulated muscles. This calibration procedure was performed only on the first day and took on average 20 min. The current amplitude values identified during calibration for all participants are provided in Supplementary Table 4. On subsequent days, the donning procedure took less than 10 min.

Testing of the developed system on participants with neurological disorders. The same walking tests of Study 1 were conducted (Fig. 2b), but here more than one session were performed (each session on a different day). Temporal profiles of motor and stimulation-related signals in the *Hybrid* condition at the beginning (stride 3) and at the steady-state (stride 60) are reported in Figs. 4 and 5 for two representative target users: a complete SCI (ID P6) and a post-stroke participant (ID P7), respectively.

In the *Cooperative* modality, the stimulation primarily drives the movement through FES-induced muscle contractions, while the motor softly tracks the target trajectory to ensure proper task execution without hindering the stimulation effect. This results in some deviations of the actual trajectory, as shown by the swing knee trajectory (Figs. 4a and 5a), due to the inherent difficulty in accurately controlling FES-induced movements[36]. For subject P6, the RMSE between the actual (solid line) and the target (dotted line) knee trajectory reached ≈18% of the range of motion (corresponding to 10.1°) and decreased to ≈13% by swing 60 (7.2°), accompanied by a 14% reduction of the estimated total motor torque integral (from 8.6 N · m · s to 7.4 N · m · s). For subject P7, the RMSE of the knee trajectory reached ≈18% of the range of motion (corresponding to 10°) and decreased to ≈10% by swing 60 (5.8°), accompanied by a 15% reduction of the estimated total motor torque integral (from 8.6 N · m · s to 7.3 N · m · s). Thus, the better tracking performance was not given by motors but rather by iterative FES modulations that increased the current amplitude over time to optimize the trajectory tracking. By stride 60, the current delivered to both Quadriceps and Hamstrings (Fig. 4c) exceeded the subject-specific movement threshold (I_{L1}) and reached the maximum tolerated one (I_{L2}).

Accurate and time-invariant target trajectory tracking is instead observed for the knee joint during the stance phase and for the hip joint throughout the entire gait cycle. This occurs because the *Overlapped* modality enforces a rigid position control with ES always provided below the movement threshold (Figs. 4 and 5), thus not affecting the task execution.

The *Side-by-Side* modality used for the non-actuated ankle joint comprises the biomimetic stimulation of the Gastrocnemius and Tibialis Anterior, with stimulation amplitude below the movement threshold.

Metrics recorded across all target users (Fig. 6 and Supplementary Fig. 6) confirmed the conclusion driven from results gathered on unimpaired subjects (Fig. 3). When considering joints under the *Overlapped* modality (light blue panels), similar metrics values can be observed comparing the *Only Exo* and *Hybrid* conditions. However, statistically significant differences were found in the RMSE of the hip joint during the swing phase, with values of 1.01° in the *Only Exo* condition and 1.02° in the *Hybrid* condition ($p = 0.02$, Wilcoxon signed-rank test). Nevertheless, despite reaching statistical significance, the minimal difference in absolute values makes it practically negligible. A small significant difference was observed in the knee joint current integral during the stance phase, with values of 6.8 A · s in the *Only Exo* condition and 6.1 A · s in the *Hybrid* condition ($p = 0.031$, Wilcoxon signed-rank test). In the *Cooperative* modality (green panels), no significant differences in angular trajectories were observed between the two tested conditions. The median RMSE values were 7.50° (13% of the range of motion) and 7.92° (14% of the range of motion) for the *Only Exo* and *Hybrid* condition, respectively, slightly higher in the latter but not significantly different ($p = 0.053$, Wilcoxon signed-rank test). In terms of power demand, the *Hybrid* condition resulted in significantly lower motor current and torque integrals ($p < 0.001$), with a reduction of ~20% (from 5.56 A · s to 4.44 A · s) in current and ~48% (from 14.47 N · m · s to 7.52 N · m · s) in torque integral.

The total energy consumption per step of the hybrid system was estimated and compared to that of the exoskeleton alone, as reported in the Supplementary Material (Supplementary Fig. 7). Overall, the median value per step, considering all subjects and sides, associated to the exoskeleton alone was 77.04 J and 72.74 J, respectively for the *Only Exo* and the *Hybrid* condition. Considering also the energy associated to ES, the overall estimated energy for the *Hybrid* condition was 72.84 J, with a contribution given by ES of 0.2%. These findings support the hypothesis that FES can effectively drive the limb motion, reducing motor power, without compromising the walking trajectory.

Although assessing therapeutic effects was beyond the scope of this study, we conducted an exploratory analysis to identify potential signs of improvement. By comparing RMSE between initial and final steps after the saturation of the stimulation current within a single session, we observed no change in subjects with complete SCI, while those with incomplete SCI and stroke showed a slight reduction in RMSE during the final steps. Given that motor and stimulation currents remained stable, this modest improvement may reflect a better recruitment of volitional contribution by the users (Supplementary Figs. 8 and 9).

As an illustrative example, the Supplementary Material includes a video of subject P5 (incomplete SCI) walking with assistance from the hybrid device (Supplementary Movie 1).

Subjective reports of participants with neurological disorders. Target users also completed three questionnaires (Fig. 2b), after testing the *Only Exo* condition (T1) and after testing the *Hybrid* one (T2). The results are reported in terms of the difference (Δ) between the score attributed to the two conditions. For all questionnaires, a higher score indicates a better evaluation.

When asked about the usability of the device with the System Usability Scale (SUS)[37] (scores from 0 to 100), 7 out of 11 users rated the *Hybrid* condition better than the *Only Exo* one, 3 did not report any difference, and one (ID P5 - iSCI) reported the *Hybrid* condition worst than the *Only Exo* one. Overall, a median improvement of SUS (5 points) across all subjects (Fig. 7a) was achieved in favor of the *Hybrid* condition, starting from a median SUS of 47.5 attributed to the *Only Exo* condition. This suggests that stimulation was beneficial for the overall system perceived usability; nevertheless, the two scores were not significantly different. Considering the User Experience Questionnaire (UEQ)[38] (scores from −3 to +3), for all six questionnaire items a median ΔUEQ equal or above zero was reported (Fig. 7b), indicating a better user experience when ES was present. The only significant difference was found for the "Efficiency" item ($p = 0.03$), in favor of the *Hybrid* condition. The "Dependability" item is balanced in between conditions which is reasonable considering that stimulation does not affect the system's autonomy.

Lastly, the Technology Acceptance Measure (TAM)[39] (scores from 1 to 5) revealed a preference for the *Hybrid* condition (positive values) on all items, except for "Demonstrability of results" (Fig. 7c). However, no statistically significant differences were found, except for the "Perceived Usefulness", with a median ΔTAM of 0.5 ($p = 0.02$) in favor of the the *Hybrid* condition. The "Perceived Ease of Use" did not change between the two conditions even though the addition of the stimulation required extra preparation.

Discussion

The primary goal of this study was to design and validate a hybrid control system for a device integrating ES within a motorized lower-limb exoskeleton to support overground locomotion in neurological subjects, leveraging on variegate modalities of integration to enhance clinical operativeness, neuromotor effect and portability. An extensive experimental procedure was carried out involving twelve non-disabled participants and eleven participants with neurological disorders performing walking tests with the device. The gathered results proved the feasibility of the developed hybrid system, which enabled personalized walking sessions with a fast calibration procedure lasting less than 20 min, only on the first training session, which is promising towards clinical adoption.

A *Cooperative* controller was implemented for the knee joint during the swing phase. For the hip joint and the knee during stance, an *Overlapped* control scheme was preferred for several factors: the need to ensure stability during the stance phase (particularly for non-ambulatory users), the antagonistic effects of the Quadriceps and Hamstrings on the hip and knee joints, and the deep positioning of hip flexors, which prevents to induce functional movement through surface electrodes[40].

The *Cooperative* controller combines impedance control for the motor with a model-free FES control based on Iterative Learning Control. The Iterative Learning Control required less than five repetitions to optimize stimulation parameters, improving trajectory

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Table 1 | Demographic and clinical data of participants with complete and incomplete SCI are reported

Study 2: Characteristics of participants with complete and incomplete SCI								
ID	**Sex**	**Age [years]**	**Lesion level**	**ASIA**	**Time since the event [months]**	**Modified Ashworth Scale**	**Pain (NRS)**	**Performed tests**
P1 (cSCI)	M	35	T7	A	32	from 2 to 3, both legs	4	10 sessions: 6 Only Exo 4 Hybrid
P2 (iSCI)	M	38	L3	D	79	from 0 to 2, more on left leg	0	6 sessions: 3 Only Exo 3 Hybrid
P3 (iSCI)	M	38	D2	B	6	from 0 to 1, both sides		1 session: X Dropout
P4 (cSCI)	M	42	T5	A	61	from 0 to 2, both legs	10	4 sessions: 2 Only Exo 2 Hybrid
P5 (iSCI)	F	42	D4	C	26	from 0 to 1, both sides	0	3 sessions: 1 Only Exo 2 Hybrid
P6 (cSCI)	M	30	T3	A	25	from 0 to 1, both legs	3	5 sessions: 2 Only Exo 3 Hybrid
P12 (cSCI)	M	66	D8	A	47	2 on Triceps	5	1 session: X dropout
P13 (iSCI)	M	38	Sacral	A	43	No spasticity	0	2 sessions: 1 Only Exo 1 Hybrid

ASIA American Spinal Injury Association, *SCI* Spinal Cord Injury, *NRS* Numerical Rating Scale, ranging from 1 (no pain) to 10 (the worst pain imaginable), *cSCI* complete Spinal Cord Injury, *iSCI* incomplete Spinal Cord Injury.

Table 2 | Demographic and clinical data of post-stroke participants

Study 2: Characteristics of stroke survivors									
ID	**Sex**	**Age [years]**	**Type of stroke**	**More impaired side**	**FAC**	**Time since stroke [months]**	**Modified Ashworth Scale**	**Pain (NRS)**	**Performed tests**
P7	M	41	Isch	Left	4	19	Quad 2	0	4 sessions: 2 Only Exo 2 Hybrid
P8	M	41	Isch	Right	4	26	0	0	4 sessions: 2 Only Exo 2 Hybrid
P9	M	48	Hemor	Right	4	8	Quad 1	0	3 sessions: 1 Only Exo 2 Hybrid
P10	M	42	Isch	Right	4	303	Tric 1+	0	3 sessions: 1 Only Exo 2 Hybrid
P11	M	48	Isch	Left	4	98	0	0	3 sessions: 1 Only Exo 2 Hybrid

FAC Functional Ambulation Categories, ranging from 0 (Nonfunctional ambulator) to 5 (Independent ambulator), *NRS* Numerical Rating Scale, ranging from 1 (no pain) to 10 (the worst pain imaginable), *Isch* Ischemic, *Hemor* Hemorrhagic.

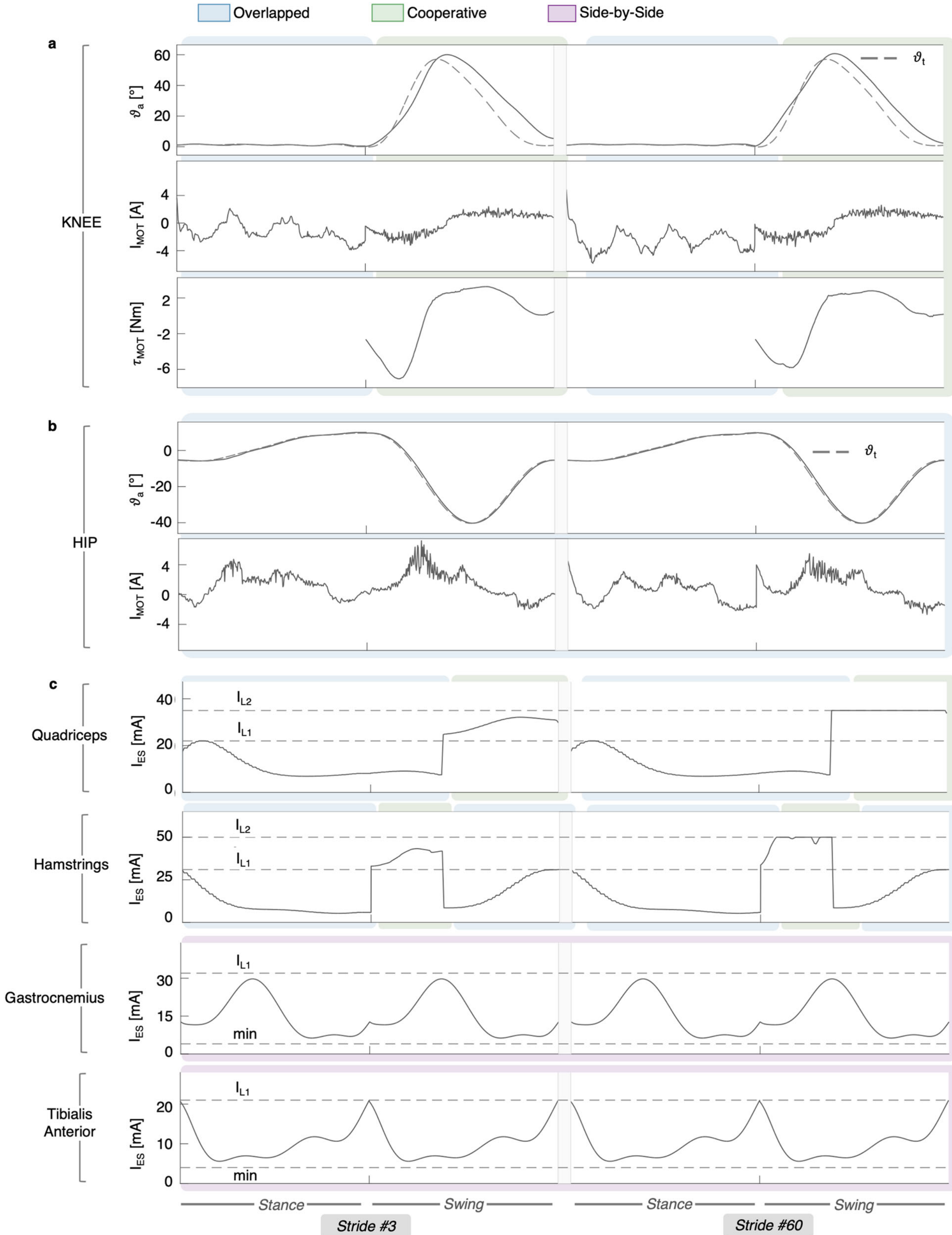

Fig. 4 | Exemplary results on one subject with complete SCI (ID P6). a Time series of the actual (θ_a [°]) and target (θ_t) angular trajectory, motor current I_{MOT} [A], torque τ_{MOT} [N · m] at the knee joint for an initial and a late stride. **b** Time series of the actual (θ_a [°]) and target (θ_t) angular trajectory and motor current I_{MOT} [A] at the hip joint for an initial and a late stride. **c** Time series of the stimulation current I_{ES} for the four stimulated muscle groups. Horizontal dotted lines represent the subject-specific limits within which the stimulation current can be modulated: *min*, the minimum current value (4 mA); I_{L1}, the movement threshold; and I_{L2}, the maximum tolerated current.

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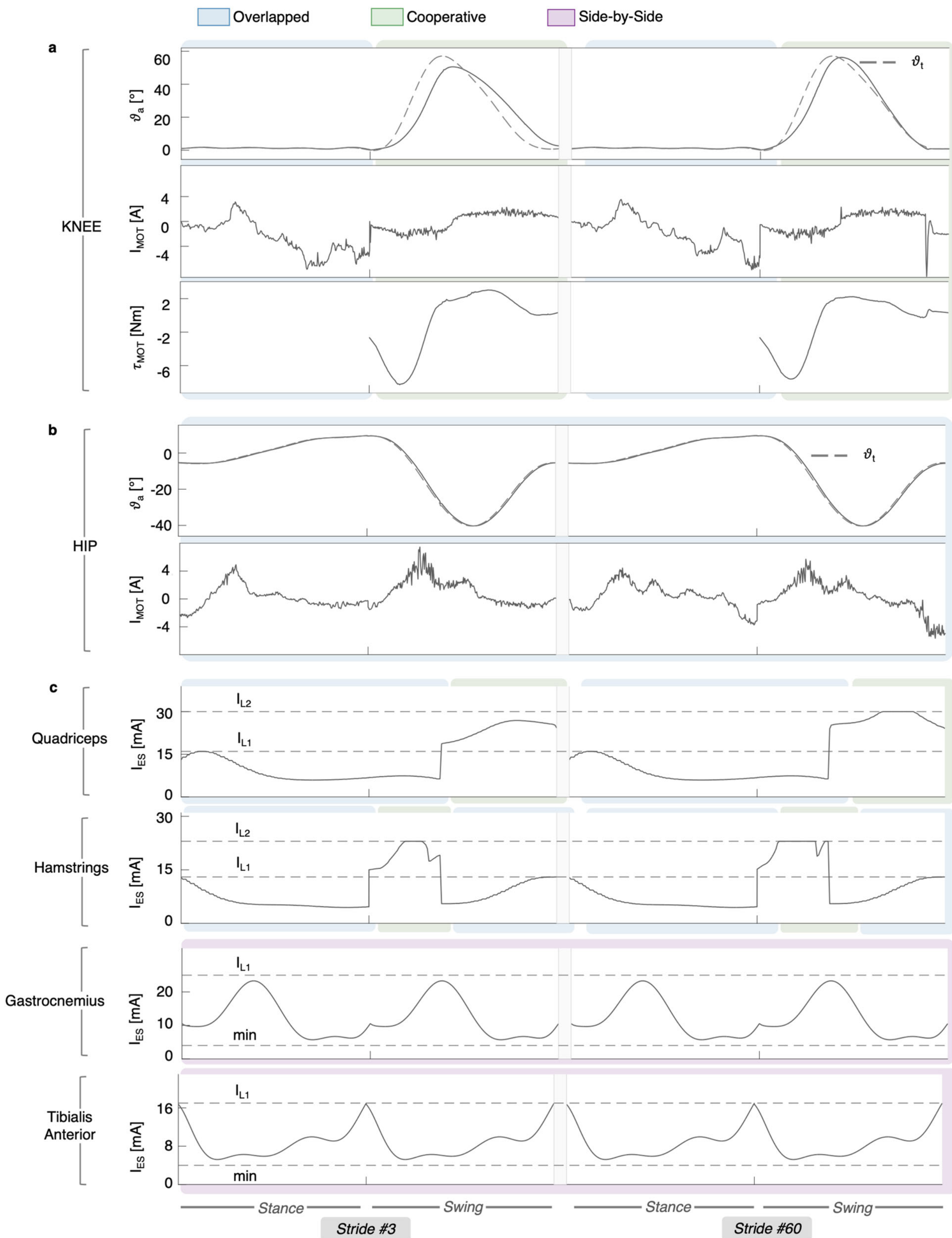

Fig. 5 | Exemplary results on one subject with left hemiparesis following stroke (ID P7). a Time series of the actual (θ_a [°]) and target (θ_t) angular trajectory, motor current I_{MOT} [A], torque τ_{MOT} [N · m] at the knee joint for an initial and a late stride. **b** Time series of the actual (θ_a [°]) and target (θ_t) angular trajectory and motor current I_{MOT} [A] at the hip joint for an initial and a late stride. **c** Time series of the stimulation current I_{ES} for the four stimulated muscle groups. Horizontal dotted lines represent the subject-specific limits within which the stimulation current can be modulated: *min*, the minimum current value (4 mA); I_{L1}, the movement threshold; and I_{L2}, the maximum tolerated current.

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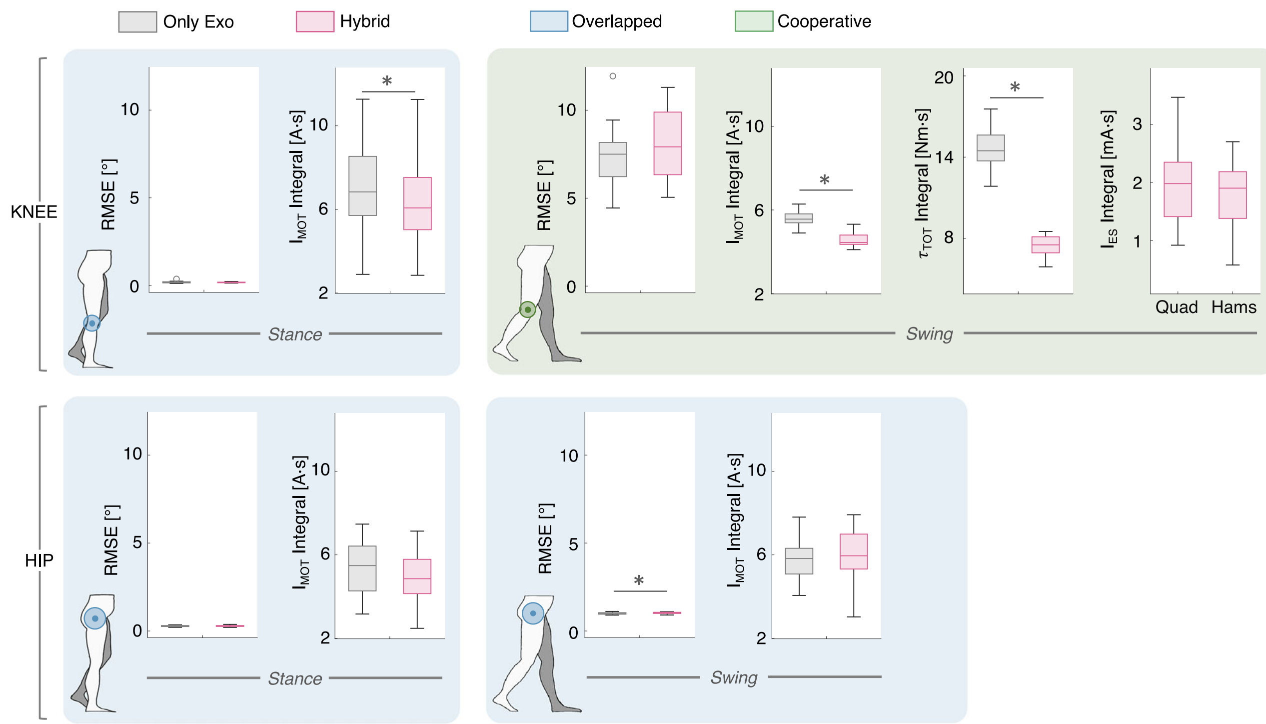

Fig. 6 | Metrics computed during walking experiments for Study 2 considering all tested subjects ($n = 11$). For each subject, the average metric of all strides, considering both sides, was computed and included in the statistical analysis. Both the *Only Exo* (gray) and *Hybrid* (pink) condition are reported and a different background-color is used for joints implementing the *Overlapped* (light blue) and the *Cooperative* (green) modality. Boxplots report position RMSE (*RMSE* [°]) and integral of the motor current (I_{MOT} Integral [A · s]) for both joints (knee and hip) and phases (stance and swing). For the sole knee joint during swing, also the estimated motor torque integral (τ_{MOT} Integral [N · m · s]) is reported, along with the stimulation current integral (I_{ES} Integral [mA · s]) delivered to Quadriceps and Hamstrings. The center line of the box represents the median, the edges of the box indicate the lower (Q1) and upper (Q3) quartiles, and the whiskers extend to the minimum and maximum values that are not considered outliers. Differences were considered statistically significant when p-value < 0.05 (Wilcoxon signed-rank test, two-sided). Significant differences were found for I_{MOT} Integral of the knee joint during stance ($p = 0.031$), I_{MOT} and τ_{MOT} Integral of the knee joint during swing ($p < 0.001$) and RMSE of the hip joint during swing ($p = 0.020$). RMSE: Root Mean Squared Error.

tracking and reducing motor torque demands (Supplementary Fig. 3a). In this framework, FES acts as a rough position controller, while the motor continuously monitors task execution, fine-tuning the movement to compensate for any stimulation inefficiencies and ensuring user safety.

Similar tracking performance was achieved for conditions with and without stimulation, with a median RMSE <7° for non-disabled subjects (Study 1) and <8° for participants with neurological disorders (Study 2). These deviations were considered acceptable as they fall within the range of inter-subject variability observed in physiological gait patterns[36]. Indeed, normative data indicate a variability of ~±10° at peak knee flexion.

This similar movement performance was achieved with a significant reduction of motor torque in the *Hybrid* condition. Specifically, a reduction of 51% was observed in non-disabled subjects and of 48% in participants with neurological disorders. Few other studies with FES-motor cooperative actuation in lower-limb exoskeletons included a clear quantification of the motor torque reduction[21]. These observations demonstrate that FES-motor cooperation on the same joint can significantly reduce motors' workload by iteratively adapting stimulation current levels to compensate for these reductions, while limiting trajectory tracking errors[32] without the need for sophisticated FES-torque models and time-consuming calibration procedures[30,40], especially in the case of cyclic tasks.

Although reducing actuator load was not the primary objective for integrating FES, when we estimated the total energy including both actuators and ES for the *Hybrid* condition, the contribution of ES on all muscles per step was less that 0.2%. This corresponded to a 22% reduction in total energy consumption at the knee joint during the swing phase, compared to the *Only Exo* condition. These findings suggest that integrating a stimulator in hybrid exoskeletons does not increase overall power demand; on the contrary, when *Cooperative* control strategies are properly implemented, it can lead to a meaningful reduction in motor power consumption.

It is worthy to highlight that, even if we observed a reduction of motor torque at the knee joint during the swing phase, for target users (Fig. 6) the power requirements were dictated by the stance phase, where the *Overlapped* modality was applied. Indeed, during the stance phase, full motor support was required for safety reasons, as using stimulation to maintain standing balance was not considered safe in the design of the study for non-ambulatory users. When metrics were analyzed separately for different target user groups (Supplementary Fig. 6), individuals with incomplete SCI exhibited lower motor current requirements at the knee joint during stance, lower even than the motor current required in the *Hybrid* condition during swing. This suggests they may have contributed to balance maintenance. A similar trend was observed in non-disabled volunteers (Fig. 3), where motor torque requirements were dictated by the swing phase, likely because these individuals relied on their natural ability to maintain balance during stance. In future studies, alternative technical solutions, such as knee locking mechanisms, could be explored to further alleviate the load on motors during the stance phase while ensuring safety, thereby contributing to power savings.

The *Cooperative* control also claims to delay the onset of muscle fatigue compared to using FES alone. However, in this study, we could not evaluate the FES-only condition due to safety concerns during walking in non-ambulatory users. This comparison was instead conducted in a previous study of our group, where a similar cooperative

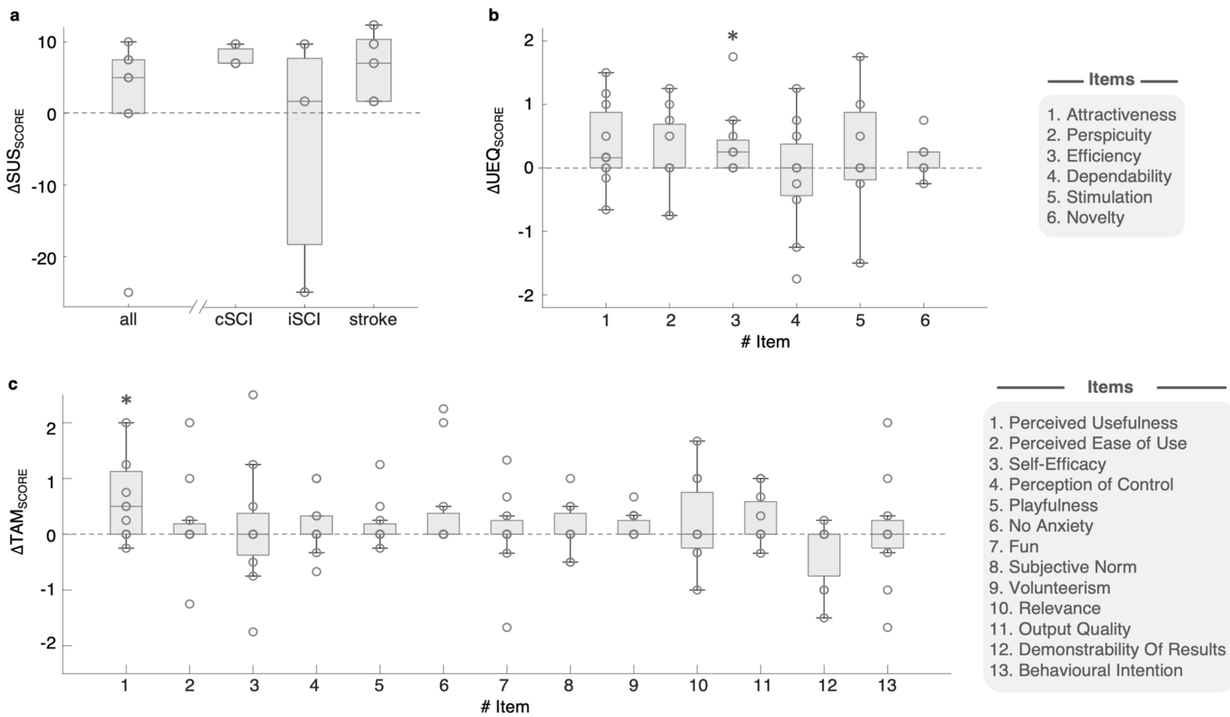

Fig. 7 | Results of the questionnaires delivered to the neurological participants (n = 11), both after testing the *Only Exo* and the *Hybrid* condition. **a** Difference between the scores assigned to the *Hybrid* condition and to the *Only Exo* condition in terms of System Usability Scale (SUS). Data are displayed dividing subjects per pathology. **b** Difference between the scores assigned to the *Hybrid* condition and to the *Only Exo* condition in terms of User Experience Questionnaire (UEQ). **c** Difference between the scores assigned to the *Hybrid* condition and to the *Only Exo* condition in terms of Technology Acceptance Measure (TAM). The center line of the box represents the median, the edges of the box indicate the lower (Q1) and upper (Q3) quartiles, and the whiskers extend to the minimum and maximum values that are not considered outliers. Each circle represents data from a single subject. Differences were considered statistically significant when p-value <0.05 (Wilcoxon signed-rank test, two-sided). Significant differences were found for Item3 of UEQ (p = 0.031) and Item1 of TAM (p = 0.023).

control approach was applied to support elbow flexion[32]. In that study, FES alone resulted in a lower number of repetitions (mean value of 21 ± 9), whereas the hybrid approach enabled 100 fatigue-free elbow flexion repetitions. In the current study, we analyzed 50 swings performed by non-disabled subjects (Supplementary Fig. 3a). No significant indicators of muscle fatigue, such as increases in RMSE or motor torque demand, were observed. However, a longer test involving 75 strides, performed only on one non-disabled participant (Supplementary Fig. 4), showed more pronounced increases in both metrics toward the final blocks, suggesting a potential onset of muscle fatigue. Based on these findings, we can conclude that the proposed controller allows for at least 50 strides without evident onset of muscle fatigue.

The combination of FES and the user's residual capability has been shown to enhance neural plasticity at the central level[11–14], improving potential therapeutic outcomes. Hybrid devices should therefore integrate the user's voluntary contribution to achieve a more synergistic human-robot interaction. Although not explicitly tested in this work, the implemented *Cooperative* control may enable this integration within the FES and motor assistance control loop. The adaptability and independence of the control from predefined models allow it to dynamically adjust based on the user's effort. We hypothesize that, when the user's volitional effort contributes effectively, tracking errors decrease, leading to reduced FES and motor feedback loop contribution. Preliminary results indicated that patients with residual motor function (e.g., post-stroke and incomplete SCI) exhibited a slight trend of reduction in RMSE over time within a single session, without corresponding changes in motor or stimulation currents (Supplementary Figs. 8 and 9). This modest improvement may therefore reflect a more synergistic contribution of residual voluntary activity during walking. While additional testing is required to validate this three-way cooperation, it presents a promising direction for the future applications of hybrid rehabilitation robotics.

For joints under the *Overlapped* control, no significantly different metrics were observed between the *Only Exo* and *Hybrid* conditions as the same motor control is implemented regardless of ES integration, which is here introduced below the motor threshold to enhance proprioception, favoring brain remapping and motor relearning[11–14].

Lastly, the *Side-by-Side* modality was introduced to add ankle dorsiflexion and plantarflexion during walking, compensating for the lack of ankle actuation in the exoskeleton. This approach leverages ES to induce active movements in non-actuated joints without adding complexity to the exoskeleton design.

Overall, the hybrid system was well-perceived by participants with neurological disorders. Notably, the inclusion of ES showed trend toward improved usability. This enhanced perception of usability may have been influenced by increased familiarity with the system, as the *Hybrid* condition was always tested after the *Only Exo* condition. However, the prolonged duration of the experimental sessions might have reduced participants' willingness to use the system. The lack of randomization between the two conditions was due to safety considerations: the protocol required participants to first demonstrate the ability to walk 10 m and perform a sit-to-stand transition with full motor assistance before testing the hybrid version, which featured reduced motor assistance. Similar positive trends were also observed with the hybrid device in terms of user experience, with users significantly perceiving the *Hybrid* condition as more efficient than the *Only Exo* condition. Additionally, in terms of technology acceptance, users rated the perceived usefulness of the hybrid device significantly higher. According to some users' reports, this was probably due to the perceived better integration of their own muscle contractions induced by ES while walking with the exoskeleton.

This study faced some limitations. The *Cooperative* control showed the capability to reduce motor power, while preserving movement performance, but it was implemented only for the knee joint during the swing phase. Future studies should test other stimulation techniques (e.g. withdrawal reflex[41]) to induce hip flexion. Another drawback is the absence of torque sensors for measuring user-robot interaction forces, which only allowed for an implicit impedance controller. In the future, direct torque sensing should be included to reject friction disturbances and improve back-drivability[42]. All users tested a single walking speed, which was quite slow (step duration of either 4 s in non-disables subjects and 3 s in target users). The evaluation of the proposed approach at faster walking speeds would be particularly beneficial for impaired subjects as it reduces their efforts in maintaining standing balance. Furthermore, the capability of the proposed hybrid solution to postpone the onset of FES-induced muscle fatigue with respect to FES-only condition was not quantitatively evaluated during walking due to safety issues. Another limitation of the study was the reliance on manual triggering for each step. Although this approach was implemented for safety reasons, it may have resulted in a non-rhythmic gait pace and increased the therapist's workload. In connection with this limitation, two operators were required to supervise the training sessions: one to assist the user during walking and the other to use the tablet for manually triggering each step. Additionally, the clinicians' perspective was not systematically included into the assessment to evaluate whether the proposed solution fully met clinical requirements. Finally, longitudinal studies should be carried out to evaluate the long-term efficacy of this hybrid solution.

In conclusion, our findings successfully addressed the initial research questions. The hybrid approach demonstrates a manageable implementation in clinical settings. Non-ambulatory users were able to successfully walk overground with minimal therapist effort and setup time, which has been found as key factors in improving therapists' adoption[43]. When applying cooperative control, the integration resulted in a reduction of motor power demand. Moreover, the hybrid device outperformed the exoskeleton alone in usability, user experience, and acceptance. Indeed, the synergy between the user's motor planning, robotic control, and direct sensorimotor activation through electrical stimulation may have contributed to a more natural interaction.

By combining high-repetition robotic training with neuromuscular electrical stimulation, enhancing proprioception and providing both local and systemic benefits, the proposed device has the potential to improve therapeutic outcomes of overground gait training. Further studies are needed to evaluate its effectiveness in enhancing locomotion in neurological patients. Additionally, future research should explore its potential as an advanced tool for exercise and verticalization, particularly for individuals with complete SCI.

Methods

Experimental setup

The Central Control Unit (CCU) of the implemented hybrid device is an ARM Cortex-M4 microcontroller programmed in C++, running at 500 Hz. System components (Fig. 1a) are hereby described:

- Motorized lower-limb exoskeleton: the Twin exoskeleton, developed by IIT-INAIL Rehab Technologies Lab (Italian Institute of Technology, IIT)[44,45], was used. Its structure comprises four actuation modules positioned at the hip and knee joints of both legs and passive Ankle-Foot Orthoses (AFOs). Each actuation module includes a motor unit (BLDC Maxon motor EC90 Flat, gearbox 100:1 and driver board) and a sensing unit (incremental encoder), working at 2 kHz. Their communication with the CCU is based on the CAN protocol.
- Stimulators: two commercial neuromuscular current-controlled electrical stimulators (RehaMove3, Hasomed GmbH) were employed, one per leg. Each of them includes four stimulation channels, connected to a pair of surface self-adhesive electrodes (Pals®from Axelgaard Manufacturing Ltd.), placed on target muscles (Quadriceps, Hamstrings, Gastrocnemius, Tibialis Anterior). Stimulators send biphasic rectangular pulses and communicate via USB with the CCU, which sets stimulation parameters: frequency *f*, pulsewidth *PW* (i.e., duration of a single wave phase), and amplitude *A*. Values of *f* and *PW* were set at constant values (40 Hz and 400 µs, respectively), while *A* was the controlled variable.

Hybrid control

A model-free strategy was defined to iteratively modulate motors and ES assistance while easing and shortening calibration procedures, which represents an essential requirement for clinical applications.

A *Cooperative* hybrid modality was developed for the knee joint during the swing phase in combination with either Hamstrings or Quadriceps stimulation to share the required assistance to fulfill the task between the two components (Fig. 8a). Differently, during the stance phase, a *Overlapped* hybrid modality was implemented, with the two components sharing the same timing but operating independently (Fig. 8b). In this case, the full support was on motors. The same approach was employed for the hip joint during the whole gait cycle, given the difficulty of stimulating deep hip flexors with transcutaneous electrodes. Lastly, a *Side-by-Side* hybrid modality was applied for managing Gastrocnemius and Tibialis Anterior stimulation over the whole gait cycle (Fig. 8c). Since the Twin exoskeleton did not include actuation at the ankle, ES was the sole source of assistance at this joint. However, the stimulation timing was synchronized with the overall movement execution.

Cooperative control. The cooperative control simultaneously modulates the knee joint motor assistance and the current amplitude delivered to either Hamstrings (early swing) or Quadriceps (late swing) muscles.

In this control (Fig. 8a), motors and FES share the same input (i.e., the trajectory tracking error) in order to fulfill the task while minimizing the motor torque: FES primarily contributes to movement generation while the motor assistance guarantees the accurate task execution.

At the motor level, a 1st order implicit impedance controller is implemented, which performs a trade-off between target trajectory tracking and human-robot interaction forces, allowing deviations from the equilibrium point[42]. Its architecture shows two nested loops: an internal torque loop and an external position-feedback loop. The former one computes the torque needed to support the movement (τ_{FF}), considering inertia and gravity of the sole exoskeleton for the *Hybrid* condition (Eq. (1)), and of both the exoskeleton and the subject for the *Only Exo* condition (Eq. (2))[32,46].

The position-feedback loop, instead, calculates the corrective torque (τ_{FB}) with a Proportional-Derivative controller based on position and velocity errors (Eq. (3)) and it is the same for the *Hybrid* and *Only Exo* condition.

$$\tau_{FF} = J_E\ddot{\theta}_t + m_E g\frac{l}{2}\sin(\theta_t) \rightarrow Hybrid \tag{1}$$

$$\tau_{FF} = (J_E + J_S)\ddot{\theta}_t + (m_E + m_S)g\frac{l}{2}\sin(\theta_t) \rightarrow OnlyExo \tag{2}$$

$$\tau_{FB} = K_s(\theta_t - \theta_a) + K_d(\dot{\theta}_t - \dot{\theta}_a) \tag{3}$$

θ_t, $\dot{\theta}_t$, $\ddot{\theta}_t$ and θ_a, $\dot{\theta}_a$, $\ddot{\theta}_a$ are target and actual angle, velocity and acceleration. J_S, m_S and J_E, m_E are the subject and exoskeleton's

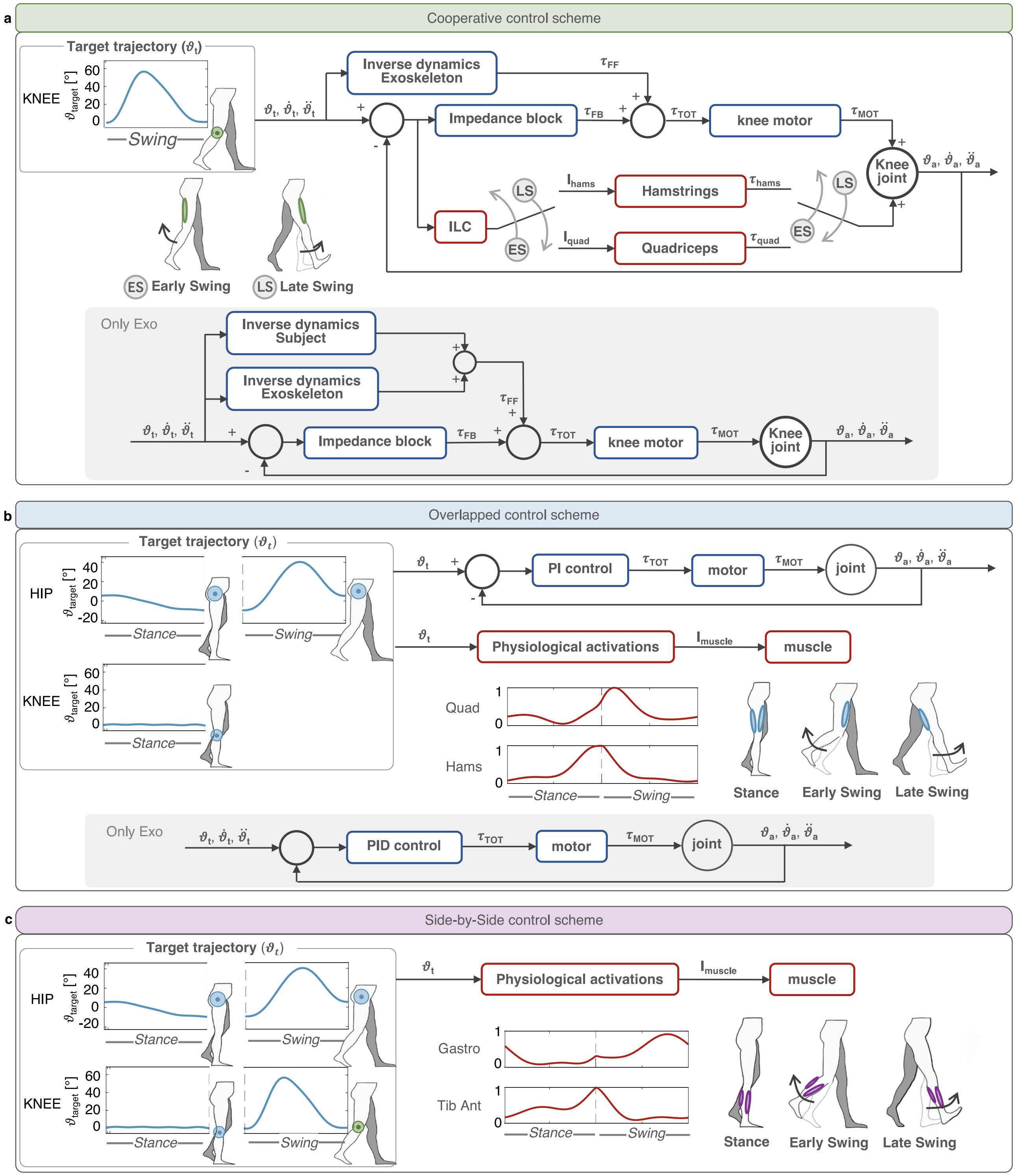

Fig. 8 | Control schemes for the three possible combinations between electrical stimulation (red blocks) and motor assistance (blue blocks). The schema of the *Only Exo* condition is reported with gray background. **a** Cooperative modality. θ_t, $\dot{\theta}_t$, $\ddot{\theta}_t$ and θ_a, $\dot{\theta}_a$, $\ddot{\theta}_a$ are target and actual angle, velocity and acceleration. τ_{TOT} is the total torque transferred to the motor and τ_{MOT} is the real exerted motor torque. τ_{TOT} is subdivided into feedforward (τ_{FF}) and feedback (τ_{FB}) components. I_{hams} and I_{quad} are stimulation currents delivered to hamstrings and quadriceps,, updated by the ILC. PI Proportional Integral. These stimulation currents result in muscle torque (τ_{hams} and τ_{quad}). ES Early Swing. LS Late Swing. ILC Iterative Learning Control. **b** Overlapped modality. I_{muscle} is the stimulation current delivered to muscles, computed from physiological activations[50,51]. PID Proportional Integral Derivative. **c** Side-by-Side modality.

moments of inertia and masses. l is the shank length and g the gravitational constant. The stiffness K_s ($5\frac{Nm}{\circ}$) and the damping K_d ($2\frac{Nm^{*}s}{\circ}$) gains define the system's rigidity and viscosity. These parameters were experimentally tuned: K_s was adjusted to allow slight deviations from the target trajectory, ensuring a compliant exoskeleton behavior that enhances the role of ES, while K_d was set to provide gentle damping, preventing abrupt velocity changes while avoiding excessive braking that could hinder smooth movement execution. Once tuned, the parameters were kept constant for all subjects and conditions.

The sum of τ_{FF} and τ_{FB} yields the overall torque (τ_{TOT}) transmitted to the motor and converted in the duty cycle of the Pulse Width Modulation (PWM).

Considering the FES control, current amplitude is stride-by-stride adapted through an Iterative Learning Controller (ILC)[47–49] intended to minimize trajectory tracking errors evaluated at previous strides. This iterative approach is well-suited for repetitive movements like walking[48]. The range of the stimulation amplitude is limited, for each channel, by user-specific thresholds: I_{L1}, defined as the current value that induced a visible muscle contraction without any movement (estimated as the first value generating a visible movement subtracted by 2 mA), and I_{L2}, which is the value that induced either a full range of motion or the maximum tolerable level. Both these values were defined during calibration, independently for each single muscle. For each stride k, the current amplitude for channel j at sample i is defined as:

$$I_j^k(i) = I_{L1,j} + K_{FES} \cdot u_j^k(i) \tag{4}$$

where K_{FES} ($4[\frac{mA*ms}{\circ}]$) represents the stimulation gain, experimentally identified and identically maintained across subjects. The resulting current is saturated to the maximum $I_{L2,\ j}$ value established for the j^{th} channel during calibration. u_j^k is the control vector (i.e., cost function), initialized as zero and updated at each stride k as:

$$\mathbf{u^k} = \mathbf{u^{k-1}} + f(\mathbf{e^k_{pos}}) \tag{5}$$

where $f(\mathbf{e^k_{pos}})$ is a function of the position errors vector for the k^{th} stride (only considering the swing phase), which is computed as:

$$f(\mathbf{e^k_{pos}}) = \lambda Q \mathbf{e^k_{pos}} \tag{6}$$

where λ ($1.25\frac{1}{ms}$) is the error gain, experimentally identified and identically maintained across subjects, and Q a Gaussian window filter[48]. To achieve good convergence in a few repetitions while avoiding current spikes, the filter window length was set to 5 samples.

Overlapped control. In this control, SAES and motor assistance are coordinated with a shared timing but operate independently. This control is implemented for the knee joint during the stance phase and for the hip joint throughout the gait cycle, in combination with stimulation of the hamstrings and quadriceps (when not involved in the *cooperative* loop).

At the motor level, a rigid position control is implemented, based on a Proportional Integral (PI) strategy that computes the PWM duty cycle to minimize position errors.

Regarding SAES, the current amplitude is modulated in open loop following a biomimetic stimulation timing to mimic muscle activations during a physiological gait, recovered from EMG recordings from the literature[50,51]. For channel j in sample i, Eq. (7) defines the amplitude of the current delivered:

$$I_j(i) = I_{min} + (I_{L1,j} - I_{min}) \cdot act_j(i) \tag{7}$$

where I_{min} is the minimum current, set at 4 mA for all channels and subjects, and I_{L1} is the current value that induces visible muscle contractions but no movement, and $act_j(i)$ is a value [0,1] that indicates the activity level of the muscle stimulated by the channel j in each sample i of the gait cycle, recovered from physiological activation patterns (Fig. 8b). Therefore, in this modality, the maximum stimulation amplitude is always below the movement threshold I_{L1} to avoid ES-induced movements that act against motors.

Side-by-side control. The Gastrocnemius and Tibialis Anterior stimulation over the whole gait cycle was managed with the same biomimetic strategy used in the *Overlapped* Control (Fig. 8c). In this case, muscles actuate the ankle joint, which is not actuated, but their stimulation is anyhow synchronized with the hip and knee motors' trajectories to ensure coordination with the overall walking movement. For stimulation channel j at sample i, Eq. (8) defines the delivered current amplitude:

$$\begin{aligned} I_j(i) &= I_{min} + (I_{L1,j} - I_{min}) \cdot act_j(i) \rightarrow \text{ below movement threshold} \\ I_j(i) &= I_{min} + (I_{L2,j} - I_{min}) \cdot act_j(i) \rightarrow \text{ above movement threshold} \end{aligned} \tag{8}$$

where I_{min} is the minimum current, set to 4 mA for all channels and subjects, I_{L1} is the current value inducing visible muscle contractions but no movement and I_{L2} is either the current amplitude accomplishing the full range of motion or the maximum tolerated value. In this modality, the current level can be either below or above the movement threshold, with the aim of inducing heel-strike and toe-off movements in the latter case.

Testing procedure

Before any experimental session, a calibration procedure was carried out. A ramp of increasing amplitude ($1\frac{mA}{s}$) was delivered to determine I_{L1} (movement threshold) and I_{L2} (maximum tolerated threshold) for each stimulated muscle.

Study 1. Single-Joint tests. This represents a preliminary study to assess the functionality of the cooperative control during single-joint movements. Participants without pathological conditions were seated while wearing the exoskeleton with only one motor (right knee) active and FES delivered to the Quadriceps muscle of the right leg to perform 90° knee extension movements. Further details and results of this testing procedure are reported in Supplementary Materials.

Walking tests. These tests were conducted to evaluate the system's functionality in participants without pathological conditions. The study protocol (Fig. 2a) began with the calibration of stimulation currents. Participants were then instructed to remain passive while walking with the device, which used, as the target trajectory, the joint-space trajectory implemented by the Twin exoskeleton[45], adjusted to a slowed step duration of 4 seconds. Initially, stimulation was applied to all four muscles, but subsequently, the Gastrocnemius and Tibialis Anterior were excluded from stimulation. This decision was made to simplify the protocol, as stimulating these muscles provided no additional value. Indeed, the efficacy of their stimulation could not be measured due to the absence of sensors at the ankle, and no benefits were expected for non-disabled participants.

Two conditions were compared:

- *Only Exo*: stimulation OFF and full feed-forward motor assistance - 20 strides (Eq. (2));
- *Hybrid*: stimulation ON and reduced feed-forward motor assistance - 50 strides (Eq. (1));

The extended duration of the latter condition was intended to evaluate the potential onset of FES-induced muscle fatigue, which was instead not expected in the former case. Walking sessions under both conditions were conducted on the same day in an indoor corridor at Politecnico di Milano and were supervised by two operators, as specified in the datasheet of the Twin exoskeleton. One operator was responsible for using a custom application on an Android tablet to set training parameters (e.g., stimulation and gait settings) and to manually trigger each step, while the second operator assisted the user during walking.

Study 2. Study 2 involved participants with neurological disorders. The inclusion criteria required participants to have either a complete or incomplete SCI or a history of stroke. Additional criteria included having anthropometric parameters compatible with the use of the Twin exoskeleton, spasticity, osteoporosis, and pain levels that did not interfere with its use, the ability to maintain an upright posture, a good muscle response to ES (assessed through visual inspection), and the capacity to provide the informed consent.

This study protocol (Fig. 2b) began with the T0 evaluation, during which participants' anamnestic and anthropometric data were collected. These data included age, sex, height, weight and previous experiences with ES and/or lower-limb exoskeletons. For participants with SCI, additional information such as lesion type and level, time since injury, and ASIA scale scale classification were registered. For post-stroke participants, data on stroke type and location, time since the event, and the Functional Ambulation Categories (FAC) scale were collected. The FAC scale, ranging from 0 to 5, assesses ambulation capacity, where 0 indicates a "non-functional ambulator" and 5 represents an "independent ambulator"). The following baseline evaluations were also collected for all participants:

- Modified Ashworth scale for spasticity[52];
- Numeric Rating Scale (NRS) for pain level[53], a 0–10 scale to evaluate pain (with 0 meaning "no pain" and 10 meaning "worst imaginable pain");
- Psychological General Well-Being Index (PGWBI)[35].

After the baseline assessment, each participant tested the device in the *Only Exo* condition (without stimulation) over a maximum of 10 sessions, conducted on different days. Each session lasted up to one hour, which included donning, calibration, training, and doffing, with the walking portion limited to a maximum of 30 minutes. Participants continued these sessions until they could walk at least 10 meters and perform sit-to-stand transitions. If a participant failed to meet these criteria, they were excluded from the study. Otherwise, the T1 evaluation was conducted. Following T1, the protocol proceeded with testing the *Hybrid* condition, during which stimulation was activated. Each participant underwent up to 4 training sessions in the *Hybrid* condition, with each session lasting one hour, including a walking portion of 30 min. The calibration of stimulation currents was performed before the first session and remained unchanged for subsequent sessions unless the participant specifically requested adjustments. Finally, the T2 evaluation was carried out. During the T1 and T2 evaluations, participants assessed the usability, acceptance, and user experience of the *Only Exo* and *Hybrid* conditions, respectively, using the following questionnaires:

- System Usability Scale (SUS)[37];
- Technological Acceptance Measure 3 (TAM-3)[38];
- User Experience Questionnaire (UEQ)[39].

In both conditions, the joint-space walking trajectory implemented in the Twin exoskeleton was used as the target trajectories[45], with a step duration of 3 s. Unlike tests conducted on non-disabled subjects, ES was delivered to four muscle groups per leg, including Gastrocnemius and Tibialis Anterior. These muscles were stimulated below the movement threshold, since for safety reasons the ankle–foot orthoses of the Twin exoskeleton were locked, maintaining the ankle at a neutral angle. Walking sessions were conducted in an indoor corridor at the Villa Beretta rehabilitation center. As in Study 1, these sessions were supervised by two operators: one was responsible for using the Android application to configure training parameters and manually trigger each step, while the other assisted the participant during walking.

Ethics

The present work consists of a usability study in which an ES-motor hybrid device was tested both in non-disabled subjects (Study 1) and in subjects with neurological disorders (Study 2).

Prior to the testing procedure, all participants provided written informed consent to participate in the study and to the publication of potentially identifiable information, such as age and self-reported sex. No form of compensation was provided to participants.

Study 1 was approved by the Ethical Committee of Politecnico di Milano (Nr 13/2021), while Study 2 was approved by the Ethical Committee of IRCCS Fondazione Don Carlo Gnocchi (Nr 0314/10/2022). As the device under evaluation was not CE-certified as a medical device, the Ethical Committee of IRCCS Fondazione Don Carlo Gnocchi required the study to be submitted to the Italian Ministry of Health in accordance with Italian regulations. Study 2 was validated by the Italian Ministry of Health on March 28, 2023. Submitted protocols and approvals from the ethics committees are provided as Supplementary Material.

Data analysis and statistics

Kinematic and dynamic data were continuously recorded at a frequency of 100 Hz, while current amplitude was sampled at 40 Hz. Data were organized into repetitions and the gait cycle was further divided into swing and stance phases. To assess trajectory tracking performance, the Root Mean Squared Error (RMSE) between the target and actual angular positions was calculated. To quantify motor assistance, integrals of the absolute value of both motor current and total estimated motor torque were computed. To quantify FES assistance in the *Cooperative* modality, the integral of the absolute value of the delivered current amplitudes was computed. Metrics were calculated for each step and then averaged across all steps performed by each subject in each condition. Metrics collected from the two legs were kept separately. For the sole condition with FES, metrics were also averaged in windows of 5 consecutive steps to assess their trend over time and the eventual onset of muscle fatigue.

All data analyses were conducted using MATLAB (R2021b version).

Finally, since the data were not normally distributed (Kolmogorov–Smirnov test), a Wilcoxon signed-rank test was performed in SPSS Statistics (IBM) to compare the two conditions. This analysis was conducted for both the averaged metrics and the questionnaires scores (only for Study 2).

Data availability

All experimental data collected during both Study 1 and Study 2 have been deposited in the online repository at https://doi.org/10.5281/zenodo.13253070. All data supporting the findings of this study are available within the article and its supplementary files. Any additional requests for information can be directed to, and will be fulfilled by, the corresponding author. Source data are provided with this paper.

Code availability

MATLAB scripts to process and analyze data from both Study 1 and Study 2 and to create data structures to reproduce figures have been deposited in the online repository at https://doi.org/10.5281/zenodo.13253070. A 'ReadMe' file is also provided for additional guidance.

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Author contributions
E.Gr., G.F., F.M., E.A. and A.P. conceived the project and assured the management of the research. F.D., M.G., E.A. and A.P. designed and developed the control architecture. S.M. and E.Gr. supported the development of the control system. F.D., E.G., L.B., F.M., E.A. and A.P. defined the experimental protocol. F.D., E.G., V.C., L.B., E.A. and A.P. performed the experiments. F.D., V.C., M.G., E.A. and A.P. performed data analysis and supported interpretation. F.D., E.A. and A.P. drafted the paper. All authors contributed to proof-edit the paper. E.A. and A.P. equally contributed to this work.

Competing interests
A.P. has collaborated in various research and educational projects funded by international entities (EU funds- FP7 program; Horizon, HE; NIH; ESA), national public institutions (MIUR PRIN, INAIL, Lombardy Region, ASI) and private institutions (Cariplo Foundation, Telethon Foundation, Valduce Foundation, FORST Foundation) and companies (Generali Wellion; Tecnobody srl; EMAC srl; Merz Therapeutics; AllyArm srl). A.P. has conducted seminars for Novartis and AccMed. M.G. and A.P. hold shares in AGADE srl and AllyArm srl. The other authors declare no competing interests.

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