Advancing on a Novel Pacifier Design Methodology to Improve Oral Health: A Comprehensive Computational Model of Pacifier Sucking

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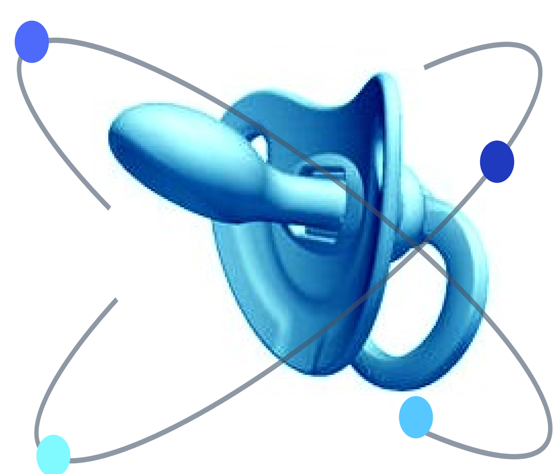
Introduction & Motivation

- The **prevalence of pacifier use** at 12 months of age is 42,5 % [1]
- **Different pacifier designs** have **different effects** on orofacial structures [9,12]
- The effects of pacifiers on primary dentition **have not yet been effectively proven** [2–8]
- Several studies show a **strong relation** between pacifier sucking and malocclusions [2–8]
- Pacifier manufacturers must **test each new pacifier design extensively** [13]
- Pacifier long-term health risks **are not addressed on manufacture process**

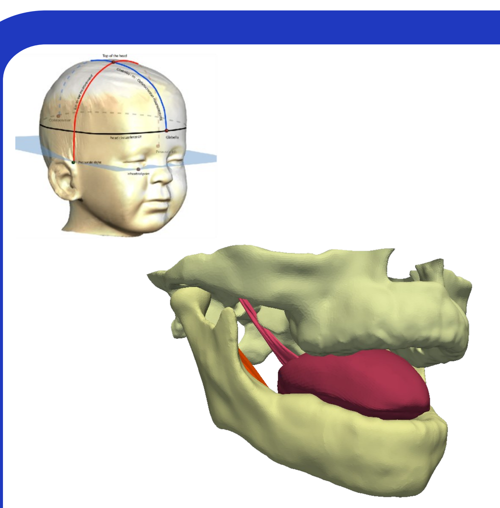
Aim of the Work



Develop Comprehensive Realistic Computational Methodology

- Support the design of improved performance pacifiers [9–12]
- Capability to assess different designs pacifier effects
- Simulate the dynamic and biomechanical characteristics during non-nutritive sucking
- Quantify sucking patterns, based on Neonatal Oral-Motor Assessment Scale (NOMAS) [14]

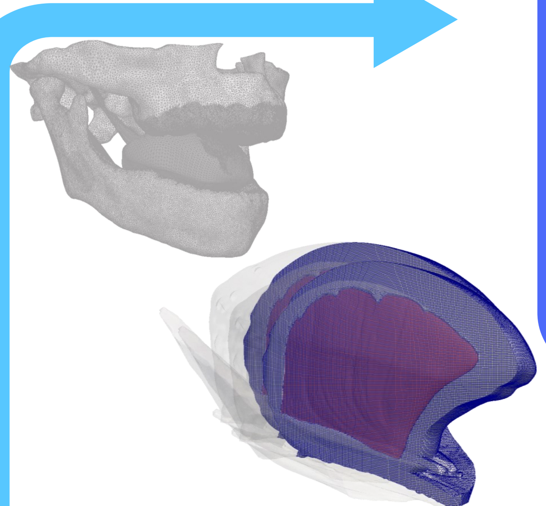
Methodology



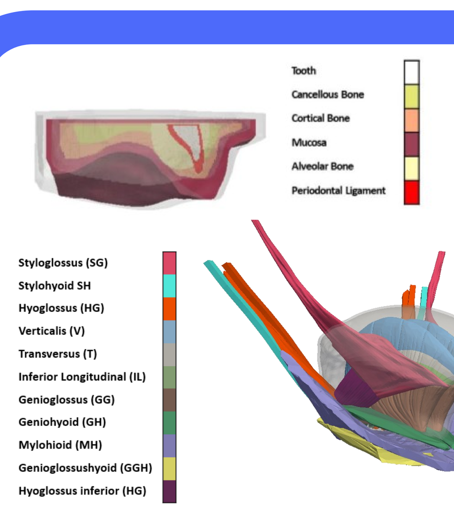
Create full model based on Z-anatomy atlas and Blender 3D Modelling Software

Geometry Modelling

Mesh Generation



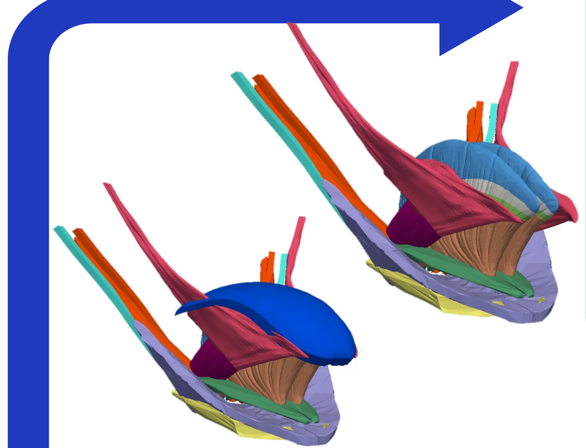
Use snappyHexMesh tool to generate computational mesh with required features



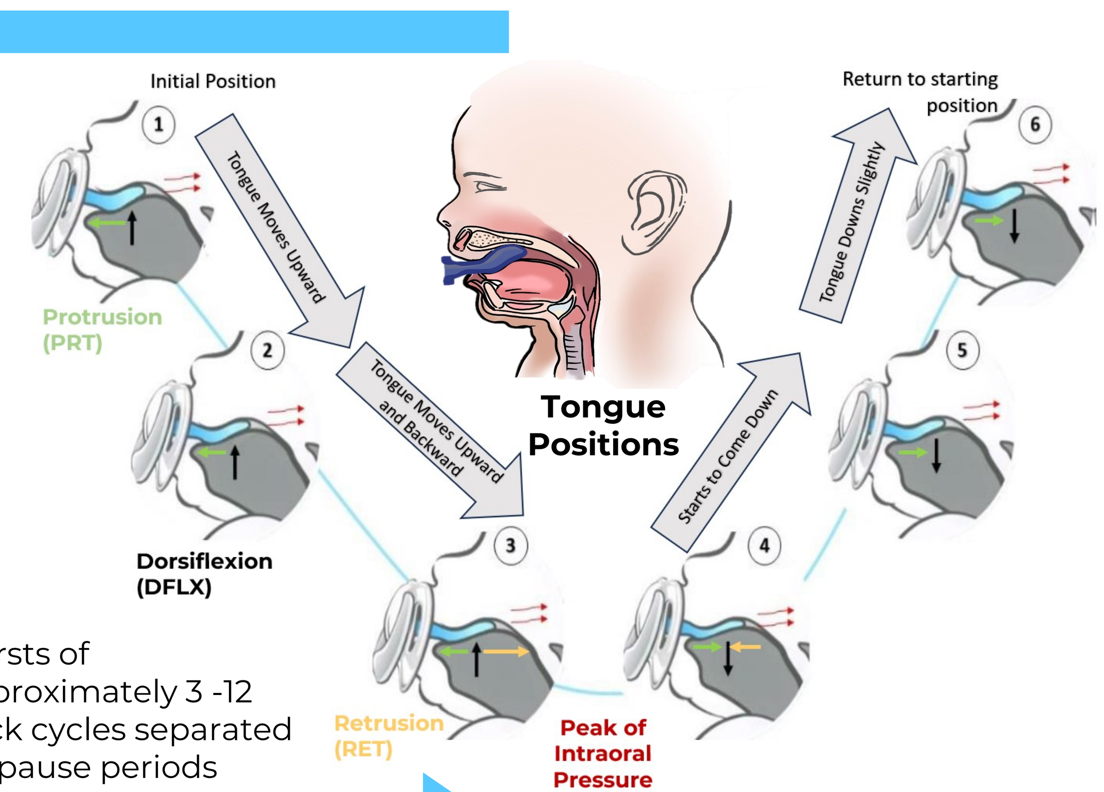
Divide the computational model in different tissue regions

Tissues Segmentation

Myofiber Modelling



Solve Laplace equation and calculate fiber length and orientation of undeformed geometry



Bursts of approximately 3-12 suck cycles separated by pause periods

Pacifier Sucking Mechanism

Enhancing the in-house solver under development with appropriate constitutive laws for muscles within the OpenFOAM solid mechanics toolbox

OpenFOAM® solids4foam

Active Stress Distribution for different tongue positions (σ_{act})			
Muscle	PRT (%)	DFLX (%)	RET (%)
GG	7.0	-	-
GH	7.0	-	-
HG	-	-	35.0
IL	-	-	28.0
SG	-	-	70.0
SL	15.0	50.0	2.0
T	33.0	-	
V	33.0	-	

Muscle and Connective Tissue Model

C_1	C_2	ρ	$[Ca^{2+}]$	β	α
375 Pa	175 Pa	1040 kg/m^3	4.35μM	0.1 N/m^2	100

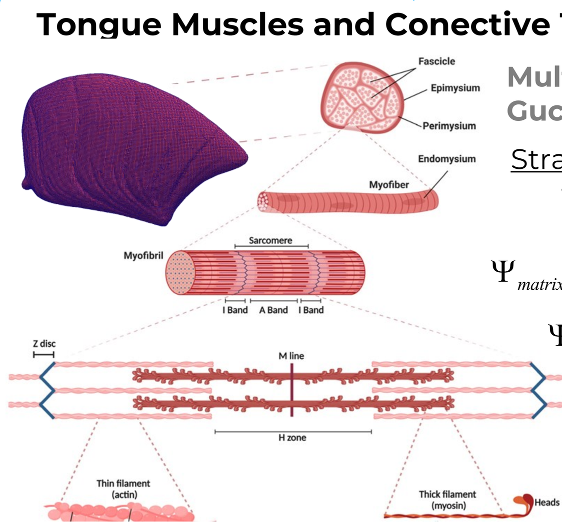
Bone Remodeling Model

C_e	b	S_r	S_F	A	μ_S
4.621×10^9 Pa	1040 kg/m^3	300 $\mu\varepsilon$	500 $\mu\varepsilon$	1×10^8	2.5×10^{-4}

Constitutive Parameters

Governing Equations & Constitutive Model

Tongue Muscles and Conective Tissue Behaviour



Multisacle Model based on Hill [15], Huxley [16], Zajac [17] Guccione [18–20] and other model [21–27]

Strain energy functions

$$\Psi_{muscle} = \Psi_{matrix}(I_1, I_2) + \Psi_J(J) + \Psi_{fiber}(I_4, I_5)$$

$$\Psi_{matrix}(I_1, I_2) = C_1(I_1 - 3) + C_2(I_2 - 3)$$ - Mooney-Rivlin model

$$\Psi_{fiber}(\lambda_f, a) = \Psi_{active}(\lambda_f, a) + \Psi_{passive}(\lambda_f)$$ - Hill-type model

Invariants of the right Cauchy Green Strain tensor

$$I_1 = tr(\underline{\underline{C}}) \quad I_2 = \frac{1}{2}\left((tr(\underline{\underline{C}}))^2 - tr(\underline{\underline{C}}^2)\right) \quad I_4 = \underline{N}\cdot\underline{\underline{C}}\cdot\underline{N} \quad I_5 = \underline{N}\cdot\underline{\underline{C}}^2\cdot\underline{N}$$

Sarcomere stretch of the undeformed fiber

$$\lambda_{sarc} = \sqrt{\underline{N}^T \underline{\underline{C}}\,\underline{N}} = \sqrt{\underline{\underline{C}} : (\underline{N}\otimes\underline{N})}$$

Active Contraction

$$\sigma_{act} = \sigma_{max}\cdot\frac{Ca_0^2}{Ca_0^2 + ECa_{50}^2}\cdot a$$

Increase calcium concentration (Ca) and activation level (a)

Length-dependent calcium sensitivity

$$^{t+\Delta t}f_{PEE}(\lambda_f) = \begin{cases} 4(^{t+\Delta t}\lambda_f - 1)^2, & ^{t+\Delta t}\lambda_f > 1 \\ 0, & ^{t+\Delta t}\lambda_f \le 1 \end{cases}$$

Myofiber stretch of the undeformed fiber:

$$\lambda_f = \frac{L}{L_0}$$

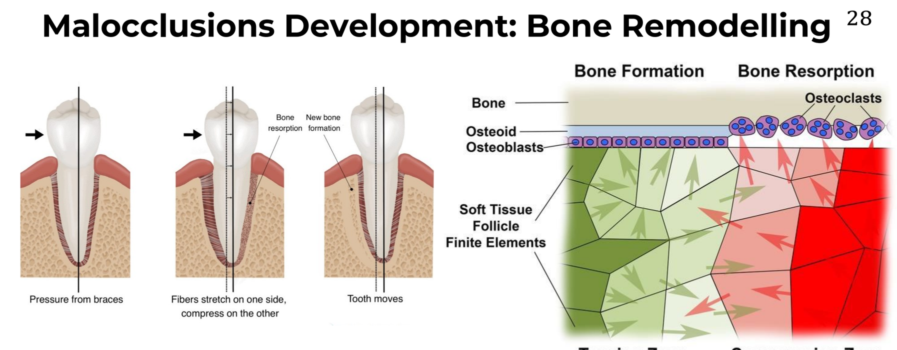
Muscle direction after deformation:

$$\underline{n} = \frac{\underline{\underline{F}}\,\underline{N}}{\lambda_f}$$

Cauchy stress derived from the strain energy function

$$\sigma = \frac{2}{J}\left[(C_1 + C_2 I_1)\underline{\underline{B}} - C_2\underline{\underline{B}}\cdot\underline{\underline{B}} - \frac{1}{3}(C_1 I_1 + 2C_2 I_2)\underline{\underline{I}}\right] + K(J-1)\underline{\underline{I}} + \frac{1}{J}\left[\sigma_{act}\cdot f_{PE}(\lambda_f) + \beta\cdot e^{\alpha(\lambda_S - 1)} - 1\right]\left[\lambda_f(n\otimes n) - \frac{1}{3}\lambda_f\underline{\underline{I}}\right]$$

Malocclusions Development: Bone Remodelling [28]



Grey scale values of the CT scan and Young's modulus relationship distribution:

$$E^i = C_e(\rho_t^i)^b$$

Current bone density is calculated using Euler Method:

$$\frac{d\rho^i}{dt} = C(\mu_s S^i - S_{ref})$$

Rate of changing density:

$$\rho_t^i = \rho_{t-1}^i + \frac{d\rho^i}{dt}\Delta t$$

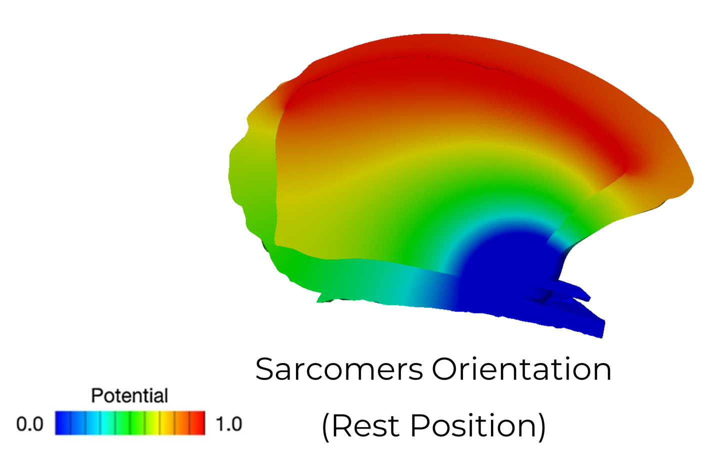
Local remodeling reaction:

$$C = A\Lambda^i$$

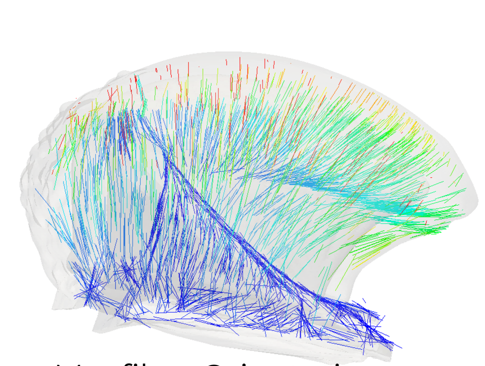
$$\Lambda^i = \begin{cases} -1, & S^i \le S_R & Resorption \\ 0, & S_R \le S^i \le S_F & 'Lazy' \\ 1, & S_F \le S^i & Formation \end{cases}$$

Preliminary Results

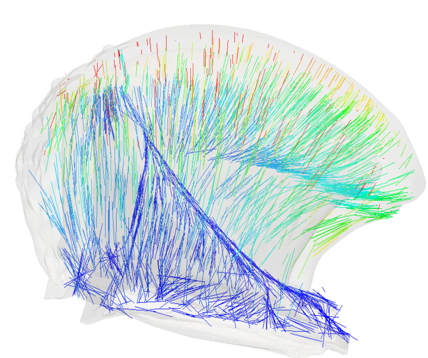
Fiber Orientation and Stretch



Sarcomers Orientation (Rest Position)



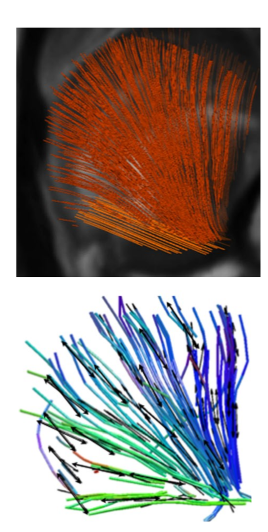
Myofiber Orientation (Rest Position)



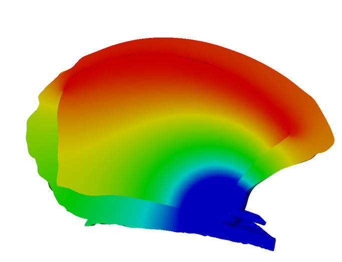
Myofiber Orientation (Dorsiflexion Deformation)

Current Work

Computational Model Validation

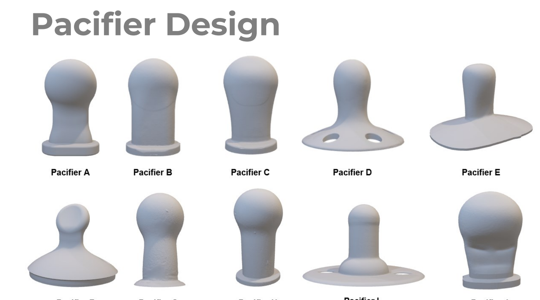


Experimental imaging results of Tractography



Myofiber deformation calculation

Assessment Different Pacifier Design



Deep Generative Design Optimization

References

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