Multi-fidelity Gaussian Process Surrogate Modeling Of Pediatric Tissue Expansion

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Background

Growth of skin in response to stretch is the basis for tissue expansion (TE), a procedure to gain new skin area for reconstruction of large defects. Unfortunately, complications and sub-optimal outcomes persist because TE is planned and executed based on physician's experience and trial and error instead of predictive quantitative tools.

Recently, we calibrated computational models of TE to a porcine animal model of tissue expansion, showing that skin growth is proportional to stretch with a characteristic time constant.

Here we use our calibrated model to predict skin growth in cases of pediatric reconstruction.

Methods

We present a case series of two pediatric cases undergoing tissue expansion. For each patient, relevant expansion protocols performed clinically were extracted. For Patient 1, five tissue expanders were placed (Figure 1). For Patient 2, a single large rectangular expander was placed in the clavicle. Expanders were filled to the desired volumes, ranging from 33 ml for the smaller expanders, up to 243 ml for the largest expander.

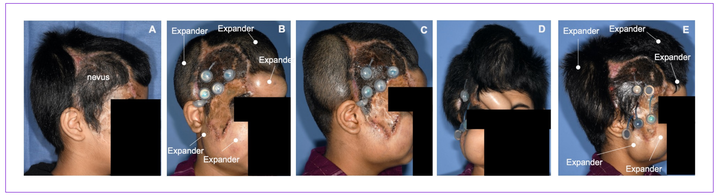

Figure 1: A pediatric patient with a giant nevus (A); four rectangular and one crescent tissue expanders were placed subcutaneously in the scalp (posterior), scalp (anterior), forehead, anterior face, lower face (B, C). End of the expansion process (D, E).

We utilized this data to create low fidelity semi-analytical models (Figure 2) and finite element models (Figure 3) for each of the clinical cases. To account for uncertainty in the response expected from translating the models from the animal experiments to the pediatric population, we create multi-fidelity Gaussian Process (GP) regression surrogates (Figure 4) to propagate mechanical and biological uncertainty

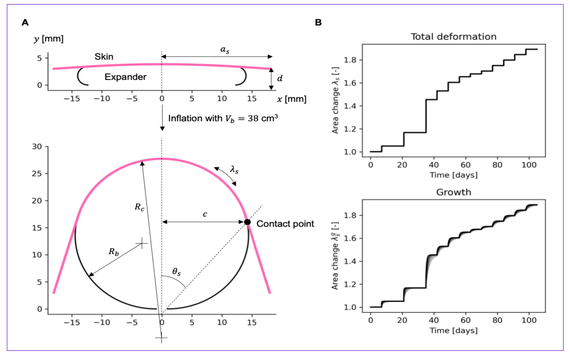

Figure 2: Semi-analytic, low-fidelity model of tissue expansion (A) and results for patient 1 with lower face expander (B).

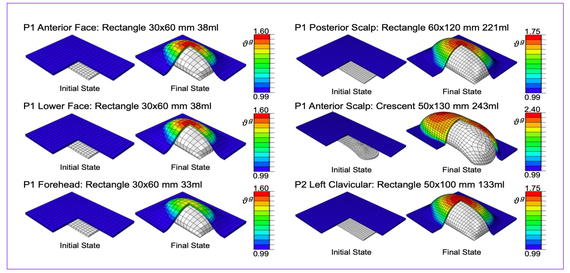

Figure 3: Finite element simulations of each expander showing initial and final time points.

Results

Our GP regression shows that skin growth increase over time $\vartheta g\ (t)$ is shown as a result of the TE protocols, with the multi-fidelity model outperforming the high- and low- fidelity models (Figure 4).

While greater deformation induces greater growth, expander volume alone was not deterministic; for the same shape, both smaller and significantly larger volumes lead to decreased mean total deformation and growth. However, expander shape, in the context of total deformation field and time, altered this relationship (Figure 5).

The total area gained expected from the TE protocols is 98.5 − 120.9 cm. From the patient photographs, it is estimated that the total defect area that needed to be resurfaced was 93.7 − 114.6 cm. Thus, the TE protocols chosen should lead to enough skin gain to resurface the majority of the defect.

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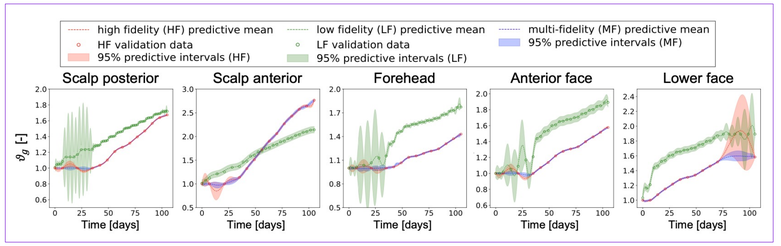

Figure 4: Posterior distribution of area growth (ϑ_g) for high fidelity, low fidelity, and multi-fidelity Gaussian process (GP) regression for five tissue expanders.

Location	Volume [ml]	ϑ_{max} [-]		ϑ_{avg} [-]		ϑ^g_{max} [-]		ϑ^g_{avg} [-]	
		E(x)	S(x)	E(x)	S(x)	E(x)	S(x)	E(x)	S(x)
Scalp anterior	243	3.59	0.13	3.05	0.07	2.76	0.11	2.26	0.06
Scalp posterior	221	2.03	0.05	1.81	0.03	1.67	0.04	1.48	0.02
Forehead	33	1.65	0.03	1.35	0.01	1.43	0.03	1.17	0.01
Anterior face	38	1.82	0.04	1.44	0.01	1.58	0.04	1.25	0.01
Lower face	38	1.82	0.04	1.44	0.01	1.58	0.04	1.25	0.01
Left clavicle	133	2.09	0.06	1.86	0.03	1.81	0.05	1.64	0.03

Table 1: Expected total and average deformation (ϑ) and standard deviation, using the multi-fidelity GP surrogate.

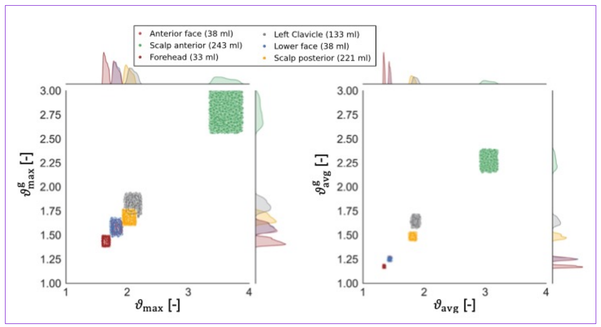

Figure 5: Scatter plots showing growth (ϑ_g) at the end of expansion showing skin deforming heterogeneously upon expansion.

Conclusions

Predictions with uncertainty for the clinical setting are essential to bridge our knowledge from the large animal experiments to guide and improve the treatment of pediatric patients. Future studies will focus on model calibration with patient-specific data - such as estimation of mechanical properties and area growth in the operating room- which may guide alterations in the standard for planning and execution of TE protocols.