

3DGS-Avatar: Animatable Avatars via Deformable 3D Gaussian Splatting

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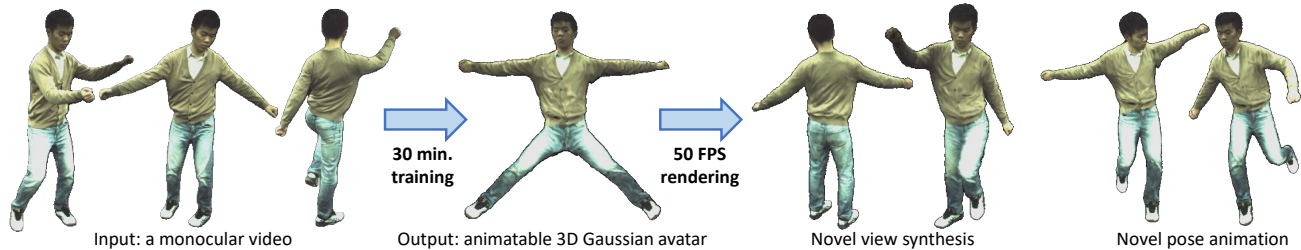


Figure 1. **3DGS-Avatar**. We develop an efficient method for creating animatable avatars from monocular videos, leveraging 3D Gaussian Splatting [14]. Given a short sequence of dynamic human with a tracked skeleton and foreground masks, our method creates an avatar within **30 minutes** on a single GPU, supports animation and novel view synthesis at over **50 FPS**, and achieves comparable or better rendering quality to the state-of-the-art [57, 58] that requires over 8 GPU days to train, takes several seconds to render a single image, and relies on pre-training on clothed human scans [57].

Abstract

We introduce an approach that creates animatable human avatars from monocular videos using 3D Gaussian Splatting (3DGS). Existing methods based on neural radiance fields (NeRFs) achieve high-quality novel-view/novel-pose image synthesis but often require days of training, and are extremely slow at inference time. Recently, the community has explored fast grid structures for efficient training of clothed avatars. Albeit being extremely fast at training, these methods can barely achieve an interactive rendering frame rate with around 15 FPS. In this paper, we use 3D Gaussian Splatting and learn a non-rigid deformation network to reconstruct animatable clothed human avatars that can be trained within 30 minutes and rendered at real-time frame rates (50+ FPS). Given the explicit nature of our representation, we further introduce as-isometric-as-possible regularizations on both the Gaussian mean vectors and the covariance matrices, enhancing the generalization of our model on highly articulated unseen poses. Experimental results show that our method achieves comparable and even better performance compared to state-of-the-art approaches on animatable avatar creation from a monocular input, while being 400x and 250x faster in training and inference, respectively. Please see our project page at <https://neurallbodies.github.io/3DGS-Avatar>.

1. Introduction

Reconstructing clothed human avatars from image inputs presents a significant challenge in computer vision, yet holds immense importance due to its applications in virtual reality, gaming, and e-commerce. Traditional methods often rely on dense, synchronized multi-view inputs, which may not be readily available in more practical scenarios. Recent advances in implicit neural fields [27, 30, 32, 36, 47, 50, 51, 53, 55, 65, 66] have enabled high-quality reconstruction of geometry [8, 38, 57, 61] and appearance [13, 20, 22, 31, 35, 37, 42, 58, 70] of clothed human bodies from sparse multi-view or monocular videos. Animation of such reconstructed clothed human bodies is also possible by learning the geometry and appearance representations in a predefined canonical pose [13, 20, 35, 57, 58, 70].

To achieve state-of-the-art rendering quality, existing methods rely on training a neural radiance field (NeRF) [27] combined with either explicit body articulation [8, 12, 13, 20, 35, 38, 57, 58, 70] or conditioning the NeRF on human body related encodings [31, 37, 48, 61]. They often employ large multi-layer perceptrons (MLPs) to model the neural radiance field, which are computationally demanding, leading to prolonged training (days) and inference (seconds) time. This computational expense poses a significant challenge for practical applications of these state-of-the-art methods in real-time applications.

With recent advances in efficient learning of implicit

neural fields, training time of NeRFs has been reduced to minutes [3, 29, 46, 52]. There are also works targeting fast inference of pretrained NeRFs [43, 67, 69]. Inspired by these developments, several avatar reconstruction methods have been tailored to fast training [7, 12] or fast inference [6, 17, 39]. However, to the best of our knowledge, there currently exists no method that simultaneously achieves both fast training and *real-time* inference for *animatable* avatar reconstruction from just monocular videos.

Point-based rendering [44, 49, 62, 71, 73, 74] has emerged as an efficient alternative to NeRFs for fast inference. With the recently proposed 3D Gaussian Splatting (3DGS) [14], it is possible to achieve state-of-the-art rendering quality using only a fraction of NeRFs’ inference time and comparatively fast training for static scene reconstruction.

Leveraging the capabilities of 3DGS, we demonstrate its application in modeling animatable clothed avatars using monocular videos. Our approach effectively integrates rigid human articulation with a non-rigid deformation field within the 3DGS framework. We use a small multi-layer perceptron (MLP) to decode color. This MLP is designed to be responsive to local non-rigid deformations and dynamic lighting conditions, ensuring a more realistic and responsive rendering of the avatar’s appearance. Furthermore, we apply as-isometric-as-possible regularizations [15, 41] to *both* the Gaussian mean vectors and the covariance matrices, which helps maintain the geometric consistency and realistic deformation of the avatar, particularly in dynamic and varied poses.

Our experimental results show that our method is comparable to or better than current state-of-the-art [57, 58] in animatable avatar creation from monocular inputs, achieving training speed 400 times faster and inference speed 250 times quicker. Compared to methods that focus on fast training [7, 12], our method, despite being slower in training, can model pose-dependent non-rigid deformation and produce significantly better rendering quality, while being 3 times faster in terms of rendering. We provide an overview of the comparison to major prior works in Tab. 1. In summary, our work makes the following contributions:

- We introduce 3D Gaussian Splatting to animatable human avatars reconstruction from monocular videos.
- We develop a simple yet effective deformation network as well as regularization terms that effectively drive 3D Gaussian Splats to handle highly articulated and out-of-distribution poses.
- Our method is the first, to our knowledge, to simultaneously deliver high-quality rendering, model pose-dependent non-rigid deformation, generalize effectively to unseen poses, and achieve fast training (less than 30 minutes) and real-time rendering speed (50+ FPS).

	pose-dependent deformation	novel pose animation	fast training	real-time rendering	monocular input	
✗	✗	✗	✗	✓		NeuralBody [37]
✓	✗	✗	✗	✓		HumanNeRF [58]
✓	✓	✗	✗	✓		ARAH [57]
✓	✗	✓	✗	✓		Instant-NVR [7]
✗	✓	✓	✗	✓		InstantAvatar [12]
✓	✓	✗	✗	✓		MonoHuman [70]
✓	✓	✗	✗	✗		UV-Volumes [6]
✓	✓	✗	✓	✗		DELIFAS [17]
✓	✓	✓	✓	✓		3DGS-Avatar (Ours)

Table 1. **Comparison to SoTA.** Instant-NVR [7] and InstantAvatar [12] achieve instant training within 5 minutes. For real-time rendering, we require a frame rate over 30 FPS. Note that while UV-Volumes [6] claims real-time freeview rendering, they only achieve 14 FPS on novel pose synthesis due to the slow generation of their UV Volume.

2. Related Works

Neural rendering for clothed human avatars. Since the seminal work of Neural Radiance Fields (NeRF) [27], there has been a surge of research on neural rendering for clothed human avatars. The majority of the works focus on either learning a NeRF conditioned on human body related encodings [31, 48, 61], or learning a canonical NeRF representation and warp camera rays from the observation space to the canonical space to query radiance and density values from the canonical NeRF [8, 12, 13, 20, 35, 38, 57, 58, 70]. Most of these works rely on large multi-layer perceptrons (MLPs) to model the underlying neural radiance field, which are computationally expensive, resulting in prolonged training (days) and inference (seconds) time.

With recent advances in accelerated data structures for neural fields, there has been several works targeting fast inference and fast training of NeRFs for clothed humans. [12] proposes to use iNGP [29] as the underlying representation for articulated NeRFs, which enables fast training (less than 5 minutes) and interactive rendering speed (15 FPS) but ignores pose-dependent non-rigid deformations. [7] also utilizes iNGP and represents non-rigid deformations in the UV space, which enables fast training and modeling of pose-dependent non-rigid deformations. However, as we will show in our experiments, [7]’s parametrization of non-rigid deformations result in blurry renderings. [6] proposes to generate a pose-dependent UV volume for efficient freeview synthesis. However, their UV-volume generation process is slow (20 FPS), making novel pose synthesis less efficient (only 14 FPS). [17] also employs UV-based rendering

to achieve real-time rendering of dynamic clothed humans, but only works on dense multi-view inputs. Extending [69], [54, 72] applied Fourier transform for compressing human performance capture data, albeit with limitations on dense multi-view data (60-80 views) and non-generalizability of the Fourier basis representation to unseen poses beyond the training dataset. In contrast to all these works, our method achieves state-of-the-art rendering quality and speed with less than 30 minutes of training time from a single monocular video input.

Dynamic 3D Gaussians. Point-based rendering [40, 44, 49, 62, 71, 73, 74] has also been shown to be an efficient alternative to NeRFs for fast inference and training. Extending point cloud to 3D Gaussians, 3D Gaussian Splatting (3DGS) [14] models the rendering process as splatting a set of 3D Gaussians onto image plane via alpha blending, achieving state-of-the-art rendering quality with real-time inference speed and fast training given multi-view inputs.

Given the great performance on both quality and speed of 3DGS, a rich set of works has further explored the 3D Gaussian representation for dynamic scene reconstruction. [14] proposed to optimize the position and shape of each 3D Gaussian on a frame-by-frame basis and simultaneously performed 6-DOF dense tracking for free. Their model size, however, increases with the temporal dimension. [59, 63] maintain a single set of 3D Gaussians in a canonical space and deform them to each frame via learning a time-dependent deformation field, producing state-of-the-art results in terms of both rendering quality and speed. [64] augments 3D Gaussians with temporal dimension into 4D Gaussian primitives to approximate the underlying spatiotemporal 4D volume of the dynamic scene. While such methods show promising results, they are only applicable to either synthetic datasets with fast camera movement and slow object motion or forward-facing real scenes with limited object movements, thus unable to handle the immense displacement of the articulated human body. To address this problem, our approach utilizes a statistical human body model [24] for articulation and applies regularization to reduce the overfitting of the deformation field.

Concurrent works. Concurrent with our method, many recent works also seek to combine 3DGS with human articulation prior for avatar reconstruction. We provide a comparison of our approach to concurrent works in Tab. 2. D3GA [75] proposed to embed 3D Gaussians in tetrahedral cages and utilize cage deformations for drivable avatar animation. However, they use dense calibrated multi-view videos as input and require an additional 3D scan to generate the tetrahedral mesh template. Li *et al.* [21] focused on generating avatars with a detailed appearance from multi-view videos by post-processing radiance field renderings with 2D CNNs, which limits their rendering speed. Along with [11, 28], these works fail to achieve fast training with

	pose-dependent deformation	novel pose animation	fast training	real-time rendering	monocular input	
✓	✓	✗	✓	✗		D3GA [75]
✓	✓	✗	✗	✗		Li <i>et al.</i> [21]
✓	✓	✗	✓	✓		SplatArmor [11]
✓	✓	✗	✗	✗		Moreau <i>et al.</i> [28]
✓	✓	✓	✓	✗		Ye <i>et al.</i> [68]
✗	✓	✓	✓	✓		HUGS [16]
✗	✓	✓	✓	✓		GART [18]
✗	✓	✓	✓	✓		Liu <i>et al.</i> [23]
✗	✗	✓	✓	✓		GauHuman [10]
✓	✓	✓	✓	✓		3DGS-Avatar (Ours)

Table 2. Comparison to Concurrent Works.

relatively complex pipelines. Similar to our approach, Ye *et al.* [68] deforms 3D Gaussians in canonical space via pose-dependent deformation and rigid articulation, but they still require 2 hours for training and do not show results on monocular inputs. HUGS [16] learns a background model along with the animatable human avatar, but they fail to take pose-dependent cloth deformation into account. Several other works [10, 18, 23] also neglect pose-dependent cloth deformation to achieve even faster training (in 5 minutes) and rendering (150+ FPS). We argue that our method strikes a good balance between quality and speed compared to concurrent works, as being the only method simultaneously achieving the properties listed in Tab. 2.

3. Preliminaries

Linear Blend Skinning. To model human articulations, a widely adopted paradigm is to represent geometry and appearance in a shared canonical space [8, 12, 13, 20, 35, 38, 57, 58] and use Linear Blend Skinning (LBS) [2, 9, 24, 33, 34, 60] to deform the parametric human body under arbitrary poses. Given a point \mathbf{x}_c in canonical space, the LBS function takes a set of rigid bone transformations $\{\mathbf{B}_b\}_{b=1}^B$ and computes its correspondence \mathbf{x}_o in the observation space:

$$\mathbf{x}_o = LBS_{\sigma_w}(\mathbf{x}_c; \{\mathbf{B}_b\}) \quad (1)$$

Assuming an underlying SMPL model, we use a total of $B = 24$ bone transformations, each represented by a 4×4 rotation-translation matrix, which are then linearly blended via a set of skinning weights $\mathbf{w} \in [0, 1]^B$, s.t. $\sum_{b=1}^B \mathbf{w}_b = 1$, modeled by a coordinate-based neural skinning field $f_{\sigma_w}(\mathbf{x}_c)$ [4, 5, 26, 45, 56]. The forward linear blend skin-

ning function can thus be formulated as:

$$\mathbf{x}_o = LBS_{\sigma_w}(\mathbf{x}_c; \{\mathbf{B}_b\}) = \sum_{b=1}^B f_{\sigma_w}(\mathbf{x}_c)_b \mathbf{B}_b \mathbf{x}_c \quad (2)$$

Compared to prior works that search canonical correspondences of points in observation space [12, 57, 58], our method requires no inverse skinning which is typically difficult to compute and often leads to multiple solutions [4, 5]. A similar technique has been employed in [73] for face avatar modeling.

3D Gaussian Splatting. 3DGS [14] utilizes a set of 3D Gaussian primitives $\{\mathcal{G}\}$ as static scene representation which can be rendered in real-time via differentiable rasterization. Each 3D Gaussian \mathcal{G} is defined by its mean \mathbf{x} , covariance Σ , opacity α and view-dependent color represented by spherical harmonics coefficients \mathbf{f} . To ensure positive semi-definiteness, the covariance matrix is represented by a scaling matrix \mathbf{S} and rotation matrix \mathbf{R} . In practice, we store the diagonal vector $\mathbf{s} \in \mathbb{R}^3$ of the scaling matrix and a quaternion vector $\mathbf{q} \in \mathbb{R}^4$ to represent rotation, which can be trivially converted to a valid covariance matrix.

The 3D Gaussians are projected to the 2D image plane during the rendering process and accumulated via alpha blending. Given a viewing transformation \mathbf{W} and the Jacobian of the affine approximation of the projective transformation \mathbf{J} , the 2D covariance matrix in camera coordinate [76] is given by $\Sigma' = (\mathbf{J}\mathbf{W}\Sigma\mathbf{W}^T\mathbf{J}^T)_{1:2,1:2}$. The pixel color C is thus computed by blending 3D Gaussian splats that overlap at the given pixel, sorted according to their depth:

$$C = \sum_i \left(\alpha'_i \prod_{j=1}^{i-1} (1 - \alpha'_j) \right) c_i \quad (3)$$

where α'_i denotes the learned opacity α_i weighted by the probability density of i -th projected 2D Gaussian at the target pixel location. c denotes the view-dependent color computed from stored SH coefficients \mathbf{f} .

The 3D Gaussians $\{\mathcal{G}\}$ are optimized via a photometric loss. During optimization, 3DGS adaptively controls the number of 3D Gaussians via periodic densification and pruning, achieving self-adaptive convergence to an optimal density distribution of 3D Gaussians that well represents the scene.

4. Methods

We illustrate the pipeline of our method in Fig. 2. The input to our method is a monocular video with a calibrated camera, fitted SMPL parameters, and foreground masks. Our method optimizes a set of 3D Gaussians in canonical space, which is then deformed to the observation space and rendered from the given camera. For a set of 3D Gaussians $\{\mathcal{G}^{(i)}\}_{i=1}^N$, we store the following properties at each point:

position \mathbf{x} , scaling factor \mathbf{s} , rotation quaternion \mathbf{q} , opacity α and a color feature vector \mathbf{f} . We start by randomly sampling $N = 50k$ points on the canonical SMPL [24] mesh surface as initialization of canonical 3D Gaussians $\{\mathcal{G}_c\}$. Inspired by HumanNeRF [58], we decompose the complex human deformation into a non-rigid part that encodes pose-dependent cloth deformation, and a rigid transformation controlled by the human skeleton.

4.1. Pose-dependent Non-rigid Deformation

We formulate the non-rigid deformation module as:

$$\{\mathcal{G}_d\} = \mathcal{F}_{\theta_{nr}}(\{\mathcal{G}_c\}; \mathcal{Z}_p) \quad (4)$$

where $\{\mathcal{G}_d\}$ represents the non-rigidly deformed 3D Gaussians. θ_{nr} represents the learnable parameters of the non-rigid deformation module. \mathcal{Z}_p is a latent code which encodes SMPL pose and shape (θ, β) using a lightweight hierarchical pose encoder [26]. Specifically, the deformation network $f_{\theta_{nr}}$ takes the canonical position \mathbf{x}_c , the pose latent code \mathcal{Z}_p as inputs and outputs the offsets of the Gaussian’s position, scale, rotation, along with a feature vector \mathbf{z} :

$$(\delta\mathbf{x}, \delta\mathbf{s}, \delta\mathbf{q}, \mathbf{z}) = f_{\theta_{nr}}(\mathbf{x}_c; \mathcal{Z}_p) \quad (5)$$

We use a multi-level hash grid [29] to encode 3D positions as spatial features, which are then concatenated with the pose latent code \mathcal{Z}_p and fed into a shallow MLP with 2 hidden layers and a width of 128. The canonical Gaussian is deformed by:

$$\mathbf{x}_d = \mathbf{x}_c + \delta\mathbf{x} \quad (6)$$

$$\mathbf{s}_d = \mathbf{s}_c \cdot \exp(\delta\mathbf{s}) \quad (7)$$

$$\mathbf{q}_d = \mathbf{q}_c \cdot [1, \delta q_1, \delta q_2, \delta q_3] \quad (8)$$

note that the \cdot operator on quaternions is equivalent to multiplying the two rotation matrices derived by the two quaternions. Since the quaternion $[1, 0, 0, 0]$ corresponds to the identity rotation matrix, we have $\mathbf{q}_d = \mathbf{q}_c$ when $\delta\mathbf{q} = \mathbf{0}$.

4.2. Rigid Transformation

We further transform the non-rigidly deformed 3D Gaussians $\{\mathcal{G}_d\}$ to the observation space via a rigid transformation module:

$$\{\mathcal{G}_o\} = \mathcal{F}_{\theta_r}(\{\mathcal{G}_d\}; \{\mathbf{B}_b\}_{b=1}^B) \quad (9)$$

where a skinning MLP f_{θ_r} is learned to predict skinning weights at the position \mathbf{x}_d . We transform the position and the rotation matrix of 3D Gaussians via forward LBS:

$$\mathbf{T} = \sum_{b=1}^B f_{\theta_r}(\mathbf{x}_d)_b \mathbf{B}_b \quad (10)$$

$$\mathbf{x}_o = \mathbf{T}\mathbf{x}_d \quad (11)$$

$$\mathbf{R}_o = \mathbf{T}_{1:3,1:3}\mathbf{R}_d \quad (12)$$

where \mathbf{R}_d is the rotation matrix derived from the quaternion \mathbf{q}_d .

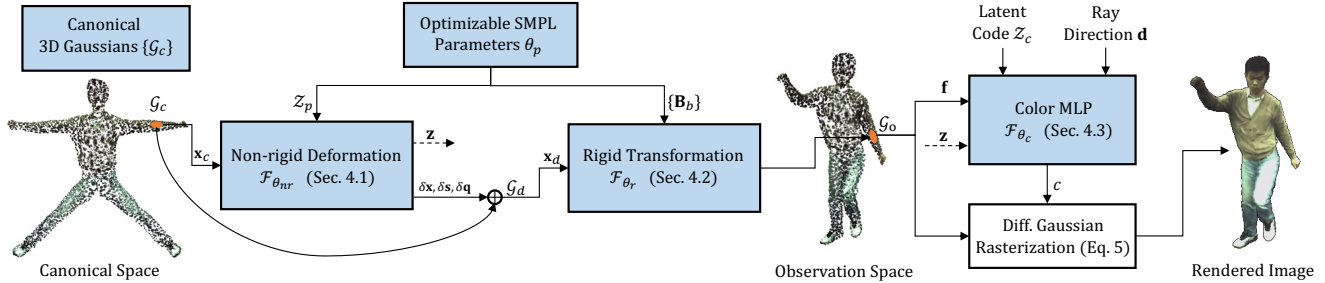


Figure 2. **Our framework for creating animatable avatars from monocular videos.** We first initialize a set of 3D Gaussians in the canonical space via sampling points from a SMPL mesh. Each canonical Gaussian \mathcal{G}_c goes through a non-rigid deformation module $\mathcal{F}_{\theta_{nr}}$ conditioned on an encoded pose vector \mathcal{Z}_p (Sec. 4.1) to account for pose-dependent non-rigid cloth deformation. This module outputs a non-rigidly deformed 3D Gaussian \mathcal{G}_d and a pose-dependent latent feature \mathbf{z} . The non-rigidly deformed 3D Gaussian \mathcal{G}_d is transformed to the observation space \mathcal{G}_o (Sec. 4.2) via LBS with learned neural skinning \mathcal{F}_{θ_r} . The Gaussian feature \mathbf{f} , the pose-dependent feature \mathbf{z} , a per-frame latent code \mathcal{Z}_c , and the ray direction \mathbf{d} are propagated through a small MLP \mathcal{F}_{θ_c} to decode the view-dependent color c for each 3D Gaussian. Finally, the observation space 3D Gaussians $\{\mathcal{G}_o\}$ and their respective color values are accumulated via differentiable Gaussian rasterization (Eq. (3)) to render the image.

4.3. Color MLP

Prior works [59, 63, 64] follow the convention of 3DGS [14], which stores spherical harmonics coefficients per 3D Gaussian to encode the view-dependent color. Treating the stored color feature \mathbf{f} as spherical harmonics coefficients, the color of a 3D Gaussian can be computed by the dot product of the spherical harmonics basis and the learned coefficients: $c = \langle \gamma(\mathbf{d}), \mathbf{f} \rangle$, where \mathbf{d} represents the viewing direction, derived from the relative position of the 3D Gaussian wrt. the camera center and γ denotes the spherical harmonics basis function.

While conceptually simple, we argue that this approach does not suit our monocular setting. Since only one camera view is provided during training, the viewing direction in the world space is fixed, leading to poor generalization to unseen test views. Similar to [38], we use the inverse rigid transformation from Sec. 4.2 to canonicalize the viewing direction: $\hat{\mathbf{d}} = \mathbf{T}_{1:3,1:3}^{-1} \mathbf{d}$, where \mathbf{T} is the forward transformation matrix defined in Eq. (10). Theoretically, canonicalizing viewing direction also promotes consistency of the specular component of canonical 3D Gaussians under rigid transformations.

On the other hand, we observe that the pixel color of the rendered clothed human avatar also largely depends on local deformation. Local fine wrinkles on clothes, for instance, would cause self-occlusion that heavily affects shading. Following [37], we also learn a per-frame latent code \mathcal{Z}_c to compensate for different environment light effects across frames caused by the global movement of the subject. Hence, instead of learning spherical harmonic coefficients, we enhance color modeling by learning a neural network that takes per-Gaussian color feature vector $\mathbf{f} \in \mathbb{R}^{32}$, local pose-dependent feature vector $\mathbf{z} \in \mathbb{R}^{16}$ from the non-rigid deformation network, per-frame latent code $\mathcal{Z}_c \in \mathbb{R}^{16}$, and

spherical harmonics basis of canonicalized viewing direction $\gamma(\hat{\mathbf{d}})$ with a degree of 3 as input and predicts the color of the 3D Gaussian:

$$c = \mathcal{F}_{\theta_c}(\mathbf{f}, \mathbf{z}, \mathcal{Z}_c, \gamma(\hat{\mathbf{d}})) \quad (13)$$

In practice, we find a tiny MLP with one 64-dimension hidden layer sufficient to model the appearance. Increasing the size of the MLP leads to overfitting and performance drop.

4.4. Optimization

We jointly optimize canonical 3D Gaussians $\{\mathcal{G}_c\}$ and the parameters $\theta_{nr}, \theta_r, \theta_c$ of the non-rigid deformation network, the skinning network and the color network, respectively.

Pose correction. SMPL [24] parameter fittings from images can be inaccurate. To address this, we additionally optimize the per-sequence shape parameter as well as per-frame translation, global rotation, and local joint rotations. We initialize these parameters θ_p with the given SMPL parameters and differentially derive the bone transformations $\{\mathbf{B}_b\}$ as input to the network, enabling direct optimization via backpropagation.

As-isometric-as-possible regularization. With monocular video as input, only one view of the human is visible in each frame, making it extremely hard to generalize to novel views and novel poses. Considering the sparsity of input, the non-rigid deformation network is highly under-constrained, resulting in noisy deformation from the canonical space to the observation space. Inspired by [41], we leverage the as-isometric-as-possible constraint [15] to restrict neighboring 3D Gaussian centers to preserve a similar distance after deformation. We further augment the con-

straint to Gaussian covariance matrices:

$$\mathcal{L}_{isopos} = \sum_{i=1}^N \sum_{j \in \mathcal{N}_k(i)} \left| d(\mathbf{x}_c^{(i)}, \mathbf{x}_c^{(j)}) - d(\mathbf{x}_o^{(i)}, \mathbf{x}_o^{(j)}) \right| \quad (14)$$

$$\mathcal{L}_{isocov} = \sum_{i=1}^N \sum_{j \in \mathcal{N}_k(i)} \left| d(\Sigma_c^{(i)}, \Sigma_c^{(j)}) - d(\Sigma_o^{(i)}, \Sigma_o^{(j)}) \right| \quad (15)$$

where N denotes the number of 3D Gaussians. \mathcal{N}_k denotes the k -nearest neighbourhood, and we set k to 5. We use L2-norm as our distance function $d(\cdot, \cdot)$.

Loss function. Our full loss function consists of a RGB loss \mathcal{L}_{rgb} , a mask loss \mathcal{L}_{mask} , a skinning weight regularization loss \mathcal{L}_{skin} and the as-isometric-as-possible regularization loss for both position and covariance $\mathcal{L}_{isopos}, \mathcal{L}_{isocov}$. For further details of the loss definition and respective weights, please refer to the Supp.Mat.

5. Experiments

In this section, we first compare the proposed approach with recent state-of-the-art methods [7, 12, 37, 57, 58], demonstrating that our proposed approach achieves superior rendering quality in terms of LPIPS, which is more informative under monocular setting, while achieving fast training and real-time rendering speed, respectively **400x and 250x faster** than the most competitive baseline [58]. We then systematically ablate each component of the proposed model, showing their effectiveness in better rendering quality.

5.1. Evaluation Dataset

ZJU-MoCap [37]. This is the major testbed for quantitative evaluation. We pick six sequences (377, 386, 387, 392, 393, 394) from the ZJU-MoCap dataset and follow the training/test split of HumanNeRF [58]. The motion of these sequences is repetitive and does not contain a sufficient number of poses for meaningful novel pose synthesis benchmarks. Thus we focus on evaluating novel view synthesis (PSNR/SSIM/LPIPS) and show qualitative results for animation on out-of-distribution poses. Note that LPIPS in all the tables are scaled up by 1000.

PeopleSnapshot [1]. We also conduct experiments on 4 sequences of the PeopleSnapshot dataset, which includes monocular videos of people rotating in front of a camera. We follow the data split of InstantAvatar [12] and compare to [12] on novel pose synthesis. For fair comparison, we use the provided poses optimized by Anim-NeRF [35] and do not further optimize it during our training.

5.2. Comparison with Baselines

We compare our approach with NeuralBody [37], HumanNeRF [58], MonoHuman [70], ARAH [57] and Instant-

NVR [7] under monocular setup on ZJU-MoCap. The quantitative results are reported in Tab. 3. NeuralBody is underperforming compared to other approaches. Overall, our proposed approach produces comparable performance to ARAH on PSNR and SSIM, while significantly outperforming all the baselines on LPIPS. We argue that LPIPS is more informative compared to the other two metrics, as it is very difficult to reproduce exactly the ground-truth appearance for novel views due to the monocular setting and the stochastic nature of cloth deformations. Meanwhile, our method is also capable of fast training and renders at a real-time rendering frame rate, being 400 times faster for training (30 GPU minutes vs. 8 GPU days) and 250 – 500 times faster for inference (50 FPS vs. 0.1 FPS for ARAH and 0.2 FPS for HumanNeRF). We also note that Instant-NVR trains on a refined version of ZJU-MoCap, which provides refined camera parameters, SMPL fittings, and more accurate instance masks with part-level annotation that is essential for running their method. Hence their metrics are not directly comparable to other methods in Tab. 3. We train our model on the refined dataset for a fair quantitative comparison, which clearly shows that our method outperforms Instant-NVR in most scenarios.

Qualitative comparisons on novel view synthesis can be found in Fig. 3. We observe that our method preserves sharper details compared to ARAH and does not produce fluctuating artifacts as in HumanNeRF caused by noisy deformation fields. Instant-NVR produces an oversmooth appearance and tends to generate noisy limbs. Additionally, we animate our learned avatars with pose sequences from AMASS [25] and AIST++ [19], shown in the rightmost column of Fig. 3. This shows that our model could generalize to extreme out-of-distribution poses.

For PeopleSnapshot, we report the quantitative comparison against InstantAvatar [12] in Tab. 4. Our approach significantly outperforms InstantAvatar on PSNR and LPIPS, while being more than 3x faster during inference.

5.3. Ablation Study

We study the effect of various components of our method on the ZJU-MoCap dataset, including the color MLP, the as-isometric-as-possible regularization and the pose correction module. The average metrics over 6 sequences are reported in Tab. 5. We show that all proposed techniques are required to reach the optimal performance, best reflected by LPIPS which is the most informative metric for novel view synthesis evaluation under a monocular setup.

We further show qualitative comparison on out-of-distribution poses in Fig. 4, which demonstrates that the as-isometric-as-possible loss helps to constrain the 3D Gaussians to comply with consistent movement during deformation, hence improving generalization on novel poses. Albeit marginally, each individual component contributes to a



Figure 3. **Qualitative Comparison on ZJU-MoCap [37].** We show the results for both novel view synthesis and novel pose animation of all sequences on ZJU-MoCap. Our method produces high-quality results that preserve cloth details even on out-of-distribution poses.

Table 3. **Quantitative Results on ZJU-MoCap [37]**. We outperform both competitive baselines [57, 58] in terms of LPIPS while being two orders of magnitude faster in training and rendering. Cell color indicates **best** and **second best**. Instant-NVR [7] is trained and tested on a refined version of ZJU-MoCap, thus is not directly comparable to other baselines quantitatively. We train our model on the refined dataset for fair quantitative comparison to Instant-NVR and the metrics are reported in the last two rows of the table.

Subject:	377			386			387			392			393			394				
Metric:	GPU↓	FPS↑	PSNR↑	SSIM↑	LPIPS↓	PSNR↑	SSIM↑	LPIPS↓	PSNR↑	SSIM↑	LPIPS↓	PSNR↑	SSIM↑	LPIPS↓	PSNR↑	SSIM↑	LPIPS↓			
NeuralBody [37]	12h	2	29.11	0.9674	40.95	30.54	0.9678	46.43	27.00	0.9518	59.47	30.10	0.9642	53.27	28.61	0.9590	59.05	29.10	0.9593	54.55
HumanNeRF [58]	>8d	0.2	30.41	0.9743	24.06	33.20	0.9752	28.99	28.18	0.9632	35.58	31.04	0.9705	32.12	28.31	0.9603	36.72	30.31	0.9642	32.89
MonoHuman [70]	4d	0.1	29.12	0.9727	26.58	32.94	0.9695	36.04	27.93	0.9601	41.76	29.50	0.9635	39.45	27.64	0.9566	43.17	29.15	0.9595	38.08
ARAH [57]	8d	0.1	30.85	0.9800	26.60	33.50	0.9781	31.40	28.49	0.9656	40.43	32.02	0.9742	35.28	28.77	0.9645	42.30	29.46	0.9632	40.76
Ours	0.5h	50	30.64	0.9774	20.88	33.63	0.9773	25.77	28.33	0.9642	34.24	31.66	0.9730	30.14	28.88	0.9635	35.26	30.54	0.9661	31.21
Instant-NVR* [7]	0.1h	3	31.28	0.9789	25.37	33.71	0.9770	32.81	28.39	0.9640	45.97	31.85	0.9730	39.47	29.56	0.9641	46.16	31.32	0.9680	40.63
Ours*	0.5h	50	30.96	0.9778	19.85	33.94	0.9784	24.70	28.40	0.9656	32.96	32.10	0.9739	29.20	29.30	0.9645	34.03	30.74	0.9662	31.00

Table 4. **Quantitative Results on PeopleSnapshot [1]**.

Subject:	female-3-casual			female-4-casual			male-3-casual			male-4-casual				
Metric:	GPU↓	FPS↑	PSNR↑	SSIM↑	LPIPS↓	PSNR↑	SSIM↑	LPIPS↓	PSNR↑	SSIM↑	LPIPS↓	PSNR↑	SSIM↑	LPIPS↓
InstantAvatar [12]	5 min.	15	27.66	0.9709	21.00	29.11	0.9683	16.70	29.53	0.9716	15.50	27.67	0.9626	30.7
Ours	45 min.	50	30.57	0.9581	20.86	33.16	0.9678	15.74	34.28	0.9724	14.92	30.22	0.9653	23.05



Figure 4. **Ablation Study** on as-isometric-as-possible regularization, which removes the artifacts on highly articulated poses.

Table 5. **Ablation Study on ZJU-MoCap [37]**. The proposed model achieves the lowest LPIPS, demonstrating the effectiveness of all components.

Metric:	PSNR↑	SSIM↑	LPIPS↓
Full model	30.61	0.9703	29.58
w/o color MLP	30.55	0.9700	31.24
w/o \mathcal{L}_{isocov}	30.61	0.9703	29.84
w/o $\mathcal{L}_{isopos}, \mathcal{L}_{isocov}$	30.59	0.9699	30.25
w/o pose correction	30.60	0.9703	29.87

better novel-view rendering quality and particularly generates more plausible results with respect to novel pose animation.

6. Conclusion

In this paper, we present 3DGS-Avatar, one of the first methods that utilize the explicit representation of 3DGS

for efficient reconstruction of clothed human avatars from monocular videos. Our method achieves photorealistic rendering, awareness of pose-dependent cloth deformation, generalization to unseen poses, fast training, and real-time rendering all at once.

Experiments show that our method is comparable to or even better than the state-of-the-art methods in terms of rendering quality while being two orders of magnitude faster in both training and inference. Furthermore, we propose to replace spherical harmonics with a shallow MLP to decode 3D Gaussian color and regularize deformation with geometric constraints, both proved to be effective in enhancing rendering quality. We hope that our new representation could foster further research in fast, high-quality animatable clothed human avatar synthesis from a monocular view.

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