

SUPPLEMENTARY MATERIAL

# Supplementary Material for: Novel Neuromuscular Controllers with Simplified Muscle Model and Enhanced Reflex Modulation: A Comparative Study in Hip Exoskeletons

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**Supplementary Table 1.** List of abbreviations and acronyms used in the article.

Abbreviation/Acronym	Description	Abbreviation/Acronym	Description
BE	Buffer element	MS	Mid-stance
CE	Contractile element	MTU	Muscle-tendon unit
ES	Early stance	NLP	Nonlinear passive element
FSM	Finite-state machine	NMC	Neuromuscular controller
GLU	Gluteus maximus	PE	Parallel element
HIL	human in the loop	PS	Pre-swing
ILPS	Illiopsoas	S	Swing
LP	Landing preparation	SE	Serial element

**Supplementary Table 2.** List of the symbols used to denote the parameters and variables in the NMC equations.

Symbol	Description	Symbol	Description
$Act$	Muscle activation signal	$\ell_{PE}$	PE length
$C$	Constant inhibition term for muscle stimulation	$\ell_{SE,slack}$	SE slack length
$\delta t$	Neural signal propagation time constant	$\ell_{SE}$	SE length
$\epsilon_{BE}$	BE length	$\ell_{slack}$	SE (tendon) slack length
$\epsilon_{PE}$	PE length	$N$	Normalized MTU force, defined as $F_{CE}/F_{max}$
$\epsilon_{SE}$	SE length	$\omega$	Constant determining the Gaussian width in the force-length relationship
$F_{BE}$	BE force	$P_i$	Generic notation for the reflex sensory inputs
$F_{max}$	Maximum MTU isometric force	$r$	MTU moment arm around the joint
$F_{MTU}$	MTU force	$r_0$	Moment arm constant
$F_{PE}$	PE force	$\rho$	Muscle pennation angle constant

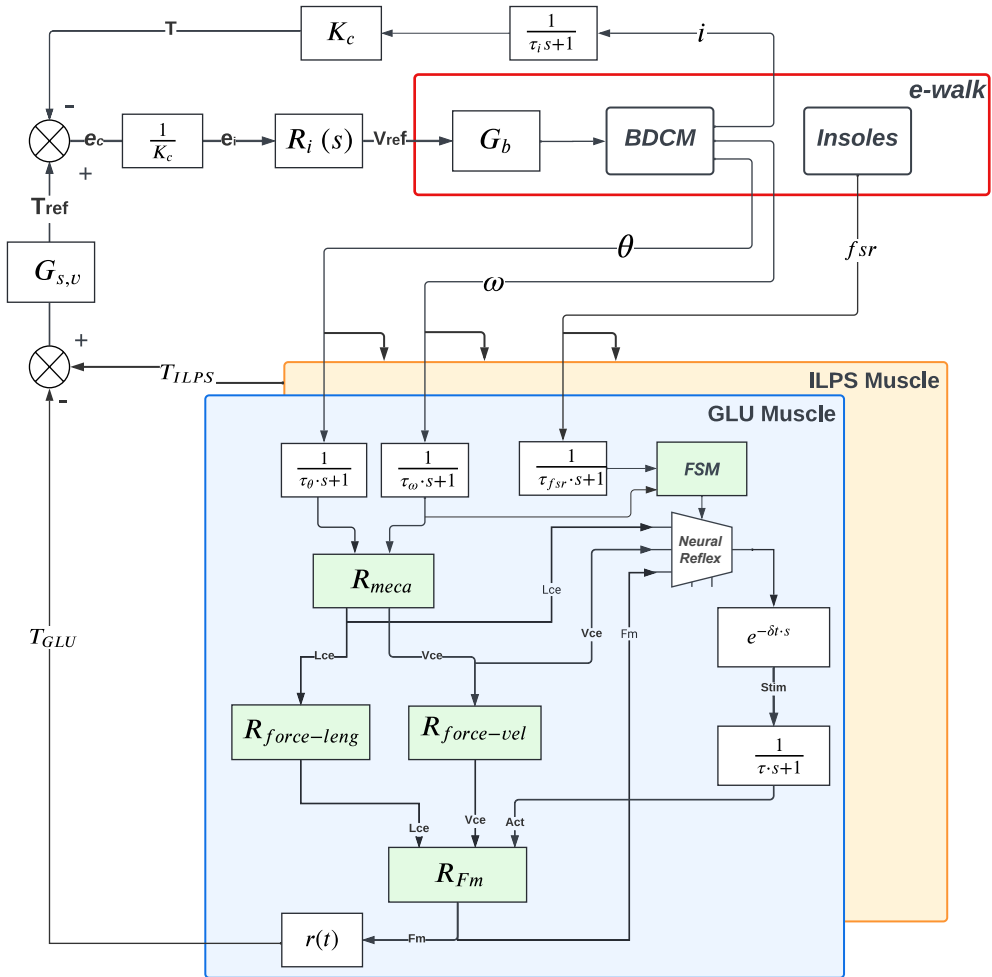
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**Supplementary Table 2** – continued from previous page.

Symbol	Description	Symbol	Description
$F_{SE}$	SE force	$Stim$	Muscle stimulation signal
$f_\ell$	Force-length relationship	$Stim_0$	Basal stimulation level
$f_v$	Force-velocity relationship	$t$	Time
$G_{s,v}$	Manually adjusted assistive torque scaling gain	$T_{assist}$	Total assistive torque generated by the NMC
$G_i$	Generic notation for the reflex gains	$T_{GLU}$	Torque generated by the (virtual) gluteus maximus around the hip joint
$G_\ell$	Length reflex gain	$T_{ILPS}$	Torque generated by the (virtual) iliopsoas around the hip joint
$K$	Curvature constant for the force-velocity relationship	$T_{MTU}$	Torque generated by a certain MTU around the corresponding joint
$\ell_{BE,slack}$	BE slack length	$\tau$	Muscle stimulation-to-activation time constant
$\ell_{BE}$	BE length	$\theta$	Joint angle
$\ell_{CE}$	CE length	$\theta_{ref}$	Reference joint angle at which $\ell_{MTU} = \ell_{opt} + \ell_{slack}$
$\ell_{MTU}$	MTU length	$v_{CE}$	CE force
$\ell_{opt}$	Optimum CE length	$v_{max}$	Maximum CE contraction velocity in the force-velocity relationship
$\ell_{PE,slack}$	PE slack length		

**Supplementary Table 3.** Neuromuscular model hip joint parameter values

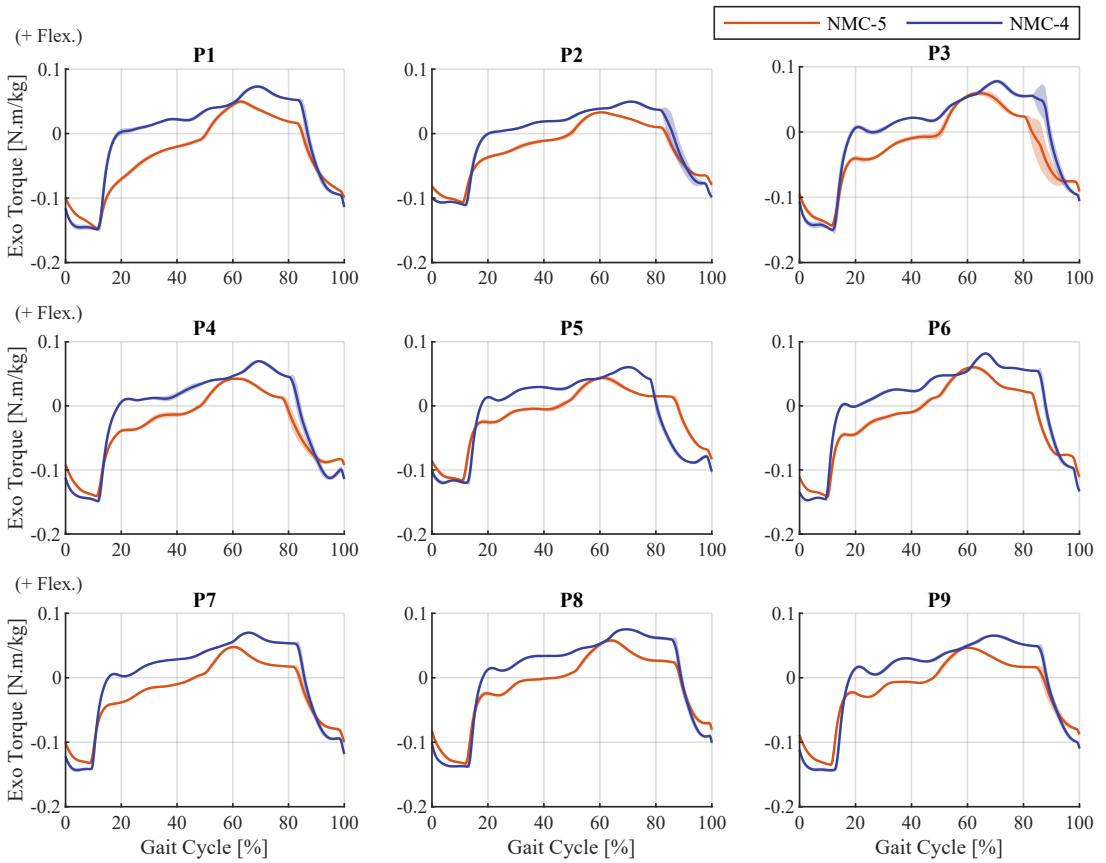
Parameter [Unit]	GLU value	ILPS value
$\ell_{slack} [m]$	0.1	0.1
$\ell_{opt} [m]$	0.157	0.13
$\theta_{ref} [deg]$	170.0	180.0
$F_{max} [N]$	1500	1500
$v_{max} [N]$	1.32	1.32
$\tau [s]$	0.1	0.01
$\omega [ ]$	0.56	0.56
$\theta_{max} [deg]$	0	0
$\theta_{off} [deg]$	0	0
$r_0 [m]$	0.1	0.1
$\rho [ ]$	0.5	0.5
$\ell_{off} [m]$	0.157	0.157
$K [ ]$	0.005	0.005
$N [ ]$	1.5	1.5
$C [ ]$	0.05	0.05
$Stim_0 [ ]$	0.01	0.01
$\delta t [s]$	0.25	0.25



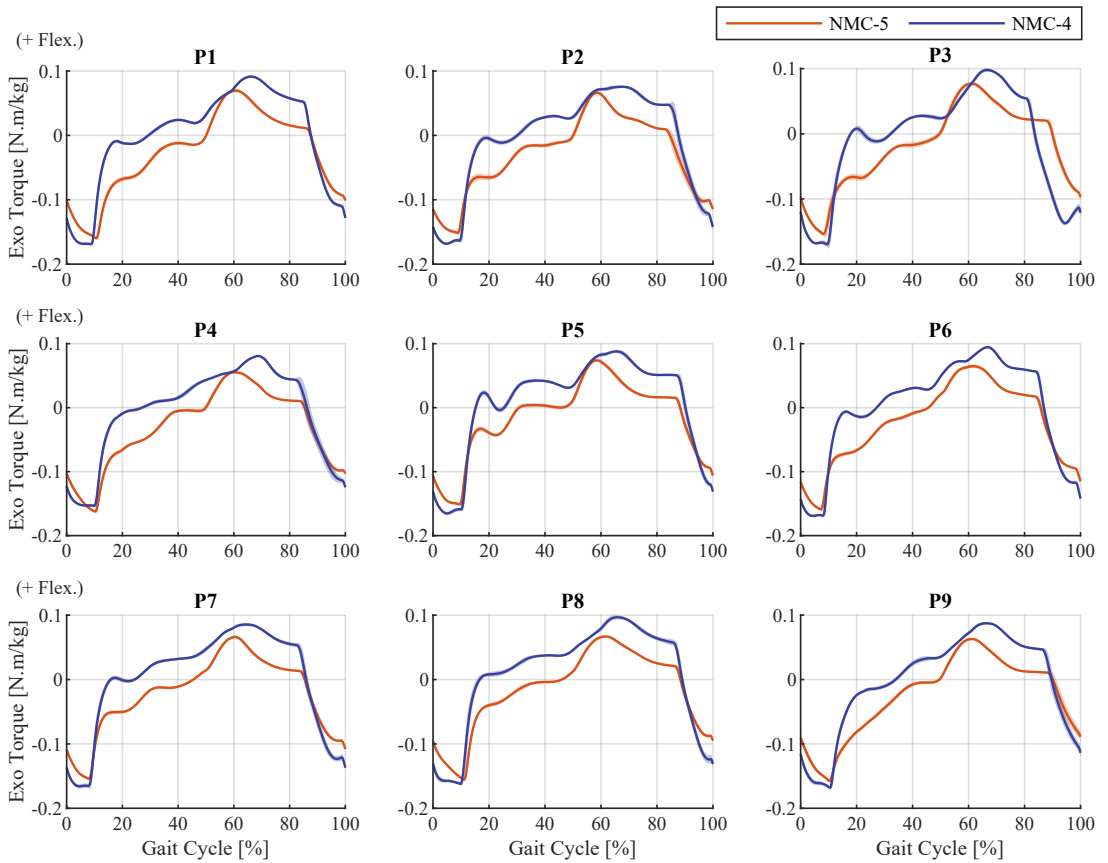
**Supplementary Figure 1.** Detailed block diagram of the novel NMC architecture, as implemented on the e-Walk V1 hip exoskeleton.  $R_{meca}$  is the set of the mechanical equations mapping the hip angle to the CE length (as in 14) and the hip angular velocity to the CE velocity (as in 15);  $R_{force-leng}$  is the force-length relationship given in equation 6;  $R_{force-vel}$  is the force-velocity relationship as in 7; the low-pass filters with time constants  $\tau_\theta$ ,  $\tau_\omega$  and  $\tau_{f_{sr}}$  were added to reduce sensor noise from the angle, angular velocity and the insole pressure signals, respectively;  $R_{Fm}$  gives the MTU force as in equation 18; the  $FSM$  block updates the gait phase according to the inputs; the  $Reflex$  multiplexer represents the selection of the proper neural reflex; the exponential term represents the stimulation's phase delay of time  $\delta t$ ; the low-pass filter with constant time  $\tau$  represents the activation-stimulation relationship as in 5.

**Supplementary Table 4.** Mean positive (W+) and negative (W-) mechanical works per stride delivered by the exoskeleton (left side only), averaged over all participants and strides under each condition.

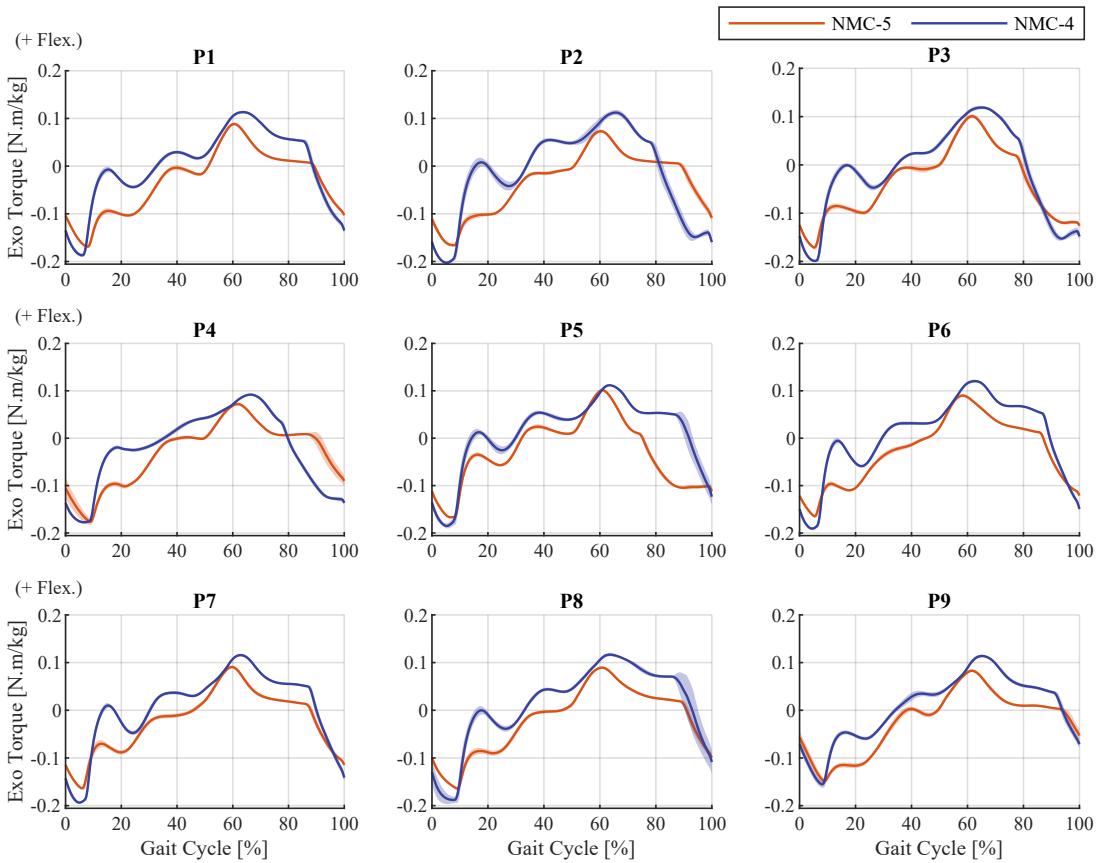
Condition	NMC-4		NMC-5	
	W+ [J/kg]	W- [J/kg]	W+ [J/kg]	W- [J/kg]
<b>C1 (0.8 m/s)</b>	0.122	-0.010	0.074	-0.003
<b>C2 (1.25 m/s)</b>	0.162	-0.013	0.103	-0.003
<b>C3 (1.8 m/s)</b>	0.195	-0.015	0.142	-0.004
<b>C4 (1.25 m/s, 10%)</b>	0.154	-0.007	0.137	0.000



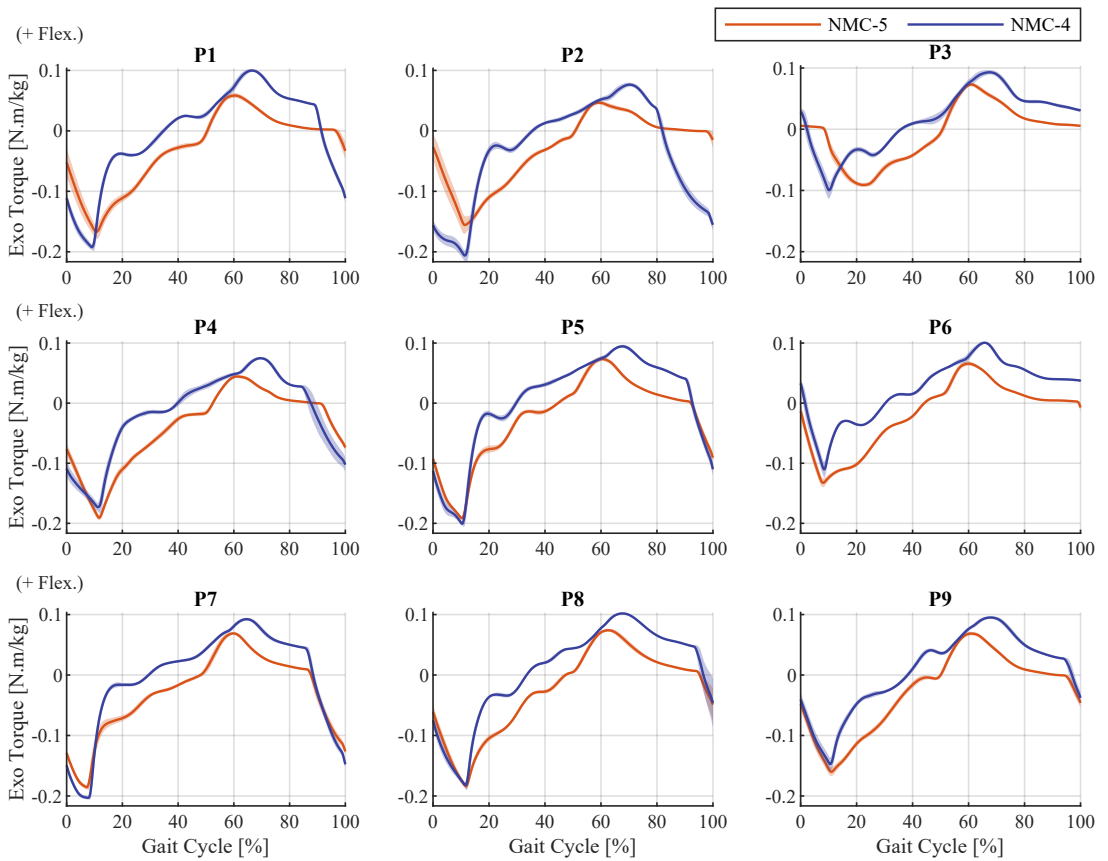
**Supplementary Figure 2.** Torque profiles generated by the four-state (NMC-4) and five-state (NMC-5) variants under condition C1 for all participants.



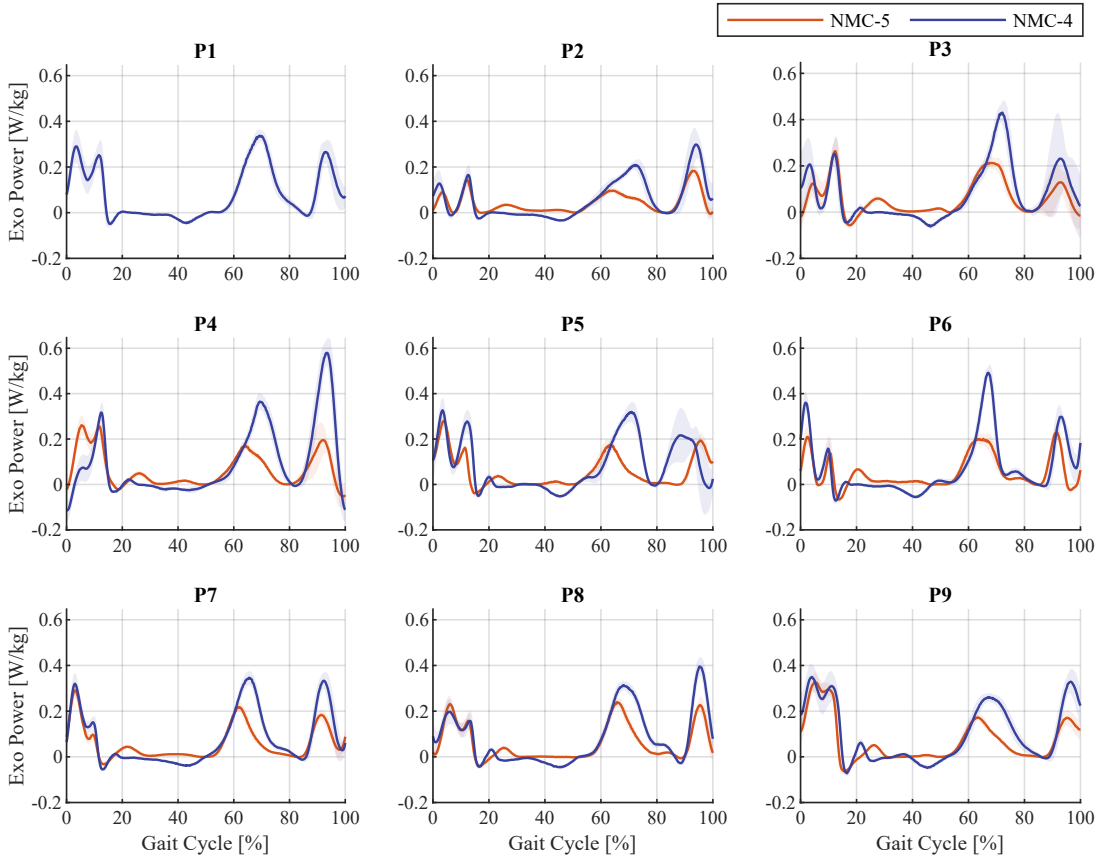
**Supplementary Figure 3.** Torque profiles generated by the four-state (NMC-4) and five-state (NMC-5) variants under condition C2 for all participants.



**Supplementary Figure 4.** Torque profiles generated by the four-state (NMC-4) and five-state (NMC-5) variants under condition C3 for all participants.

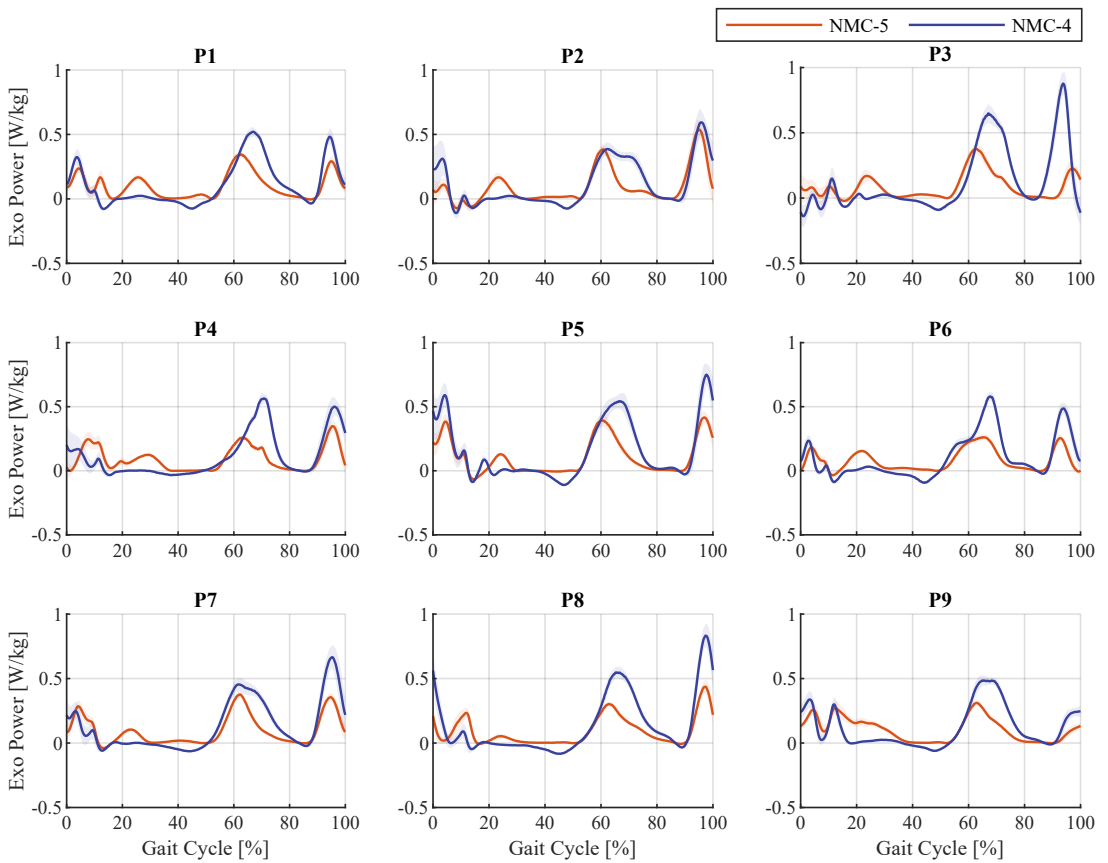


**Supplementary Figure 5.** Torque profiles generated by the four-state (NMC-4) and five-state (NMC-5) variants under condition C4 for all participants.

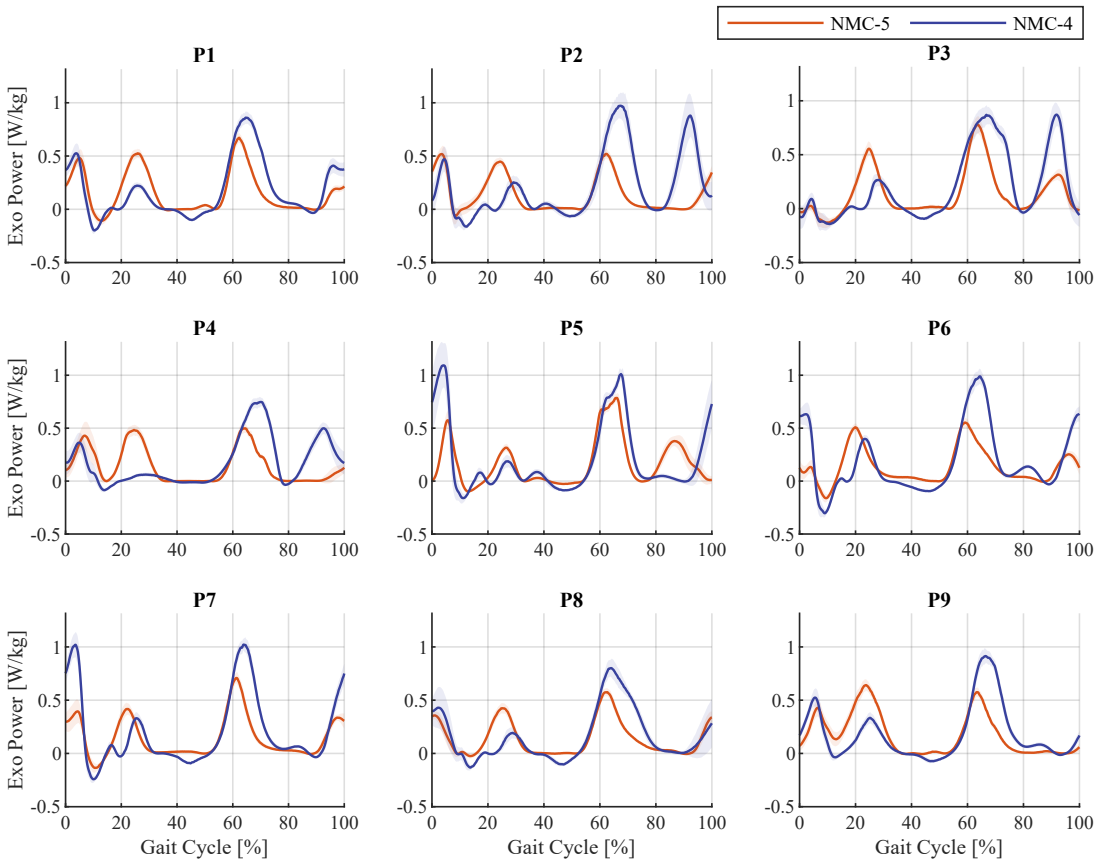


**Supplementary Figure 6.** Exoskeleton mechanical power output profiles with the four-state (NMC-4) and five-state (NMC-5) variants under condition C1 for all participants. Note that for participant P1, due to an issue in the logging system, the power profile for NMC-5 was not available.

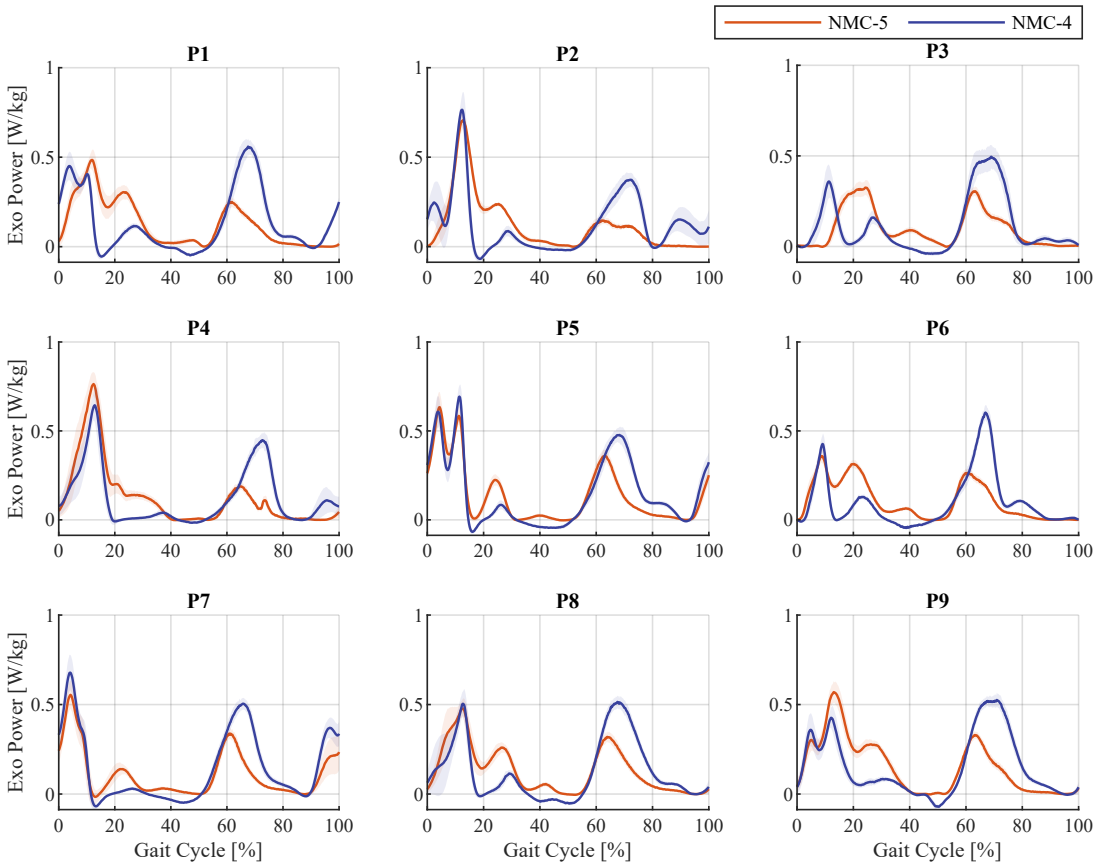




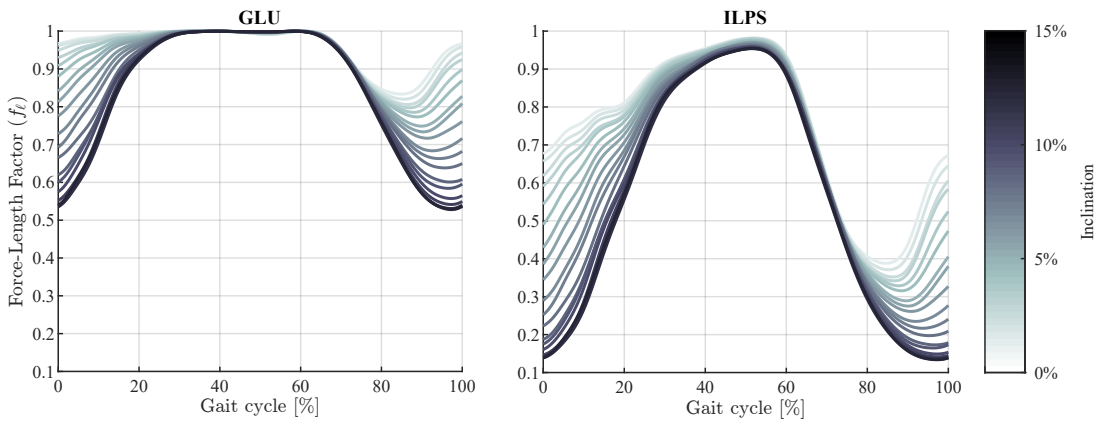
**Supplementary Figure 7.** Exoskeleton mechanical power output profiles with the four-state (NMC-4) and five-state (NMC-5) variants under condition C2 for all participants.



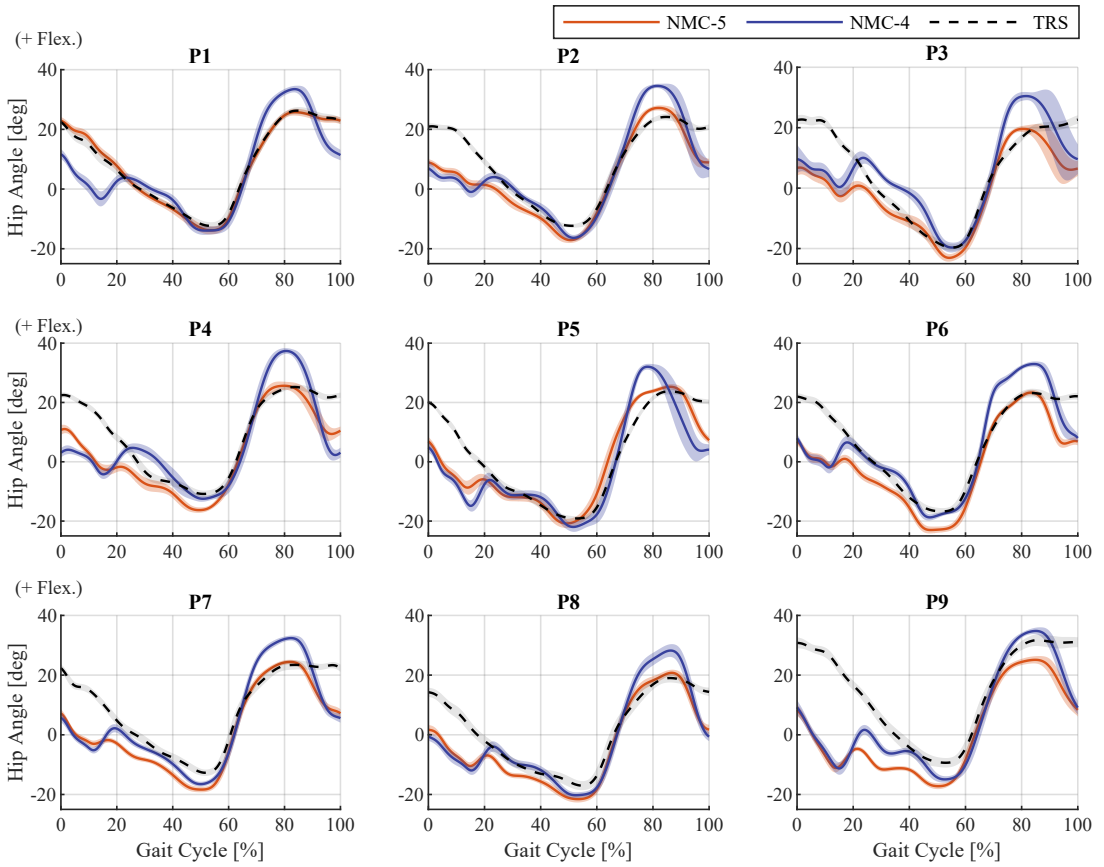
**Supplementary Figure 8.** Exoskeleton mechanical power output profiles with the four-state (NMC-4) and five-state (NMC-5) variants under condition C3 for all participants.



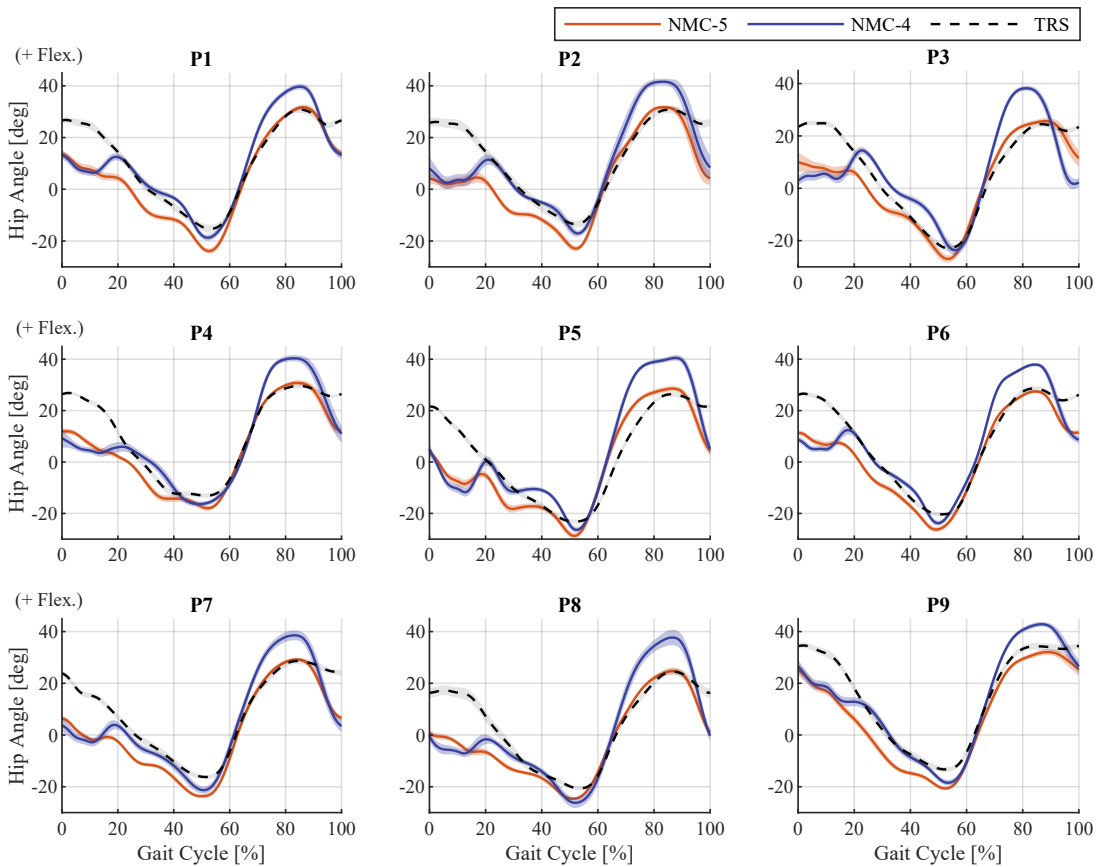
**Supplementary Figure 9.** Average exoskeleton mechanical power output profiles with the four-state (NMC-4) and five-state (NMC-5) variants under condition C4 for all participants.



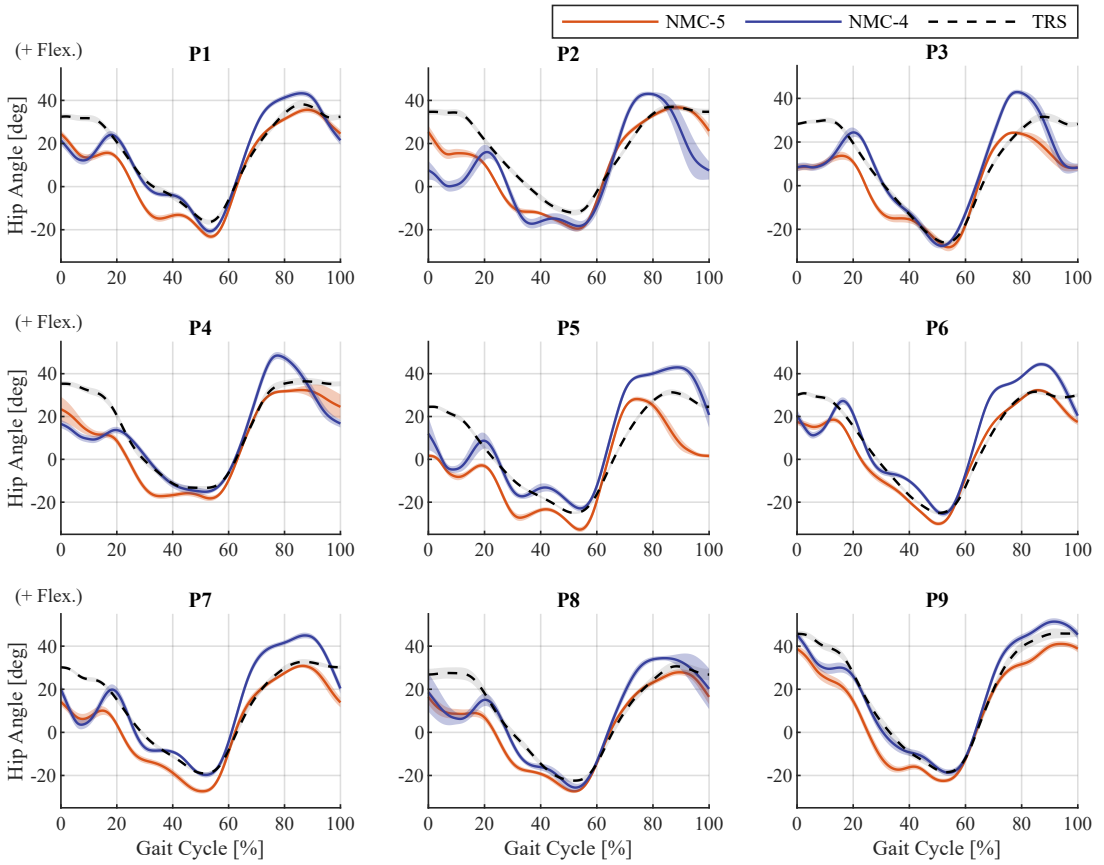
**Supplementary Figure 10.** Evolution of the force-length factor ( $f_l$ ) for the extensor (gluteus maximus, Glu) and flexor (iliopsoas, Iips) virtual muscles in NMC-5 during variable-inclination walking (C5), averaged over the six valid participants.



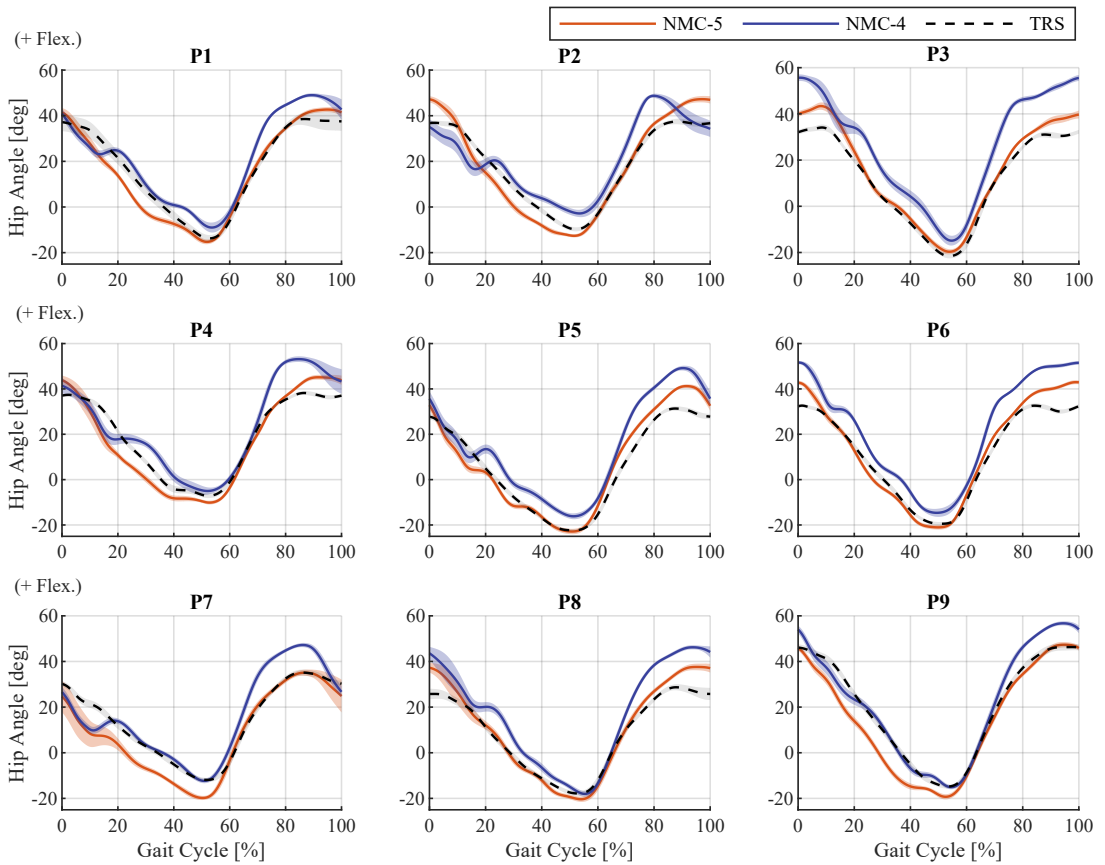
**Supplementary Figure 11.** Average hip angle profiles in assisted walking (NMC-4 and NMC-5) and unassisted mode (TRS) for all participants under condition C1.



**Supplementary Figure 12.** Average hip angle profiles in assisted walking (NMC-4 and NMC-5) and unassisted mode (TRS) for all participants under condition C2.



**Supplementary Figure 13.** Average hip angle profiles in assisted walking (NMC-4 and NMC-5) and unassisted mode (TRS) for all participants under condition C3.



**Supplementary Figure 14.** Average hip angle profiles in assisted walking (NMC-4 and NMC-5) and unassisted mode (TRS) for all participants under condition C4.