HAND ARM VIBRATION

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Development of a Novel Rat-tail Model for Studying Finger Vibration Health Effects

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Background

The relationships between the biomechanical responses and biological effects have not been quantified.

Biomechanical Processes

Hand-transmitted Vibration Hazards:
- Vibration type
- Vibration magnitude
- Vibration duration
- Vibration frequency
- Vibration direction

Biomechanical Responses:
Static and dynamic tissue stress, strain, energy absorption, etc.

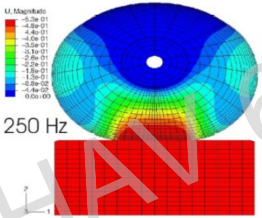
Other biomechanical hazards: grip force, push/pull force, awkward hand or arm postures, etc.

Environmental and Organization Factors: temperature, humidity, noise, culture, training, etc.

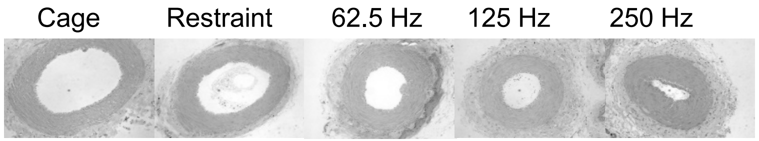
Individual Factors: anthropometry, physical strength/condition, age, gender, past injury histories, smoking, leisure activities, etc.

Biological Effects: psychophysical, physiological, and pathological effects

HAVS



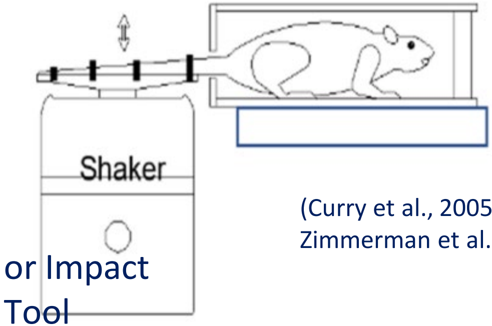
(Wu et al., 2003)



Biological Process

(Krajnak et al., 2010)

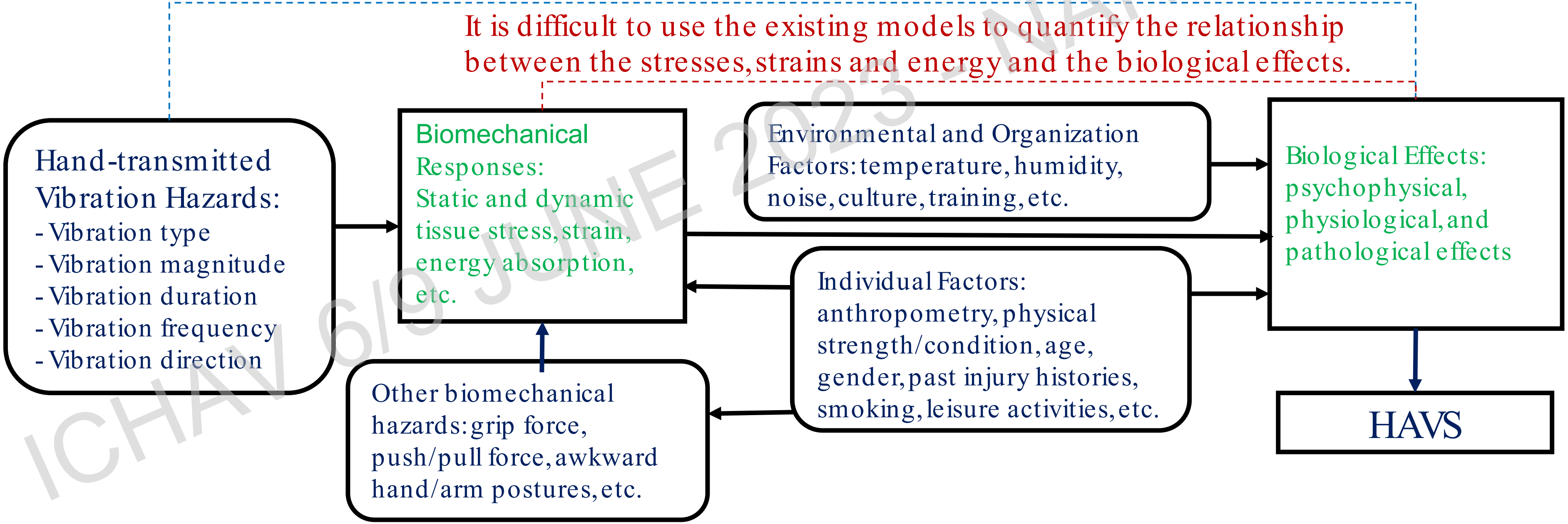
Available Rat-tail Models



or Impact Tool

(Curry et al., 2005; Krajnak et al., 2006; 2013; Zimmerman et al., 2020)

These models are designed to study the relationship between input vibration and biological effects.



It is difficult to use the existing models to quantify the relationship between the stresses, strains and energy and the biological effects.

Hand-transmitted Vibration Hazards:
- Vibration type
- Vibration magnitude
- Vibration duration
- Vibration frequency
- Vibration direction

Biomechanical Responses:
Static and dynamic tissue stress, strain, energy absorption, etc.

Environmental and Organization Factors: temperature, humidity, noise, culture, training, etc.

Biological Effects: psychophysical, physiological, and pathological effects

Individual Factors: anthropometry, physical strength/condition, age, gender, past injury histories, smoking, leisure activities, etc.

Other biomechanical hazards: grip force, push/pull force, awkward hand/arm postures, etc.

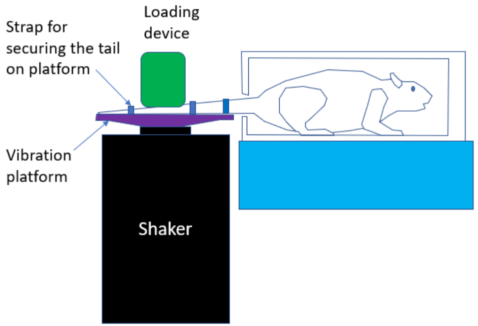
HAVS

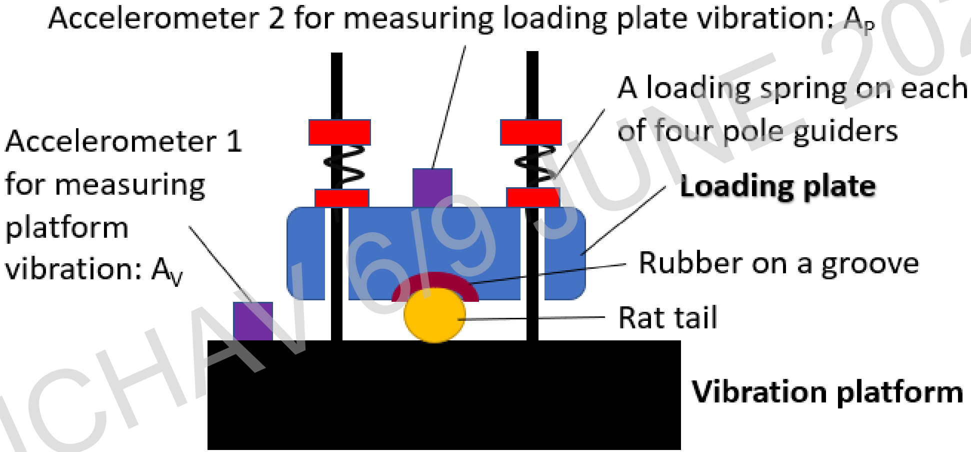
Objective

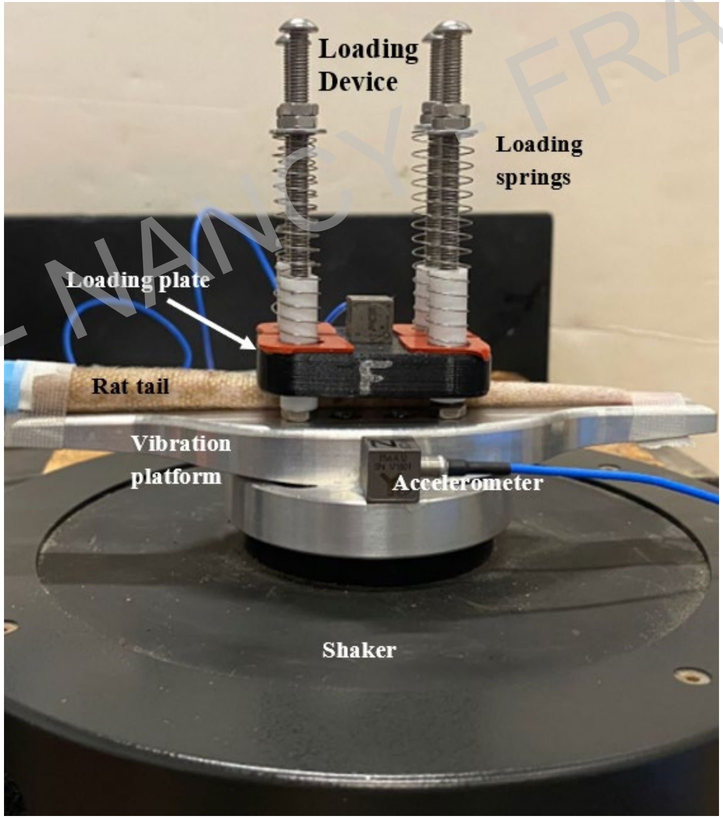
To develop a novel rat-tail vibration model for studying the quantitative relationship between vibration biomechanical responses and biological effects. The model should meet the following requirements:

1) A contact force/pressure can be conveniently and reliably applied on the rat tail to simulate the finger grip force or contact pressure during the tail vibration exposure.
2) The biomechanical responses such as static and dynamic stresses and strains in the tail can be quantified and controlled.
3) The loading device used to apply the static and dynamic forces to the tail in the model should not block the tail blood circulation or injure the tail.

Design of a New Rat-tail Model







Quantification of Rat-tail Biomechanical Responses and Vibration Exposure Doses

Five biomechanical responses: static stress (σ_{static}) and strain (ε_{static}), dynamic or vibration stress (σ_{dyn}) and strain (ε_{dyn}), and vibration power absorption density (VPAD)

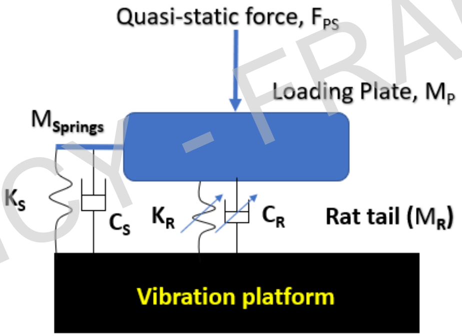
$$\sigma_{\text{static or dyn}} \approx \frac{|\mathrm{F_{PS}} \text{ or } \mathbf{F_{PD}}|}{\mathrm{L_t} \cdot \mathrm{b_t}}$$

$$\varepsilon_{static} \approx \frac{\delta}{\mathrm{h_t}} \qquad \varepsilon_{dyn} \approx \frac{|\mathbf{D_P}-\mathbf{D_V}|}{\mathrm{h_t}} = \frac{\left|\frac{\mathbf{A_V}-\mathbf{A_P}}{\omega^2}\right|}{\mathrm{h_t}}$$

$$\text{VPAD} \approx \frac{\mathbf{C_R} \cdot |\mathbf{V_P}-\mathbf{V_V}|^2}{\text{Tail section volume}}$$

F_{PS}: Applied static force
F_{PD}: Plate dynamic force acting on the tail
L_t: Tail section length
b_t: Tail average contact width

A_P: Plate acceleration	A_V: Platform acceleration
D_P: Plate displacement	D_V: Platform displacement
V_P: Plate velocity	V_V: Platform velocity
δ: Tail static deformation	h_t: Deformed tail height



Three vibration exposure doses: They were derived based on the three dynamic responses (vibration stress, vibration strain, and VPAD). Each of them (*Γ*) can be expressed as the multiplication of the response index (*I*) and exposure duration (*T*):

$$\Gamma_\sigma = \sigma \cdot f^\alpha \cdot T = I_\sigma \cdot T \qquad I_\sigma = \frac{\left|M_{PE}\mathbf{T}_P - \left[\frac{K_S}{(2\pi f)^2} + \frac{\mathrm{j}C_S}{2\pi f}\right](1-\mathbf{T}_P)\right| A_V}{b_t \cdot L_t} f^\alpha$$

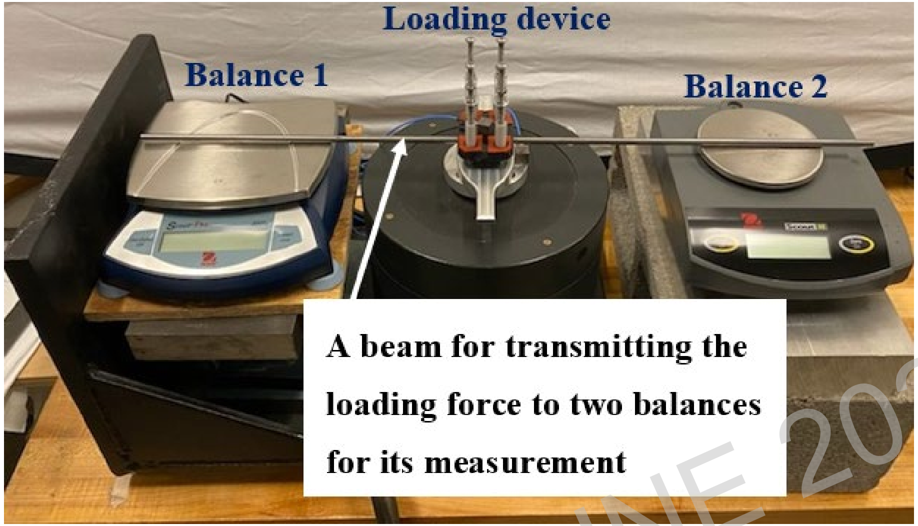
$$\Gamma_\varepsilon = \varepsilon \cdot f^\beta \cdot T = I_\varepsilon \cdot T \qquad I_\varepsilon = \frac{|\mathbf{A}_V-\mathbf{A}_P|}{\omega^2}\frac{f^\beta}{h_t} = \frac{|(1-\mathbf{T}_P)A_V|}{4\pi^2}\frac{f^{\beta-2}}{h_t}$$

$$\Gamma_{VPAD} = \text{VPAD} \cdot T = I_{VPAD} \cdot T \qquad I_{VPAD} = \frac{C_R \cdot \left[\frac{|(\mathbf{T_P}-1)\mathrm{A_V}|}{2\pi f}\right]^2}{v}$$

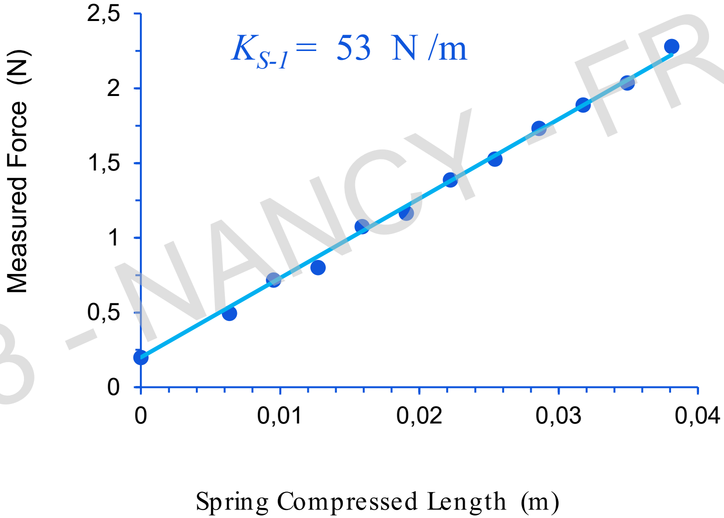
T_P: Plate transfer function (= **A**p/**A**v)
f: Vibration frequency (Hz)
α: Frequency power index for stress
β: Frequency power index for strain
ν: Tail section volume

M_P: Plate mass
M_R: Rat tail section mass
M_{Spring}: Spring mass
K_S: Overall spring stiffness
K_R: Rat tail section stiffness
C_S: Loading device damping value
C_R: Rat tail section damping value

In-situ Calibration Test of Loading Springs for Determining Loading Spring Stiffness (K_S)



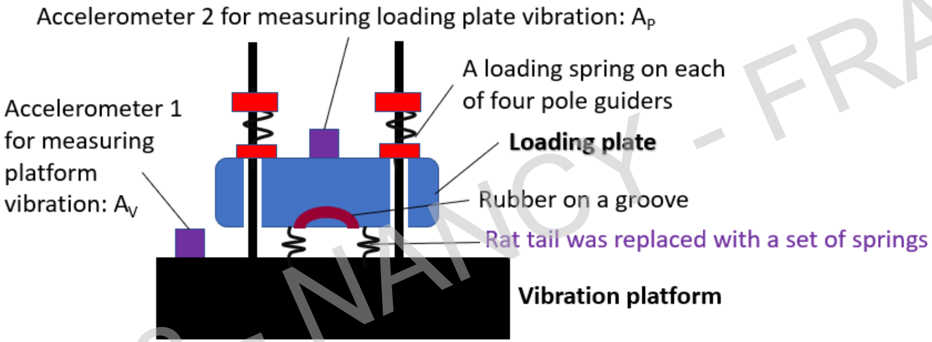
A beam for transmitting the loading force to two balances for its measurement



- Because the spring stiffness is very small, the compression length was manually measured.
- The springs-applied force was measured using two balances.
- Two sets of springs (S-1, S-2) were considered in this study: K_{S-1} = 53 N/m ; K_{S-2} = 236 N/m.
- With the calibration data, the static force required in a biological test can be applied by measuring and controlling the compression length of the springs.

The Vibration Test for Estimating the Damping Value (C_S) of Loading Device

Theory: The springs and other materials are likely to have little damping; the damping value results primarily from the friction between the loading plate and the four guides. Hence, the damping value of the loading device (C_S) can be estimated from a vibration test with the rat tail replaced with a set of springs.

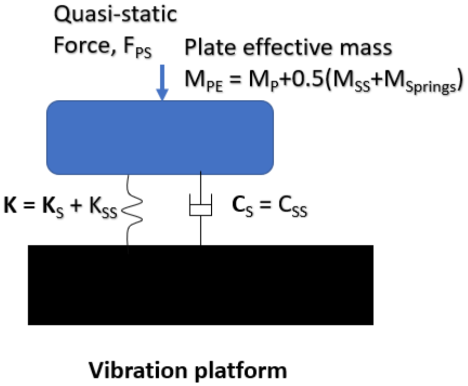


Testing method:

- Three static forces: $F_{PS} = 1.46; 3.54;$ and 6.09 N.
- Three sinusoidal vibration magnitudes at each of the one-third octave bands from 20 to 500 Hz: $A_V = 3.48; 5.21,$ and 8.00 m/s^2.

1-D model for estimating C_S:

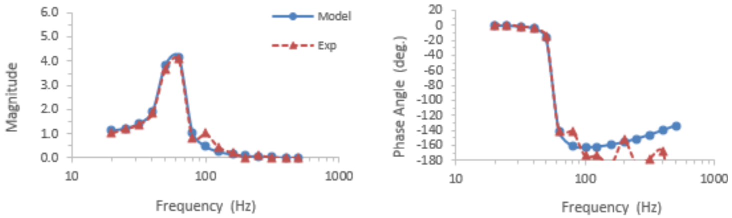
- For each testing treatment, the entire system can be simulated using a linear model.
- The mass values can be directly measured; Mss is the spring mass replacing the tail.
- Css and Kss can be estimated using the plate transfer function (T_P = Ap/Av) measured in the vibration test.



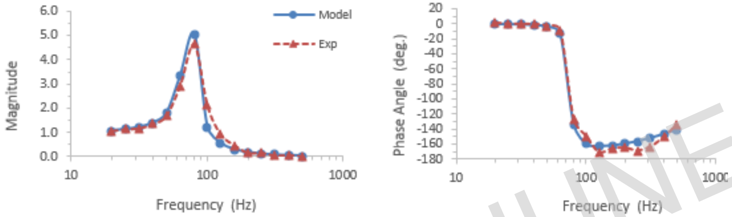
Modeling Estimation of Loading Device Damping Value (C_S)

Use the transfer function calculated with the 1-D model to fit the measured transfer function by sequentially varying the C_S and Kss values; when the modeling results have the best fit, the C_S and Kss are determined.

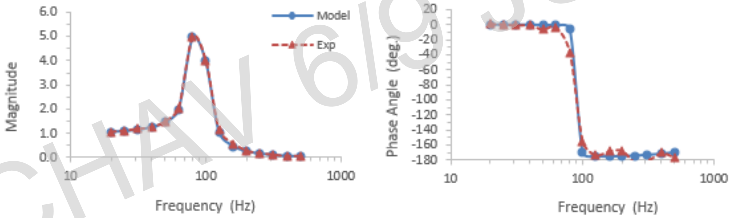
(a) F_{PS} = 1.41 N

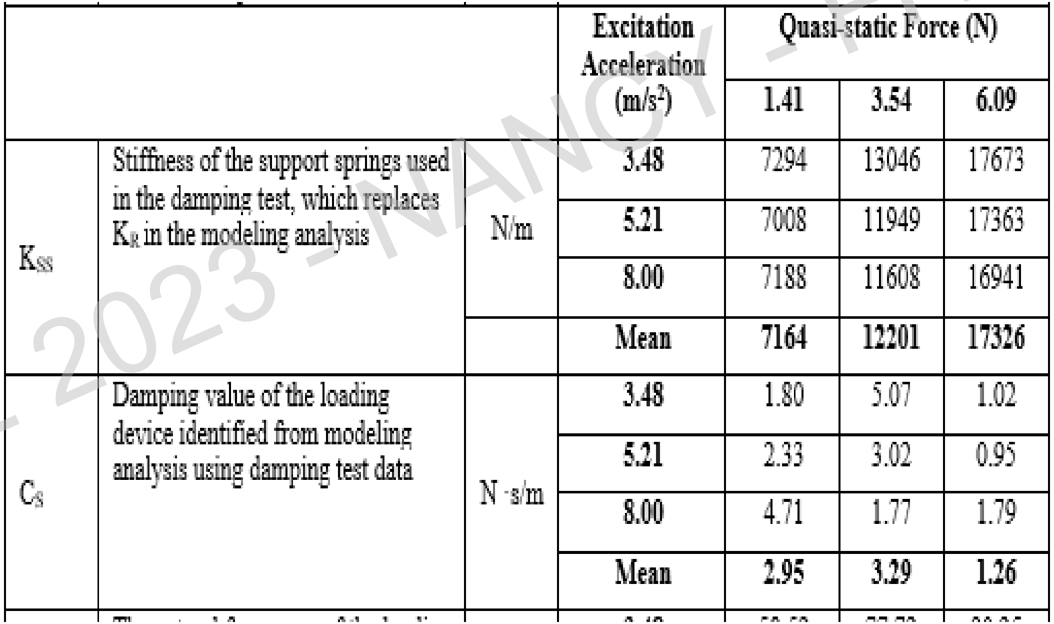


(b) F_{PS} = 3.54 N



(c) F_{PS} = 6.09 N



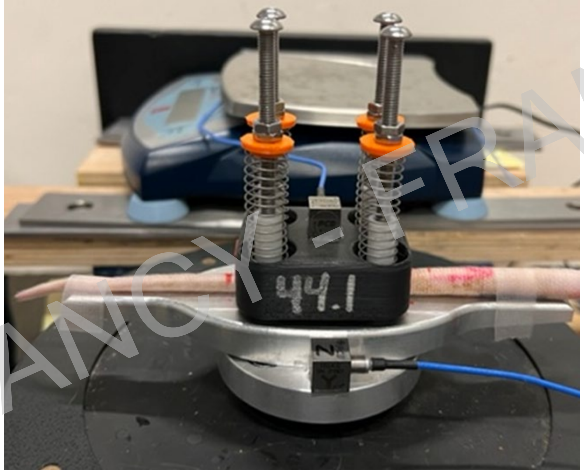


			Excitation Acceleration (m/s^2)	Quasi-static Force (N)		
				1.41	3.54	6.09
K_{SS}	Stiffness of the support springs used in the damping test, which replaces K_R in the modeling analysis	N/m	3.48	7294	13046	17673
			5.21	7008	11949	17363
			8.00	7188	11608	16941
			Mean	**7164**	**12201**	**17326**
C_S	Damping value of the loading device identified from modeling analysis using damping test data	N ·s/m	3.48	1.80	5.07	1.02
			5.21	2.33	3.02	0.95
			8.00	4.71	1.77	1.79
			Mean	**2.95**	**3.29**	**1.26**

Rat Tail Tests

Two series of rat tail vibration tests were conducted:

- Aims of the first test: to verify the concept of the new model and to help improve the model; the results are included in the abstract.
- Aims of the second test: to verify the model improvement and to characterize the biomechanical responses of the rat tail; the improved method and testing results are presented here.

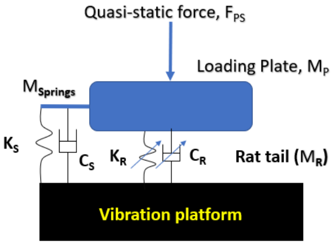


The method and conditions used in the second test:

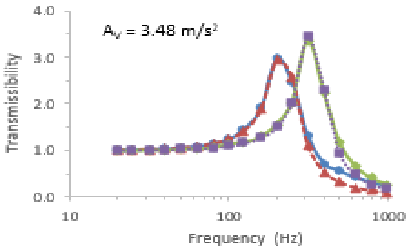
- 6 tails dissected from rat cadavers served as air controls in an inhalation study.
- 2 static forces: F_{PS}= 2.21 and 4.59 N.
- 3 magnitudes of a sinusoidal vibration at each of the one-third octave bands from 20 to 1000 Hz: A_V = 3.48; 5.21, and 8.00 m/s^2.
- 2 testing trials for each treatment
- 5 seconds for each trial
- Av and Ap were measured;Tp was evaluated using H1 function built in B&K Pulse Program.

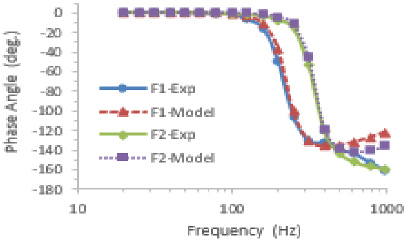
Animal ID	Proximal diameter (mm)	Distal diameter (mm)	Tail cut length (mm)	Tail mass of cut portion (g)	Mean diameter (d_t) (mm)	Tail mass of loaded portion (L_t=53 mm), M_r (g)
1	8.5	6.5	58.0	2.48	7.50	2.27
2	8.5	6.0	57.0	2.52	7.50	2.34
3	8.0	6.5	57.5	2.54	7.25	2.34
4	7.5	6.5	55.5	2.37	7.00	2.26
5	8.0	6.5	57.5	2.44	7.25	2.25
6	8.0	5.5	59.0	2.75	6.75	2.47
Mean	8.1	6.3	57.4	2.52	7.21	2.32

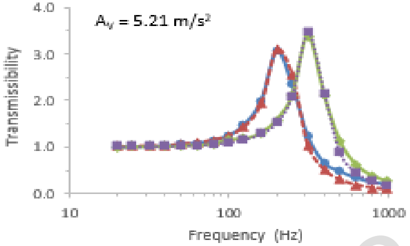
Results and Modeling of Rat Tail Tests

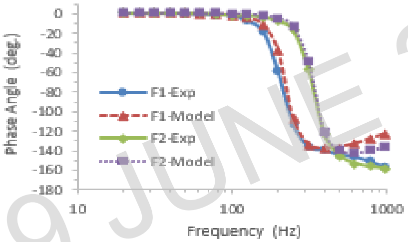


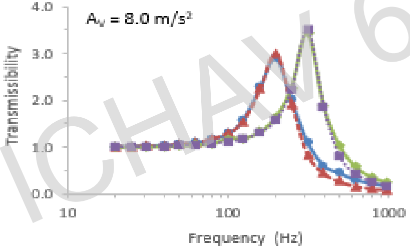
Modeling assumptions: The tail stiffness and damping value may vary with the static force, but they can be locally linearized in the vibration response under a given static force.

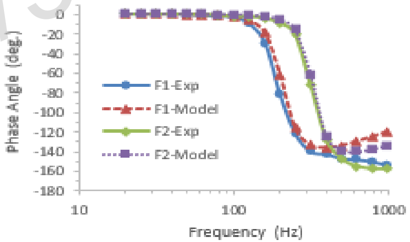












Parameter	Av (m/s^2)	F_{PS} = 2.21 N, K_S = 53 N/m (with soft springs, $M_{Springs}$ = 1.6 g)						
		Tail 1	Tail 2	Tail 3	Tail 4	Tail 5	Tail 6	Mean
Tail stiffness, K_R (N/m)	**3.48**	93440	110006	107876	139434	112735	100218	**110618**
	5.21	102355	107128	90854	110479	102110	109685	**103769**
	8.00	101878	75383	101913	108599	71917	98561	**93042**
Tail damping value, C_R (N·s/m)	**3.48**	19.87	21.98	23.14	26.92	18.84	18.30	**21.51**
	5.21	20.56	19.92	22.21	22.37	18.04	19.28	**20.40**
	8.00	21.61	18.87	22.30	21.25	14.96	19.68	**19.78**
Natural frequency, f_n (Hz)	**3.48**	210	228	225	256	231	217	**228**
	5.21	220	225	207	228	219	227	**221**
	8.00	219	188	219	226	184	216	**209**
Damping ratio, ζ	**3.48**	0.16	0.16	0.17	0.17	0.14	0.14	**0.16**
	5.21	0.16	0.15	0.18	0.16	0.14	0.14	**0.15**
	8.00	0.16	0.17	0.17	0.16	0.14	0.15	**0.16**

Parameter	Av (m/s^2)	F_{PS} = 4.59 N, K_S = 236 N/m (with stiff springs, $M_{Springs}$ = 6.1 g)						
		Tail 1	Tail 2	Tail 3	Tail 4	Tail 5	Tail 6	Mean
Tail stiffness, K_R (N/m)	**3.48**	274210	212883	244062	278307	262037	315137	**264439**
	5.21	208612	234797	263147	277086	271562	279121	**255721**
	8.00	236563	240777	263748	216520	200208	273915	**238622**
Tail damping value, C_R (N·s/m)	**3.48**	29.18	25.83	28.35	31.16	27.09	38.25	**29.98**
	5.21	27.04	28.30	30.61	30.34	27.54	33.98	**29.63**
	8.00	29.41	28.57	31.75	29.37	26.08	32.44	**29.60**
Natural frequency, f_n (Hz)	**3.48**	352	310	332	355	344	378	**345**
	5.21	307	326	345	354	351	355	**340**
	8.00	327	330	346	313	301	352	**328**
Damping ratio, ζ	**3.48**	0.13	0.13	0.13	0.13	0.12	0.15	**0.13**
	5.21	0.14	0.13	0.14	0.13	0.12	0.15	**0.13**
	8.00	0.14	0.13	0.14	0.14	0.13	0.14	**0.14**

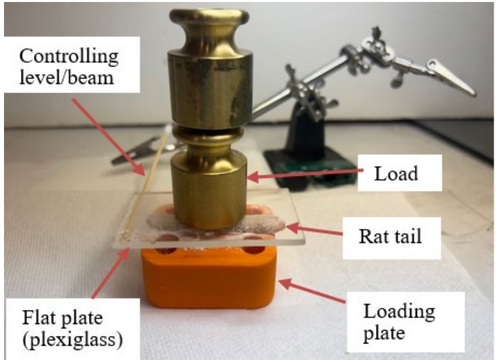
Basic Characteristics of Rat Tail Dynamic Properties

- Increasing the applied static force increased the tail stiffness and damping value; as a result, the system natural frequency was also increased.
- The tail stiffness was marginally reduced with the increase in the input vibration, which suggests that the tail has a nonlinear stiffness behavior in its vibration response.
- The input vibration magnitude had little effect on the tail damping value.

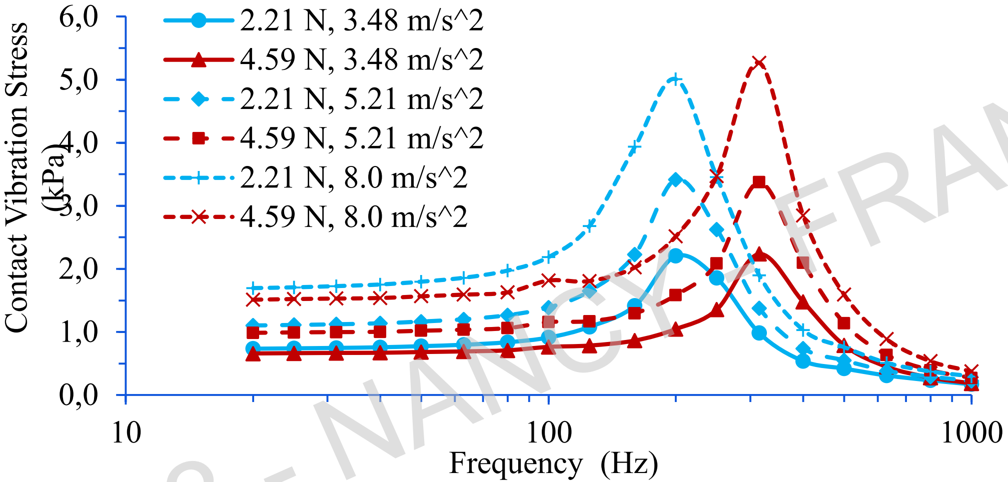
Basic Characteristics of Rat Tail Stresses

$$\sigma_{\text{static or dyn}} \approx \frac{|F_{PS} \text{ or } \mathbf{F}_{PD}|}{L_t \cdot b_t}$$

Measurement of the tail contact width (b_t)



F_{PS} (N)	Tail Contact Width b_t (mm)	$b_t \cdot L_t$ (mm^2)	$\sigma_{Av\text{-}D}$ (kPa)
2.21	4.78	254	8.72
4.59	5.55	294	15.60

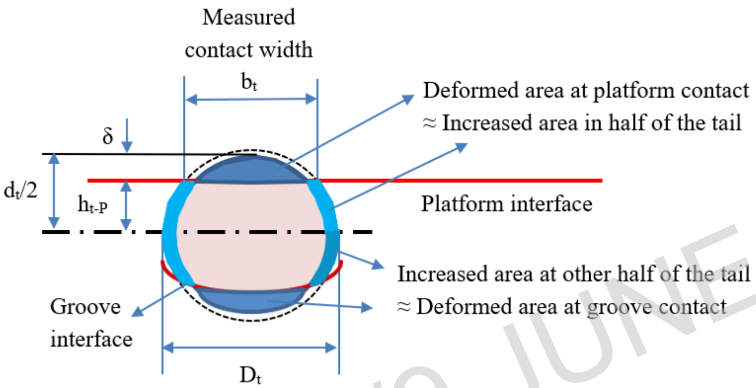


- The shape and characteristics of the stress spectra were similar to those of the loading plate transmissibility. The stress resonant frequency is at the same resonant frequency of the loading plate. Hence, <u>the plate controls the tail vibration stress</u>.
- Under each static force, increasing the input vibration almost proportionally increased the tail vibration stress.
- Under the same input vibration, increasing the static force increased the static stress and the stress resonant frequency but it reduced the vibration stress in the lower frequency range.
- The vibration stress can become comparable with the static stress by increasing the input vibration.

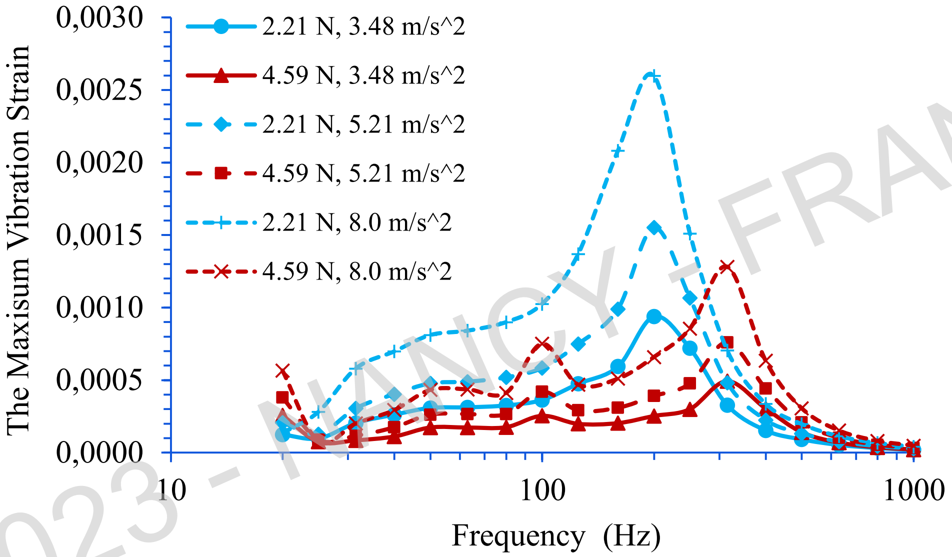
Basic Characteristics of Rat Tail Strains

$$\varepsilon_{\text{static}} \approx \frac{\delta}{h_{t-P}} \qquad \varepsilon_{\text{dyn}} \approx \frac{|D_P - D_V|}{h_t} = \frac{\left|\frac{A_V - A_P}{\omega^2}\right|}{h_t}$$

An approximate method for estimating the tail static deformation (h_t) from contact

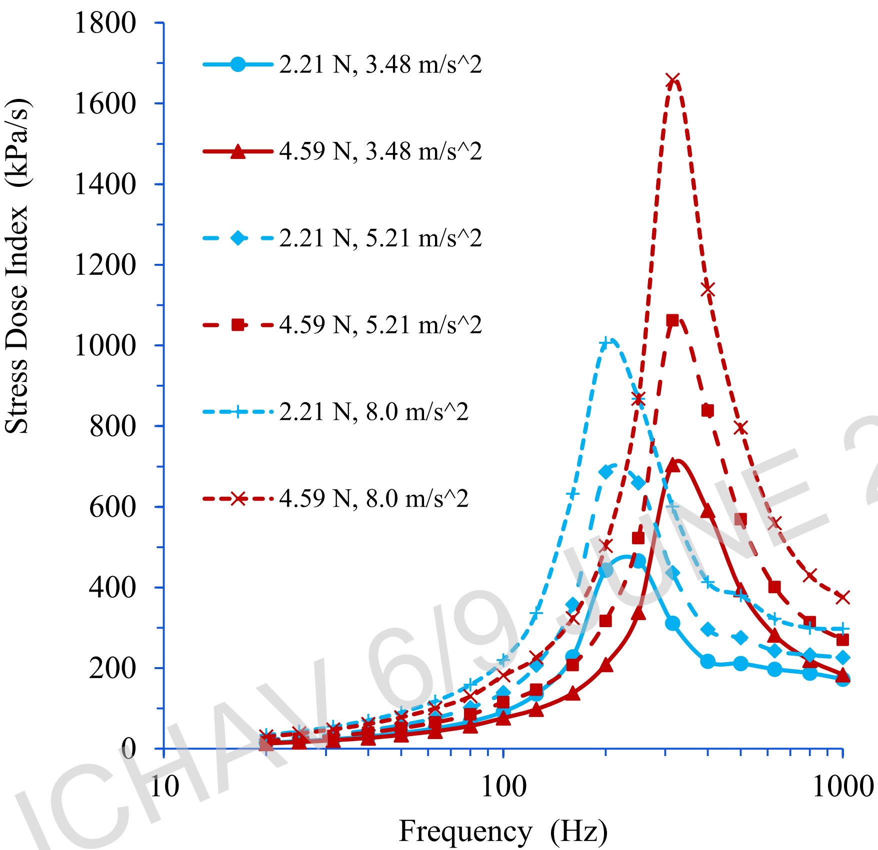


F_{PS} (N)	Tail Contact Width b_t (mm)	δ (mm)	h_{t-P} (mm)	ε_{Max-S}
2.21	4.78	0.75	2.86	0.21
4.59	5.55	1.01	2.59	0.28



- The static strain was generally more than 100 times higher than the vibration strain, including those in the resonant frequency range.
- The vibration strain peak was also at the resonant frequency of the loading plate; it was also controlled by the loading plate response.
- Increasing the static force increased the static strain but it generally reduced the vibration strain, including the resonant strain. This is because the increased tail stiffness reduces the vibration strain.

The Effects of Static Force and Vibration Magnitude on Tail Vibration Stress Dose



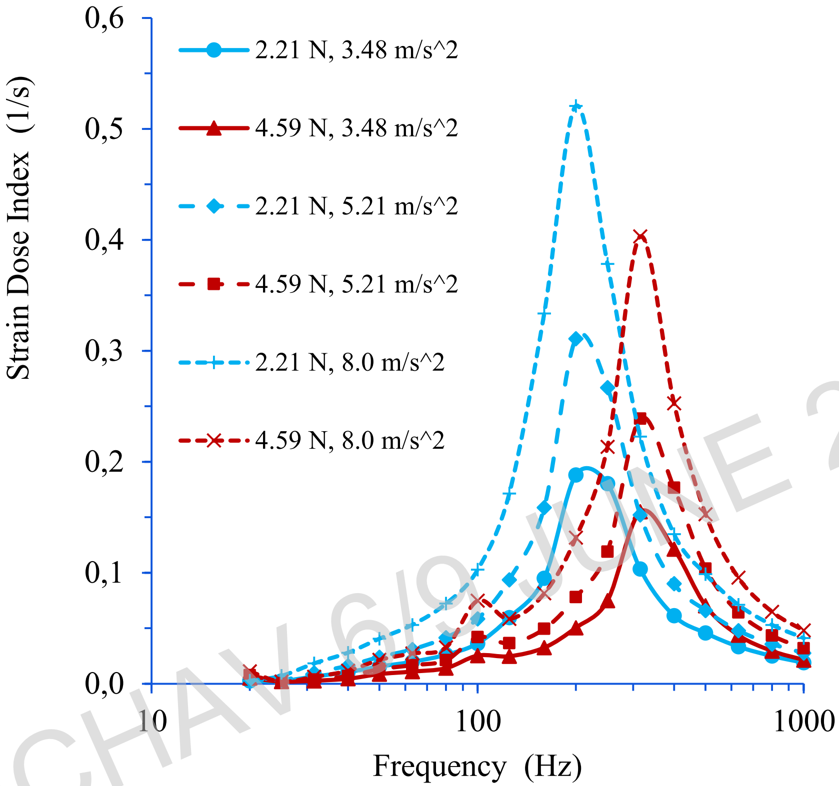
$$I_\sigma = \frac{\left| M_{PE}\mathbf{T}_P - \left[\frac{K_S}{(2\pi f)^2} + \frac{jC_S}{2\pi f}\right](1-\mathbf{T}_P)\right| A_V}{b_t \cdot L_t} f^{\alpha}$$

$\alpha = 1$ in the calculation

Observation and Discussion:

- Increasing the vibration magnitude almost proportionally increases the vibration stress dose at each frequency.
- The dose resonant frequency is marginally higher than that of vibration transmissibility or stress. Increasing the static force increased the vibration stress dose in the resonant frequency range.
- The stress dose formula and spectra indicate that the vibration frequency plays two different roles in determining the vibration exposure dose: (1) it determines the biodynamic response; and (2) it determines the number of actions (stress/strain cycles) per second.
- The frequency power index (α) is a measure of the second role; its value can be determined from biological studies in which the biodynamic response is kept unchanged at each frequency. This can be achieved by controlling the loading plate response.

The Effects of Static Force and Vibration Magnitude on Tail Vibration Strain Dose



$$I_\varepsilon = \frac{|\mathbf{A}_V - \mathbf{A}_P|}{\omega^2} \frac{f^\beta}{h_t} = \frac{|(1-\mathbf{T}_P)A_V|}{4\pi^2} \frac{f^{\beta-2}}{h_t}$$

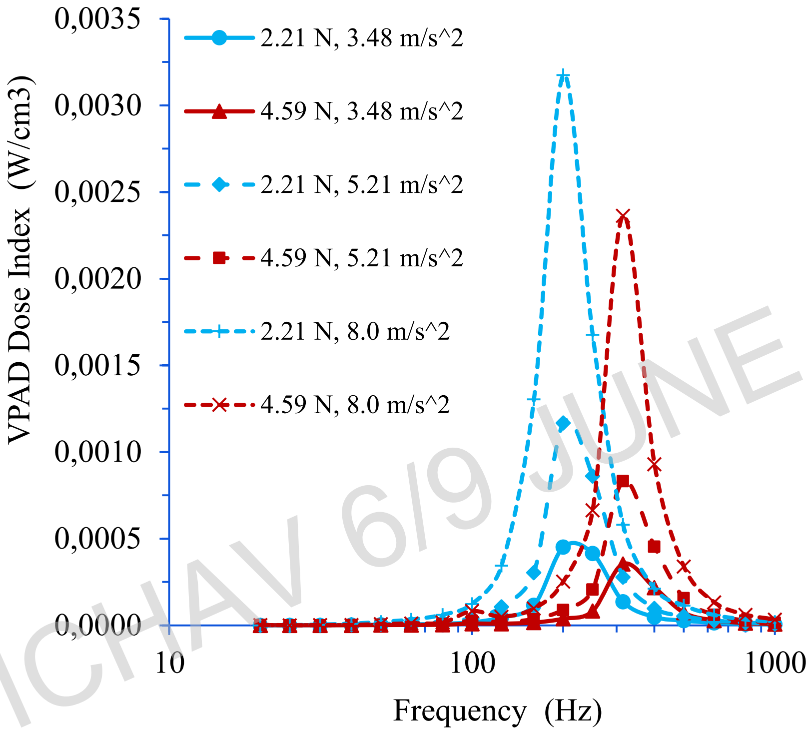
β = 1 in the calculation

Observation and Discussion:

- Increasing the vibration magnitude almost proportionally increases the vibration strain dose at each frequency.
- Increasing the static force reduced the vibration strain dose in the resonant frequency range.
- Similar to that observed in the stress dose spectra, the vibration frequency plays two different roles in determining the strain dose. The strain frequency power index (β) can be determined from further biological studies.

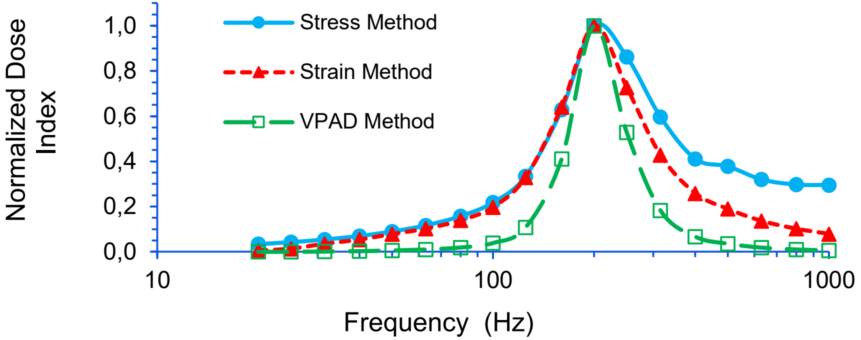
The Effects of Static Force and Vibration Magnitude on Tail VPAD Dose

$$I_{VPAD} = \frac{C_R \cdot \left[\frac{|(T_P - 1)A_V|}{2\pi f}\right]^2}{v}$$



Observation and Discussion:

- The vibration power (VPAD) dose spectrum had the characteristics similar to those of the strain method.
- The normalized spectra of the three dose indexes indicate that their maximum dose weightings are at similar resonant frequencies. Below the resonant frequency, the relative frequency weightings of the stress and strain methods are similar to each other. At higher frequencies, the stress method has a higher weighting than other two methods. The VPAD method has more weighting in the resonant frequency range than that in the other frequency range.



Questions?

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