

Supplementary Information for

Interaction-based rapid heuristic optimization of exoskeleton assistance during walking

Jianyu Chen^{1,2,3}, Weihao Yin^{1,2,4}, Jianquan Ding^{1,2,4}, Jiaqi Han^{1,2,4}, Lihai Zhang^{5,6},
Jianda Han^{1,2,4}, Juanjuan Zhang^{1,2,4*}

¹College of Artificial Intelligence, Nankai University, Tianjin, PRC.

²Institute of Robotics and Automatic Information System, Nankai University, Tianjin, PRC.

³Hangzhou Zhiyuan Research Institute Co., Ltd, Zhejiang, PRC.

⁴Academy for Advanced Interdisciplinary Studies, Nankai University, Tianjin, PRC.

⁵National Clinical Research Center for Orthopedics, Sports Medicine and Rehabilitation, Beijing, PRC.

⁶School of Medicine, Nankai University, Tianjin, PRC.

*To whom correspondence should be addressed; E-mail: juanjuanzhang@nankai.edu.cn.

This PDF file includes:

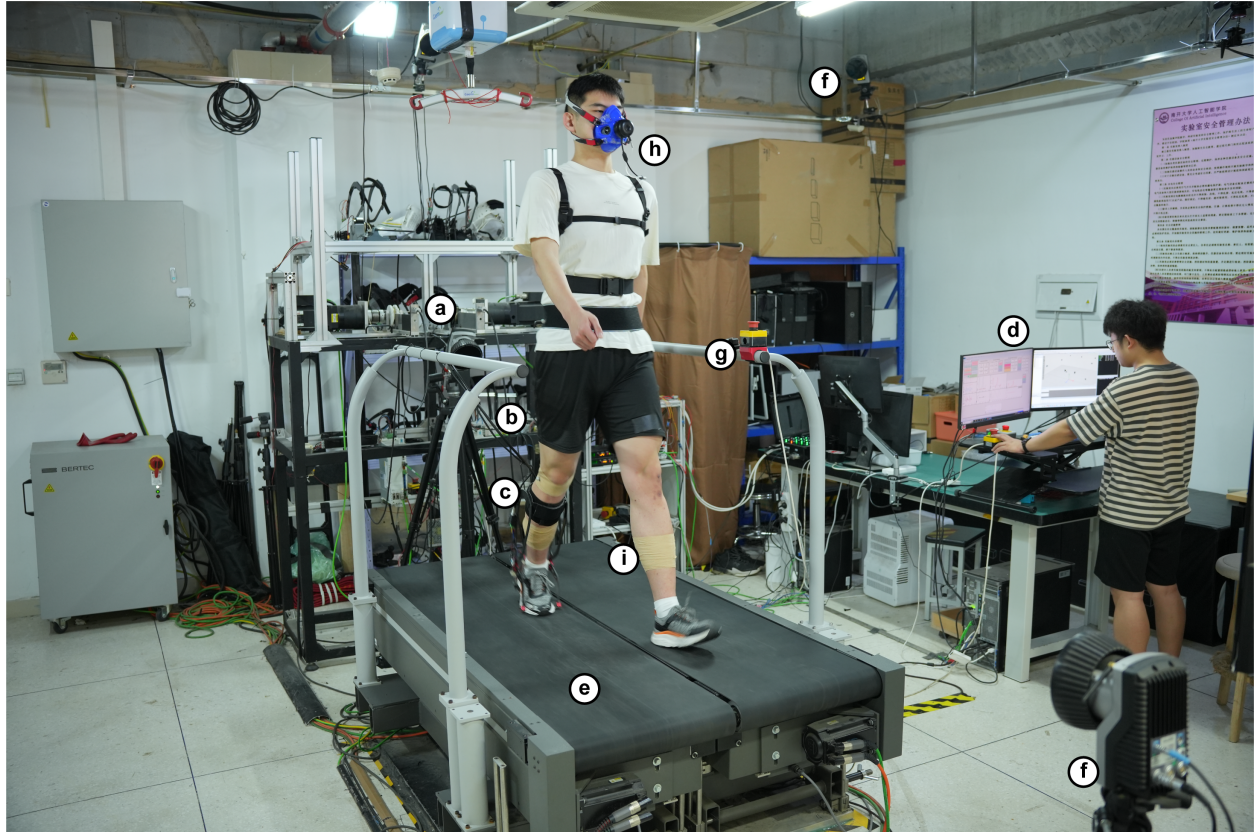
Supplementary Figures 1 to 14

Supplementary Tables 1 to 4

Other Supplementary Materials for this manuscript:

Supplementary Movie 1

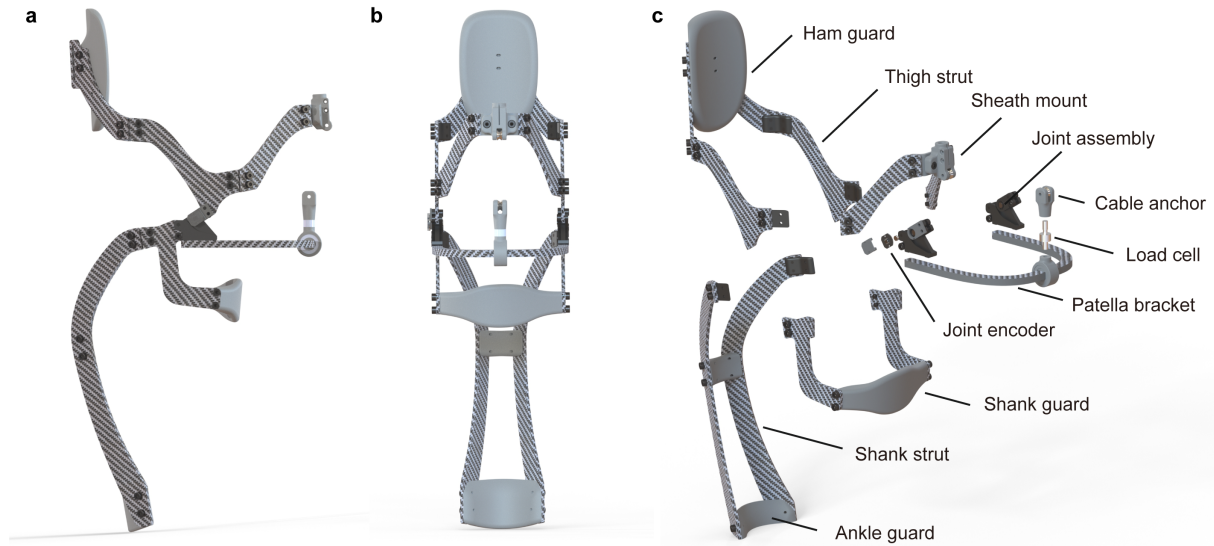
Supplementary Data 1



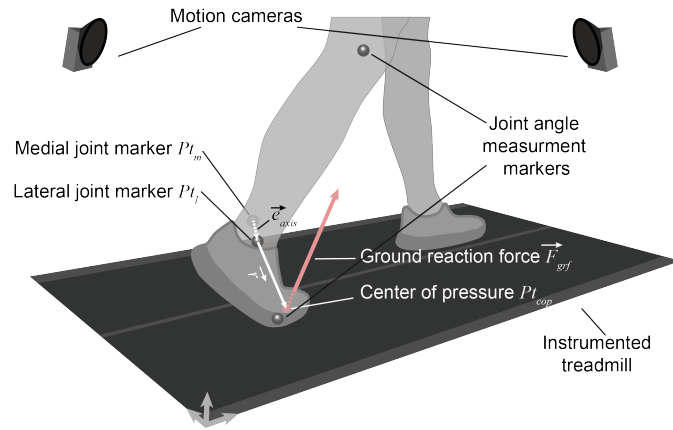
Supplementary Figure 1 | Photograph of the tethered exoskeleton experimental setup. The tethered exoskeleton system consisted of (a) powerful off-board motors; (b) flexible Bowden cables that transmitted the assistance force from motors to exoskeleton end-effectors; (c) a lightweight, compliant exoskeleton end-effector worn on the right ankle in the main study; (d) a real-time controller measuring exoskeleton signals and calculating the motor driving commands to provide torque assistance; (e) an instrumented split-belt treadmill that measured the ground reaction forces; (f) ten optical cameras capturing human motion; (g) an emergency stop button for safety; (h) a portable respiratory equipment to measure the metabolic energy consumption; (i) a wireless electromyography system measuring the muscle activity.



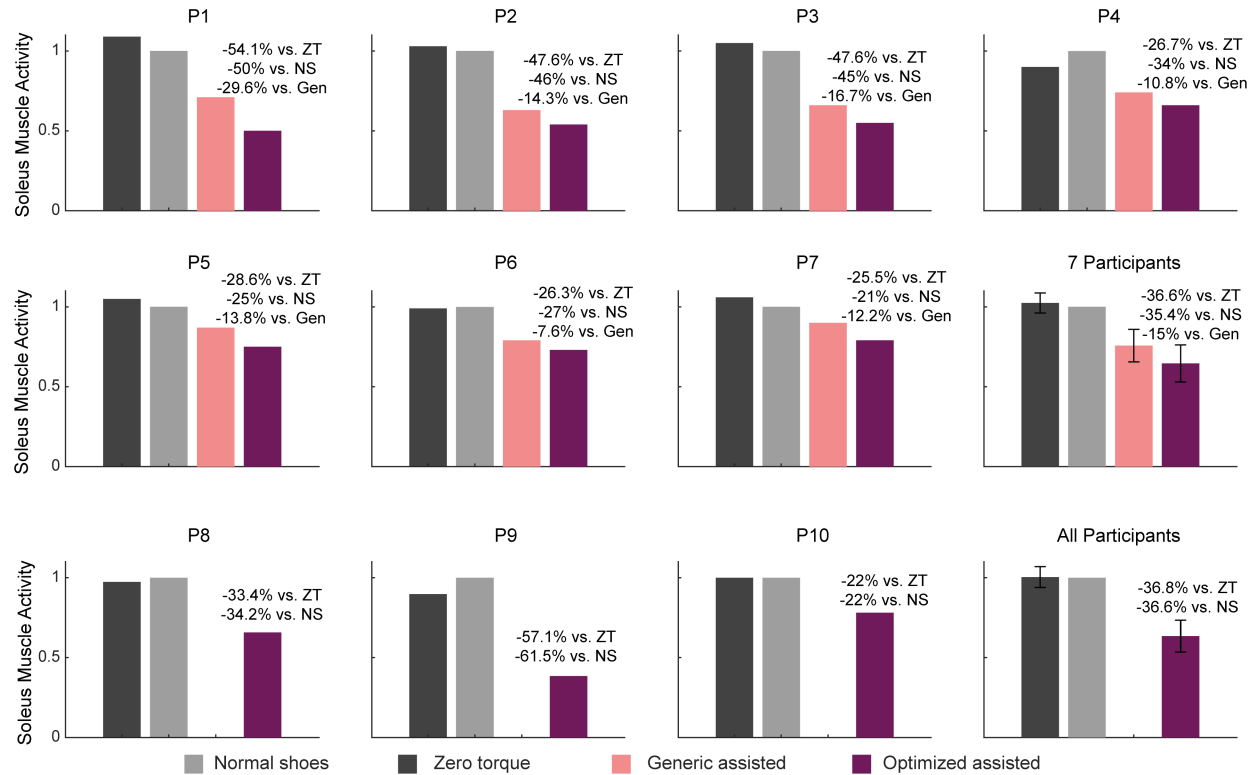
Supplementary Figure 2 | Photograph of outdoor walking with mobile ankle exoskeleton. The mobile unilateral ankle exoskeleton consisted of (a) a lightweight ankle exoskeleton end-effector worn on the right ankle; (b) a 4700-mA h portable lithium battery that allows for 3 hours of continuous assisted walking; (c) a waist actuation pack; (d) flexible Bowden and signal cables that connected the end-effector and the actuation system; (e) an arrayed pressure insole; the waist actuation pack comprised (f) two brushless DC geared motors; (g) an embedded control circuit board that implemented real-time closed-loop control and assistance optimization; (h) output pulleys driving the inner Bowden cables and protected by (i) the pulley covers; (j) two Bowden mounts that fixed the Bowden sheath; (k) two bridging boards connecting the signal cables. The pressure insole comprised (l) an acquisition unit and (m) a filmy insole containing 16 arrayed pressure sensors, with (n) the forefoot zone sensors used for outdoor ankle moment estimation.



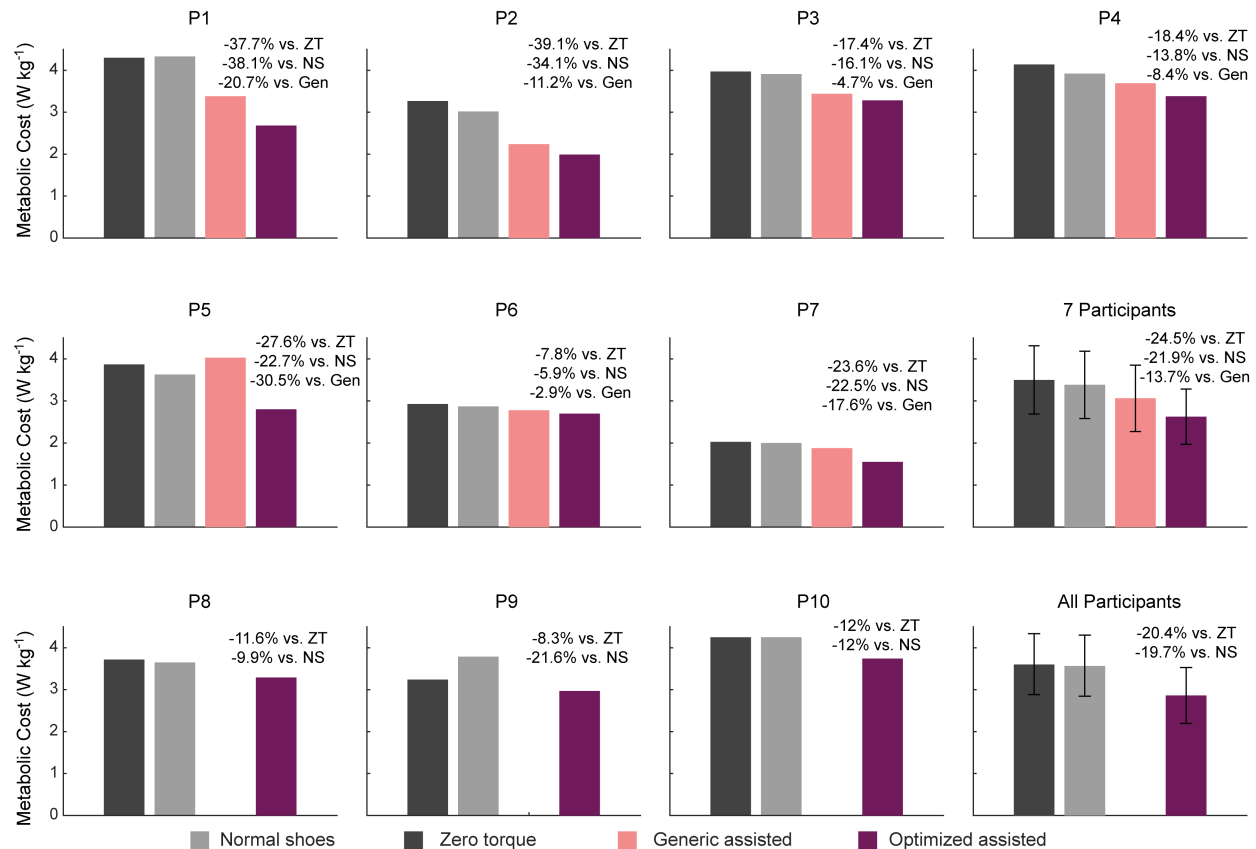
Supplementary Figure 3 | Lateral, front and exploded views of the knee exoskeleton end-effector used in generality study. The end-effector interfaced with human leg by the ham, shank, and ankle guards. A U-shaped patella bracket provided a long driving lever arm and series elasticity. Bowden sheath was fixed to the mount on the thigh segment, with its inner cable connected to the anchor of the patella bracket and providing extension assistance. Joint assemblies had a rotational range from -5° to 90° , preventing hyperextension of the knee.



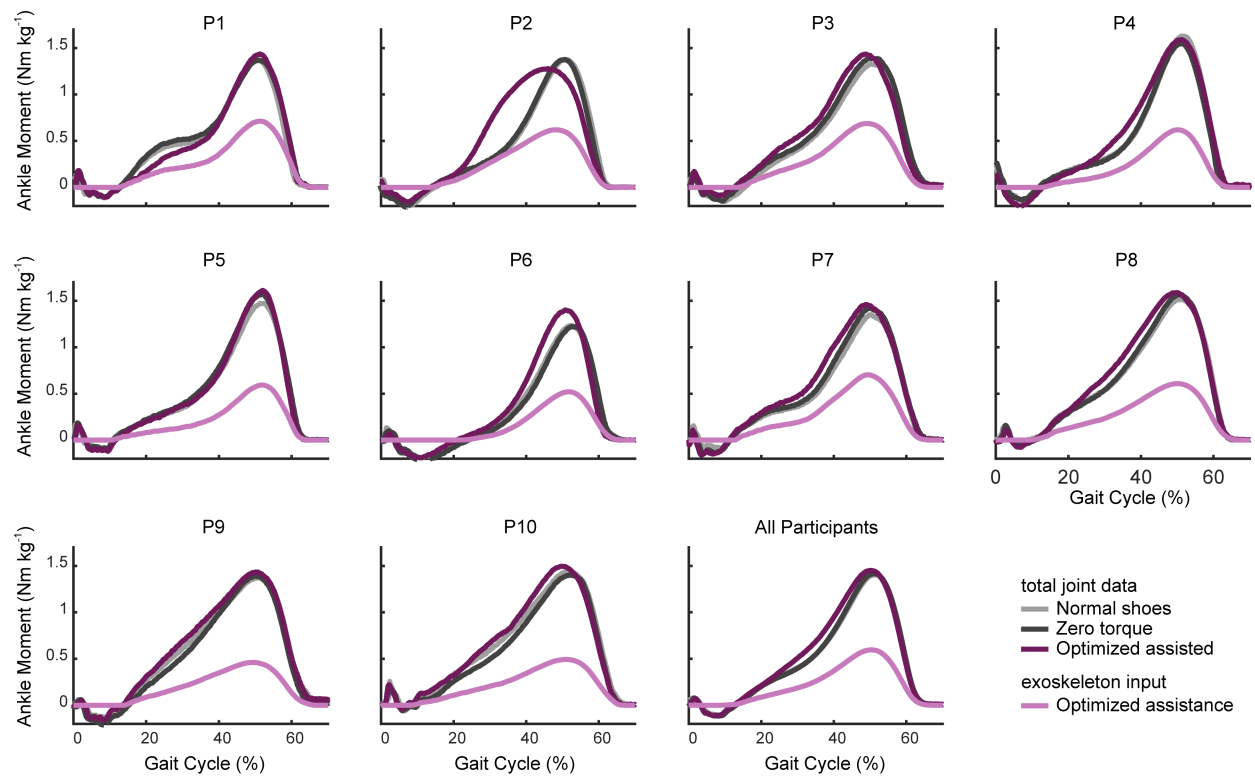
Supplementary Figure 4 | Schematic of real-time biomechanics estimation. The real-time human-device joint moments during the tethered exoskeleton study were estimated from the ground reaction force measured by instrumented split-belt treadmill and the joint position detected by motion capture cameras.



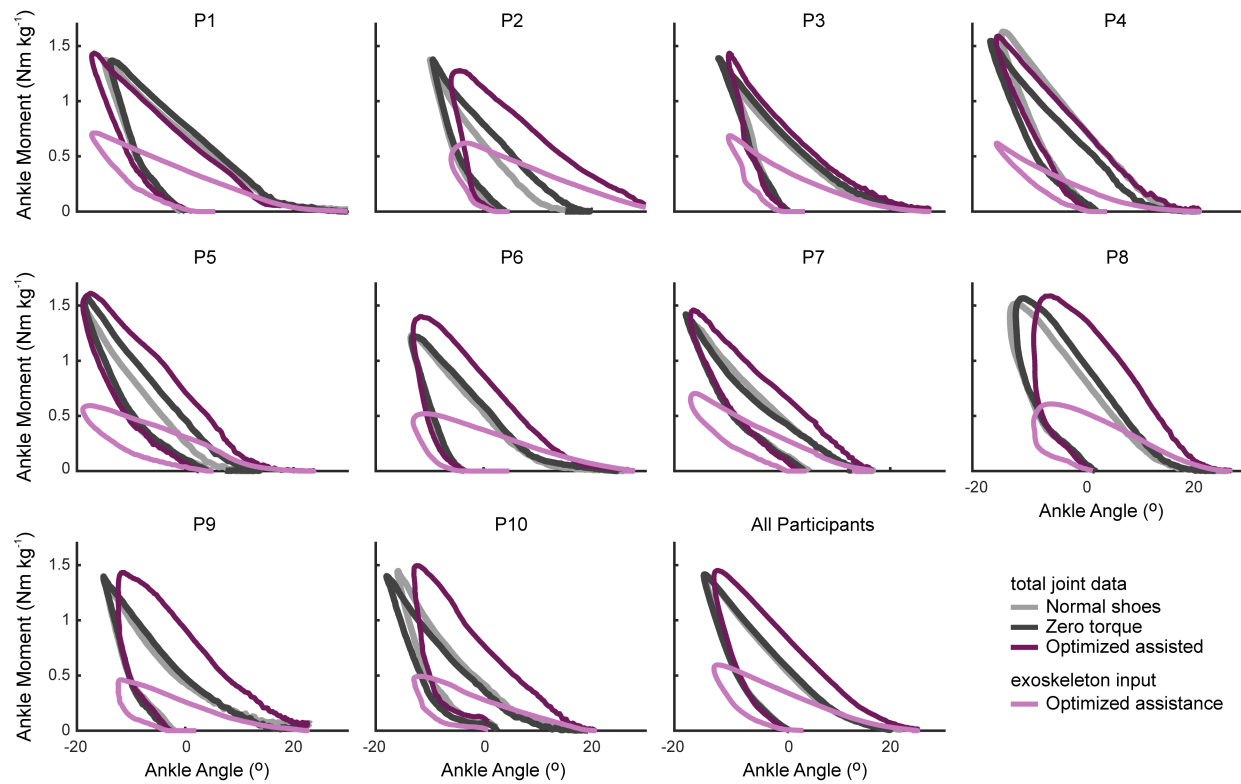
Supplementary Figure 5 | Soleus muscle activity of walking for individual participants in the main study. Human calf muscle economy was significantly improved for all participants in validation. Optimized assistance reduced the activity of soleus muscle on the assisted side by $36.8 \pm 13.3\%$ (mean $\pm$ standard deviation) compared to zero-torque ($n=10$, paired t test, Holm-Bonferroni correction, adjusted $p = 1.1E-4$), ranging from 22% to 57.1%, by $36.6 \pm 13.6\%$ compared to normal-shoe mode ($n=10$, paired t test, adjusted $p = 1.1E-4$), ranging from 21% to 61.5%, and by $15.0 \pm 7.0\%$ compared to the generic condition ($n=7$, paired t test, adjusted $p = 3.0E-3$), ranging from 7.6% to 29.6%.



Supplementary Figure 6 | Metabolic cost of walking for individual participants in the main study. Optimized assistance reduced participants' net walking metabolic cost by $20.4 \pm 11.4\%$ compared to zero-torque ($n=10$, paired t test, adjusted $p = 3.0E-3$), ranging from 7.8% to 39.1%, and by $19.7 \pm 10.3\%$ compared to normal-shoe mode ($n=10$, paired t test, adjusted $p = 3.0E-3$), ranging from 5.9% to 38.1%. Optimized assistance led to lower metabolic costs compared to the generic assistance for 7 of the 10 participants, with a reduction of $13.7 \pm 9.8\%$ ($n=7$, paired t test, adjusted $p = 2.8E-2$), ranging from 2.9% to 30.5%.

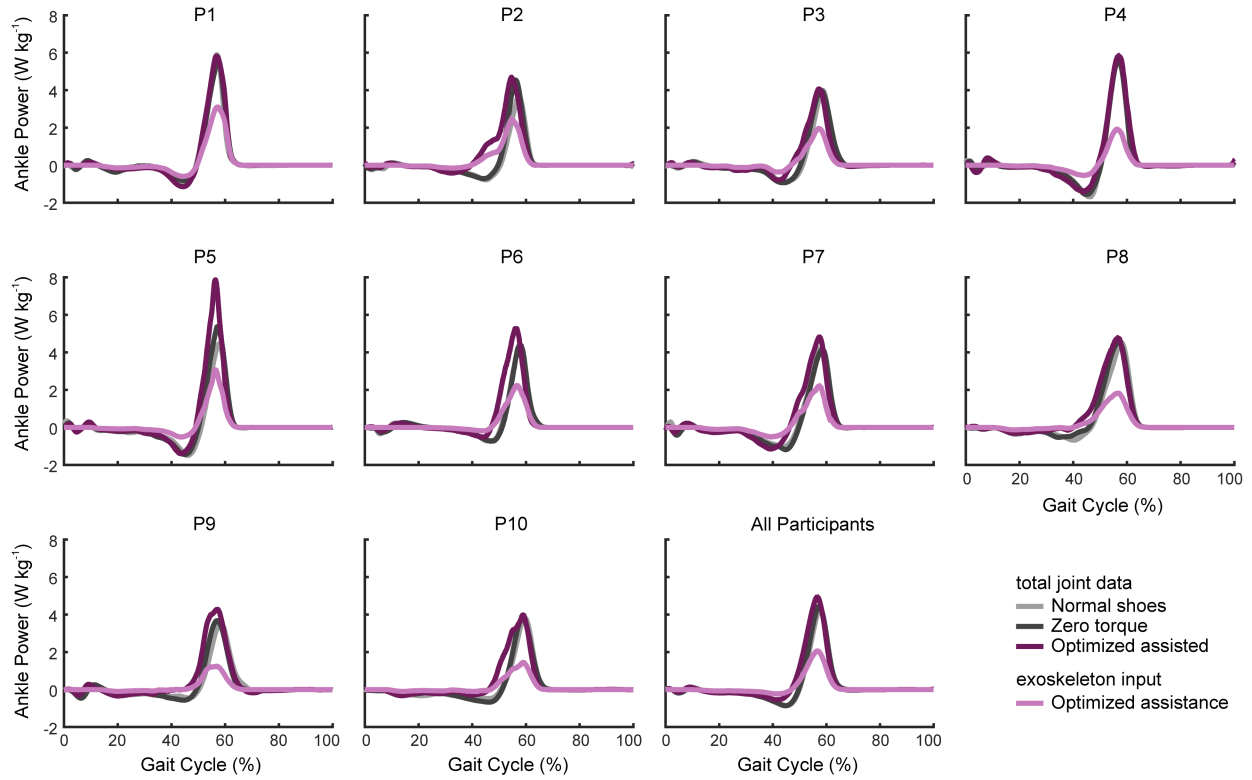


Supplementary Figure 7 | Ankle moments and optimized assistance for each individual in the main study. Total ankle moments of different conditions (optimized, zero-torque and normal-shoe) and optimized assistance torque for each individual participants in the main study.

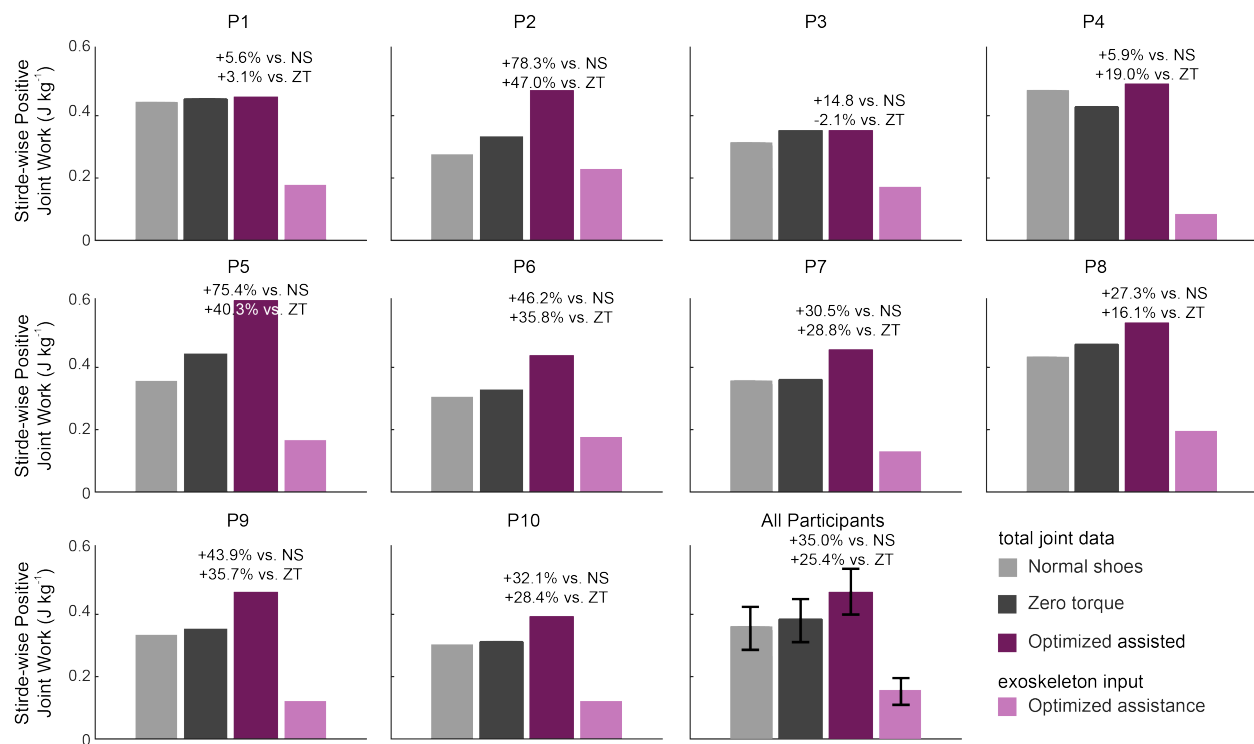


Supplementary Figure 8 | Work loops during walking for each individual in the main study.

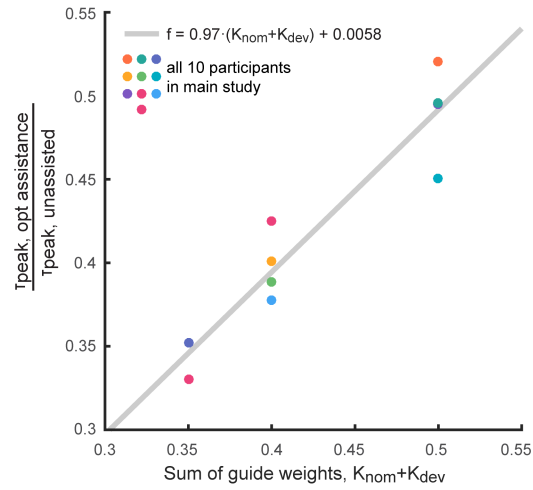
Average joint moments versus angle curves of different conditions (normal-shoe, zero-torque, and optimized) and optimized assistance torque versus angle curves for each individual participants in the main study.



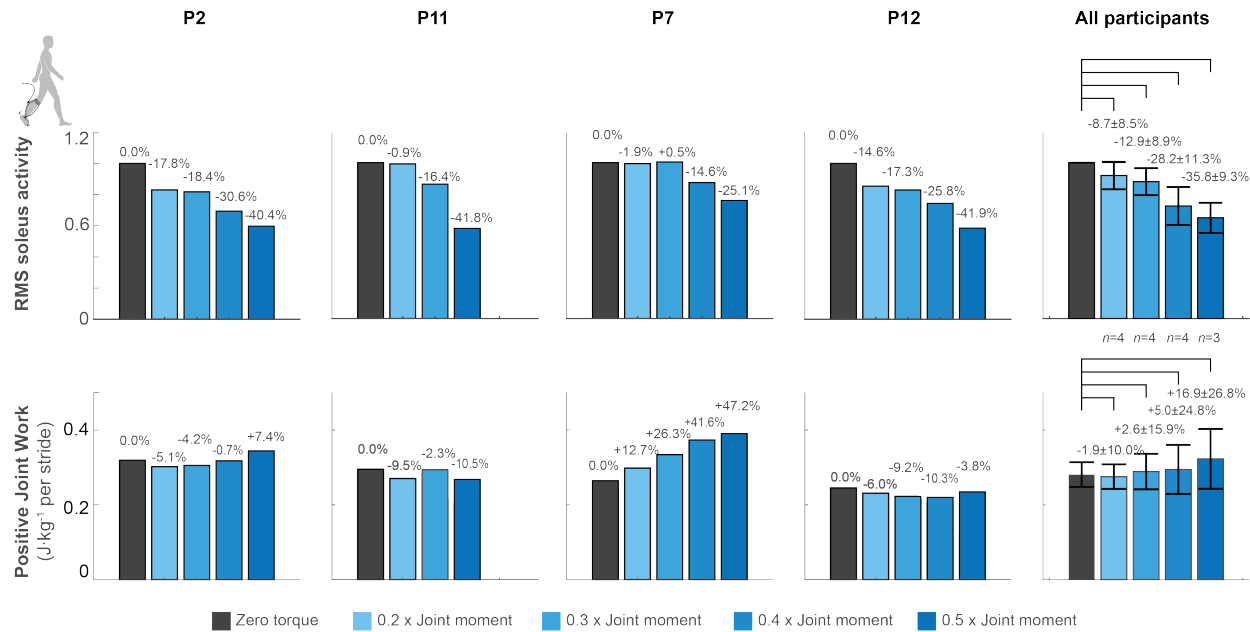
Supplementary Figure 9 | Total ankle power in various conditions (optimized assisted, zero-torque and normal-shoe) and exoskeleton input power under optimized assistance for each individual in the main study.



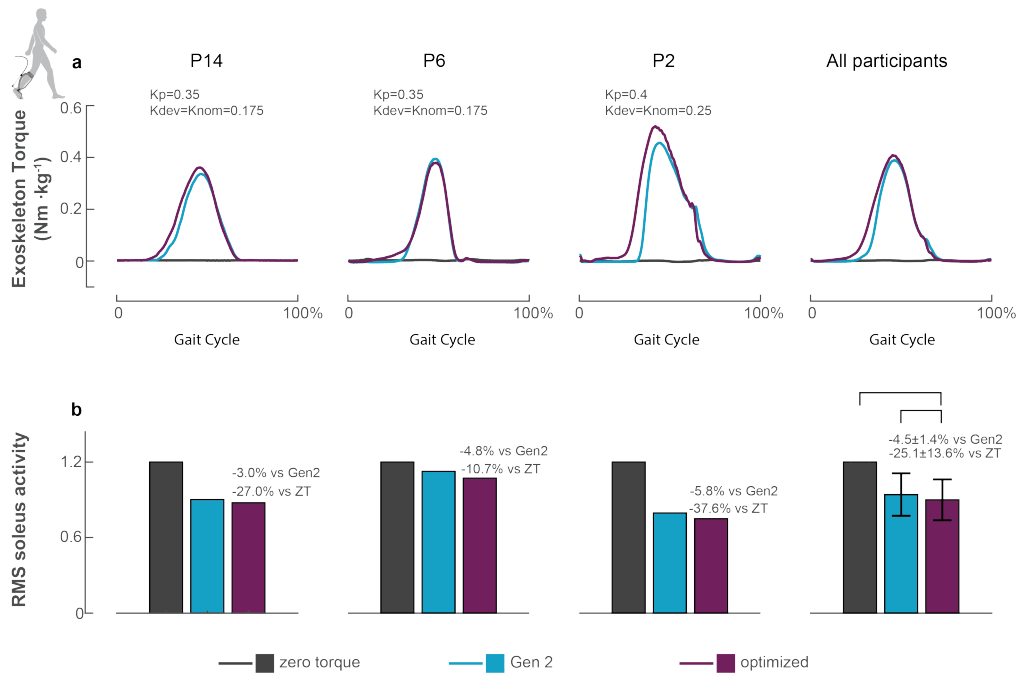
Supplementary Figure 10 | Stride-wise positive ankle mechanical work and exoskeleton assisting work for each individual in the main study. Optimized assistance increased average positive ankle work by $25.4 \pm 15.7\%$ ($n=10$, paired t test, adjusted $p = 3.0E-3$) compared to zero-torque, ranging from -2.1% to 47.0%, and by $36.0 \pm 25.6\%$ ($n=10$, paired t test, adjusted $p = 3.0E-3$) compared to wearing normal shoes, ranging from 3.2% to 221.1%.



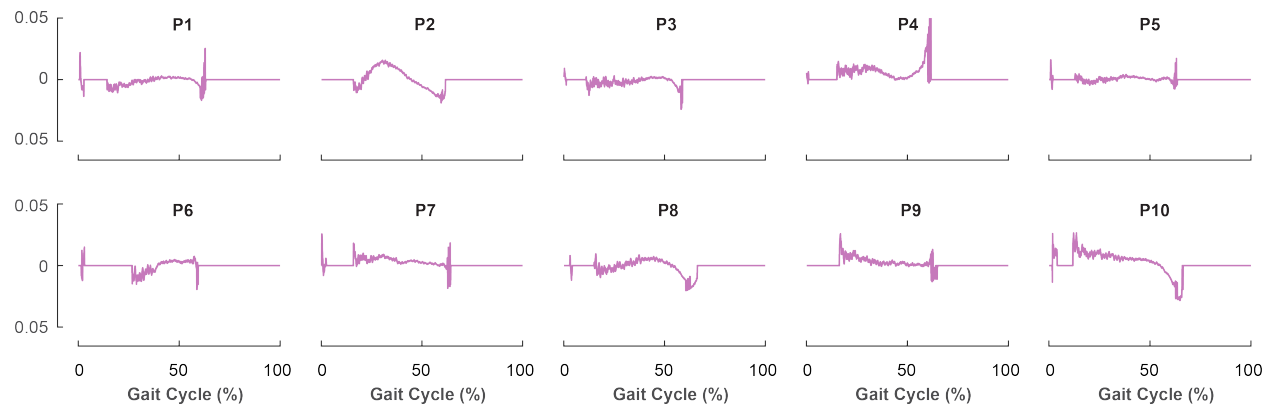
Supplementary Figure 11 | The peak optimized assistance torque relative to the peak unassisted torque for participants in main study versus respective guide weights.



Supplementary Figure 12 | Experiment results of asserting exoskeleton assistance torque proportional to real-time joint moment estimates. Soleus activity reduced $8.7 \pm 8.5\%$ ($K_f = 0.2$, $n = 4$, paired t test, Holm-adjusted $P = 0.67$), $12.9 \pm 8.9\%$ ($K_f = 0.3$, $n = 4$, adjusted $P = 0.38$), $28.2 \pm 11.3\%$ ($K_f = 0.4$, $n = 4$, adjusted $P = 0.12$) and $35.8 \pm 9.3\%$ ($K_f = 0.5$, $n = 3$, adjusted $P = 0.15$) with the four proportional gains respectively, from zero-torque condition. Stride-wise positive ankle work increased by $-1.9 \pm 10.0\%$ ($K_f = 0.2$, $n = 4$, paired t test, adjusted $P = 1$), $2.6 \pm 15.9\%$ ($K_f = 0.3$, $n = 4$, paired t test, adjusted $P = 0.77$), $5.0 \pm 24.8\%$ ($K_f = 0.4$, $n = 4$, paired t test, adjusted $P = 1$) and $16.9 \pm 26.8\%$ ($K_f = 0.5$, $n = 3$, paired t test, adjusted $P = 1$).



Supplementary Figure 13 | Experimental comparison between the proposed method and as- serting exoskeleton assistance torque proportional to zero-torque joint moment. a, Exoskele- ton assistance torque profiles of various participants. **b,** Soleus activity of optimized assistance decreased by $25.1 \pm 13.6\%$ ($n = 3$, 10.7% to 37.6%, adjusted $P = 0.85$) from zero-torque mode, and by $4.5 \pm 1.4\%$ ($n = 3$, 3.0% to 5.8%, adjusted $P = 0.70$) from Gen2 mode.



Supplementary Figure 14 | Estimated ρ value along the stride cycle averaged through optimization for all 10 participants of main experimental study.

Supplementary Table 1 | Participant characteristics

Participant	Sex	Body mass (kg)	Height (m)	Age (yrs)
P1	M	68	1.72	25
P2	M	83	1.88	23
P3	M	75	1.75	26
P4	F	70	1.70	23
P5	F	65	1.70	24
P6	M	72	1.75	24
P7	M	65	1.80	23
P8	M	51	1.65	23
P9	M	63	1.73	23
P10	M	70	1.75	24
Mean $\pm$ SD	8 M, 2 F	68.2 $\pm$ 8.4	1.74 $\pm$ 0.06	23.8 $\pm$ 1.0

Supplementary Table 2 | Optimization parameters and resulted peak torque

Participant	K_{nom}	K_{dev}	$K_{nom} + K_{dev}$ ($2K_{nom}$, or $2K_{dev}$)	τ_{peak} (Nm kg ⁻¹)	τ_{peak} (% of peak unassisted torque)
P1	0.25	0.25	0.5	0.712	52.1
P2	0.25	0.25	0.5	0.620	45.0
P3	0.25	0.25	0.5	0.687	49.5
P4	0.2	0.2	0.4	0.619	40.1
P5	0.2	0.2	0.4	0.593	37.8
P6	0.2	0.2	0.4	0.520	42.5
P7	0.25	0.25	0.5	0.704	49.6
P8	0.2	0.2	0.4	0.609	38.9
P9	0.175	0.175	0.35	0.461	33.0
P10	0.175	0.175	0.35	0.493	35.2

Supplementary Table 3 | Proportional Real-time Joint Moment Participant characteristics

Participant	Sex	Body mass (kg)	Height (m)	Age (yrs)	Succeeded?	In main study?
P2	M	83	1.88	25	Yes	Yes
P5	F	65	1.70	26	No	Yes
P7	M	63	1.80	25	Yes	Yes
P11	M	75	1.85	23	Yes	No
P12	M	70	1.78	24	Yes	No
P13	F	52	1.72	23	No	No
Mean $\pm$ SD	4 M, 2 F	68.0 $\pm$ 10.7	1.79 $\pm$ 0.07	24.3 $\pm$ 1.2	Both	
Mean $\pm$ SD	4 M	72.8 $\pm$ 8.4	1.83 $\pm$ 0.05	24.3 $\pm$ 0.96	Yes	

Supplementary Table 4 | Proportional Zero-torque Joint Moment Participant characteristics

Participant	Sex	Body mass (kg)	Height (m)	Age (yrs)	In main study?	K_{dev}, K_{nom}, K_p
P14	M	80	1.75	23	No	0.175, 0.175, 0.35
P6	M	67	1.75	25	Yes	0.175, 0.175, 0.35
P2	M	82	1.88	26	Yes	0.2, 0.2, 0.5
Mean $\pm$ SD	3 M	76.3 $\pm$ 8.1	1.79 $\pm$ 0.08	24.7 $\pm$ 1.5		