Exploring the Impact of Passive Ankle Exoskeletons on Lower-Limb Neuromechanics during Walking on Sloped Surfaces: Implications for Device Design

James L. Williamson[1*], Glen A. Lichtwark[2], Taylor J. M. Dick[1]

[1]School of Biomedical Sciences, University of Queensland, St Lucia, Queensland, Australia; t.dick@uq.edu.au

[2]School of Exercise & Nutrition Sciences, Queensland University of Technology, Queensland Australia; glen.lichtwark@qut.edu.au

[*]Corresponding Author

*** Correspondence: James Williamson (0000-0001-6079-4947)**

Email: james.williamson@uq.net.au

Tables and Figures

Table S1. Peak plantarflexion, peak dorsiflexion, peak knee extension, peak knee flexion, peak hip extension, and peak hip flexion joint angles during level, incline, and decline walking, with and without exoskeleton assistance.

	Joint angle (°)	0 Nm rad^{-1}	50 Nm rad^{-1}	120 Nm rad^{-1}	220 Nm rad^{-1}	280 Nm rad^{-1}
Level	**peak plantar-flexion**	112.5 ± 6.5	112.3 ± 5.7	112.5 ± 5.4	112.8 ± 5.8	112.2 ± 6.1
	peak dorsiflexion	80.9 ± 5.5	81.3 ± 6.0	81.6 ± 6.1	82.4 ± 6.1 *	81.6 ± 6.1
	peak knee extension	176.1 ± 1.6	176.9 ± 1.0 *	176.8 ± 1.1 *	176.9 ± 1.1	176.5 ± 1.0
	peak knee flexion	116.2 ± 3.9	114.6 ±5 .0	115.3 ± 4.7	115.7 ± 4.1	115.7 ± 4.1
	peak hip extension	192.7 ± 3.7	193.3 ± 3.8	193.7 ± 3.2	193.5 ± 3.5	193.2 ± 3.6
	peak hip flexion	150.6 ± 4.8	150.7 ± 5.3	150.2 ± 5.2	150.4 ± 5.3	150.3 ± 5.3
Incline	**peak plantar-flexion**	114.1 ± 7.8	114 ± 7.4	113.6 ± 7.6	114 ±7 .2	114.2 ± 7.6
	peak dorsiflexion	78.7 ± 5.1	79.6 ± 5.5	79.9 ± 5.2 *	80.6 ± 5.8 *	80 ± 5.6 *
	peak knee extension	174 ± 2.5	174.4 ± 2.5	174.7 ± 2.8	174.7 ± 2.3	174 ± 2.3
	peak knee flexion	119.0 ± 3.8	117.3 ± 4.1	118 ± 4.6	117.9 ± 5.0	117.3 ± 3.8
	peak hip extension	190.5 ± 4.5	191.4 ± 3.9	191.0 ± 4.39	190.2 ± 4.1	190.0 ± 4.0
	peak hip flexion	139.6 ± 5.3	139.1 ± 5.4	139.0 ± 5.0	138.8 ± 4.8	139.0 ± 5.6
Decline	**peak plantar-flexion**	108.8 ± 3.7	109.2 ± 3.4	108.6 ± 4.5	108.9 ± 3.5	108.2 ± 4.3
	peak dorsiflexion	81.0 ± 3.6	80.7 ± 4.2	81.4 ± 6.1	81.9 ± 5.9	80.3 ± 5.3
	peak knee extension	176.2 ± 1.9	176.7 ± 1.2	176.7 ± 1.3	176.9 ± 1.0	176.6 ± 1.1
	peak knee flexion	112.6 ± 4.8	111.7 ± 5.2	112.1 ± 5.2	112.0 ± 5.3	112 ± 4.9
	peak hip extension	190.8 ± 4.1	191.0 ± 4.4	192.1 ± 3.9	191.4 ± 4.9	191.4 ± 4.6
	peak hip flexion	139.6 ± 5.3	139.1 ± 5.4	139.0 ± 5.0	138.8 ± 4.8	139.0 ± 5.6

Values are reported as mean ± standard deviation. Significant differences to the 0 Nm rad^{-1} condition according to the Tukey post hoc test are denoted by * ($p < 0.05$).

Table S2. Peak positive and negative ankle, knee, and hip moments during level, incline, and decline walking, with and without exoskeleton assistance. Positive joint moments represent the action to extend the joint and negative joint moments represent flexion.

	Moment (N m kg^{-1})	0 Nm rad^{-1}	50 Nm rad^{-1}	120 Nm rad^{-1}	220 Nm rad^{-1}	280 Nm rad^{-1}
Level	**peak ankle positive**	1.50 ± 0.12	1.50 ± 0.10	1.51 ± 0.10	1.49 ± 0.09	1.49 ± 0.11
	peak ankle negative	0.23 ± 0.07	0.23 ± 0.07	0.24 ± 0.06	0.24 ± 0.08	0.25 ± 0.06
	peak knee positive	0.61 ± 0.18	0.64 ± 0.18	0.64 ± 0.15	0.58 ± 0.15	0.60 ± 0.18
	peak knee negative	0.42 ± 0.05	0.44 ± 0.05	0.44 ± 0.06	0.44 ± 0.06	0.44 ± 0.7
	peak hip positive	0.85 ± 0.14	0.87 ± 0.14	0.83 ± 0.14	0.84 ± 0.14	0.87 ± 0.14
	peak hip negative	0.44 ± 0.08	0.47 ± 0.08	0.45 ± 0.09	0.46 ± 0.06	0.46 ± 0.08
Incline	**peak ankle positive**	1.99 ± 0.1	2.02 ± 0.11	2.02 ± 0.14	2.02 ± 0.08	2.01 ± 0.11
	peak negative	0.06 ± 0.02	0.06 ± 0.02	0.05 ± 0.02	0.07 ± 0.03	0.06 ± 0.02
	peak knee positive	0.19 ± 0.11	0.18 ± 0.14	0.15 ± 0.16	0.16 ± 0.10	0.17 ± 0.13
	peak knee negative	0.85 ± 0.1	0.87 ± 0.11	0.86 ± 0.13	0.89 ± 0.09	0.88 ± 0.11
	peak hip positive	1.49 ± 0.19	1.55 ± 0.19	1.58 ± 0.20 *	1.55 ± 0.22	1.55 ± 0.19
	peak hip negative	0.38 ± 0.09	0.37 ± 0.08	0.36 ± 0.11	0.35 ± 0.08	0.37 ± 0.09
Decline	**peak ankle positive**	0.83 ± 0.13	0.78 ± 0.11	0.78 ± 0.13	0.79 ± 0.09	0.8 ± 0.1
	peak negative	0.69 ± 0.23	0.71 ± 0.32	0.70 ± 0.29	0.64 ± 0.14	0.68 ± 0.13
	peak knee positive	1.65 ± 0.39	1.70 ± 0.34	1.75 ± 0.35	1.66 ± 0.27	1.68 ± 0.31
	peak knee negative	0.37 ± 0.05	0.37 ± 0.06	0.38 ± 0.08	0.39 ± 0.07	0.37 ± 0.05
	peak hip positive	0.53 ± 0.12	0.53 ± 0.11	0.55 ± 0.15	0.56 ± 0.13	0.54 ± 0.12
	peak hip negative	1.0 ± 0.19	1.03 ± 0.2	0.98 ± 0.22	1.04 ± 0.2	1.03 ± 0.18

Values are reported as mean ± standard deviation. Significant differences to the 0 Nm rad^{-1} condition according to the Tukey post hoc test are denoted by * ($p < 0.05$).

Table S3. Positive and negative work performed at the ankle, knee, and hip during level, incline, and decline walking, with and without exoskeleton assistance.

	Work (J kg^{-1})	0 Nm rad^{-1}	50 Nm rad^{-1}	120 Nm rad^{-1}	220 Nm rad^{-1}	280 Nm rad^{-1}
Level	**positive ankle**	0.47 ± 0.07	0.48 ± 0.07	0.45 ± 0.07	0.45 ±0.1	0.49 ±0.06
	negative ankle	0.2 ± 0.03	0.2 ± 0.04	0.20 ± 0.04	0.21 ± 0.06	0.19 ± 0.03
	positive knee	0.21 ± 0.06	0.21 ± 0.07	0.2 ± 0.06	0.19 ± 0.07	0.22 ± 0.07
	negative knee	0.21 ± 0.03	0.22 ± 0.03	0.2 ± 0.03	0.22 ± 0.05	0.22 ± 0.02
	positive hip	0.37 ± 0.05	0.39 ± 0.07	0.39 ± 0.06	0.39 ± 0.08	0.38 ± 0.06
	negative hip	0.05 ± 0.03	0.06 ± 0.03	0.05 ± 0.03	0.06 ± 0.06	0.06 ± 0.02
Incline	**positive ankle**	0.72 ± 0.1	0.73 ± 0.09	0.7 ± 0.1	0.72 ± 0.08	0.73 ± 0.13
	negative ankle	0.25 ± 0.05	0.27 ± 0.1	0.25 ± 0.07	0.25 ±0.05	0.25 ± 0.05
	positive knee	0.34 ± 0.06	0.37 ± 0.11	0.35 ± 0.6	0.35 ± 0.07	0.36 ± 0.09
	negative knee	0.22 ± 0.04	0.26 ±0.06 *	0.26 ± 0.06	0.26 ± 0.05 *	0.24 ± 0.05
	positive hip	0.96 ± 0.1	1.02 ±0.14	0.99 ± 0.13 *	0.99 ± 0.13	0.99 ± 0.13
	negative hip	0.05 ± 0.04	0.05 ± 0.05	0.05 ± 0.03	0.04 ± 0.04	0.04 ± 0.04
Decline	**positive ankle**	0.32 ± 0.09	0.31 ± 0.08	0.29 ± 0.07	0.29 ± 0.06	0.31 ± 0.08
	negative ankle	0.19 ± 0.05	0.19 ± 0.07	0.17 ± 0.04	0.17 ± 0.04	0.19 ± 0.06
	positive knee	0.3 ± 0.09	0.33 ± 0.12	0.32 ± 0.11	0.31 ± 0.1	0.32 ± 0.08
	negative knee	0.68 ± 0.15	0.72 ± 0.17	0.7 ± 0.13	0.7 ± 0.12	0.73± 0.15
	positive hip	0.28 ± 0.05	0.26 ± 0.06	0.28 ± 0.05	0.27 ± 0.04	0.29 ± 0.06
	negative hip	0.43 ± 0.07	0.42 ± 0.09	0.43 ± 0.087	0.43 ± 0.1	0.42 ± 0.09

Values are reported as mean ± standard deviation. Significant differences to the 0 Nm rad^{-1} condition according to the Tukey post hoc test are denoted by * ($p < 0.05$).

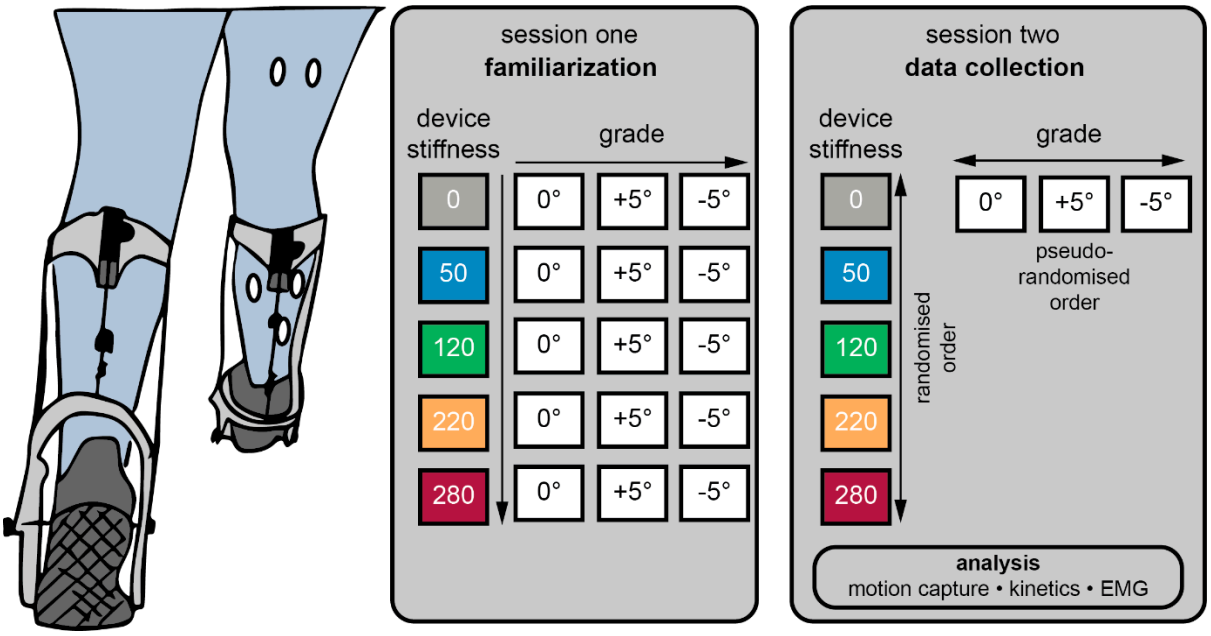

Figure S1. An illustration of the experimental paradigm. Participants attended the laboratory for two days of experimentation. On the first day, participants completed a familiarization session. In this familiarization session, participants walked at 1.25 m s^{-1} for five minutes at each exoskeleton stiffness (0, 50, 120, 220, and 280 Nm rad^{-1}) on level, incline (+5°), and decline (-5°) surfaces. In session two, participants completed an exoskeleton-walking protocol, whereby exoskeleton stiffnesses was randomized and grade was pseudo-randomized. Simultaneously, 3D motion capture and an instrumented treadmill were used to measure lower-limb kinematics and kinetics, respectively, and surface electromyography was used to measure lower-limb muscle activation.

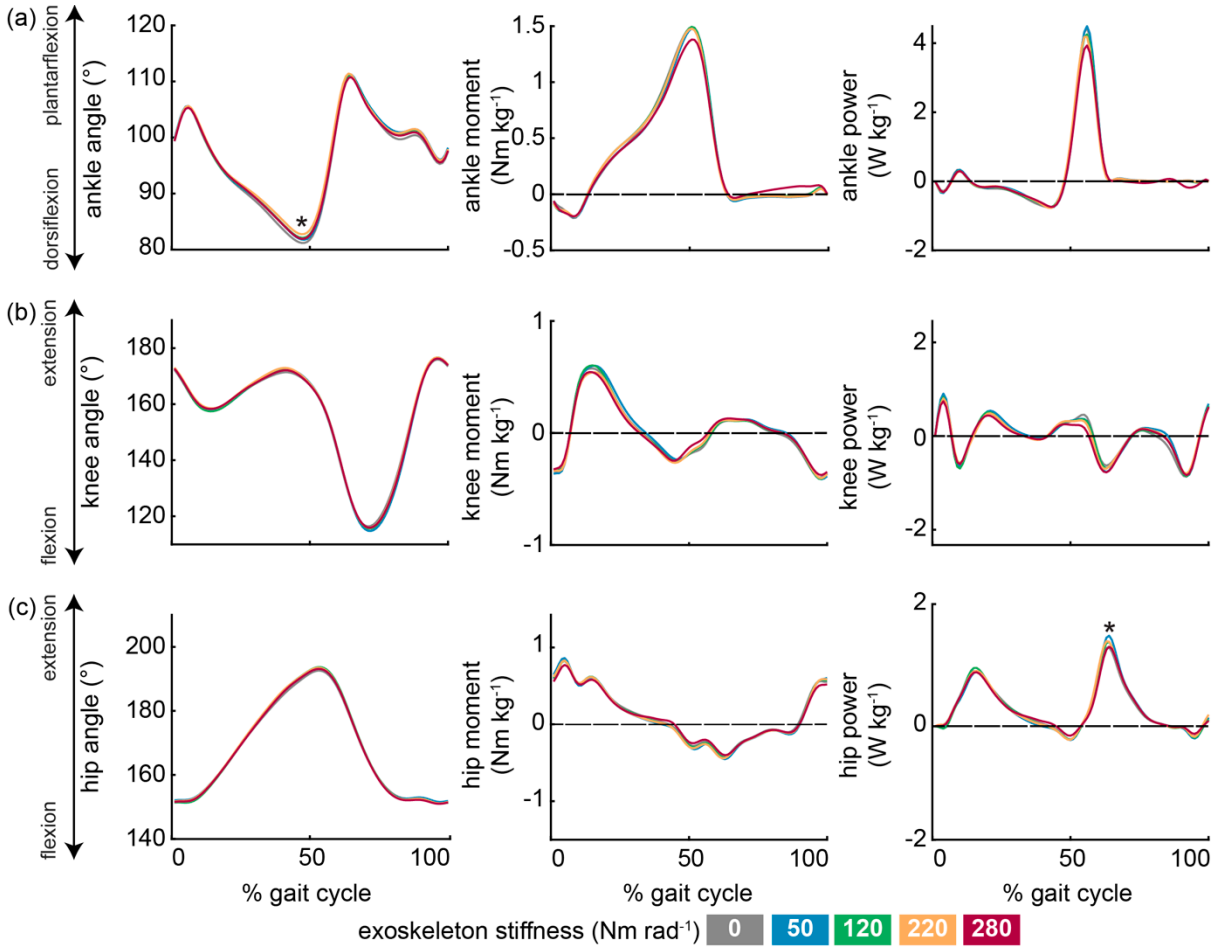

Figure S2. The influence of passive ankle exoskeletons on ankle, knee, and hip joint mechanics during level walking. Group mean ankle (**a**), knee (**b**), and hip (**c**) joint angles (°) (left panel), moments (Nm kg^{-1}) (center panel), and powers (W kg^{-1}) (right panel). Group mean curves were time normalized and represented as 0-100% of the gait cycle. Exoskeleton conditions (0, 50, 120, 220, and 280 Nm rad^{-1}) are denoted by color. The black dashed line indicates zero moment or power. In this figure, ankle moments were not partitioned into the biological and device contribution. A main effect of exoskeleton assistance on peak joint angle, moment, or power are denoted by * ($p < 0.05$).

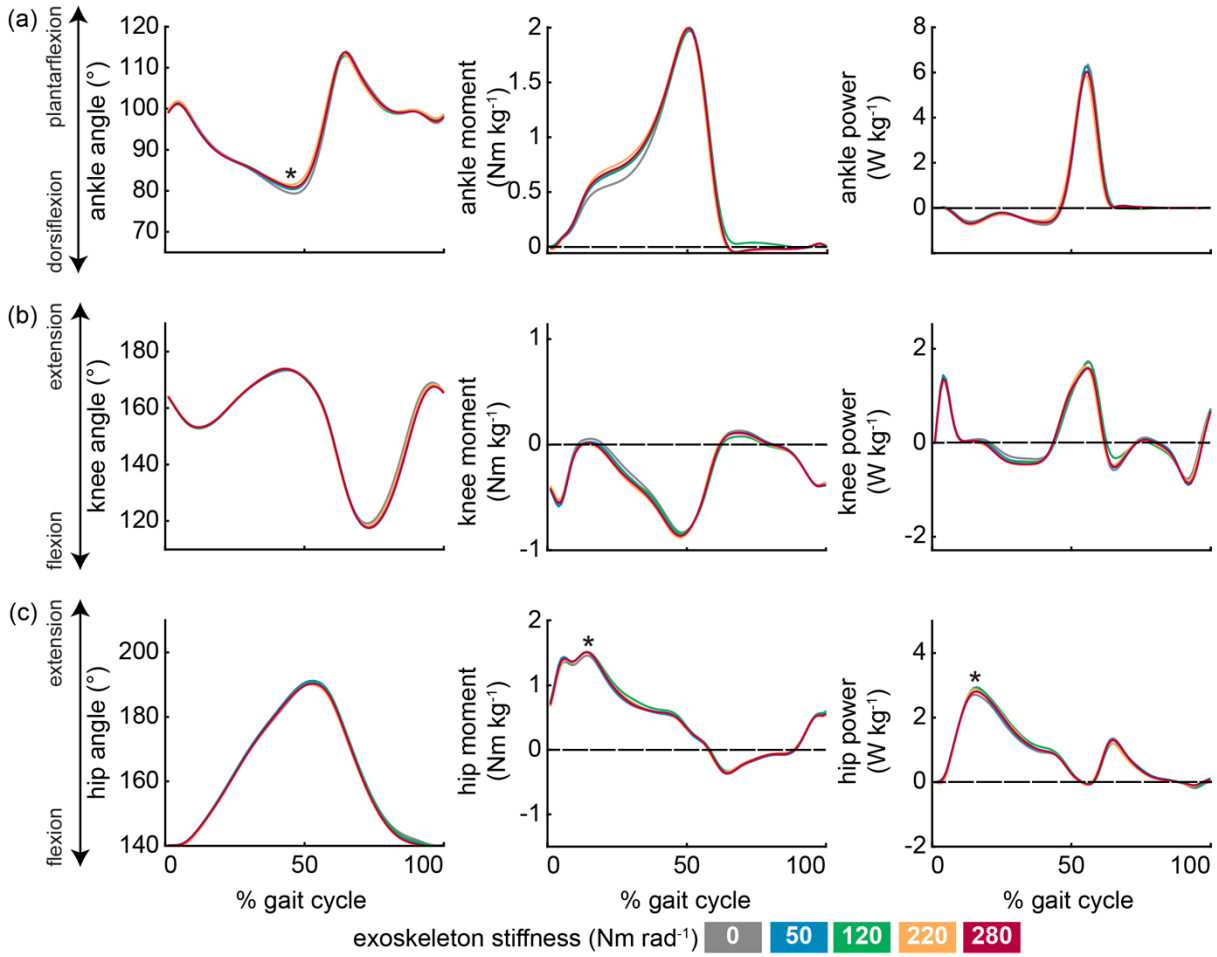

Figure S3. The influence of passive ankle exoskeletons on ankle, knee, and hip joint mechanics during incline walking. Group mean ankle (**a**), knee (**b**), and hip (**c**) joint angles (°) (left panel), moments (Nm kg^{-1}) (center panel), and powers (W kg^{-1}) (right panel). Group mean curves were time normalized and represented as 0-100% of the gait cycle. Exoskeleton conditions (0, 50, 120, 220, and 280 Nm rad^{-1}) are denoted by color. The black dashed line indicates zero moment or power. In this figure, ankle moments were not partitioned into the biological and device contribution. A main effect of exoskeleton assistance on peak joint angle, moment, or power are denoted by * ($p < 0.05$).

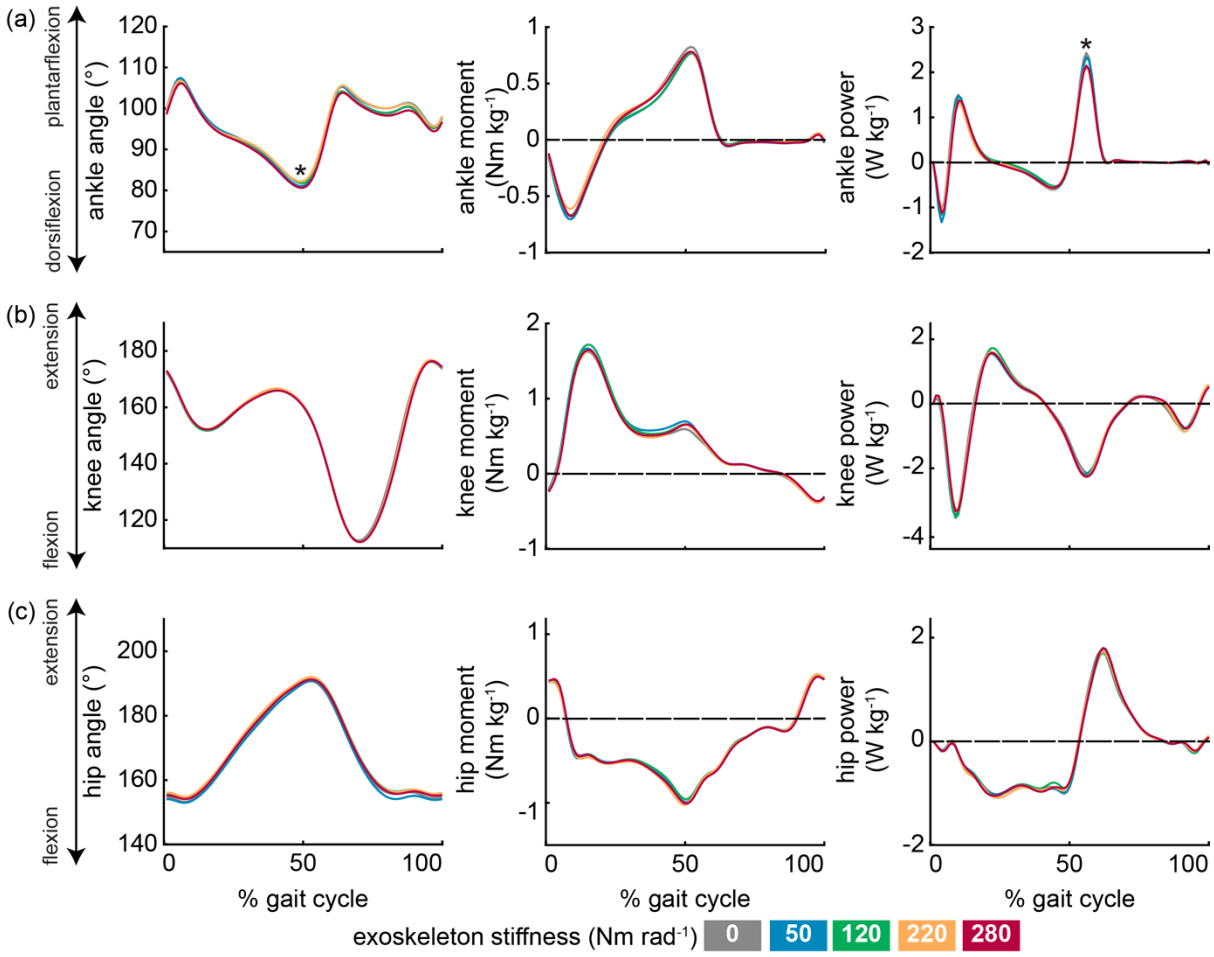

Figure S4. The influence of passive ankle exoskeletons on ankle, knee, and hip joint mechanics during decline walking. Group mean ankle (**a**), knee (**b**), and hip (**c**) joint angles (°) (left panel), moments (Nm kg^{-1}) (center panel), and powers (W kg^{-1}) (right panel). Group mean curves were time normalized and represented as 0-100% of the gait cycle. Exoskeleton conditions (0, 50, 120, 220, and 280 Nm rad^{-1}) are denoted by color. The black dashed line indicates zero moment or power. In this figure, ankle moments were not partitioned into the biological and device contribution. A main effect of exoskeleton assistance on peak joint angle, moment, or power are denoted by * ($p < 0.05$).