Supplementary Document: Joint torque estimation from daily living motion for passive sarcopenia monitoring in older adults

Contents

S.1 Hyperparameter of Different Models

Table S1 indicates the common training configuration and different models. Optimizer configuration is also indicated in Table S2.

More detailed information can be found in our github address: https://github.com/Jaebeom-git/cop-limiter

Table S1: Common Training Configuration

Parameter	**Value**
Checkpoint Directory	./checkpoints
Device	CUDA
Automatic Mixed Precision (AMP)	Enabled
Epochs	100
Random Seed	42
Batch Size	32
History Length	100
Stride	1
Window Stride	10
Unbalanced Stride	Enabled

Table S2: Optimizer Configuration

Parameter	**Value**
Optimizer	ScheduleFreeAdamW
Learning Rate	1.0×10^{-4}
Beta Parameters	β_1 = 0.95, β_2 = 0.999
Weight Decay	0.05
Epsilon	1.0×10^{-8}
Warmup Step Ratio	5
R Parameter	0.0
Weight LR Power	2.0

Table S3: Loss Configuration Parameters

Parameter	**BL Models**	**CL Models**
Force Mask Threshold	1.0	
Moment Scale	0.1	
COP Scale	1	
Force Weight Scale Parameters	[0.5, 1.0, 0.5]	
COP Weight Scale Parameters	[1.0, 0.1, 0.01]	
Force Scale	1	
TCLoss Scale	1.0×10^{-3}	
MPJVE Scale	1.0×10^{-2}	
Use COP Limiter	Disabled	Enabled

Table S4: Feed-Forward Network (FFN) Model Configuration for GRF Estimation

Parameter	**Value**
Hidden Dimensions	[4096, 4096, 4096, 4096, 4096, 4096, 4096, 4096]
Number of Layers	8 layers with 4096 units each
Dropout Rate	0.1

Table S5: Transformer Model Configuration for GRF Estimation

Parameter	**Value**
Use RoPE	Enabled
Maximum Sequence Length	4096
Number of Temporal Blocks	7
Embedding Dimension	1024
Number of Attention Heads	8
Causal Attention	Disabled
Dropout Rate	0.1
Drop Path Rate	0.1
MLP Ratio	4.0

Table S6: Mamba Model Configuration for GRF Estimation

Parameter	**Value**
Mamba Version	Mamba2
Number of Temporal Blocks	6
Temporal Embedding Dimension	1024
Temporal D State	256
Temporal D Conv	2
Temporal Expand	2
Dropout Rate	0.1
Drop Path Rate	0.1
MLP Ratio	4.0

S.2 Correlation Metrics with Effect Size

Table S7–S10 report the Pearson correlation r on the first line and the Holm–Bonferroni–corrected p value in parentheses on the second line. p values are adjusted across all correlations within this task. Corrected correlation coefficients that satisfy both $|r| \geq 0.50$ and $p < 0.05$ are marked in **bold**. Metrics are mass-normalized values. PT is Peak Torque ($\mathrm{Nm/kg}$), RTD is Rate of Torque Development ($\mathrm{Nm/(s \cdot kg)}$), and PR is Power Range ($\mathrm{Nm/(s \cdot kg)}$). HGS is Hand Grip Strength, ASMI is Appendicular Skeletal Muscle Mass Index, BMI is Body Mass Index, CC is Calf Circumference, SARC-F is Strength, Assistance with walking, Rising from a chair, Climbing stairs, and Falls questionnaire score, FTSTS is Five Times Sit-to-Stand test, TUG is Timed Up and Go test.

Table S7: Correlations between joint torque metrics and Sarcopenia criteria during the 5-times Chair Stand task.

Joint	Side	Metric	HGS	ASMI	BMI	CC	SARCF	FTSTS	Gait Speed	TUG
Ankle	-	PT	0.42	**0.50**	0.02	0.40	**-0.62**	-0.09	0.41	-0.39
			(0.007)	(< 0.001)	(1.000)	(0.012)	(< 0.001)	(1.000)	(0.007)	(0.017)
		RTD	0.35	0.26	-0.07	0.04	-0.05	-0.31	0.30	-0.24
			(0.069)	(0.610)	(1.000)	(1.000)	(1.000)	(0.177)	(0.249)	(0.934)
		PR	**0.55**	0.41	-0.21	0.19	-0.39	-0.48	0.37	-0.29
			(< 0.001)	(0.009)	(1.000)	(1.000)	(0.018)	(< 0.001)	(0.038)	(0.298)
Knee	-	PT	**0.61**	0.41	-0.44	0.33	-0.47	-0.49	0.36	-0.15
			(< 0.001)	(0.009)	(0.003)	(0.118)	(< 0.001)	(< 0.001)	(0.043)	(1.000)
		RTD	**0.72**	**0.57**	-0.30	0.46	**-0.56**	**-0.60**	**0.53**	-0.24
			(< 0.001)	(< 0.001)	(0.249)	(0.001)	(< 0.001)	(< 0.001)	(< 0.001)	(0.934)
		PR	**0.67**	0.44	-0.42	0.33	-0.44	**-0.68**	0.49	-0.26
			(< 0.001)	(0.003)	(0.007)	(0.124)	(0.003)	(< 0.001)	(< 0.001)	(0.638)
Hip	-	PT	**0.73**	**0.51**	-0.29	0.35	-0.48	-0.28	**0.72**	-0.44
			(< 0.001)	(< 0.001)	(0.283)	(0.067)	(< 0.001)	(0.436)	(< 0.001)	(0.003)
		RTD	0.44	0.46	-0.14	0.26	-0.32	-0.44	**0.52**	-0.36
			(0.003)	(0.001)	(1.000)	(0.613)	(0.134)	(0.002)	(< 0.001)	(0.043)
		PR	**0.72**	0.48	-0.23	0.36	-0.42	-0.42	**0.66**	-0.39
			(< 0.001)	(< 0.001)	(1.000)	(0.051)	(0.007)	(0.005)	(< 0.001)	(0.014)

Table S8: Correlations between joint torque metrics and Sarcopenia criteria during the Chair Stand task.

Joint	Side	Metric	HGS	ASMI	BMI	CC	SARCF	FTSTS	Gait Speed	TUG
Ankle	-	PT	0.42	0.43	-0.08	0.20	-0.42	0.01	0.15	0.04
			(0.005)	(0.003)	(1.000)	(1.000)	(0.004)	(1.000)	(1.000)	(1.000)
		RTD	0.28	0.11	-0.22	0.01	-0.21	-0.02	0.11	0.04
			(0.578)	(1.000)	(1.000)	(1.000)	(1.000)	(1.000)	(1.000)	(1.000)
		PR	0.45	0.42	-0.29	0.27	-0.41	-0.31	0.34	-0.22
			(0.001)	(0.005)	(0.476)	(0.640)	(0.007)	(0.320)	(0.085)	(1.000)
Knee	-	PT	0.33	0.35	-0.35	0.28	-0.25	-0.28	0.03	0.10
			(0.143)	(0.064)	(0.070)	(0.495)	(0.961)	(0.576)	(1.000)	(1.000)
		RTD	**0.57**	0.27	-0.26	0.30	-0.45	-0.26	0.30	-0.17
			(< 0.001)	(0.686)	(0.717)	(0.346)	(0.001)	(0.756)	(0.360)	(1.000)
		PR	0.47	0.45	-0.36	0.31	-0.35	-0.27	0.15	0.06
			(< 0.001)	(0.001)	(0.046)	(0.259)	(0.058)	(0.686)	(1.000)	(1.000)
Hip	-	PT	0.38	0.28	-0.19	0.18	-0.40	-0.05	**0.55**	-0.42
			(0.023)	(0.572)	(1.000)	(1.000)	(0.011)	(1.000)	(< 0.001)	(0.005)
		RTD	**0.59**	0.27	-0.27	0.19	-0.40	-0.09	0.37	-0.20
			(< 0.001)	(0.613)	(0.600)	(1.000)	(0.010)	(1.000)	(0.038)	(1.000)
		PR	0.43	0.25	-0.20	0.20	-0.35	-0.06	**0.54**	-0.32
			(0.003)	(1.000)	(1.000)	(1.000)	(0.057)	(1.000)	(< 0.001)	(0.193)

Table S9: Correlations between joint torque metrics and Sarcopenia criteria during the Pick-Up task.

Joint	Side	Metric	HGS	ASMI	BMI	CC	SARCF	FTSTS	Gait Speed	TUG
Ankle	-	PT	0.43	0.15	-0.41	-0.03	-0.05	-0.49	0.14	-0.04
			(0.004)	(1.000)	(0.008)	(1.000)	(1.000)	(< 0.001)	(1.000)	(1.000)
		RTD	0.27	0.25	-0.20	0.21	-0.11	-0.34	0.31	-0.21
			(0.645)	(0.891)	(1.000)	(1.000)	(1.000)	(0.136)	(0.238)	(1.000)
		PR	**0.58**	0.26	-0.32	0.08	-0.26	**-0.62**	0.27	-0.11
			(< 0.001)	(0.886)	(0.183)	(1.000)	(0.866)	(< 0.001)	(0.670)	(1.000)
Knee	-	PT	0.33	0.27	-0.10	0.10	-0.30	-0.28	0.39	-0.34
			(0.156)	(0.670)	(1.000)	(1.000)	(0.305)	(0.645)	(0.018)	(0.112)
		RTD	0.32	0.35	-0.20	0.20	-0.25	-0.33	0.45	-0.39
			(0.191)	(0.087)	(1.000)	(1.000)	(0.910)	(0.167)	(0.002)	(0.016)
		PR	0.34	0.17	-0.27	0.09	-0.27	**-0.52**	0.09	-0.04
			(0.114)	(1.000)	(0.645)	(1.000)	(0.670)	(< 0.001)	(1.000)	(1.000)
Hip	-	PT	0.44	0.46	-0.12	0.21	-0.36	-0.25	**0.50**	-0.39
			(0.003)	(< 0.001)	(1.000)	(1.000)	(0.066)	(0.930)	(< 0.001)	(0.022)
		RTD	0.43	0.31	-0.23	0.12	-0.28	-0.46	0.47	-0.39
			(0.003)	(0.277)	(1.000)	(1.000)	(0.540)	(0.001)	(< 0.001)	(0.022)
		PR	0.40	0.44	-0.32	0.17	-0.31	-0.42	0.44	-0.28
			(0.014)	(0.002)	(0.190)	(1.000)	(0.286)	(0.007)	(0.002)	(0.585)

Table S10: Correlations between joint torque metrics and Sarcopenia criteria during the Step-Up task.

Joint	Side	Metric	HGS	ASMI	BMI	CC	SARCF	FTSTS	Gait Speed	TUG
Ankle	Lead	PT	0.23	0.10	-0.08	0.07	-0.22	-0.20	0.26	-0.08
			(0.363)	(1.000)	(1.000)	(1.000)	(0.587)	(1.000)	(0.094)	(1.000)
		RTD	0.29	0.15	-0.10	0.06	-0.25	-0.34	0.25	-0.13
			(0.023)	(1.000)	(1.000)	(1.000)	(0.204)	(0.002)	(0.183)	(1.000)
		PR	0.09	0.05	-0.07	0.07	-0.07	-0.16	0.19	-0.07
			(1.000)	(1.000)	(1.000)	(1.000)	(1.000)	(1.000)	(1.000)	(1.000)
	Lag	PT	**0.59**	0.24	-0.27	0.12	-0.40	**-0.64**	0.39	-0.28
			(< 0.001)	(0.224)	(0.055)	(1.000)	(< 0.001)	(< 0.001)	(< 0.001)	(0.049)
		RTD	0.16	0.01	-0.26	-0.16	0.08	-0.25	-0.03	0.06
			(1.000)	(1.000)	(0.126)	(1.000)	(1.000)	(0.237)	(1.000)	(1.000)
		PR	-0.06	-0.06	0.18	-0.09	0.07	-0.11	-0.09	-0.05
			(1.000)	(1.000)	(1.000)	(1.000)	(1.000)	(1.000)	(1.000)	(1.000)
Knee	Lead	PT	0.21	0.08	-0.46	-0.01	-0.10	-0.32	0.11	-0.02
			(0.935)	(1.000)	(< 0.001)	(1.000)	(1.000)	(0.006)	(1.000)	(1.000)
		RTD	0.41	0.11	-0.45	-0.09	-0.20	-0.43	0.29	-0.20
			(< 0.001)	(1.000)	(< 0.001)	(1.000)	(1.000)	(< 0.001)	(0.018)	(1.000)
		PR	0.20	0.02	**-0.55**	-0.15	-0.06	-0.36	0.16	-0.09
			(1.000)	(1.000)	(< 0.001)	(1.000)	(1.000)	(< 0.001)	(1.000)	(1.000)
	Lag	PT	-0.09	0.16	-0.03	-0.12	0.25	-0.12	-0.15	0.16
			(1.000)	(1.000)	(1.000)	(1.000)	(0.207)	(1.000)	(1.000)	(1.000)
		RTD	0.10	0.08	-0.24	-0.09	0.03	-0.00	-0.01	0.10
			(1.000)	(1.000)	(0.226)	(1.000)	(1.000)	(1.000)	(1.000)	(1.000)
		PR	0.05	-0.01	-0.48	-0.27	0.08	0.02	-0.10	0.19
			(1.000)	(1.000)	(< 0.001)	(0.072)	(1.000)	(1.000)	(1.000)	(1.000)
Hip	Lead	PT	0.00	0.11	0.37	0.04	0.09	0.33	-0.05	0.08
			(1.000)	(1.000)	(< 0.001)	(1.000)	(1.000)	(0.003)	(1.000)	(1.000)
		RTD	0.45	0.31	0.04	0.10	-0.31	-0.25	0.36	-0.32
			(< 0.001)	(0.008)	(1.000)	(1.000)	(0.006)	(0.179)	(< 0.001)	(0.004)
		PR	-0.10	0.01	0.35	-0.13	0.25	0.19	-0.05	0.02
			(1.000)	(1.000)	(< 0.001)	(1.000)	(0.200)	(1.000)	(1.000)	(1.000)
	Lag	PT	-0.01	0.38	0.14	0.15	0.16	0.04	-0.05	0.03
			(1.000)	(< 0.001)	(1.000)	(1.000)	(1.000)	(1.000)	(1.000)	(1.000)
		RTD	-0.10	-0.10	-0.21	-0.14	0.05	0.09	-0.22	0.17
			(1.000)	(1.000)	(0.857)	(1.000)	(1.000)	(1.000)	(0.641)	(1.000)
		PR	0.09	0.00	-0.22	-0.16	0.04	0.03	-0.12	0.16
			(1.000)	(1.000)	(0.615)	(1.000)	(1.000)	(1.000)	(1.000)	(1.000)

S.3 Direct Propagation Sensitivity Analysis Without RRA

This section reports an additional direct propagation sensitivity analysis performed to quantify how task-wise errors in GRF, GRM, and CoP affect inverse-dynamics–derived joint torques and the downstream torque-derived metrics PT, RTD, and PR. To isolate the direct contribution of external-load perturbations, joint torques were recomputed without OpenSim Residual Reduction Algorithm (RRA) compensation and with the residual wrench fixed to zero. Perturbation magnitudes were defined from the task-wise component mean absolute errors (MAEs) of the zero-shot Mamba+CL model, which yielded the lowest CoP error in the zero-shot setting.

S.3.1 Method

Joint torques were recomputed by inverse dynamics. In the absence of external contact wrenches, the inverse-dynamics torque vector is given by $\boldsymbol{\tau} = \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q})$, where $\mathbf{M}$ is the generalized inertia matrix, $\mathbf{c}$ denotes the Coriolis and centrifugal term, and $\mathbf{g}$ denotes the gravitational term. Also, $\ddot{\mathbf{q}}$, $\dot{\mathbf{q}}$ and $\mathbf{q}$ denote the generalized acceleration, velocity, and configuration from the measured motion, respectively. In the presence of external contact loads, the inverse dynamics equation becomes

$$\boldsymbol{\tau} = \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) - \sum_{k=1}^{K} \mathbf{J}_{b_k}^{\top} \mathbf{w}_k, \tag{1}$$

where $\mathbf{J}_{b_k}$ is the spatial Jacobian of contact body b_k, and $\mathbf{w}_k$ is the external spatial wrench applied to body b_k. Because the external wrench enters Eq. 1 through $-\mathbf{J}_{b_k}^{\top}\mathbf{w}_k$, perturbations in the applied external contact wrenches propagate directly to the computed joint torques when the kinematics are held constant. Because the musculoskeletal model is a floating-base system, six unactuated root DoFs are typically represented as residual forces and moments. In the present analysis, the Residual Reduction Algorithm (RRA) was intentionally excluded, and the pelvis residual wrench was fixed to zero in order to isolate the direct torque contribution from ground-contact inputs.

External wrenches were applied to the left and right foot, with the ground-contact wrench for side $s \in \{L, R\}$ defined as

$$\mathbf{w}_s = \begin{bmatrix} \mathbf{m}_s^{\mathrm{GRM}} + \mathbf{r}_s^{\mathrm{CoP}} \times \mathbf{f}_s^{\mathrm{GRF}} \\ \mathbf{f}_s^{\mathrm{GRF}} \end{bmatrix}, \qquad s \in \{L, R\}, \tag{2}$$

where $\mathbf{f}_s^{\mathrm{GRF}}$, $\mathbf{m}_s^{\mathrm{GRM}}$, and $\mathbf{r}_s^{\mathrm{CoP}}$ are the ground reaction force, free moment, and center-of-pressure position vector, all expressed in the root frame. Eq. 2 makes the propagation pathway explicit: GRF perturbations affect both the force term and the moment-arm term $\mathbf{r}_s^{\mathrm{CoP}} \times \mathbf{f}_s^{\mathrm{GRF}}$, GRM perturbations act directly on the free moment term, and CoP perturbations modify the applied wrench through the moment arm.

Using Eq. 1, baseline joint torques were first recomputed from the ground-truth kinematics and ground-truth external loads with the residual wrench fixed to zero. Task-wise component errors of the Mamba+CL model were then computed separately for each signal ($\mathrm{GRF}, \mathrm{GRM}, \mathrm{CoP}$) and axis ($x, y, z$); the resulting task-wise component MAEs are listed in Table S11.

Let $\epsilon_{g,s,a}$ denote the task-wise component MAE for task group g, signal s, and axis a, and let the perturbation magnitude be defined as $\Delta u_{g,s,a}(\alpha) = \alpha\, \epsilon_{g,s,a}$ with $\alpha \in \{0.25, 0.5, 0.75, 1.0, 1.25, 1.5\}$. For each trial, one perturbed component was applied at a time in both positive and negative directions across all three signals, all three axes, and all six α levels, yielding $3 \times 3 \times 6 \times 2 = 108$ perturbed inverse-dynamics cases per trial. This design isolates first-order directional sensitivity rather than defining a bound under simultaneous multicomponent perturbations. GRF and GRM perturbations were added directly to the corresponding force and moment components, whereas CoP perturbations were introduced through the moment-arm term via external-wrench reconstruction. Joint-torque time series were then recomputed for all perturbed cases, and PT, RTD, and PR were extracted using the same metric-extraction pipeline as in the main analysis.

Table S11: Task-Wise Mean Absolute Error Used for Direct Perturbation Scaling

Signal	Unit	Axis	5-times Chair Stand	Chair Stand	Pick-Up	Step-Up	
						Lead	Lag
GRF	N/kg	x	0.300	0.313	0.291	0.259	0.254
		y	0.845	0.728	0.394	0.796	0.999
		z	0.170	0.206	0.211	0.105	0.119
GRM	Nm/kg	x	0.097	0.081	0.077	0.063	0.028
		y	0.225	0.175	0.148	0.192	0.191
		z	0.019	0.016	0.014	0.017	0.011
CoP	m	x	0.026	0.022	0.020	0.029	0.028
		y	0.013	0.017	0.016	0.018	0.017
		z	0.011	0.013	0.015	0.018	0.020

$\Delta u(\alpha) = \alpha\,\epsilon$, where ϵ denotes the task-wise component MAE for each signal-axis pair. The Mamba+CL model was used to define the perturbation scales for direct propagation sensitivity analysis.

S.3.2 Results

Figure S1 summarizes the sensitivity magnitude at the reference perturbation level $\alpha = 1.0$. It shows the corresponding reference-level sensitivity separately for ankle, knee, and hip flexion. Table S12 compares these propagated perturbations with the statistically significant group differences reported in Table 4 of the main manuscript.

At the reference perturbation level $(\alpha = 1.0)$, mean joint torque deviations of approximately 0.048 Nm/kg were observed across tasks (Fig. S1). This analysis represents an upper-bound-like first-order characterization of direct propagation because RRA was excluded, the perturbation magnitudes were derived from a zero-shot model without adaptation to the target population, and perturbations were applied without compensatory adjustments across coupled components.

Table S12 summarizes the largest of the separately applied GRF-, GRM-, and CoP-specific propagated perturbations at $(|\alpha| = 1.0)$ for each statistically significant group difference reported in Table 4 of the main manuscript, together with its ratio to the observed group difference. Across the 13 statistically significant findings, the dominant propagated perturbation remained smaller than the observed group difference in 11 cases. In 10 of these 11 cases, the perturbation-to-effect-size ratios ranged from 6.0% to 37.0%. One additional case, Step-Up lag ankle PT, remained below the observed group difference but showed a relatively large ratio of 48.9%. The two findings in which the propagated perturbation exceeded the observed group difference were Step-Up lead hip PT (115.4%) and Step-Up lag hip PR (279.0%). Overall, these results indicate that most group-level effects were larger than the first-order propagated perturbation at the reference error scale, although a small subset of task-metric combinations appeared more vulnerable.

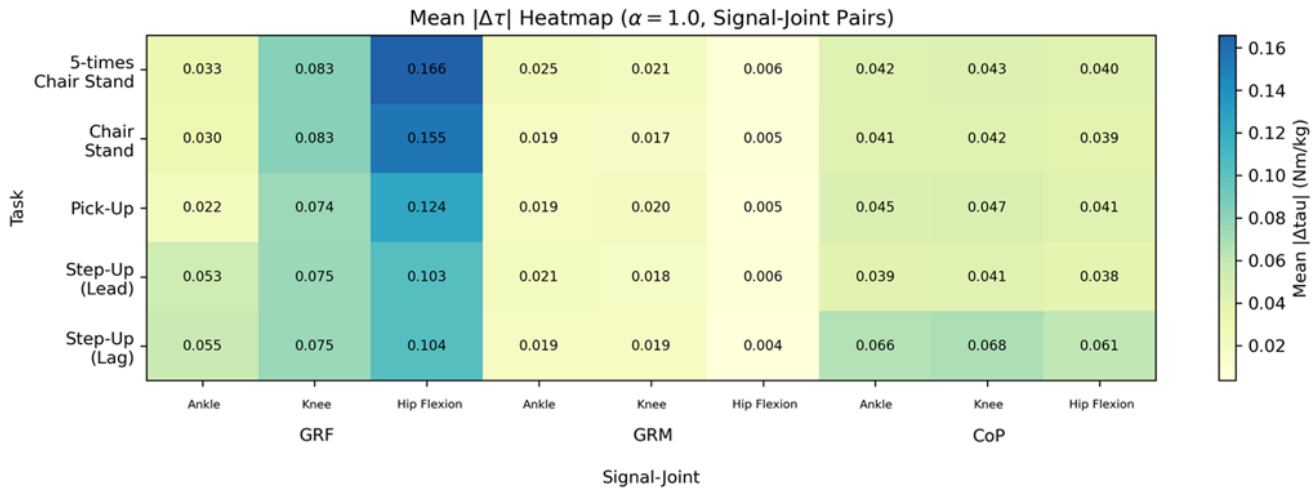

Figure S1: Reference-level heatmap of signal-joint-specific direct propagation sensitivity of mean joint-torque change across the displayed three-joint subset. Each cell shows mean absolute $\Delta\tau$ (Nm/kg) at α = 1.0 for one signal-joint pair, retaining GRF, GRM, CoP and Ankle, Knee, Hip Flexion separately on the horizontal axis.

Table S12: Comparison between statistically significant group differences in Table 4 of the manuscript and the dominant propagated perturbation at the reference perturbation level ($|\alpha| = 1.0$), defined as the largest of the separately applied GRF, GRM, and CoP specific propagated perturbations.

Metric	Joint	5-times Chair Stand	Chair Stand	Pick-Up	Step-Up	
					Lead	Lag
PT	Ankle	–	–	–	–	$0.18/0.088032$ (48.9%, CoP)
	Knee	$0.18/0.066523$ (37.0%, CoP)	–	–	–	–
	Hip	–	–	–	$0.11/0.126886$ (115.4%, GRF)	–
RTD	Ankle	–	–	–	$0.59/0.173777$ (29.5%, CoP)	$0.75/0.094659$ (12.6%, GRF)
	Knee	$2.25/0.381073$ (16.9%, CoP)	–	–	$1.11/0.305811$ (27.6%, CoP)	–
	Hip	$3.80/0.227166$ (6.0%, GRF)	–	–	$0.77/0.232939$ (30.3%, GRF)	–
PR	Ankle	$0.18/0.030523$ (17.0%, GRF)	–	$0.11/0.029119$ (26.5%, CoP)	–	–
	Knee	$1.11/0.246414$ (22.2%, GRF)	–	–	–	–
	Hip	–	–	–	–	$0.06/0.167412$ (279.0%, GRF)

Only statistically significant entries from Table 4 of the manuscript are included. For each populated cell, the first line reports $\Delta_{\mathrm{group,diff}}/\Delta_{\mathrm{dom,error}}$, where $\Delta_{\mathrm{group,diff}}$ denotes the magnitude of Healthy–Sarcopenia mean difference reported in Table 4 and $\Delta_{\mathrm{dom,error}}$ denotes the largest magnitude of propagated change among the GRF-, GRM-, and CoP-specific perturbations for the matched task, joint, and metric. The second line reports the corresponding ratio ($\Delta_{\mathrm{dom,error}}/\Delta_{\mathrm{group,diff}} \times 100$) together with the dominant signal. Blank cells indicate non-significant comparisons in Table 4.