Supplementary Information

Exercise with Wearable Hip-assist Robot Improved Physical Functional and Walking Efficiency in Older Adults

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EX1 assistance algorithm

Delayed output feedback control (DOFC) for gait assistance

As shown in Supplementary Fig. S1(A), this time-delayed, self-excited feedback control method does not include a gait phase estimator as well as a reference lookups for generating assistive torques. The assistive torques are immediately applied following the movement of the user by updating the change of hip motion at every control period (100Hz). Supplementary Fig. S1(B) shows the control flow of the DOFC based assistance.

1. Smoothing hip sensor data with low pass filter (LPF)

The left and right hip angles $q_r(t)$, $ql(t)$ are obtained from the angular sensors located at the hip joints. We then calculate the state variable $y_{raw} = \sin q_r(t) - \sin q_l(t)$, to represent the current gait behavior. The original control state y_{raw} is smoothed by passing through a first-order low-pass filter:

$$y^{cur} = (1 - \alpha)y^{prv} + \alpha y^{cur}_{raw}, \quad (0 < \alpha < 1) \tag{1}$$

where y^{cur} is the currently smoothed state value, y^{prv} is the previously smoothed hip angle, y^{cur}_{raw} is the currently sensed original state, α is the smoothing factor. The smoothing factor α = 0.05 (cut-off frequency $f_c \approx 0.84$ Hz) in Eq. (1) was selected to generate the smoothed output torque.

2. Assistive torque from delayed state feedback

Using the defined output state $y(t)$, the assistance torque τ is generated from a combination of appropriate time delays Δt and control gain κ.

$$\tau(t) \quad = \quad \kappa y(t-\Delta t) \tag{2}$$

where Δt is the time-delay and κ is the feedback gain.

3. Synergetic hip extension and flexion assistance

The basic assistance strategy (Supplementary Fig. S1(B)) can be extended for both right/left hip assistive torque generation $\tau_{r,des}$, $\tau_{l,des.}$ as the following form:

Right hip flexion, left hip extension assistance:

$$\tau_{r,des}(t) = -\tau(t) \tag{3}$$

$$\tau_{l,des}(t) = \tau(t)$$

Left hip flexion, right hip extension assistance:

$$\tau_{l,des}(t) = \tau(t) \tag{4}$$

$$\tau_{r,des}(t) = -\tau(t)$$

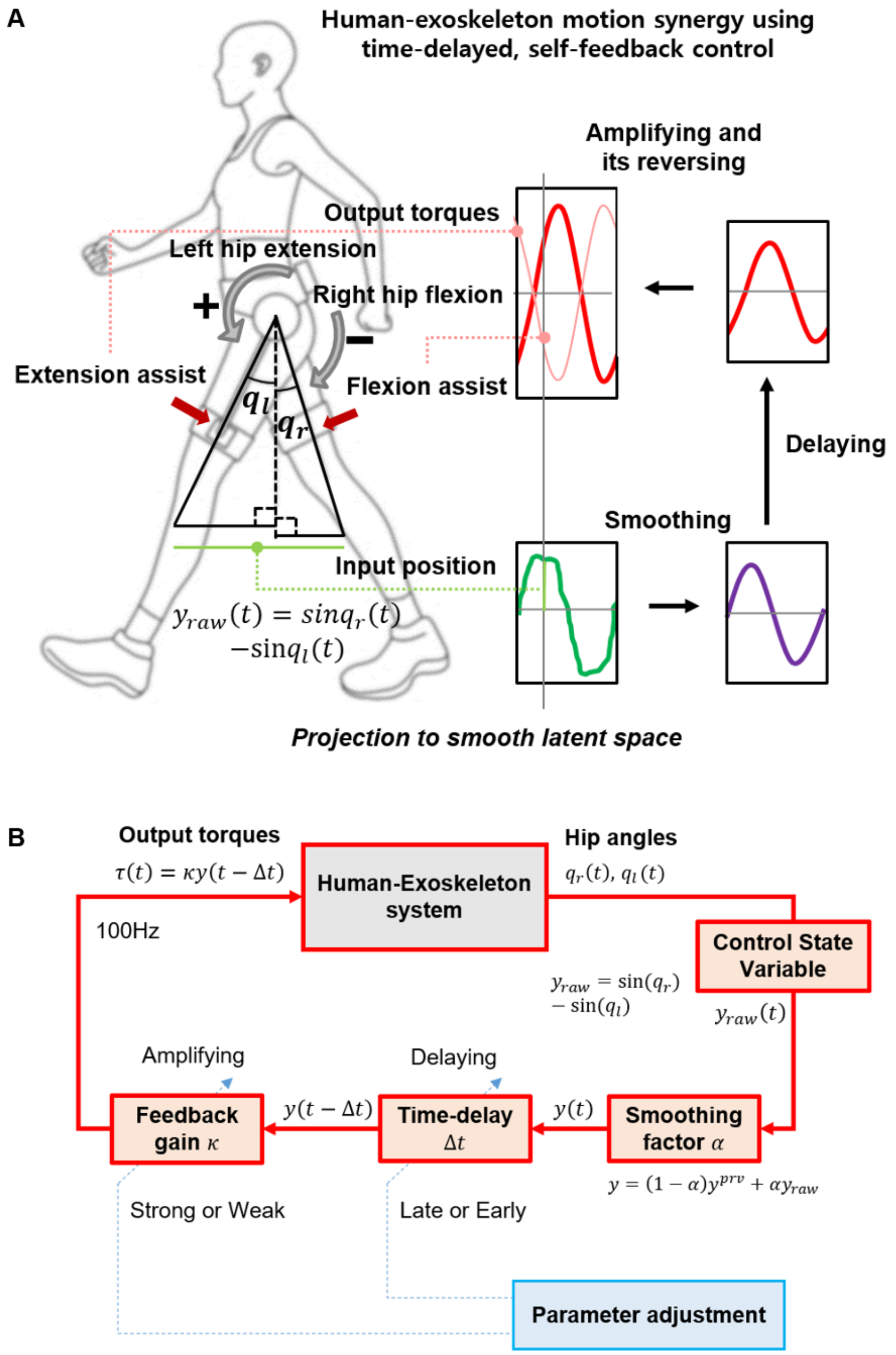
The same hip extension and flexion torques are simultaneously generated for (propulsive) gait synergy.

4. Tunable control parameters of DOFC based assistance

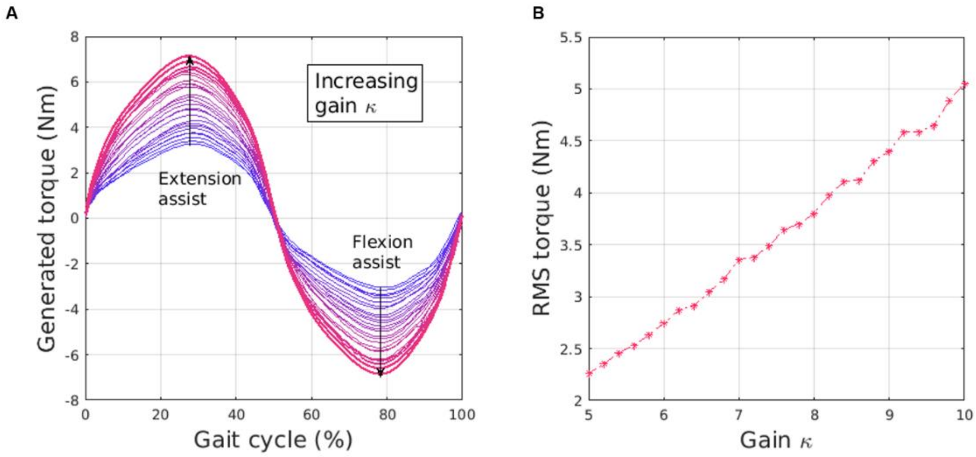
In this controller, there are two main control parameters time-delay Δt and feedback gain κ. By increasing or decreasing the default time-delay value Δt = 0.25 s in Eq. (2), we can smoothly adjust the assistance response. For example, with the maximum swing speed as a reference point (near the intersection of both legs), maximum assistance may come in beforehand (early timing) or may come later (late timing). The self-selected walking speed of the elderly participated was slow, and the default value of 0.25 was used in most cases. If the walking speed is over 4 km/h, it may be necessary to reduce it to 0.2 s for fast response. We can also adjust the strength (strong or weak) by adjusting the default feedback gain κ = 7.0. As shown in Supplementary Fig. S2, we can fine-tune the assist intensity linearly for each patient condition by adjusting the gain value (See the relationship between the root means square (RMS) torque value and gain in Fig. S2(B).

5. Seamless assistance in changing walking speed

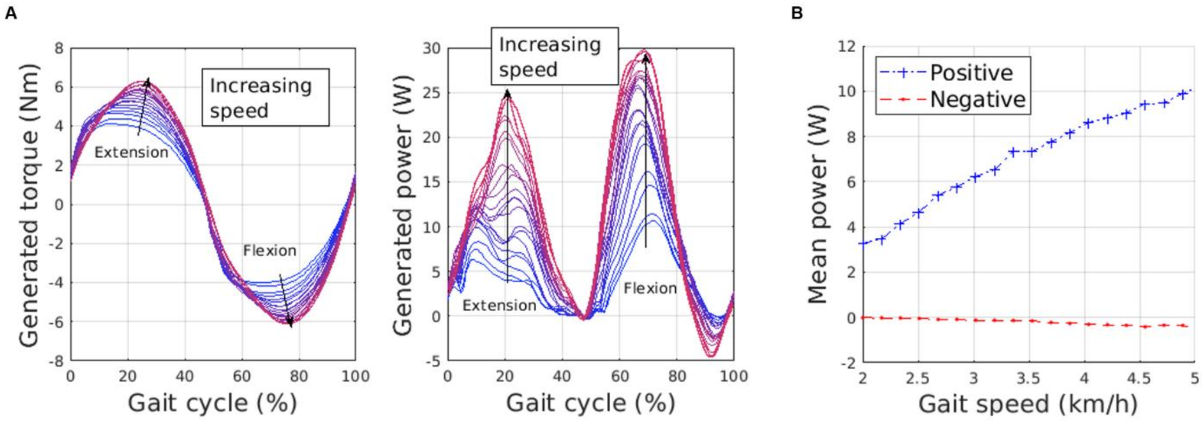
Supplementary Figure S3(A) illustrates how the assistance torque profile changed as the walking speed changed with the fixed delay and gain parameters (Δt = 0.25 s, κ = 8). Human walking requires higher hip power (or torque) as the walking speed increases. Therefore, generating a larger assistive power when a larger power is required may be a desirable characteristic. The large positive (assistive) power compared to the small negative (resistive) power in Supplementary Fig. S3(B) indicates that the DOFC controller can operate under various speed condition with minimum human-exoskeleton mismatch.



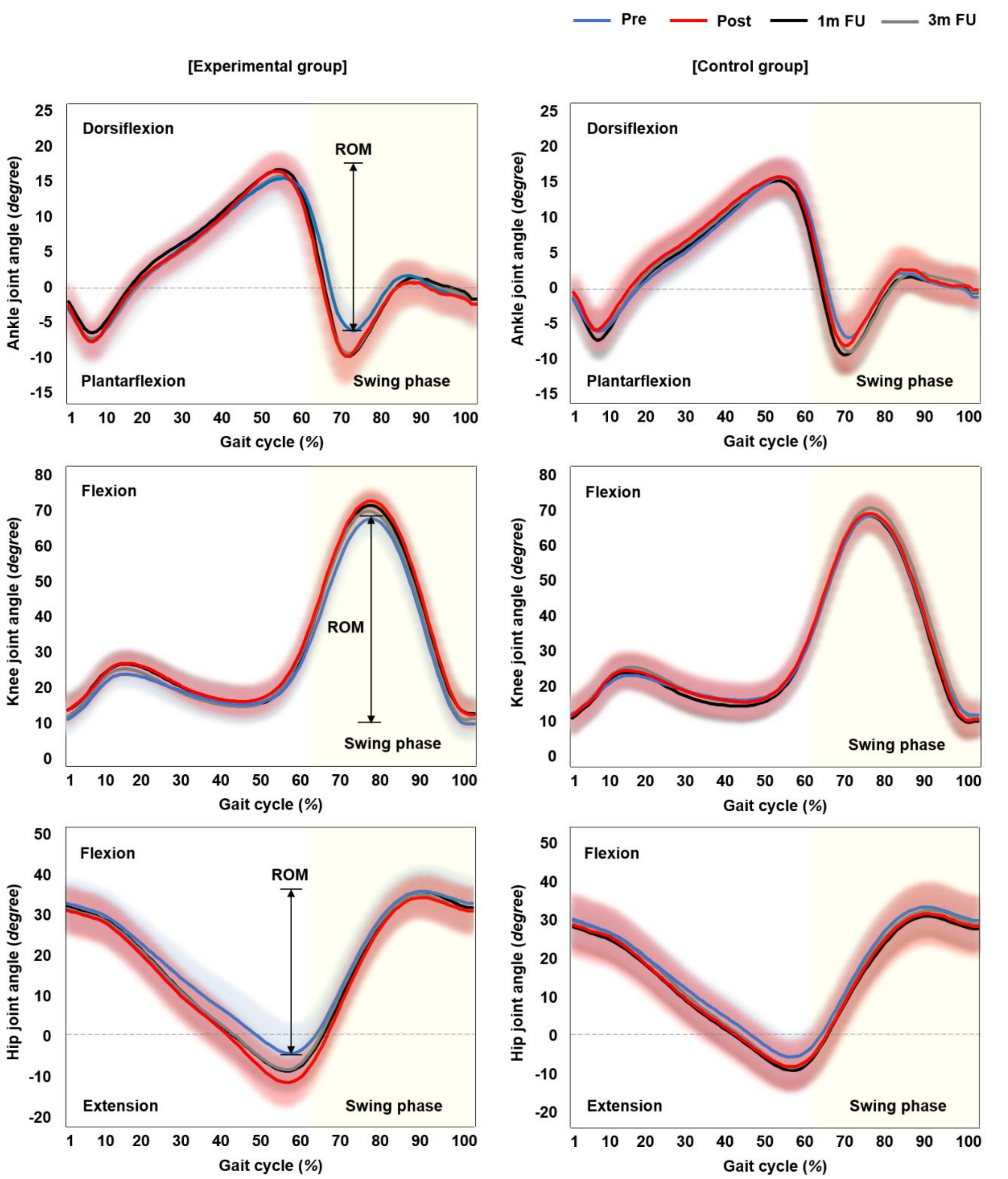
Supplementary Figure S1. Gait assistance strategy with delayed output feedback control. q_r and ql are the right and left hip angles, respectively. Δt is the time-delay and κ is the feedback gain. **(A)** Hip assistance strategy. **(B)** Self-excited feedback control loop.



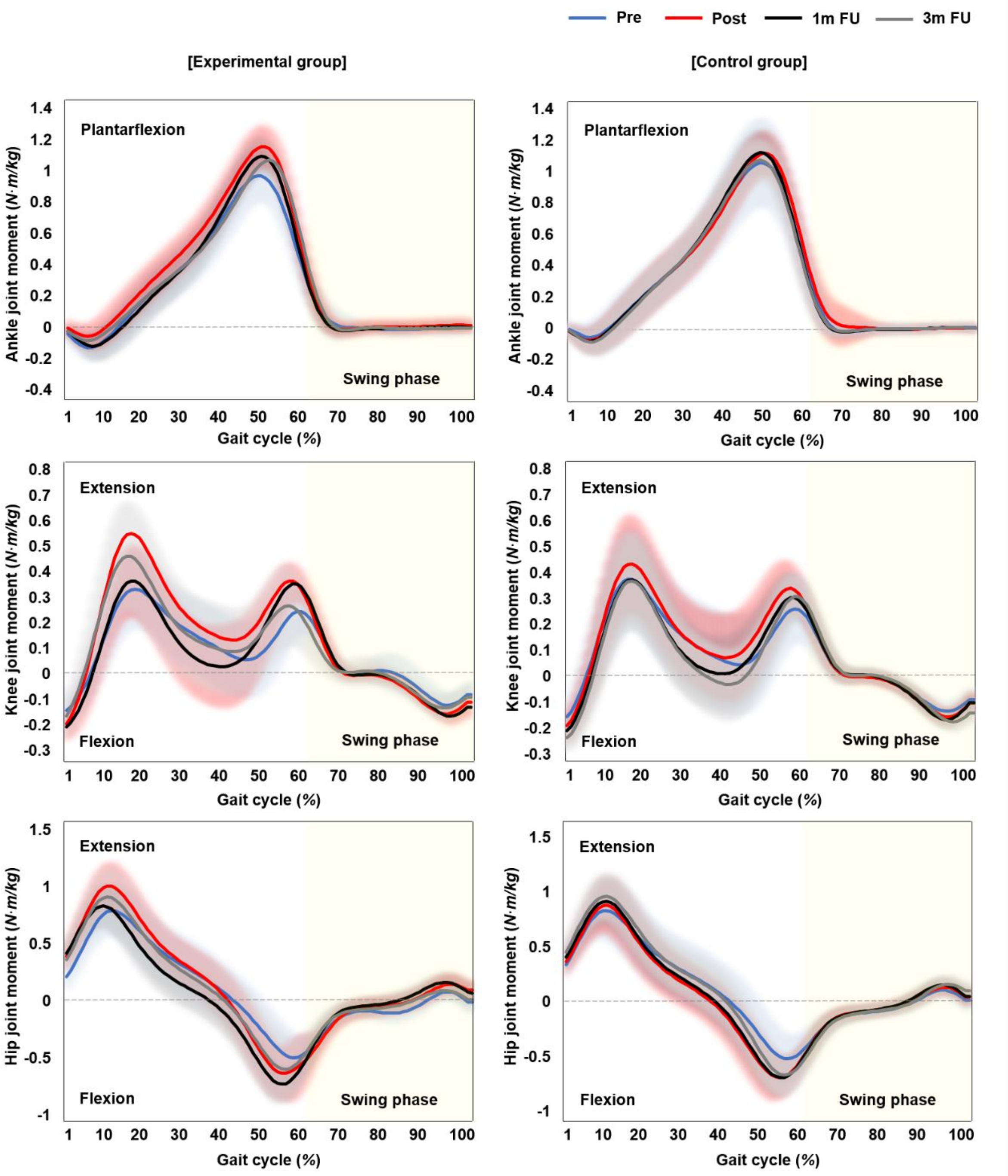
Supplementary Figure S2. Torque changes generated by input gain changes. The feedback gain κ was increased from 5 to 10 with 0.2 increments for every two steps (1 walking cycle). The treadmill walking speed is 4km/h and the time-delay Δt is fixed to 0.25 s. **(A)** Generated torque. **(B)** RMS torque.



Supplementary Figure S3. Torque and power changes generated by walking speed changes. The treadmill speed was increased from 2 to 5 km/h with fixed control parameters $\Delta t = 0.25$ s, $\kappa = 8$. Positive: mean positive power, Negative: mean negative power. **(A)** Generated torque and power. **(B)** Mean power.

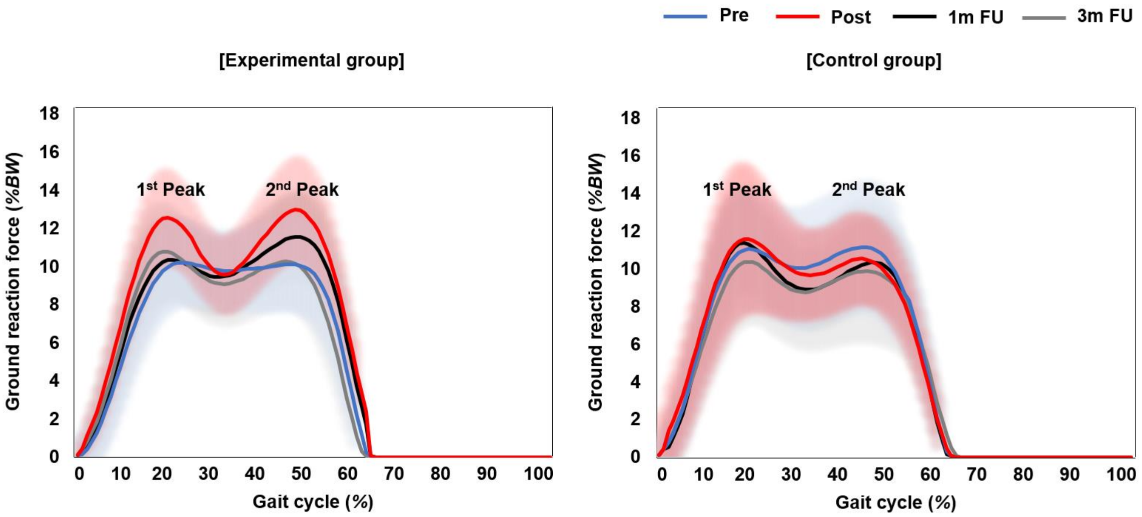


Supplementary Figure S4. Joint angle. Diagrams showing differences in mean joint angle during the gait cycle (%) at Pre, Post, 1m and 3m FU in the experimental and control groups. FU: follow up, ROM: range of motion



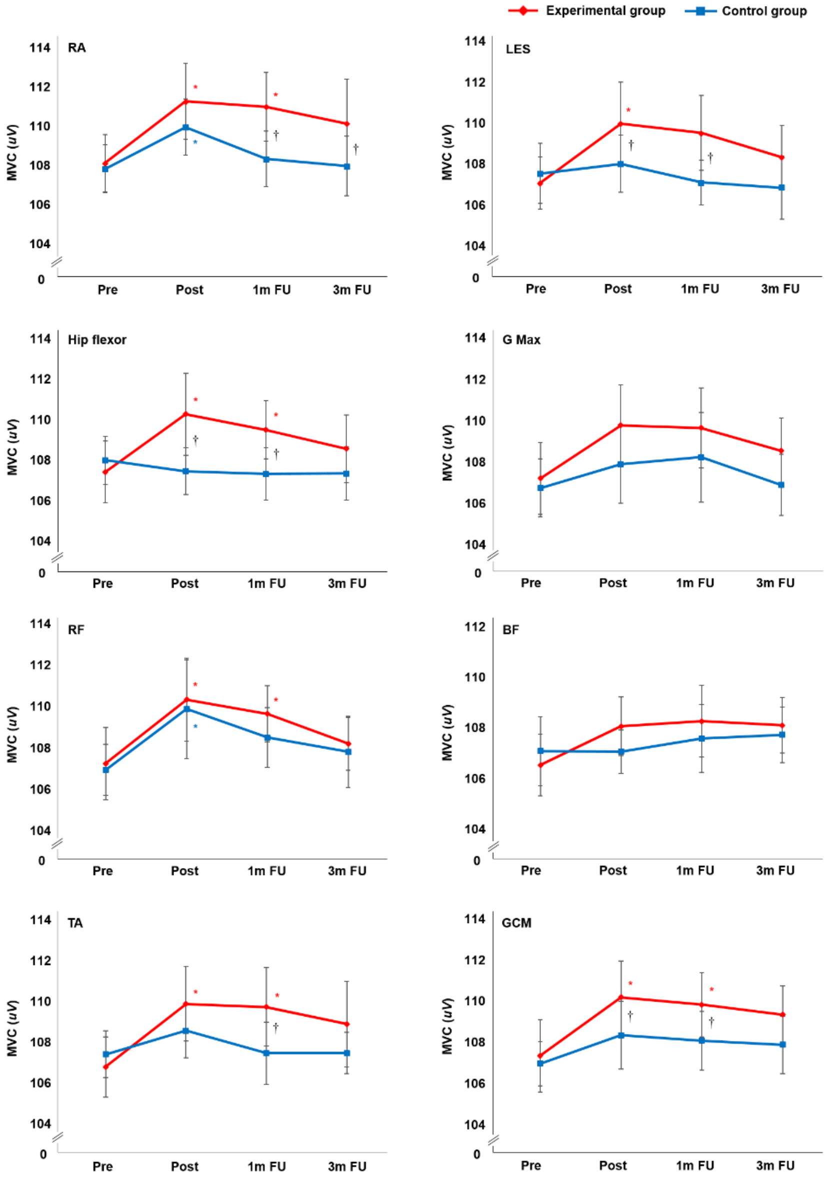
Supplementary Figure S5. Joint moment. Diagrams showing differences in mean joint moment during the gait cycle (%) at Pre, Post, 1m and 3m FU in the experimental and control groups.

FU: follow up



Supplementary Figure S6. Vertical ground reaction force. Diagrams showing differences in mean ground reaction force during the gait cycle (%) at Pre, Post, 1m and 3m FU in the experimental and control groups.

FU: follow up



Supplementary Figure S7. Maximum voluntary contraction. Changes in MVC at Pre, Post, 1m and 3m FU in the experimental and control group and different effects of clinical measures between the experimental and control groups.

FU: follow up, MVC: maximum voluntary contraction, RA: rectus abdominis, LES: lumbar extensor spinae, G Max: gluteus maximus, RF: rectus femoris, BF: biceps femoris, TA: tibialis anterior, GCM: gastrocnemius medialis

*Significant change compared with Pre ($P < 0.05$), †Independent t test ($P < 0.05$)

Supplementary Table S1. Effect of EX1 exercise on muscle effort (%MVC)

	Experimental group				Control group				Between groups
	Pre	Post	1m FU	3m FU	Pre	Post	1m FU	3m FU	*P* value
RA	7.18 (1.34)	6.88 (0.62)*	7.01 (0.74)	7.05 (1.38)	7.70 (1.47)	7.84 (2.82)	7.73 (2.13)	7.73 (1.53)	0.001
LES	26.09 (4.97)	25.09 (4.87)**	25.22 (4.29)**	25.41 (3.57)*	25.15 (4.68)	24.71 (5.30)	25.03 (5.82)	24.90 (4.78)	0.448
Hip flexor	14.46 (3.49)	13.44 (2.33)**	13.65 (3.78)**	14.04 (4.67)	13.89 (3.74)	14.02 (3.80)	14.20 (4.03)	14.58 (4.23)	0.580
G Max	21.73 (5.47)	21.30 (5.97)	21.29 (6.66)	21.56 (5.65)	22.80 (6.83)	21.71 (7.90)	22.44 (7.67)	22.33 (6.01)	0.339
RF	19.91 (5.87)	18.52 (7.97)*	18.73 (7.64)	18.83 (6.66)	19.87 (6.26)	18.89 (8.39)*	19.21 (7.53)	19.23 (6.35)	0.751
BF	17.66 (5.98)	16.76 (8.22)*	16.77 (9.96)	17.25 (6.46)	18.18 (7.13)	17.41 (9.26)	17.47 (9.86)	17.64 (8.24)	0.620
TA	20.78 (7.52)	19.08 (6.90)**	19.37 (5.22)*	19.93 (3.91)	20.70 (6.58)	19.85 (6.57)**	19.86 (7.84)*	20.36 (9.01)	0.667
GCM	22.78 (12.58)	21.86 (10.04)*	21.91 (12.21)*	22.20 (13.19)*	23.03 (10.35)	22.74 (9.25)	22.71 (9.12)	22.77 (10.53)	0.687

Data are expressed as the mean (Standard deviation).

*Significant change compared with Pre ($P < 0.05$), **Significant change compared with Pre ($P < 0.01$)

FU: follow up , MVC: maximum voluntary contraction, RA: rectus abdominis, LES: lumbar extensor spinae, G Max: gluteus maximus, RF: rectus femoris, BF: biceps femoris, TA: tibialis anterior, GCM: gastrocnemius medialis