ETH zürich

DITET
Computer Vision Lab

Mermaid and Voxelmorph framework for medical image registration

Luca Adrian Blum

20.08.2021

Outline

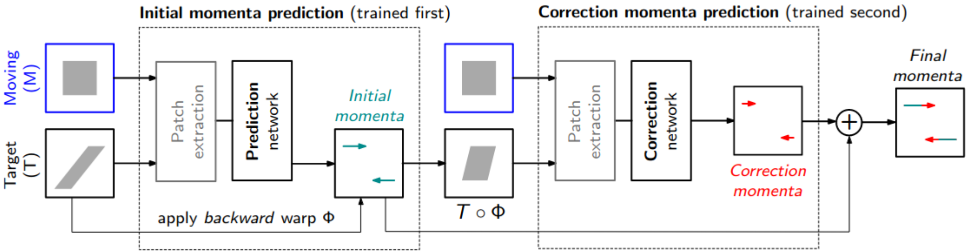
1. Mermaid

2. Voxelmorph

Mermaid

- supervised NN — Quicksilver
- spatially varying regularizer
- affine and non-parametric network combined — ASVM
- ASVM + spatio-temporal regularizer — RDMM

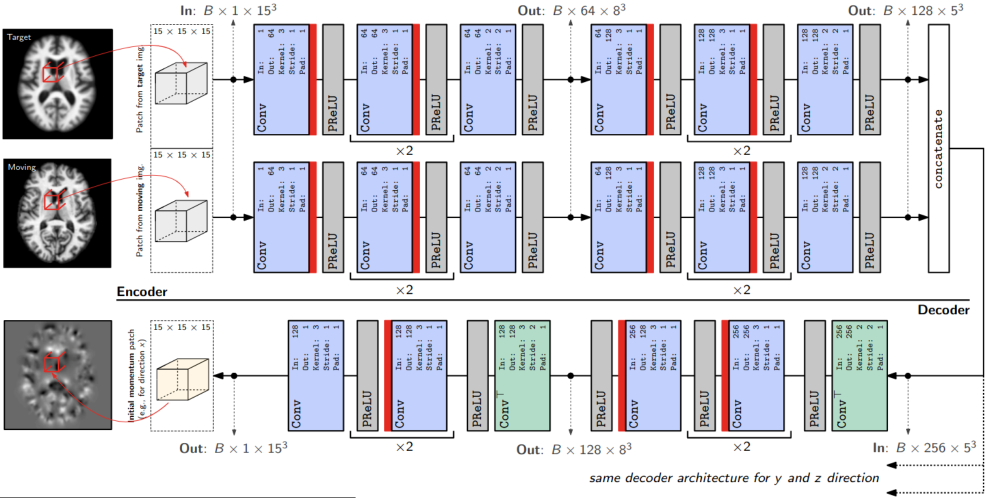
Quicksilver



[1]

[1] Xiao Yang et al. 2017. “Quicksilver: Fast predictive image registration–a deep learning approach.” *NeuroImage* 158:378–396.

Quicksilver network architecture



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[2] Yang et al. 2017.

Metric learning

$$v = \left(\sum_{i=0}^{N-1} w_i G_i \right) \star m, \qquad w_i > 0, \qquad \sum_{i=0}^{N-1} w_i = 1$$

Metric learning

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$$\widehat{OMT}(w) = \left| log \frac{\sigma_{N-1}}{\sigma_0} \right|^{-r} \sum_{i=0}^{N-1} w_i \left| log \frac{\sigma_{N-1}}{\sigma_i} \right|^{r}$$

Metric learning

$$v_0(x) = \sum_{i=0}^{N-1} \sqrt{w_i(x)} \int_y G_i(|x-y|) \sqrt{w_i(y)} m_0(y) dy$$

Metric learning

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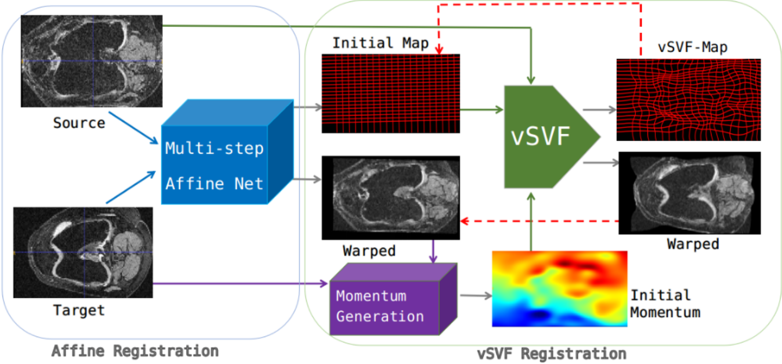
$$w_i(x) = G_{\sigma_{small}} \star \omega_i(x)$$

Metric learning

$$conv(d+1, n_1) \rightarrow BatchNorm \rightarrow lReLU$$
$$\rightarrow conv(n_1, N) \rightarrow BatchNorm \rightarrow weighted - linear - softmax$$

ASVM - affine-vSVF-Mapping



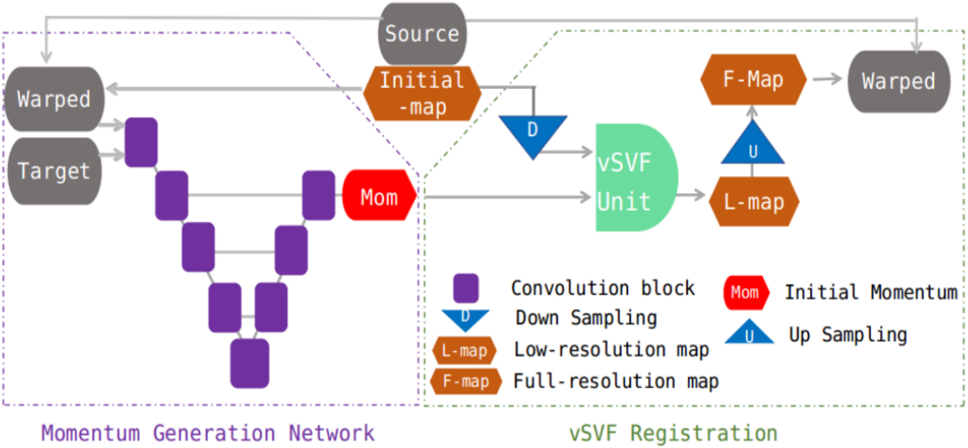
[3]

[3] Zhengyang Shen et al. 2019. “Networks for Joint Affine and Non-parametric Image Registration.” In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition,* 4224–4233.

ASVM loss function

$$
\begin{aligned}
L_a(M,T,\Gamma,\Gamma^{tm}) =& L_{a-sim}(M,T,\Gamma) + L_{a-sim}(T,M,\Gamma^{tm}) + \\
& L_{a-reg}(\Gamma) + L_{a-reg}(\Gamma^{tm}) + \\
& L_{a-sym}(\Gamma,\Gamma^{tm})
\end{aligned}
$$

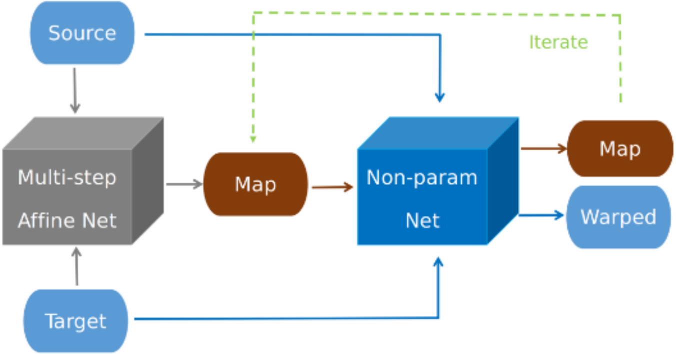
ASVM - multi-step non-rigid registration



[4]

[4] Shen et al. 2019.

RDMM - Region-specific Diffeomorphic Metric Mapping



[5]

[5] Zhengyang Shen, François-Xavier Vialard, and Marc Niethammer. 2019. "Region-specific Diffeomorphic Metric Mapping." *NeurIPS: Neural Information Processing Systems.*

RDMM

$$v(x,t) = K(x,t) \star m = \sum_{i_0}^{N-1} w_i(x,t) K_{\sigma_i} \star (w_i(x,t)m), \quad w_i(x,t) \geq 1$$

RDMM

$$v(x,t) = K(x,t) \star m = \sum_{i_0}^{N-1} w_i(x,t) K_{\sigma_i} \star (w_i(x,t)m), \quad w_i(x,t) \geq 1$$

$$w_i(x,0) = G_\sigma h_i(x,0) \qquad s.t. \quad h_i(x,0) \geq 0$$

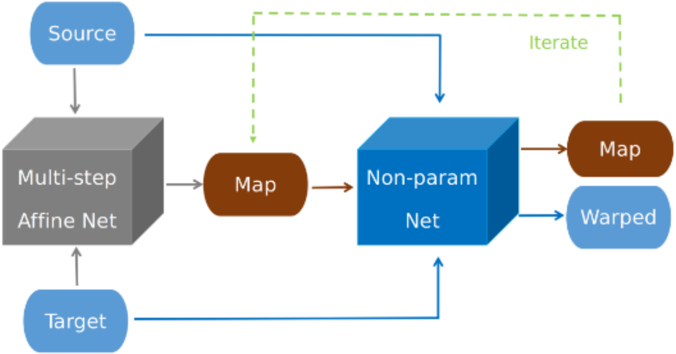
RDMM

$$v(x,t) = K(x,t) \star m = \sum_{i_0}^{N-1} w_i(x,t) K_{\sigma_i} \star (w_i(x,t)m), \quad w_i(x,t) \geq 1$$

$$w_i(x,0) = G_\sigma h_i(x,0) \qquad s.t. \quad h_i(x,0) \geq 0$$

$$Reg(\{h_i(x,0)\}, T) = \lambda_{OMT}(T) OMT(\{h_i(x,0)\}) + \lambda_{Range}(T) Range(\{h_i(x,0)\}$$

RDMM



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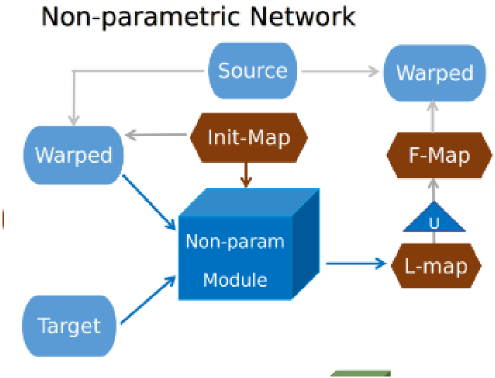
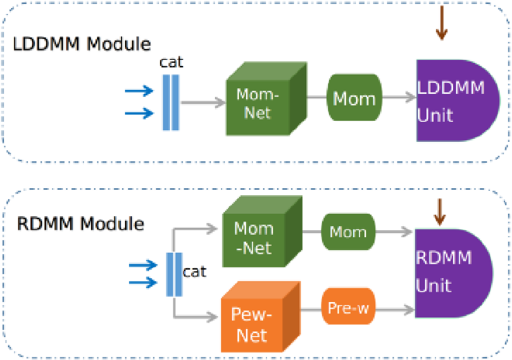
[6]Shen, Vialard, and Niethammer 2019.

RDMM

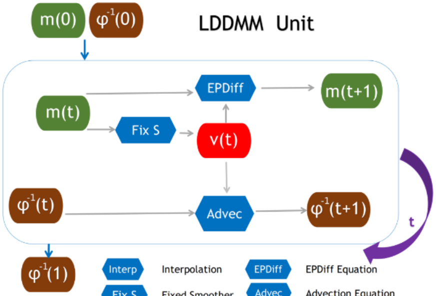


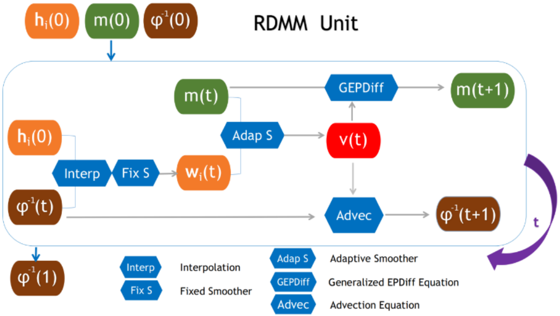


[7]

[7] Shen, Vialard, and Niethammer 2019.

RDMM





[8]

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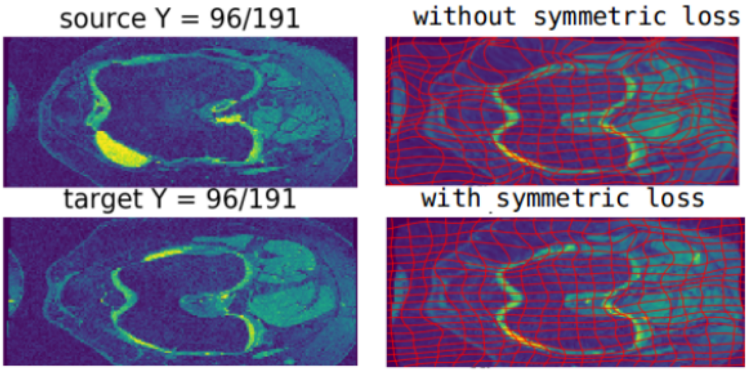
[8] Shen, Vialard, and Niethammer 2019.

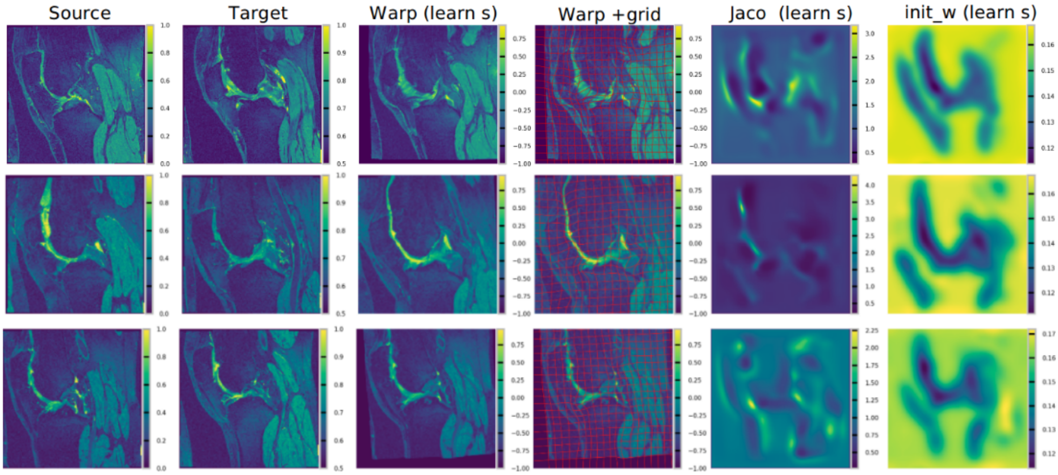
Results - ASVM



[9]

[9]Shen et al. 2019.

Results - RDMM



[10]

[10] Shen, Vialard, and Niethammer 2019.

Results - RDMM

RDMM with pre-defined regularizer

Outline

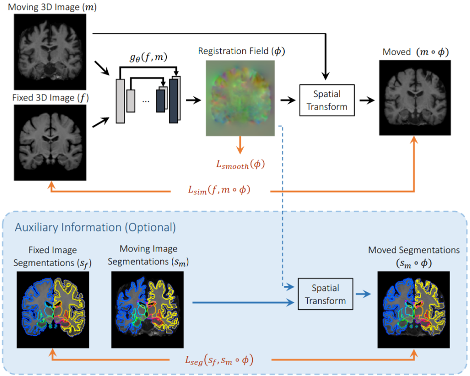
1. Mermaid

2. Voxelmorph

Voxelmorph

• unsupervised NN	Voxelmorph
• Probabilistic version	
• Learning conditional and unconditional templates	
• Learning image registration with synthetic data	SynthMorph
• Learning Hyperparameters	HyperMorph

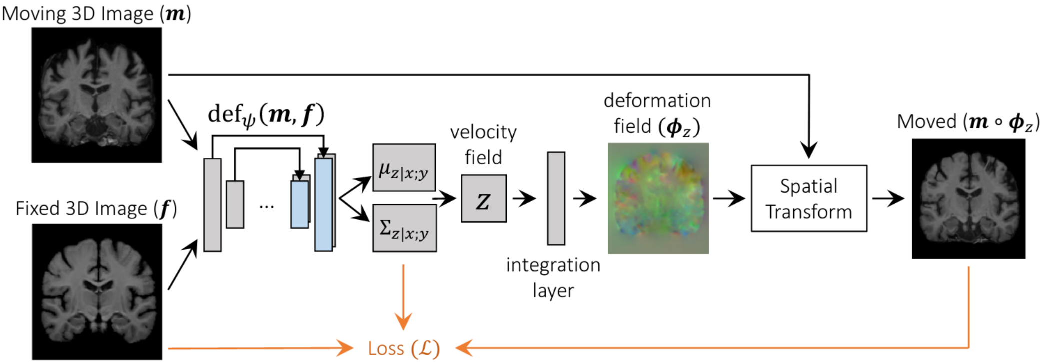
Voxelmorph base model



[11]

[11] Guha Balakrishnan et al. 2019. "VoxelMorph: A Learning Framework for Deformable Medical Image Registration." *IEEE TMI: Transactions on Medical Imaging* 38 (8): 1788–1800.

Probabilistic Voxelmorph



[12]

[12] Adrian V. Dalca et al. 2019b. “Unsupervised Learning of Probabilistic Diffeomorphic Registration for Images and Surfaces.” *Medical Image Analysis* 57:226–236.

Probabilistic Voxelmorph

Goal: $p(z|T, M)$

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negative variational lower bound: $\min_\psi KL\left[q_\psi(z \mid T; M) \| p(z)\right] - \mathbb{E}_q\left[log\ p(T \mid z, M)\right]$

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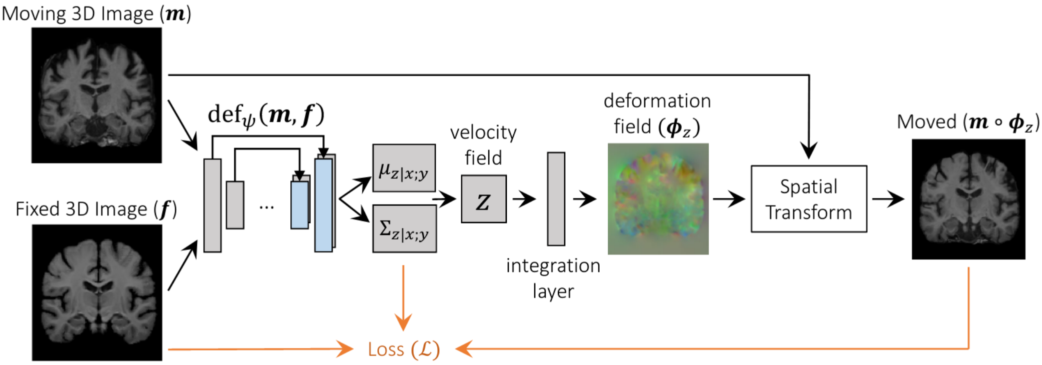
target image: $p(T \mid z; M) = \mathcal{N}(T; M \circ \varphi, \sigma_I^2 \mathcal{I})$

Probabilistic Voxelmorph



13

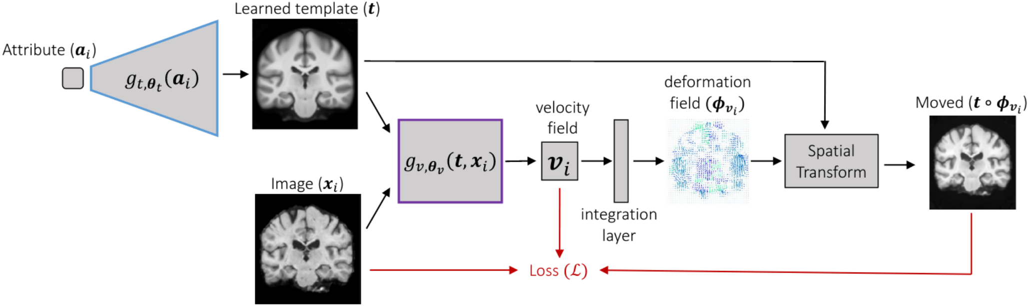
[13] Adrian V. Dalca et al. 2019b.

Probabilistic Voxelmorph + segmentation

extend negative lower bound: $NLB - \mathbb{E}_q \left[log\ p(s_T \mid z; s_M) \right]$

segmentation target image: $p(s_T \mid z; s_M) = \mathcal{N}(s_T; s_M \circ \varphi_z, \sigma_s^2 \mathcal{I})$

Conditional and unconditional atlases



[14]

[14] Adrian V Dalca et al. 2019a. "Learning Conditional Deformable Templates with Convolutional Networks." *NeurIPS: Neural Information Processing Systems.*

Conditional and unconditional atlases

$$
\begin{aligned}
L(\theta_t, \theta_v, v_i, x_i, a_i) &= -\, log\ p_\theta(x_i \mid v_i, a_i) - log\ p_\theta(v_i) \\
&= -\, \frac{1}{2\sigma^2} \left\| x_i - g_{t,\theta_t}(a_i) \circ \varphi_{v_i} \right\|^2 \\
&\quad - \gamma \left\| \overline{u} \right\|^2 - \lambda_d \frac{d}{2} \sum_i \left\| u_i \right\|^2 + \frac{\lambda_a}{2} \sum_i \left\| \nabla u_i \right\|^2
\end{aligned}
$$

Conditional and unconditional atlases

$$p_\theta(V) \propto exp\{-\gamma \left\| \overline{u} \right\|^2\} \prod_i \mathcal{N}(u_i, 0, \Sigma_u)$$

$$\overline{u} = \frac{1}{n} \sum_i u_i$$

$$\Sigma_u^{-1} = \lambda_d D - \lambda_a C$$

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$$log\ p_\theta(V) = -\gamma \left\|\overline{u}\right\|^2 - \lambda_d \frac{d}{2} \sum_i \left\|u_i\right\|^2 + \frac{\lambda_a}{2} \sum_i \left\|\nabla u_i\right\|^2$$

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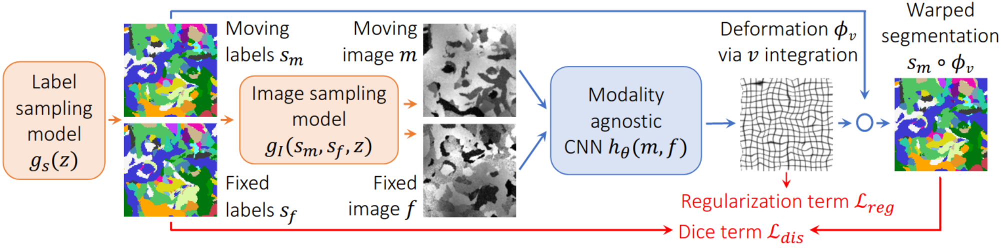
\end{aligned}
$$

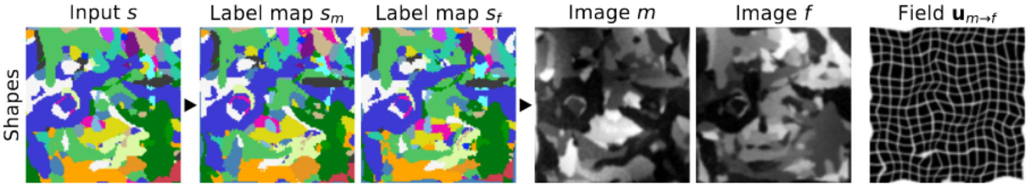
SynthMorph



15

[15] Malte Hoffmann et al. 2020. *Learning image registration without images.* arXiv: 2004.10282 [cs.CV].

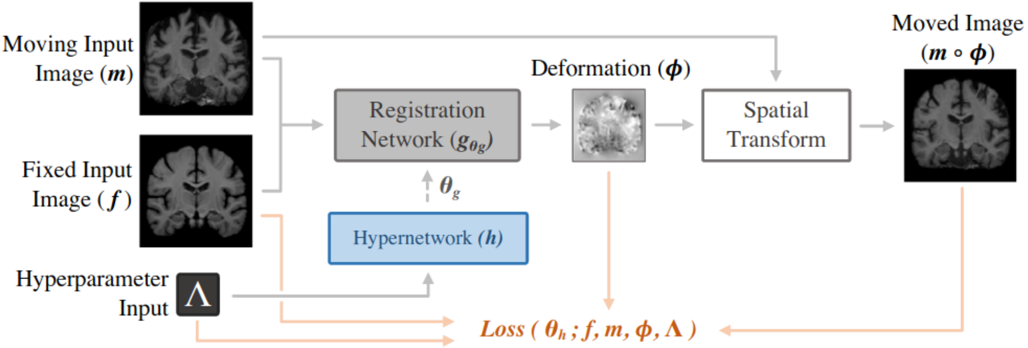
SynthMorph



[16]

[16] Hoffmann et al. 2020.

Hypermorph



17

[17] Andrew Hoopes et al. 2021. “HyperMorph: Amortized Hyperparameter Learning for Image Registration.” *arXiv preprint arXiv:2101.01035.*

HyperMorph

$$L_h(\theta_h; D) = \mathbb{E}_{\Lambda \sim p(Lambda)} \left[L(\theta_h; D, \Lambda) \right]$$

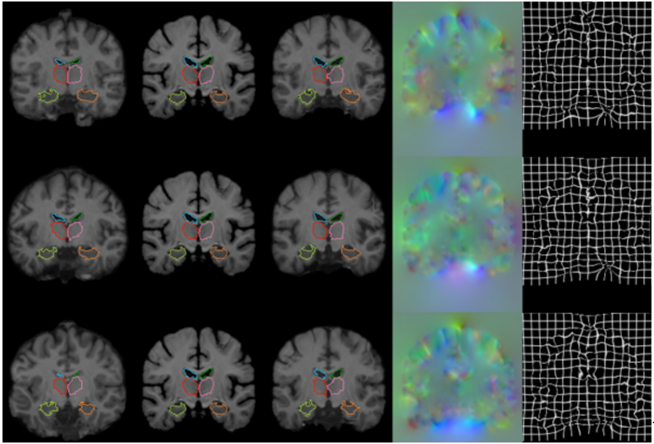
HyperMorph

$$L_h(\theta_h; D) = \mathbb{E}_\Lambda \left[\sum_{M,T \in D} \left((1-\lambda)\, L_{sim}(T, M \circ \varphi; \lambda_{sim}) + \lambda L_{reg}(\varphi; \lambda_{reg}) \right) \right]$$

HyperMorph

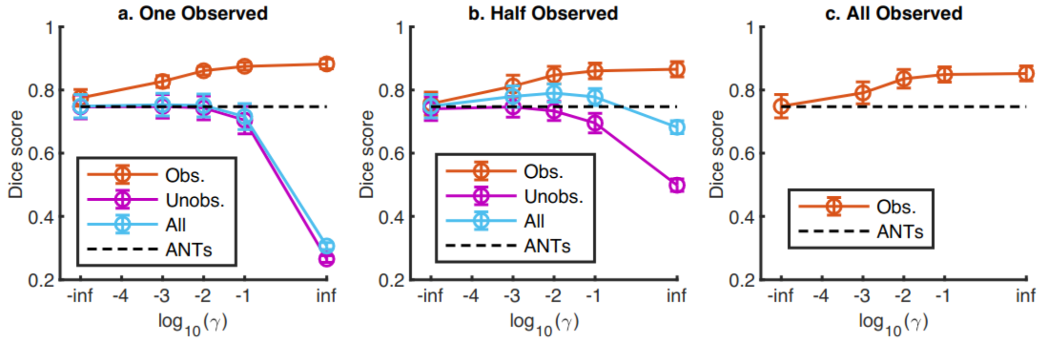
$$L_h(\theta_h; D) = \mathbb{E}_\Lambda \sum_{M,T \in D} [(1-\lambda)\,(1-\gamma)\,L_{sim}(T, M \circ \varphi; \lambda_{sim})]$$
$$+ \lambda L_{reg}(\varphi; \lambda_{reg}) + (1-\lambda)\,\gamma L_{seg}(s_T, s_M \circ \varphi)]$$

Results - Voxelmorph


[18]

[18] Balakrishnan et al. 2019.

Results - Voxelmorph



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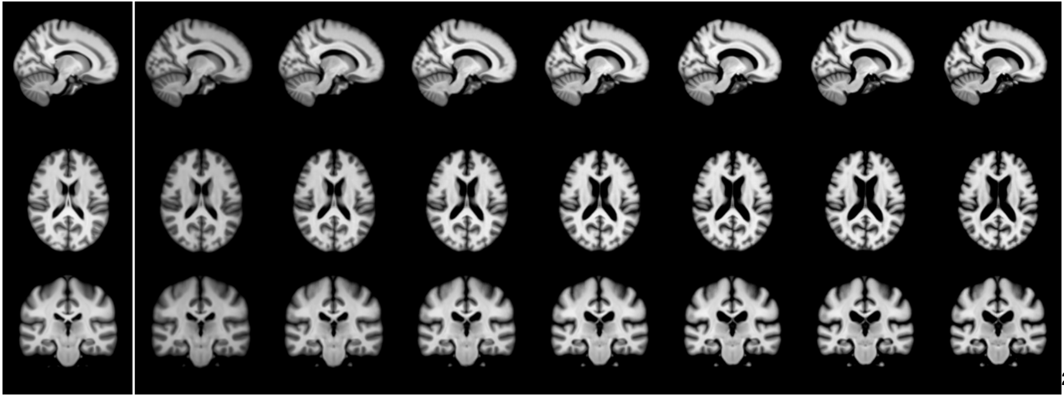
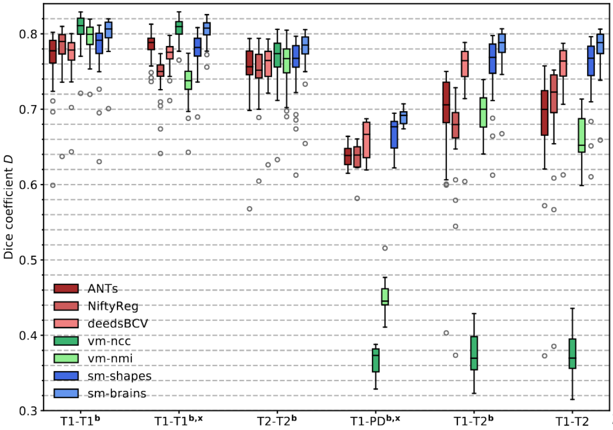
[19] Balakrishnan et al. 2019.

Results - Atlases

[20]

[20] Adrian V Dalca et al. 2019a.

Results - Synthmorph



[21]

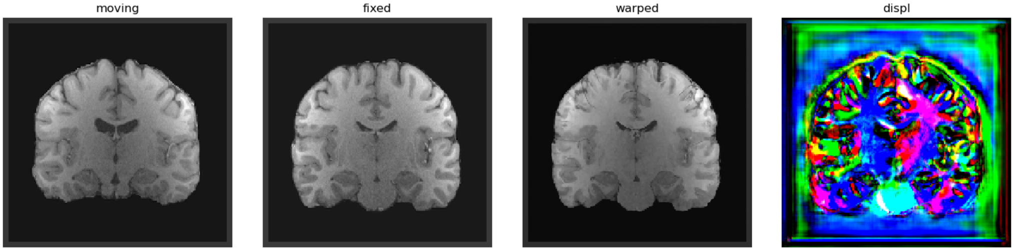
[21] Hoffmann et al. 2020.

Experiments

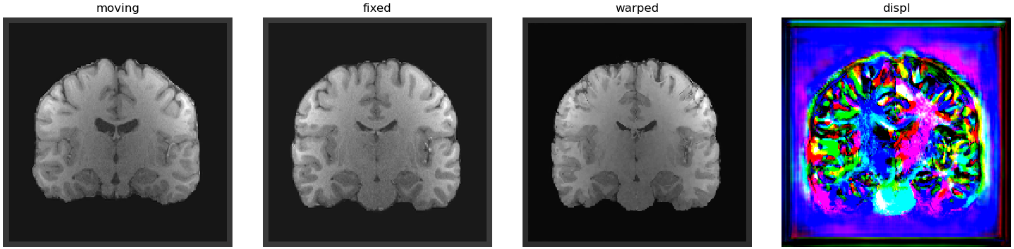
Preprocessing

1. skull-stripping
2. affine alignment
3. intensity normalization

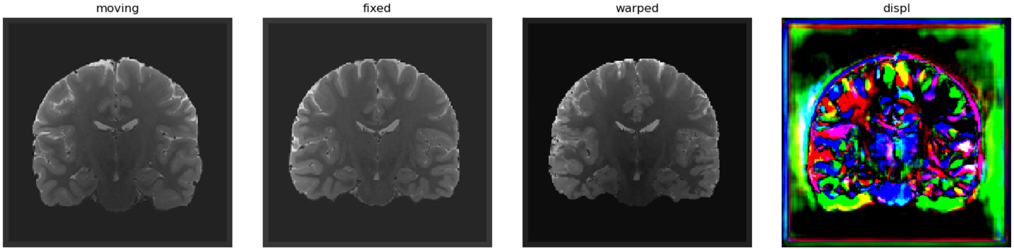
intra-modal T1w brain scans 40 epochs



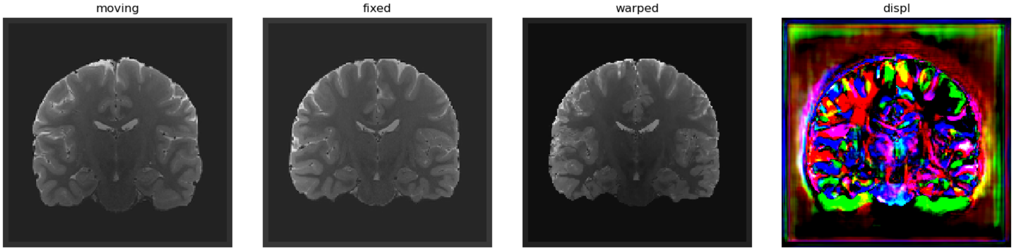
intra-modal T1w brain scans 80 epochs



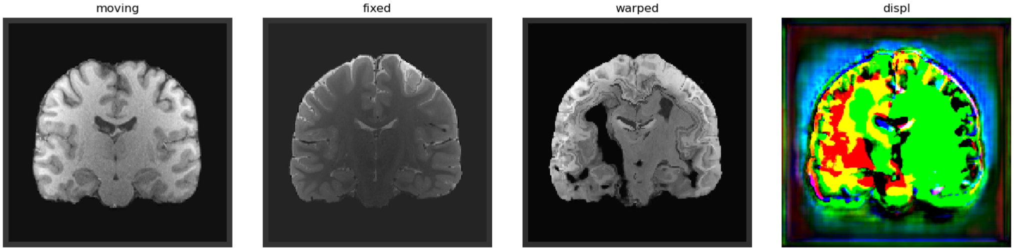
intra-modal T2w brain scans 40 epochs



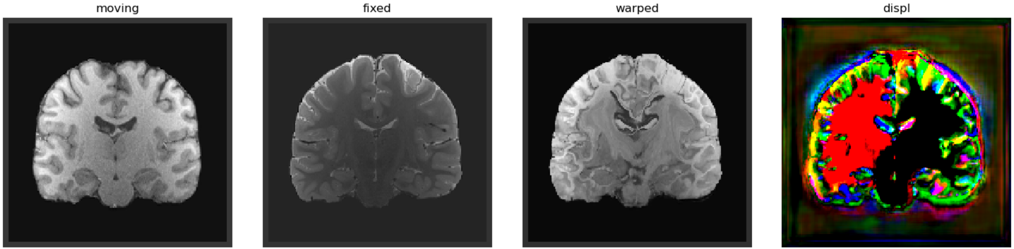
intra-modal T2w brain scans 80 epochs



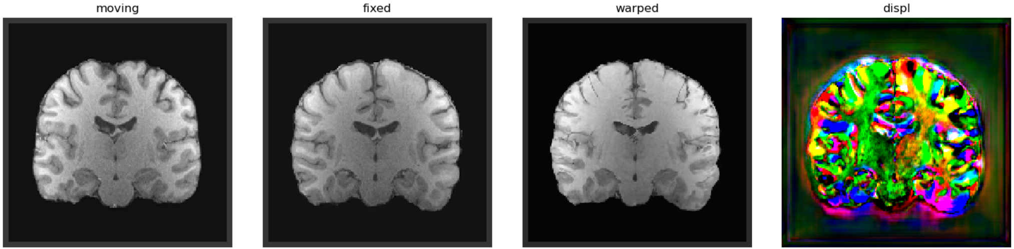
inter-modal T1w-T2w brain scans 40 epochs



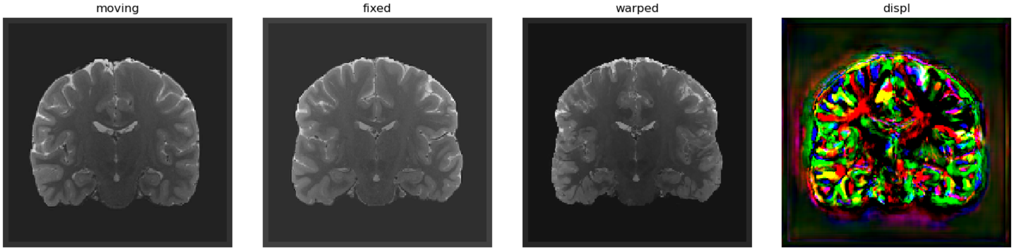
inter-modal T1w-T2w brain scans 80 epochs



intra-modal T1w-T1w brain scans 80 epochs



intra-modal T2w-T2w brain scans 80 epochs



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References II

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Isensee, Fabian, Marianne Schell, Irada Pflueger, Gianluca Brugnara, David Bonekamp, Ulf Neuberger, Antje Wick, et al. 2019. *Automated brain extraction of multi-sequence MRI using artificial neural networks,* August.

Niethammer, Marc, Roland Kwitt, and François-Xavier Vialard. 2019. “Metric Learning for Image Registration.” *CoRR* abs/1904.09524. arXiv: 1904.09524. http://arxiv.org/abs/1904.09524.

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Shen, Zhengyang, Xu Han, Zhenlin Xu, and Marc Niethammer. 2019. "Networks for Joint Affine and Non-parametric Image Registration." In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition,* 4224–4233.

Shen, Zhengyang, François-Xavier Vialard, and Marc Niethammer. 2019. "Region-specific Diffeomorphic Metric Mapping." *NeurIPS: Neural Information Processing Systems.*

References V

Yang, Xiao, Roland Kwitt, and Marc Niethammer. 2016. "Fast Predictive Image Registration." In *DLMIA: International Workshop on Deep Learning in Medical Image Analysis,* 48–57.

Yang, Xiao, Roland Kwitt, Martin Styner, and Marc Niethammer. 2017. "Quicksilver: Fast predictive image registration–a deep learning approach." *NeuroImage* 158:378–396.

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