APPENDIX A

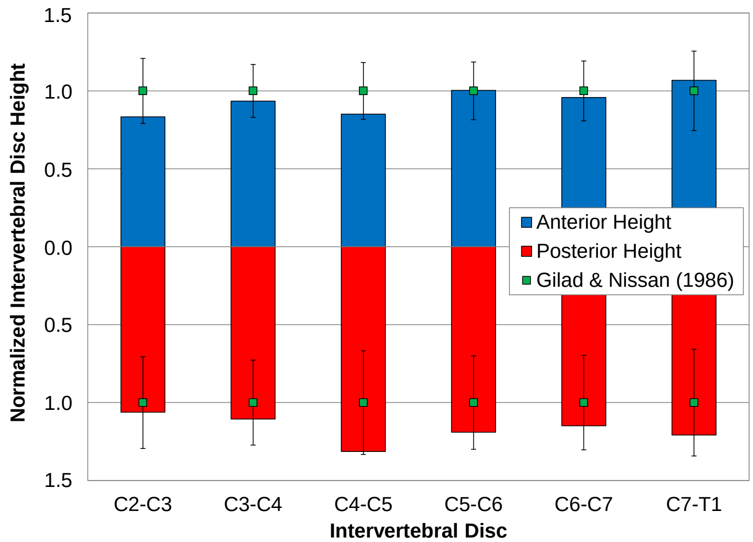


Figure A1: Model intervertebral disc height compared to experimental measurements (mean ± 1 SD)

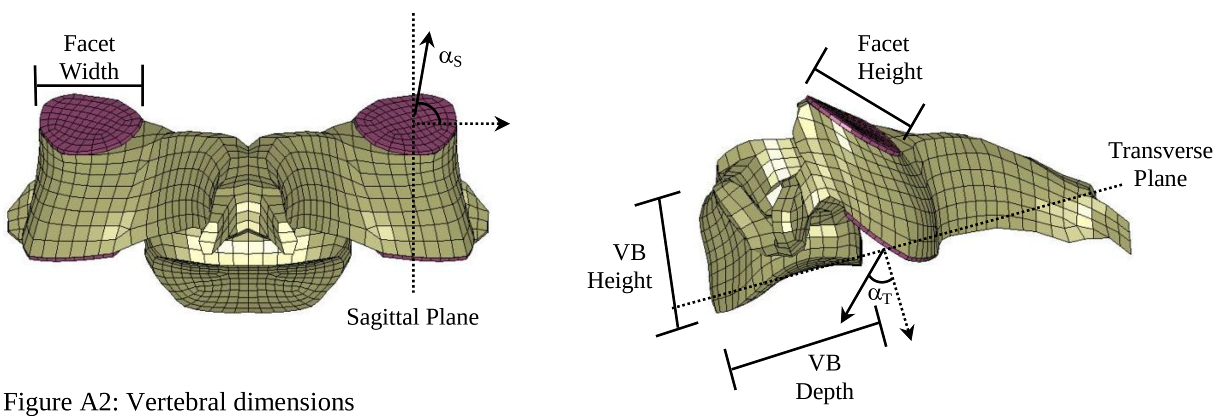


Figure A2: Vertebral dimensions

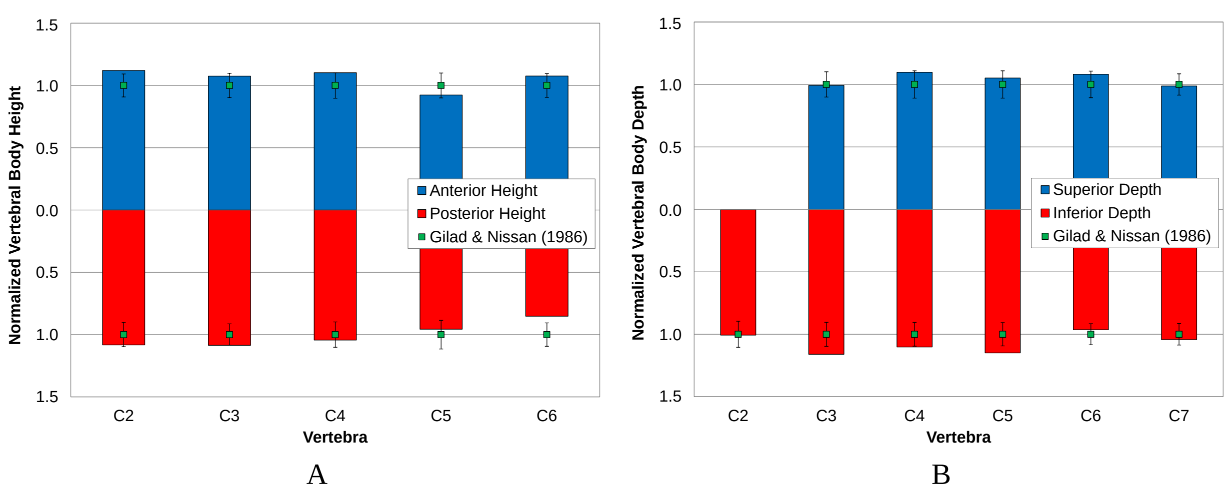


Figure A3: Model vertebral body height (A) and depth (B) compared to experimental measurements (mean ± 1 SD)

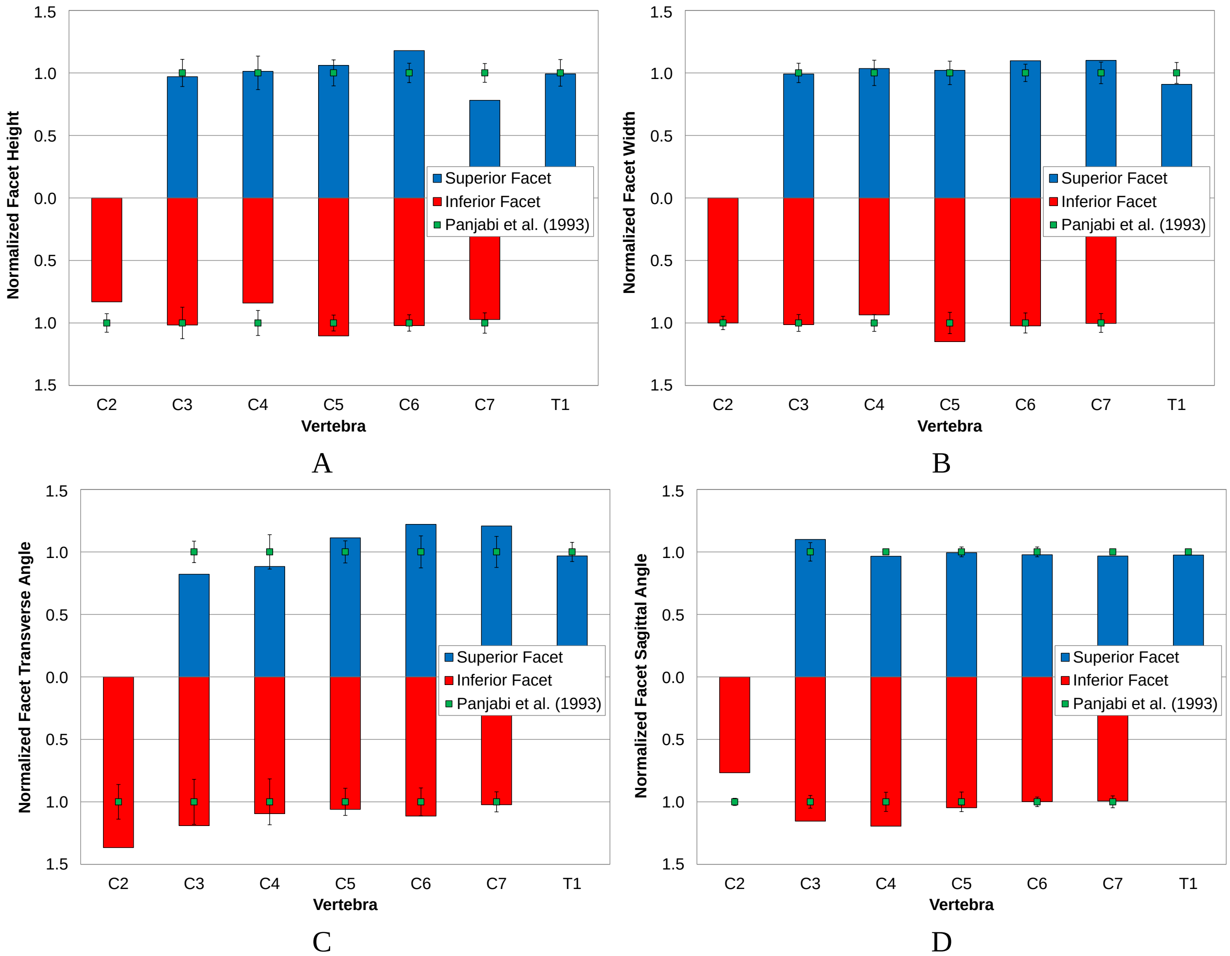


Figure A4: Model facet height (A), depth (B), transverse angle (C) and sagittal angle (D) compared to experimental measurements (mean ± 1 SD)

APPENDIX B

Table B1: Force deflection points for the ligaments in the cervical spine model

Ligament	Level	Point A		Point B		Point C	
		d (mm)	F (N)	d (mm)	F (N)	d (mm)	F (N)
Anterior longitudinal (ALL)	C2-C5	1.22	10.04	4.48	79.89	5.8	93
	C5-T1	1.37	15.66	5.02	124.56	6.5	145
Posterior longitudinal (PLL)	C2-C5	0.88	6.96	2.71	55.31	3.5	71
	C5-T1	1.53	18.42	4.72	146.45	6.1	188
Ligamentum flavum (LF)	C2-C5	1.86	25.29	4.95	108.05	6.5	121
	C5-T1	2.69	26.96	7.16	115.20	9.4	129
Capsular ligament (CL)	C0-C1	1.50	49.28	4.35	275.20	5.7	320
	C1-C2	3.06	48.36	8.85	270.04	11.6	314
	C2-C5	2.69	18.48	7.78	103.20	10.2	120
	C5-T1	2.06	27.87	5.95	155.66	7.8	181
Interspinous ligament (ISL)	C1-C5	1.94	7.84	4.69	35.45	6.3	39
	C5-T1	2.06	7.84	4.98	35.45	6.7	39
Tectorial membrane	C0-C2	3.14	11.70	9.08	65.36	11.9	76
A. altanto-occipital	C0-C1	4.99	35.73	14.42	199.52	18.9	232
A. altanto-axial	C1-C2	2.19	40.50	6.33	226.18	8.3	263
P. altanto-occipital	C0-C1	4.78	12.78	13.81	71.38	18.1	83
P. altanto-axial	C1-C2	2.53	17.09	7.32	95.46	9.6	111
Apical	C0-C2	2.11	32.96	6.10	184.04	8.0	214
Alars (occipital)	C0-C2	3.72	54.98	10.76	307.02	14.1	357
Alars (atlantal)	C1-C2	3.72	54.98	10.76	307.02	14.1	357
Transverse	C1-C2	1.32	54.52	3.82	304.44	5.0	354
Vertical crus	C0-C2	3.30	67.14	9.54	374.96	12.5	436

APPENDIX C

The Hill-type muscle model was used to simulate the active and passive muscle behavior in the model. Active muscle force is a function of muscle length, velocity, and active state dynamics (Equation C1). The product of these functions determines the scale-factor that is applied to the maximum isometric force (F_{max}) produced in the muscle. F_{max} is a product of the muscle physiological cross-sectional area (PCSA) and the maximum muscle stress. Force-length (f_{FL}) and force-velocity (f_{FV}) relationships are nonlinear phenomena based on the current state (length and velocity) of the muscle. The force-length relationship describes isometric muscle force development based on the current length of the muscle and its optimal length (Equation C2). The force-velocity relationship describes the muscle force development as a function of shortening or lengthening, relative to the isometric force (Equation C3). Both the force-length and force-velocity relationships used in the cervical spine model can be seen in Figure C1.

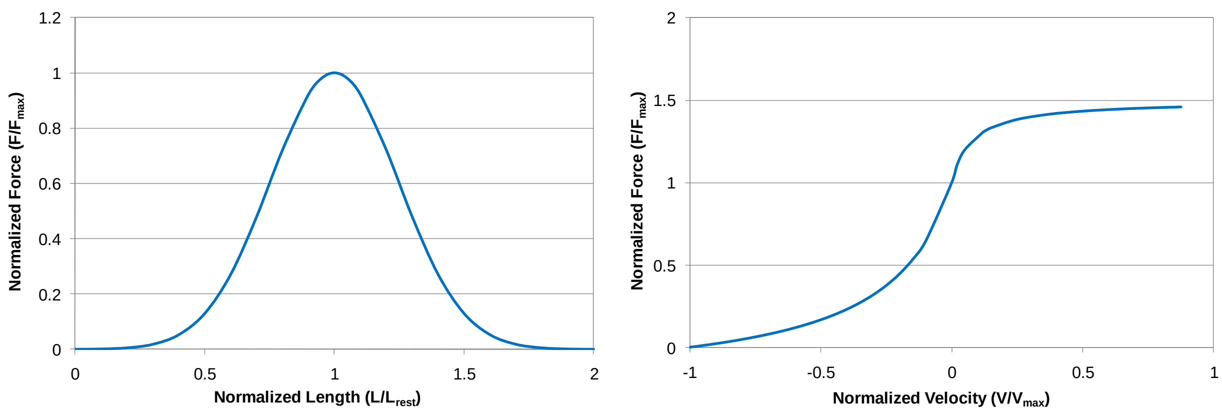
$$F_{Active} = F_{max} \cdot f_{FL} \cdot f_{FV} \cdot A(t) \qquad \text{Equation C1}$$

$$f_{FL} = e^{-S_k(|L|-L_{opt})^2} \qquad \text{Equation C2}$$

$$f_{FV} = \frac{1+{}^{V}/_{V_{max}}}{1-{}^{V}/_{V_{max}} \cdot CE_{sh}} \quad \textit{for } V < 0$$

Equation C3

$$f_{FV} = \frac{1+{}^{V}/_{V_{max}} \cdot {}^{CE_{ml}}/_{CE_{shl}}}{1+{}^{V}/_{V_{max}} \cdot CE_{shl}} \quad \textit{for } V > 0$$



A B

Figure C1: Muscle relationships for force-length (A) and force-velocity (B)

Active state dynamics (A) is a time-dependent function based on neural input to the muscle. Neural excitation (and de-excitation) represents the process of converting an idealized neural input into an output signal resembling an EMG output. Active (and de-active) state dynamics represents the transient dynamics between the neural excitation and muscle contraction. Neural excitation and active state dynamics are described using two 1st order systems [48]:

$$\frac{dE}{dt} = \frac{u(t) - E(t)}{\tau_{ne}} \qquad \text{Equation C4}$$

$$\frac{dA}{dt} = \frac{E(t) - A(t)}{\tau_a} \qquad \text{Equation C5}$$

where u(t) is the idealized neural input ($0 < u(t) < 1$), τ_{ne} is the neural excitation time constant, and τa is the active state time constant. When E > A, the muscle is in a state of activation, and $\tau_a = \tau_{ac}$; when E < A, the muscle is in a state of de-activation, and $\tau_a = \tau_{dc}$. The activation time constant (τ_{ac}) is smaller than the deactivation time constant

(τ_{dc}), which results in muscle activation responding faster than muscle de-activation. The activation state for the flexor and extensor muscles in the cervical spine model, with neural excitation u(t) beginning at 74 ms and ending at 174 ms, is shown in Figure C2.

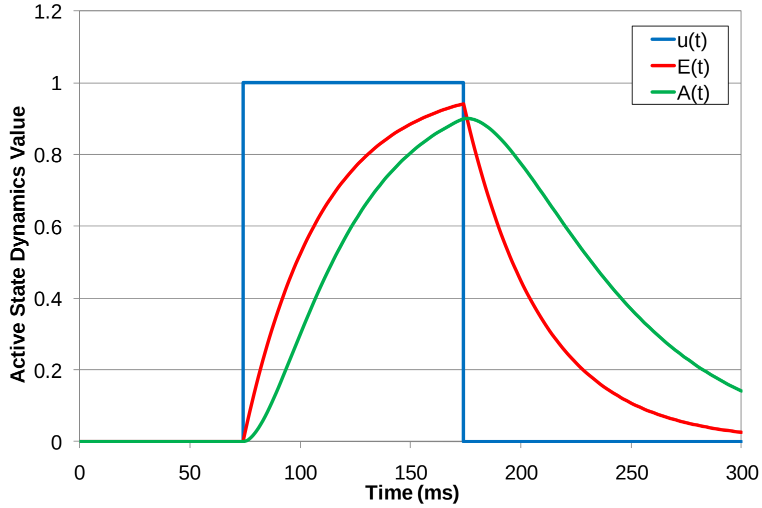
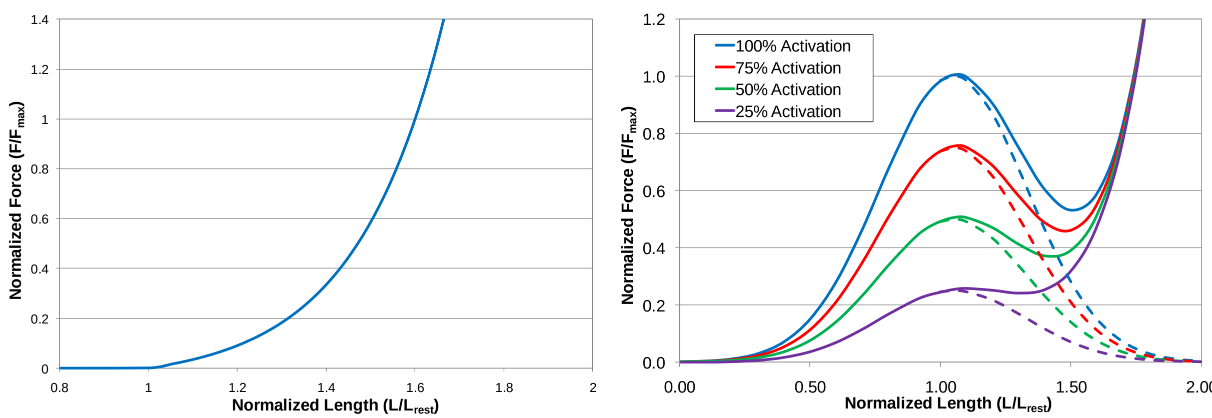


Figure C2: Muscle activation for neural input between 74 and 174 ms for frontal impact simulation

The parallel (passive) element of the Hill muscle model represents the tensile behavior of relaxed muscle and surrounding tissue. This portion the muscle behavior typically does not generate significant force in tension until the muscle is stretched to the limits of physiological loading [69]. There is also an assumption that the passive muscle does not carry compressive load. The force generated in the muscle by passive resistance is calculated by Equation C6, and the passive force response used in the cervical spine model is shown in Figure C3A.

$$F_{Passive} = \frac{F_{max}}{e^{K_{sh-1}}}\left[e^{\frac{K_{sh}}{L_{max}}\left(\frac{L}{L_{rest}}-1\right)} - 1\right] \quad for\ L > L_{rest} \qquad \text{Equation C6}$$

The total muscle response is the sum of both the active and passive components. Figure C3B shows the total isometric force in the muscle over a range of muscle length and activation levels. All Hill-model parameters used in the cervical spine muscle model can be found in Table C1 and all physical muscle properties used the model can be found in Table C2.



A B

Figure C3: (A) Passive muscle response and (B) the total isometric muscle response for various levels of activation (dashed line indicates active contribution only)

Table B1: Hill-type muscle model parameters

Parameter	Range in literature	Value in model	Reference
σ_{max}	0.20 – 1.00 MPa	0.5 MPa	[39, 67]
PCSA		Table B2	
Sk		6.25	[67]
L_{opt}		1.05	[67]
v_{max}	2 (L_{rest}) – 8 (L_{rest}) /s	5 (L_{rest}) /s	[66]
CE_{sh}	0.1 – 1	0.55	[66]
CE_{shl}		0.1065	
CE_{ml}	1.1 – 2.0	1.3	[66]
τ_{ne}	20 – 50 ms	35 ms	[39]
τ_{ac}	5 – 20 ms	15 ms	[39, 67]
τ_{dc}	20 – 60 ms	40 ms	[39, 67]
L_{max}	0.6 – 0.7	0.6	[67]
K_{sh}	3 – 6	3	[67]

Table B2: Cervical spine muscle geometry

Muscle segment	PCSA (cm^2)	Total volume (g/cm^3)
Oblique capitus inferior	1.95	8.13
Oblique capitus superior	0.88	3.03
Rectus capitus major	1.68	5.37
Rectus capitus minor	0.92	1.82
Longus capitis	1.37	11.09
Longus colli	2.75	13.79
Rectus capitis ant	1.30	1.36
Rectus capitis lat	1.30	1.74
Anterior scalene	1.88	9.56
Middle scalene	1.36	10.38
Posterior scalene	1.05	6.38
Sternocleido mastoid	4.92	56.09
Iliocostalis cervicis	1.04	7.21
Longissimus capitis	0.98	12.33
Longissimus cervicis	1.49	9.71
Multifidus	2.35	24.64
Semisplenius capitus	5.52	44.67
Semisplenius cervicis	3.06	24.19
Splenius capitis	3.09	30.67
Splenius cervicis	1.43	14.38
Levator scapula	3.12	37.83
Minor rhomboid	1.02	7.47
Trapezius	13.73	132.09
Omohyoid	1.18	6.35
Sternohyoid	1.18	5.81