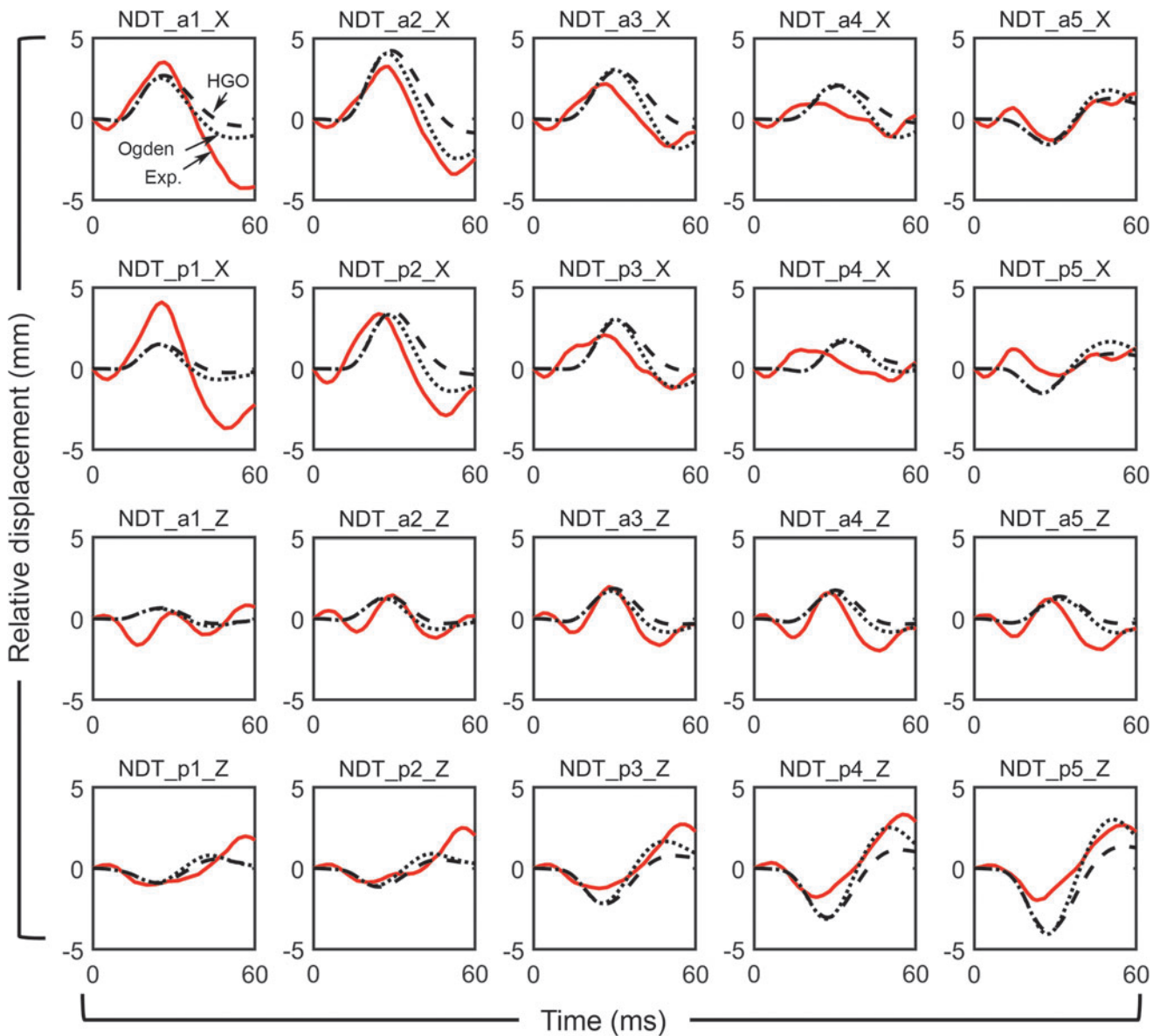


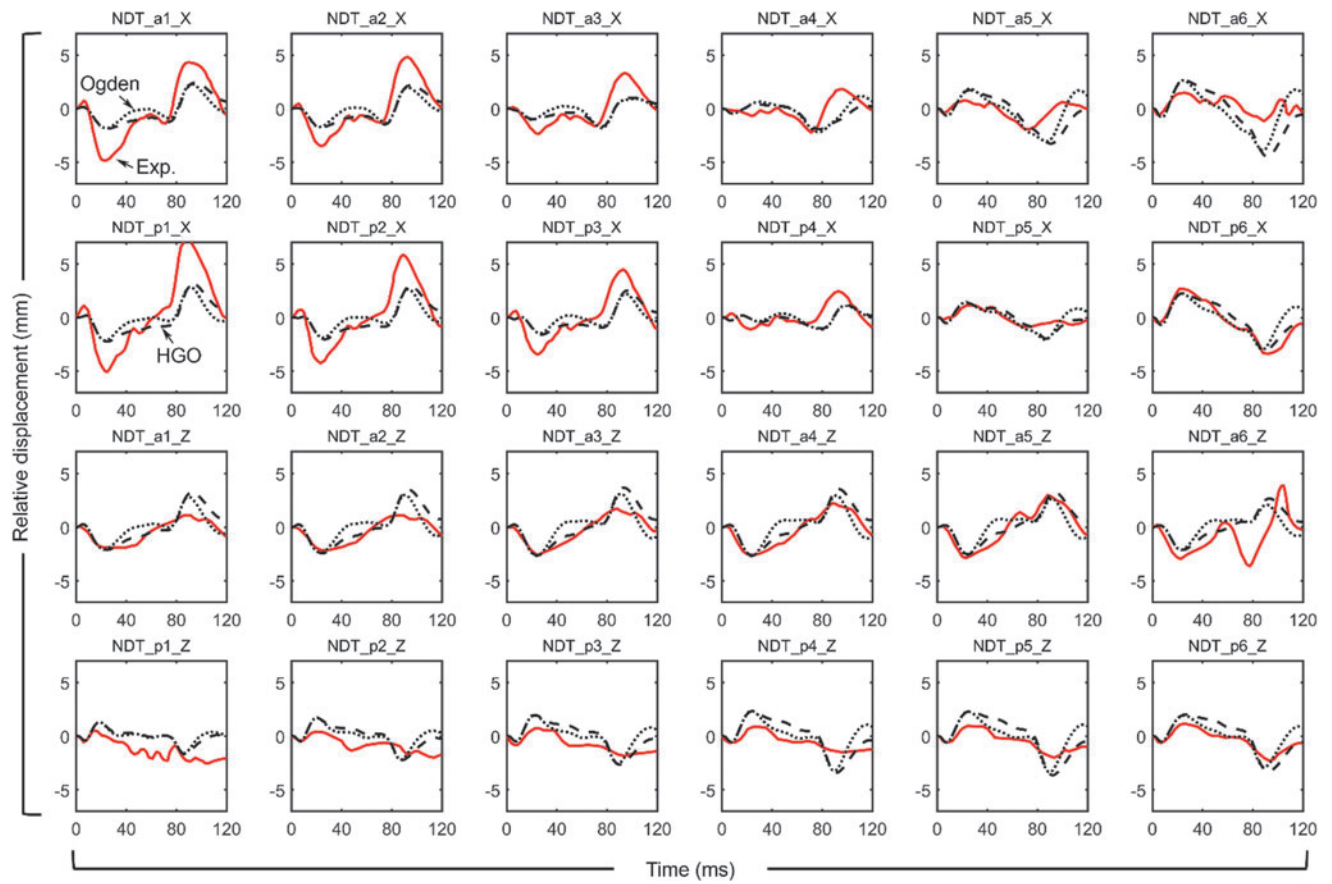
Supplementary Data

Model-estimated brain-skull displacements at neutral density target (NDT) locations were compared with the measurements in six cadaveric impacts (Figs. A1–A6). For consistency with the previous version of WHIM^{11,46}, we reported the correlation score (CS) based on Normalized Integral Square Error

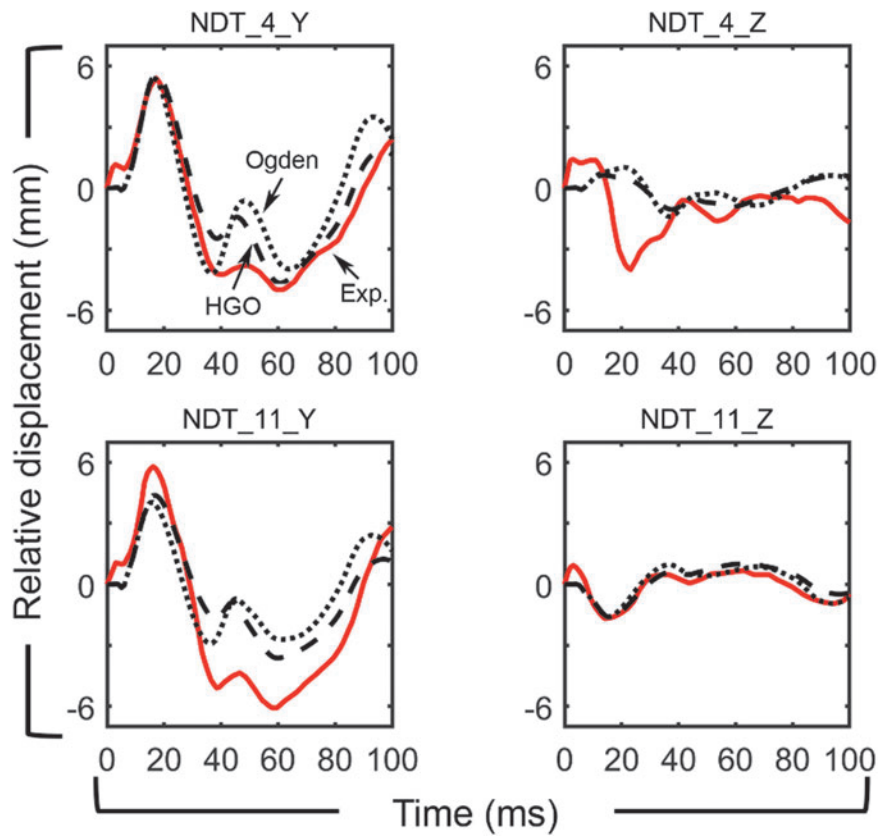
(NISE)⁷¹, as well as the CORrelation and Analysis (CORA) metric in order to compare performances with other head injury models⁴³ (Tables A1–A6, summarized in Table A7). CS and CORA scores for the *in vivo* case are summarized in Table A8.



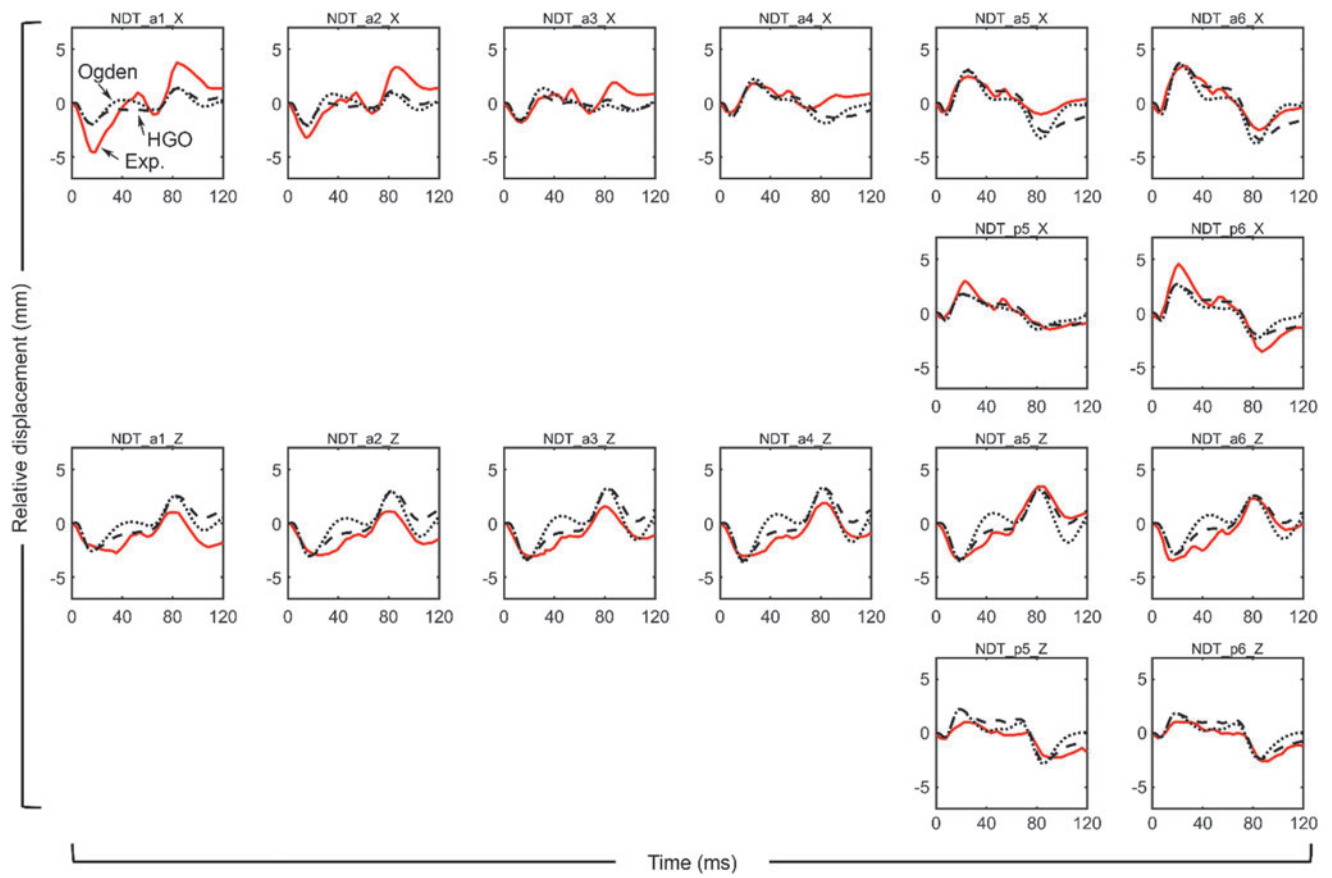
SUPPLEMENTARY FIG. A1. WHIM-estimated relative brain-skull displacements at each NDT location along with experimental results for C755-T2 using the HGO and Ogden material properties.



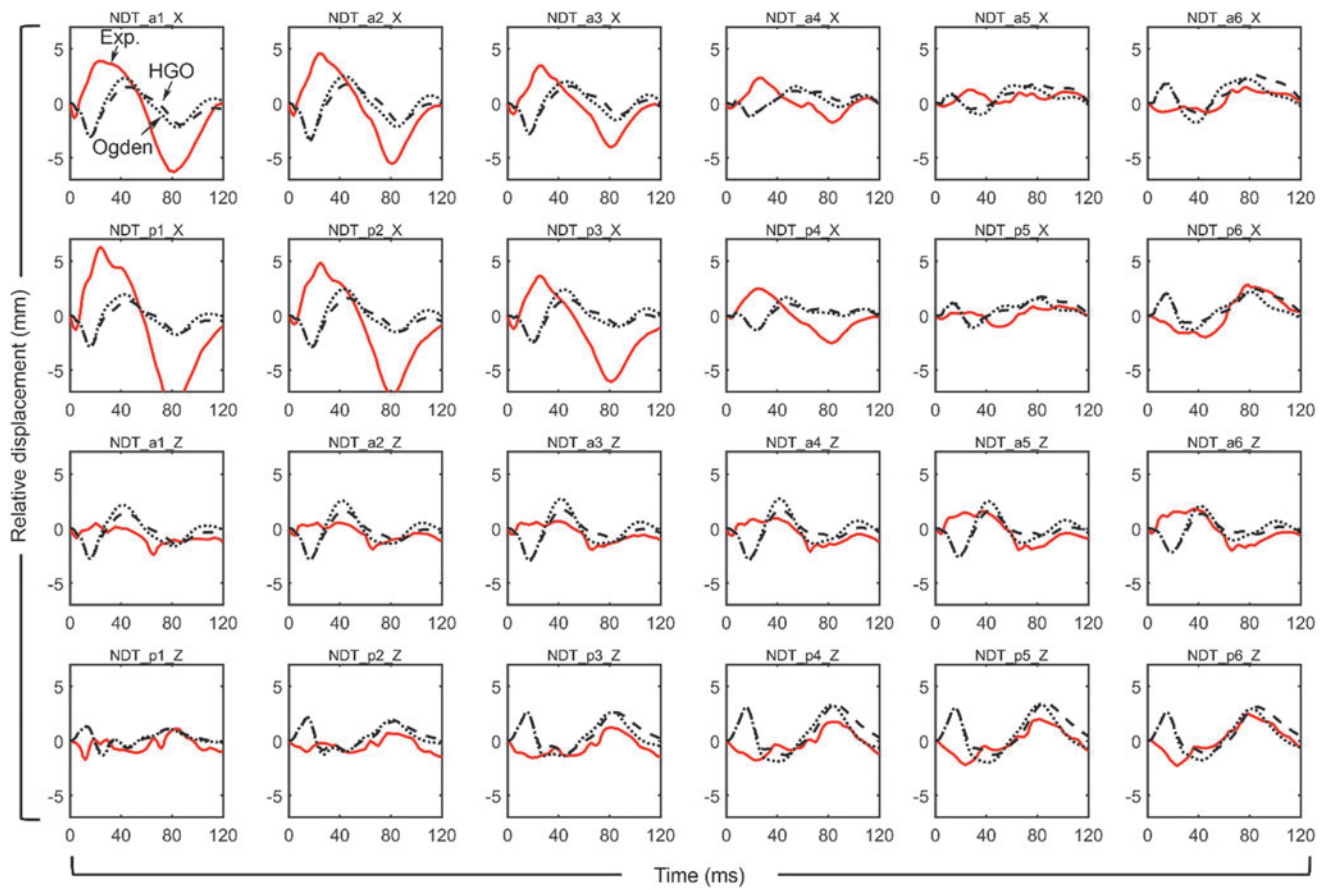
SUPPLEMENTARY FIG. A2. Relative brain-skull displacements comparisons for C383-T1.



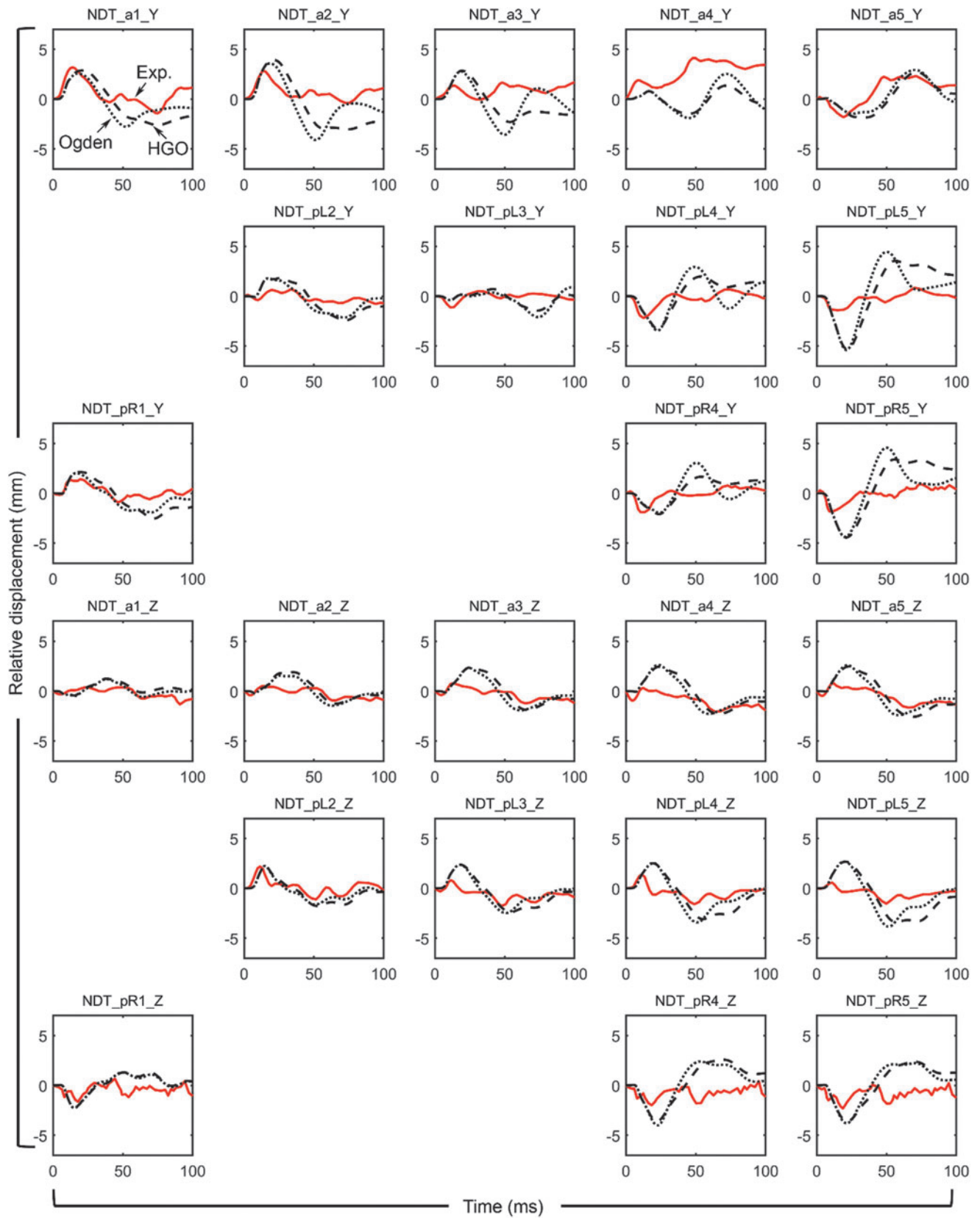
SUPPLEMENTARY FIG. A3. Relative brain-skull displacements comparisons for C393-T4.



SUPPLEMENTARY FIG. A4. Relative brain-skull displacements comparisons for C383-T3.



SUPPLEMENTARY FIG. A5. Relative brain-skull displacements comparisons for C383-T4.



SUPPLEMENTARY FIG. A6. Relative brain-skull displacements comparisons for C291-T1.

SUPPLEMENTARY TABLE A1. CS AND CORA SCORES AT EACH NDT LOCATION FOR C755-T2 USING THE HGO AND OGDEN MATERIAL PROPERTIES

C755-T2	location	CS _N – phase		CS _N – amp		CS _N – shape		Average		CORA	
		HGO	Ogden	HGO	Ogden	HGO	Ogden	HGO	Ogden	HGO	Ogden
X	NDT_a1	95.78	99.81	86.80	82.81	72.86	88.91	85.15	90.51	0.57	0.674
	NDT_a2	91.61	97.61	99.99	99.96	72.68	95.08	88.10	97.55	0.446	0.620
	NDT_a3	76.94	83.98	97.75	95.92	84.83	96.71	86.51	92.20	0.36	0.503
	NDT_a4	56.52	70.55	87.59	85.58	88.81	99.34	77.64	85.16	0.248	0.323
	NDT_a5	96.70	95.94	100	97.79	93.76	94.78	96.82	96.17	0.668	0.526
	NDT_p1	98.67	99.42	62.05	55.20	79.57	94.99	80.10	83.20	0.367	0.483
	NDT_p2	72.59	84.09	98.86	97.46	81.14	99.88	84.20	93.81	0.358	0.447
	NDT_p3	72.00	81.82	97.41	97.12	94.47	99.59	87.96	92.84	0.341	0.504
	NDT_p4	0.00	10.10	96.81	97.23	87.59	87.12	61.46	64.82	0.263	0.281
Z	NDT_p5	68.87	69.48	99.07	91.35	69.92	85.57	79.29	82.14	0.373	0.227
	NDT_a1	40.50	32.33	84.73	79.77	57.36	78.80	60.86	63.63	0.267	0.311
	NDT_a2	98.15	92.28	99.24	98.24	63.23	80.29	86.87	90.27	0.409	0.444
	NDT_a3	95.09	98.48	98.86	97.84	72.63	87.86	88.86	94.73	0.451	0.564
	NDT_a4	92.47	96.28	97.57	95.81	52.08	73.63	80.71	88.58	0.366	0.419
	NDT_a5	84.42	80.89	95.65	93.47	43.47	74.66	74.51	83.01	0.353	0.376
	NDT_p1	95.90	76.58	85.09	85.71	79.02	89.77	86.67	84.02	0.620	0.426
	NDT_p2	98.90	84.08	89.51	88.42	61.65	82.31	83.36	84.94	0.705	0.642
	NDT_p3	98.91	98.17	98.43	99.73	72.76	84.72	90.03	94.21	0.586	0.693
average	NDT_p4	95.98	93.68	99.56	99.78	73.46	82.63	89.67	92.03	0.493	0.698
	NDT_p5	93.32	97.53	97.51	92.54	78.88	89.54	89.90	93.20	0.436	0.591
average		81.17	82.16	93.62	91.59	74.01	88.31	82.93	87.35	0.434	0.488

SUPPLEMENTARY TABLE A2. CS AND CORA SCORES AT EACH NDT LOCATION FOR C383-T1

<i>C383-T1</i>	<i>location</i>	CS_N - phase		CS_N - amp		CS_N - shape		<i>Average</i>		<i>CORA</i>	
		<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>
X	NDT_a1	94.22	99.45	79.48	68.97	99.02	95.20	90.90	87.87	0.575	0.492
	NDT_a2	95.44	100	83.21	74.04	95.96	89.04	91.54	87.69	0.589	0.477
	NDT_a3	90.09	95.28	82.47	83.10	90.41	73.87	87.66	84.08	0.476	0.347
	NDT_a4	67.25	55.96	99.13	99.96	50.80	83.73	72.39	79.88	0.365	0.414
	NDT_a5	55.37	82.85	82.05	84.41	99.96	91.98	79.13	86.41	0.281	0.398
	NDT_a6	98.03	99.92	76.85	83.55	66.97	60.74	80.62	81.40	0.233	0.273
Z	NDT_p1	94.20	99.55	74.42	63.20	97.93	94.02	88.85	85.59	0.517	0.512
	NDT_p2	87.21	96.97	81.67	69.83	99.72	95.24	89.53	87.35	0.533	0.507
	NDT_p3	90.20	96.43	84.84	74.32	93.17	89.07	89.41	86.60	0.530	0.454
	NDT_p4	67.55	69.27	88.32	89.40	81.34	71.91	79.07	76.86	0.443	0.386
	NDT_p5	96.07	99.47	94.92	94.78	79.06	70.19	90.02	88.15	0.472	0.423
	NDT_p6	99.60	91.46	98.77	96.18	96.93	91.57	98.43	93.07	0.766	0.641
	NDT_a1	95.60	96.80	96.24	99.90	83.23	76.48	91.69	91.06	0.493	0.493
	NDT_a2	96.27	98.41	95.55	99.62	82.52	71.45	91.45	89.83	0.465	0.435
	NDT_a3	96.38	98.24	97.10	99.90	91.63	78.97	95.04	92.37	0.609	0.497
	NDT_a4	96.62	98.10	99.69	99.48	94.79	80.77	97.03	92.78	0.642	0.486
	NDT_a5	96.13	98.62	99.42	96.61	97.80	82.00	97.78	92.41	0.683	0.504
	NDT_a6	86.49	48.64	95.68	86.20	58.86	86.18	80.35	73.67	0.312	0.208
	NDT_p1	97.49	95.58	89.30	89.16	35.99	32.08	74.26	72.27	0.289	0.297
	NDT_p2	100	100	99.93	99.52	41.89	27.56	80.61	75.69	0.337	0.362
	NDT_p3	100	93.20	99.34	99.99	62.27	57.19	87.20	83.46	0.267	0.371
	NDT_p4	100	89.86	89.57	95.06	71.10	67.60	86.89	84.17	0.226	0.328
	NDT_p5	99.24	95.14	87.40	95.18	84.42	78.60	90.35	89.64	0.345	0.520
	NDT_p6	98.92	94.56	90.82	98.25	91.53	88.85	93.76	93.89	0.436	0.639
average		91.60	91.41	90.26	89.19	81.14	76.43	87.66	85.68	0.454	0.436

SUPPLEMENTARY TABLE A3. CS AND CORA SCORES AT EACH NDT LOCATION FOR C393-T4

<i>C393-T4</i>	<i>location</i>	CS_N - phase		CS_N - amp		CS_N - shape		<i>Average</i>		<i>CORA</i>	
		<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>
y	NDT_4	99.29	100.00	98.92	98.90	96.13	86.08	98.11	94.99	0.728	0.559
	NDT_11	60.08	38.19	70.57	74.50	82.74	87.17	71.13	66.62	0.535	0.404
Z	NDT_4	99.36	100.00	87.29	84.62	95.40	86.87	94.02	90.50	0.406	0.379
	NDT_11	99.44	99.76	99.94	99.96	84.86	89.16	94.74	96.29	0.592	0.646
average		89.54	84.49	89.18	89.49	89.78	87.32	89.50	87.10	0.565	0.497

SUPPLEMENTARY TABLE A4. CS AND CORA SCORES AT EACH NDT LOCATION FOR C383-T3

C383-T3	location	CS _N – phase		CS _N – amp		CS _N – shape		Average		CORA		
		HGO	Ogden	HGO	Ogden	HGO	Ogden	HGO	Ogden	HGO	Ogden	
X	NDT_a1	99.54	97.44	71.14	67.11	90.04	88.23	86.91	84.26	0.476	0.492	
	NDT_a2	98.84	97.56	75.56	84.34	83.71	61.15	86.04	81.02	0.475	0.389	
	NDT_a3	73.37	34.89	87.77	95.99	74.31	99.76	78.48	76.88	0.383	0.422	
	NDT_a4	97.49	97.14	99.56	98.74	41.61	54.31	79.55	83.40	0.623	0.498	
	NDT_a5	96.33	100	93.26	95.52	85.04	84.15	91.54	93.22	0.584	0.512	
	NDT_a6	98.42	98.78	97.77	99.93	96.56	93.56	97.59	97.42	0.74	0.703	
	NDT_p1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
	NDT_p2											
	NDT_p3											
	NDT_p4											
	NDT_p5	99.93	98.06	97.49	96.02	96.06	95.83	97.83	96.64	0.761	0.723	
	NDT_p6	99.88	98.53	93.24	87.58	97.67	96.37	96.93	94.16	0.722	0.625	
Z	NDT_a1	98.09	99.67	99.46	97.43	56.83	59.61	84.79	85.57	0.534	0.367	
	NDT_a2	99.41	97.28	99.90	99.17	65.46	67.20	88.26	87.89	0.533	0.384	
	NDT_a3	99.23	97.13	99.99	99.92	76.28	72.95	91.83	90.00	0.562	0.432	
	NDT_a4	99.05	95.27	100	99.98	82.12	76.97	93.72	90.74	0.568	0.45	
	NDT_a5	99.24	100.00	98.23	98.45	98.51	74.19	98.66	90.88	0.757	0.494	
	NDT_a6	99.72	97.94	97.26	96.82	90.45	73.36	95.81	89.37	0.637	0.412	
		NDT_p1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		NDT_p2										
		NDT_p3										
		NDT_p4										
		NDT_p5	97.17	89.70	98.68	100	83.77	79.62	93.21	89.77	0.433	0.506
	NDT_p6	99.49	94.19	99.79	99.01	88.51	87.86	95.93	93.69	0.594	0.639	
average		97.20	93.35	94.32	94.75	81.68	79.07	91.07	89.06	0.586	0.503	

SUPPLEMENTARY TABLE A5. CS AND CORA SCORES AT EACH NDT LOCATION FOR C383-T4

<i>C383-T4</i>	<i>location</i>	CS_N - phase		CS_N - amp		CS_N - shape		<i>Average</i>		<i>CORA</i>	
		<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>
X	NDT_a1	66.86	92.56	70.35	83.65	86.41	58.34	74.54	78.18	0.262	0.292
	NDT_a2	48.01	79.80	77.48	89.33	86.15	60.12	70.54	76.41	0.264	0.288
	NDT_a3	24.29	61.13	82.06	91.87	94.55	70.71	66.97	74.57	0.254	0.269
	NDT_a4	2.94	18.96	95.87	95.77	63.78	66.82	54.20	60.52	0.261	0.28
	NDT_a5	75.01	50.82	94.26	96.66	86.20	83.74	85.16	77.07	0.285	0.248
	NDT_a6	97.61	80.80	89.16	90.54	72.72	80.76	86.50	84.03	0.291	0.279
Z	NDT_p1	80.73	97.76	55.93	73.76	79.62	51.45	72.09	74.32	0.246	0.268
	NDT_p2	64.45	86.73	63.67	80.67	82.27	52.72	70.13	73.37	0.264	0.292
	NDT_p3	57.76	78.32	68.93	84.95	72.36	45.82	66.35	69.70	0.246	0.243
	NDT_p4	18.39	38.32	85.65	90.63	54.46	48.88	52.83	59.28	0.22	0.221
	NDT_p5	73.35	30.33	89.92	91.67	82.39	98.93	81.89	73.65	0.201	0.241
	NDT_p6	95.79	96.01	98.56	96.58	75.40	71.11	89.92	87.90	0.447	0.357
	NDT_a1	81.20	95.41	99.74	98.94	51.42	34.74	77.45	76.36	0.296	0.282
	NDT_a2	70.62	97.57	97.04	94.95	58.35	39.24	75.33	77.25	0.348	0.298
	NDT_a3	74.65	98.91	98.94	96.69	51.59	37.15	75.06	77.58	0.33	0.312
	NDT_a4	82.65	94.85	99.94	98.14	38.68	38.97	73.76	77.32	0.319	0.299
	NDT_a5	86.40	94.95	99.55	99.93	23.10	32.14	69.68	75.67	0.319	0.329
	NDT_a6	70.69	93.07	97.55	99.67	34.31	30.18	67.52	74.30	0.282	0.327
	NDT_p1	34.21	36.20	99.02	99.34	74.04	68.67	69.09	68.07	0.294	0.293
	NDT_p2	30.55	82.13	96.02	97.69	79.72	36.86	68.76	72.23	0.262	0.212
	NDT_p3	95.91	71.22	99.11	97.31	22.04	60.28	72.35	76.27	0.256	0.272
	NDT_p4	100	98.20	95.54	95.05	38.74	42.02	78.09	78.42	0.266	0.312
	NDT_p5	89.74	100.00	94.98	96.01	55.94	49.73	80.22	81.92	0.314	0.347
	NDT_p6	79.62	93.09	98.28	99.11	75.98	65.66	84.63	85.95	0.375	0.442
average		66.73	77.80	89.48	93.29	64.18	55.21	73.46	75.43	0.288	0.292

SUPPLEMENTARY TABLE A6. CS AND CORA SCORES AT EACH NDT LOCATION FOR C291-T1

<i>C291-T1</i>	<i>location</i>	<i>CS_N – phase</i>		<i>CS_N – amp</i>		<i>CS_N – shape</i>		<i>Average</i>		<i>CORA</i>		
		<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>	
Y	NDT_a1	88.91	96.41	97.77	98.42	67.59	44.66	84.76	79.83	0.463	0.373	
	NDT_a2	93.57	0.00	99.90	96.07	25.46	84.16	72.97	60.08	0.377	0.131	
	NDT_a3	88.23	87.53	98.19	96.17	43.83	49.50	76.75	77.73	0.253	0.239	
	NDT_a4	83.78	92.19	93.65	91.46	66.51	61.92	81.31	81.86	0.206	0.213	
	NDT_a5	89.75	96.24	99.90	96.86	96.69	96.12	95.45	96.41	0.615	0.687	
	NDT_pL2	99.18	71.05	95.36	87.35	66.15	82.73	86.90	80.37	0.403	0.342	
	NDT_pL3	77.06	71.51	52.14	47.96	72.96	82.25	67.39	67.24	0.163	0.204	
	NDT_pL4	92.50	89.49	60.29	64.40	66.37	63.98	73.05	72.62	0.169	0.165	
	NDT_pL5	100.00	99.80	82.54	89.76	62.72	58.65	81.75	82.73	0.237	0.271	
	NDT_pR1	92.58	96.06	69.51	73.50	81.89	85.55	81.33	85.04	0.278	0.33	
	NDT_pR4	96.01	92.76	63.61	72.50	64.50	56.78	74.71	74.01	0.091	0.08	
	NDT_pR5	98.13	98.48	67.34	74.87	64.68	65.23	76.72	79.53	0.224	0.224	
	Z	NDT_a1	98.21	95.33	93.96	94.69	54.71	52.80	82.29	80.94	0.283	0.287
		NDT_a2	81.26	85.77	93.15	93.05	45.47	43.50	73.29	74.11	0.284	0.254
		NDT_a3	99.98	99.09	94.13	93.97	80.06	74.94	91.39	89.33	0.431	0.412
NDT_a4		99.81	99.62	97.18	96.81	66.92	63.83	87.97	86.76	0.336	0.335	
NDT_a5		99.78	99.15	97.56	93.77	88.19	85.09	95.18	92.67	0.555	0.602	
NDT_pL2		84.82	94.33	82.30	86.81	76.17	68.59	81.10	83.24	0.269	0.27	
NDT_pL3		88.61	94.10	81.49	85.36	87.81	79.00	85.97	86.15	0.326	0.375	
NDT_pL4		82.12	89.81	82.96	86.76	93.61	86.94	86.23	87.84	0.323	0.321	
NDT_pL5		63.24	79.02	99.70	99.78	87.44	81.29	83.46	86.69	0.386	0.445	
NDT_pR1		93.80	87.71	99.21	91.45	1.73	21.59	64.91	66.92	0.181	0.201	
NDT_pR4		82.99	69.92	90.24	87.58	29.26	43.92	67.50	67.14	0.192	0.206	
NDT_pR5		88.48	65.55	98.52	98.98	17.56	39.50	68.18	68.01	0.264	0.318	
average			90.12	85.45	87.11	87.43	62.84	65.52	80.02	79.47	0.305	0.304

SUPPLEMENTARY TABLE A7. CORA SCORES AND RANKS AS COMPARED TO FIVE OTHER HEAD INJURY MODELS FOR THE SELECTED CADAVERIC IMPACTS. AMONG THOSE HAVING BEEN VALIDATED AGAINST THE SAME SET OF IMPACTS (SHADED AREA, CORA SCORES DRAWN FROM THE LITERATURE⁴³), BOTH VERSIONS OF WHIM RANKED THE HIGHEST CORA SCORES, ALTHOUGH THE ANISOTROPIC VERSION HAD A SLIGHTLY HIGHER VALUE

	<i>C755-T2</i> (N=10; 60ms)	<i>C383-T1</i> (N=12, 120ms)	<i>C291-T1</i> (N=12, 100ms)	<i>C383-T3</i> (N=8; 120ms)	<i>C383-T4</i> (N=12; 120ms)	<i>C393-T4</i> (N=2; 100ms)	Rank
WHIM (HGO)	0.434	0.454	0.295	0.586	0.288	0.565	3, 1, 3, 1, 5
WHIM (Ogden)	0.488	0.436	0.310	0.503	0.292	0.497	1, 2, 4, 2, 4
ABM	0.449	0.393	0.385	0.306	0.347	-	2, 4, 2, 3, 3
SIMon	0.340	0.412	0.388	0.209	0.423	-	5, 3, 1, 5, 1
GHBMC	0.433	0.352	0.221	0.232	0.378	0.322* ^{▲,■,○,75}	4, 5, 6, 4, 2
THUMS	0.313	0.306	0.246	0.186	0.251	0.319* ^{▲,■,○,75}	6, 6, 5, 6, 6
KTH (M-R)	0.475 ⁴³	0.407 ⁴³	0.358** ^{, 43}	N/A	0.445* ^{,○,68}	-	N/A
KTH (Ogden)	0.390 ^{◆,43}	0.256 ⁴³	0.389** ^{,43}	N/A	N/A	0.460* ^{▲,■,○,75}	N/A
KTH (HGO) ○	0.480 ^{◆, 29}	0.312*** ^{,◆, 29}	0.356** ^{,◆, 29}	N/A	N/A	0.574* ^{▲,■, 75}	N/A

* N=6

** N=9

*** N=10

▲ First 40 ms

◆ First 50 ms

■ Along x, y and z directions

○ Calculated from digitization of published curves

SUPPLEMENTARY TABLE A8. CS AND CORA SCORES OF ABOVE-THRESHOLD AREA FRACTIONS OF THE
 RADIAL-CIRCUMFERENTIAL SHEAR STRAINS FOR THE TWO VERSION OF WHIM USING EITHER HGO OR ODGEN
 MATERIAL PROPERTIES FOR THE BRAIN

<i>Threshold</i>	$CS_N - \text{phase}$		$CS_N - \text{amp}$		$CS_N - \text{shape}$		<i>Average CS</i>		<i>CORA</i>	
	<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>	<i>HGO</i>	<i>Ogden</i>
0.02	86.90	96.64	90.79	90.60	92.13	98.25	89.94	95.16	0.712	0.547
0.04	95.10	95.88	61.19	85.90	96.97	99.89	84.42	93.89	0.386	0.466
0.06	92.13	48.97	96.97	92.15	97.91	99.97	95.67	80.36	0.428	0.330
Average	91.38	80.50	82.98	89.55	95.67	99.37	90.01	89.80	0.509	0.448