Biplanar Ankle Assistance for Dropfoot Gait Post-Stroke with Multi-objective Human-in-the-Loop Optimization: A Case Study

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Exoskeletons have shown great potential in enhancing mobility, and notable progress has been made in customizing control strategies. However, limited efforts have focused on optimizing control specifically for individuals with motor disorders, who often have heterogenous gait deviations. This study aims to evaluate our recent soft ankle exoskeleton prototype with a multi-objective human-in-the-loop (HIL) optimization approach in a participant exhibiting a dropfoot gait following a stroke. We identified assistive profiles that simultaneously improved multiple gait metrics. We demonstrate the feasibility of a flexible, individualized framework capable of tailoring exoskeleton assistance to multiple functional goals.

Exoskeleton

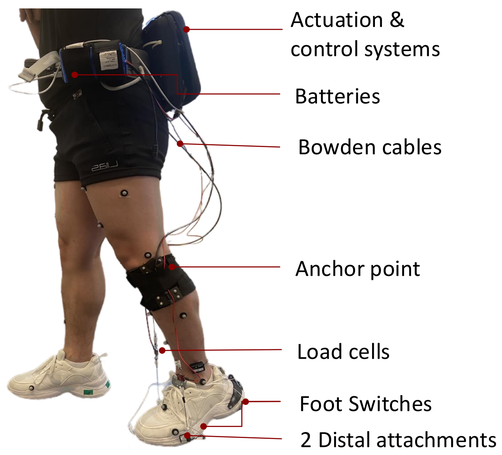


Fig 1. Soft ankle exoskeleton, developed in-house. Two motors pull cables attached to the medial and lateral forefoot between foot-off and early stance. The devices weighs 3.1 kg.

Method

Participant:

Experiments were performed on one woman in chronic phase after stroke (159 cm, 73 kg, 47 yrs).

Exoskeleton assistive profiles:

Control was parametrized as 1) combined torque of the motors, & 2) torque ratio between lateral & medial motors.

Experimental protocol:

The participant walked at her preferred speed in 4 sessions:

- ***NoExo***: with normal shoes
- ***Familiarization***: 20-30 minutes with the exoskeleton and different assistive profiles
- ***UnpowExo***: with the unpowered exoskeleton
- ***PowExoHIL***: with the powered exoskeleton and three generations of assistive profiles

Multi-objective HIL Optimization:

- ***Optimization algorithm****:*
  Non-dominated Sorting Genetic Algorithm II (NSGA-II)
- ***Variables and constraints:***
  Sum of the torque magnitudes, t_p
  Torque ratio between motors, r_{lm}
- ***Multiple objective functions*** *(gait quality metrics):*
  - Foot kinematics deviation, defined by foot inclination angle (α) & clearance height (H) of paretic (p) & non-paretic (np) sides:

$$\min Dev_{foot} = \left(\left|\frac{\alpha_p - \alpha_{np}}{\alpha_{np}}\right| + \left|\frac{H_p - H_{np}}{H_{np}}\right|\right) \times 100\%$$

  - Step length asymmetry (L):

$$\min ASI_{SL} = 2\left|\frac{L_p - L_{np}}{L_p + L_{np}}\right| \times 100\%$$

- ***Iterations:***
  - 3 generations * 10 assistive profiles

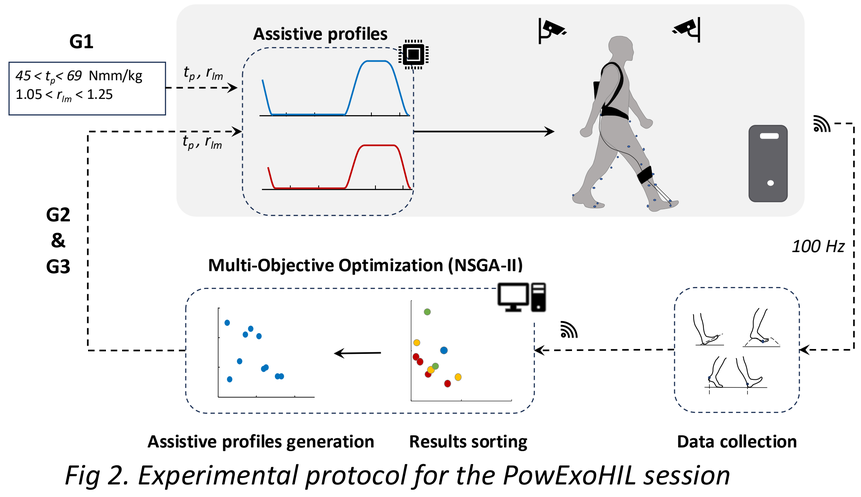


Fig 2. Experimental protocol for the PowExoHIL session

Results

With multi-objective HIL optimization, the solutions progressively converged toward the origin, indicating symmetry. A family of optimal solutions (Pareto front) were obtained; these represent a balanced trade-off that improve both gait quality metrics (cost functions) to varying degrees.

With solutions on the Pareto front in general, we observed

- More natural ankle joint kinematics
- Increased foot inclination angle at initial contact (from -2° to 10°)
- Increased foot clearance during swing (from 31 mm to 44 mm)
- Decreased step length asymmetry (from 12% to 6%)

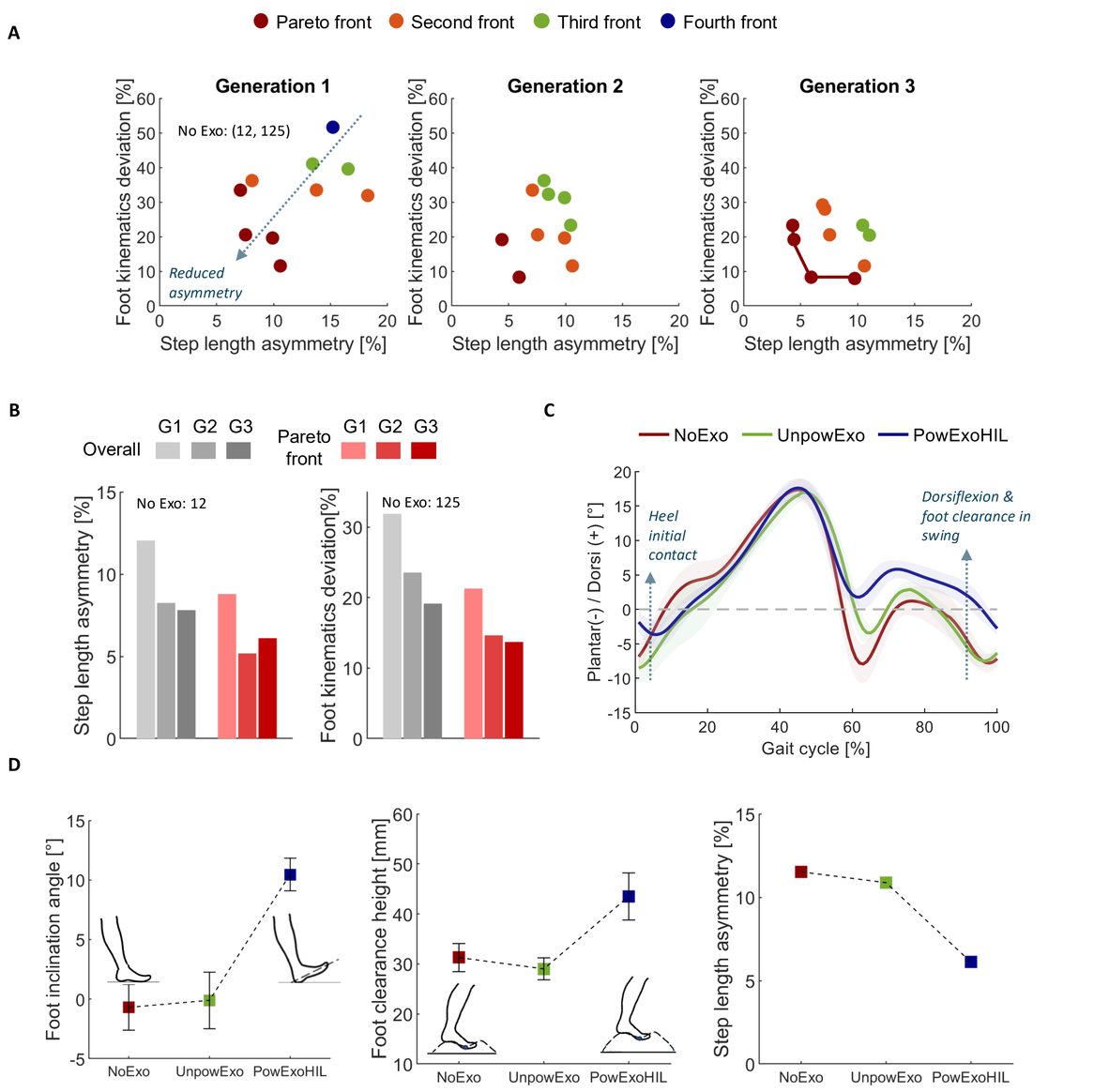


Fig 3. (A) Results in HIL optimization process, (B) Mean cost function values of the overall and Pareto front solutions across three generations, (C) The participant's sagittal ankle angle in a gait cycle, (D) Gait quality metrics without the exo, with the unpowered exo and with the powered exo after HIL.

Conclusions

The exoskeleton successfully increased symmetry of the foot kinematics and step length in this participant and in a subsequent pilot group of persons in chronic phase after stroke. To the best of our knowledge, this is the first device designed to provide assistance for dropfoot gait in two anatomical planes, using an individualized human-in-the-loop approach that seeks optimality of two objectives simultaneously. The generated family of optimal solutions can be considered as several individualized "good" alternatives to select from based on context, goals and preference.

Acknowledgments

We gratefully acknowledge valuable input from Dr. Ruoli Wang (KTH MoveAbility), Dr. Susanne Palmcrantz (Karolinska Institutet), Dr. Yi-Xing Liu (ETH Singapore) and Antea Destro (KTH MoveAbility).