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Supplementary Materials for

A soft robotic exosuit improves walking in patients after stroke

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Other Supplementary Material for this manuscript includes the following:
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Materials and Methods

Exosuit-generated assistive forces

An iterative, force-based, position controller was implemented to deliver a consistent force profile to assist paretic ankle PF and DF (see (*33*), (*49*), and *Materials and methods: Soft exosuit design and operation*). In brief, a closed-loop controller utilized position measurements from linear potentiometers located in the actuation unit and force measurements from load cells integrated into the exosuit textiles (**Fig. 1B**) to iteratively adapt Bowden cable position trajectories and generate desired PF and DF assistive force profiles.

PF controller overview

The PF controller iteratively adapted the cable position trajectory such that PF force was delivered during the paretic stance phase starting from one of two fixed onset timings selected as a percentage of the paretic gait cycle (%GC) (see *PF assistance timing* and **Fig. 4B**) and with the peak magnitude of the PF force set to 25% of participants' body weight (%bw) (see **table S1**). On the other hand, the timings of peak PF force and of PF force cessation (**Fig. 4B**) were not directly controlled; rather, they depended on the wearer's ankle kinematics during paretic pre-swing. For example, although a commanded retraction of the PF cable is the direct method by which exosuit operators may increase the PF force delivered, an increase in PF force is also possible when the cable is commanded to maintain a specific position but the wearer continues to DF the ankle (anterior translation of the tibia on the foot).

DF controller overview

The DF controller adapted the DF cable position trajectory to achieve a consistent force onset and off timing and cable retraction magnitude during swing phase. More specifically, the onset and off timings were selected by the research team such that DF assistance was triggered at the beginning of swing phase and diminished after initial foot contact. Unlike PF cable actuation, the DF cable retraction magnitude was selected by the research team before testing and set to facilitate paretic ankle neutral during swing phase as identified through visual observation. With this approach, the magnitude of DF force that was delivered to the wearer during swing phase within and across steps varies with the wearer's gait in a manner that maintains the commanded cable position, and thus ankle angle.

Timing

The exosuit controller utilizes measurements from shoe-mounted gyroscopes to detect ground contact events (initial contact and foot off) for each limb. Exosuit-generated forces are delivered to the wearer based on subphases of the gait cycle determined by these gait events. Our previous work (*33*) showed that the exosuit controller can robustly detect these key events during both the paretic and nonparetic gait cycles and effectively scale the duration of force delivery on a step-to-step basis using these gait events.

Adaptive control

The exosuit controller utilizes the measurements from the textile-integrated load cells to enable iterative, force-based position control; however, it is important to note that the while the load cells measure exosuit-generated force, this force is a composite outcome of the Bowden cable position, the wearer's joint kinematics, and the exosuit-human series stiffness—a parameter that accounts for the mechanical properties of the textile anchors, Bowden cables, and the compliance of the human tissue that supports the textile anchors (**Fig. 4A**) (*41*). Because of this, a simple closed loop position controller cannot consistently achieve the desired assistive force profiles. To overcome this limitation, the exosuit controller iteratively adapts the cable position trajectories. Specifically, the PF controller adapts the baseline cable position and the cable position before and after cable retraction in a manner that ensures that tensile force begins to be generated at the commanded onset timing (see *PF assistance timing*). Moreover, the PF controller adapts the maximum cable pull position relative to the baseline position such that the peak force magnitude is consistently 25% of the wearers' body weight for each stride. Similarly, the DF controller adapts the baseline DF cable position such that the cable tensile force starts to build at a commanded onset timing (paretic foot off and thus the start of swing phase) and diminishes after initial foot contact. Unlike the PF controller, as described previously, the maximum DF pull position is fixed to the position of a neutral ankle.

Passive exosuit study

To evaluate our hypothesis that an exosuit worn unpowered would not influence walking after stroke, five individuals in the chronic phase of stroke recovery participated in evaluating the effects of wearing an exosuit unpowered compared to not wearing the exosuit. Two primary outcomes were evaluated: 1) the propulsive force generated from each limb and 2) the energy cost of walking. Participants were 53±6 y old, 5.1±0.8y since stroke, 40% female, and 60% left hemiparetic. Testing for this secondary study consisted of two 8-min walking bouts on an instrumented treadmill at participants' overground self-selected walking speed, one bout per condition. The treadmill recorded ground reaction force data and indirect calorimetry was used to measure energy consumption. Paired t-tests were used to evaluate differences between conditions. As hypothesized, walking with the passive exosuit did not significantly modify participants' generation of propulsion from their paretic and nonparetic limbs, nor energy cost of walking (**fig. S1**).

Overground walking with an untethered exosuit

To evaluate our hypothesis that overground gait assistance delivered from an untethered exosuit would improve paretic limb ground clearance during swing phase and propulsion during stance phase, nine individuals in the chronic phase of stroke recovery participated in evaluating the effects of wearing an untethered exosuit powered compared to unpowered. The untethered exosuits used for this proof-of-principle overground walking study were comparable to the tethered exosuits used for treadmill walking, except that a 3.2 kg actuator and battery pack was mounted to the waist belt and the proximal attachment of the PF module was moved from the waist belt to the calf wrap (**Fig. 5**). Two primary outcomes were evaluated: 1) peak paretic ankle dorsiflexion angle during swing phase and 2) interlimb propulsion asymmetry. This testing was conducted overground. Participants were 49±13 y old, 4.7±1.7 y since stroke, 44% female, and 56% left hemiparetic. Testing for this study consisted of participants walking at a self-selected, comfortable walking speed over two ground-level forceplates that collected ground reaction force data (AMTI OR-6 force plates; 2160 Hz) until at least five usable strides were captured per condition. Concurrently, 3D ankle joint kinematics were measured by a motion-capture system. Paired t-tests were used to evaluate differences between conditions. Consistent with our findings on the treadmill, walking overground with an untethered exosuit (**Fig. 5A**) powered versus unpowered resulted in increased paretic ankle dorsiflexion during swing phase (**Fig. 5B**), increased paretic limb propulsion, and reduced interlimb propulsion asymmetry (**Fig. 5C**).

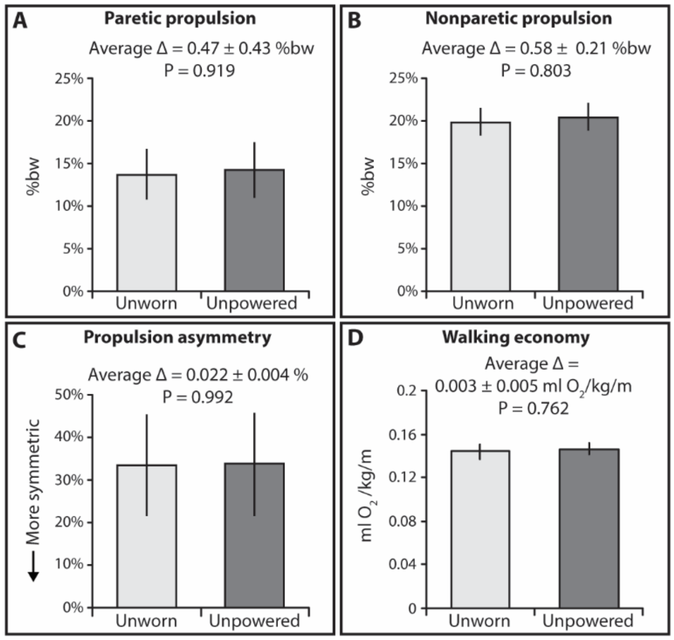

Fig. S1. Effects of wearing a passive exosuit on poststroke propulsion and energy expenditure. (**A**) Paretic propulsion, (**B**) non-paretic propulsion, (**C**) propulsion asymmetry, and (**D**) walking economy (energy expenditure per meter ambulated) for unworn and unpowered exosuit conditions. Means and standard error are presented. N = 5.

Table S1. Tethered exosuit ankle PF assistive forces.

Participant parameters				**Exosuit plantarflexion (PF) force parameters**			
Participant	**Weight (kg)**	**Weight (N)**	**Peak paretic PF ankle moment (Nm/kg)**	**Commanded peak PF force (N)**	**Delivered PF moment arm (m)**	**Delivered peak PF torque (Nm/kg)†**	**Delivered peak PF torque (% of peak paretic PF ankle moment)**
1	49	480	1.01	120	0.066	0.16	16%
2	73	715	1.47	180	0.059	0.15	10%
3	90	882	1.09	220	0.055	0.13	12%
4	79	774	1.21	195	0.075	0.18	15%
5	73	715	0.78	180	0.073	0.18	23%
6	80	784	1.88	200	0.062	0.16	8%
7	60	588	1.41	150	0.065^	0.16	12%

^Moment arm data for this participant were not available. Given the low variability in moment arm values across the other 6 participants, the average across participants (0.065 m) was used for this participant.

†Exosuit peak PF torque values are computed as: $(Commanded\ Peak\ PF\ Force\ x\ PF\ Moment\ Arm)/\ Weight)$

Video S1. Video demonstration of exosuit-assisted treadmill walking. A demonstration of ankle plantarflexion assistance during stance phase and dorsiflexion during swing phase delivered by a tethered exosuit during treadmill walking for a healthy individual and two individuals with poststroke hemiparesis.