HumanMM: Global Human Motion Recovery from Multi-shot Videos

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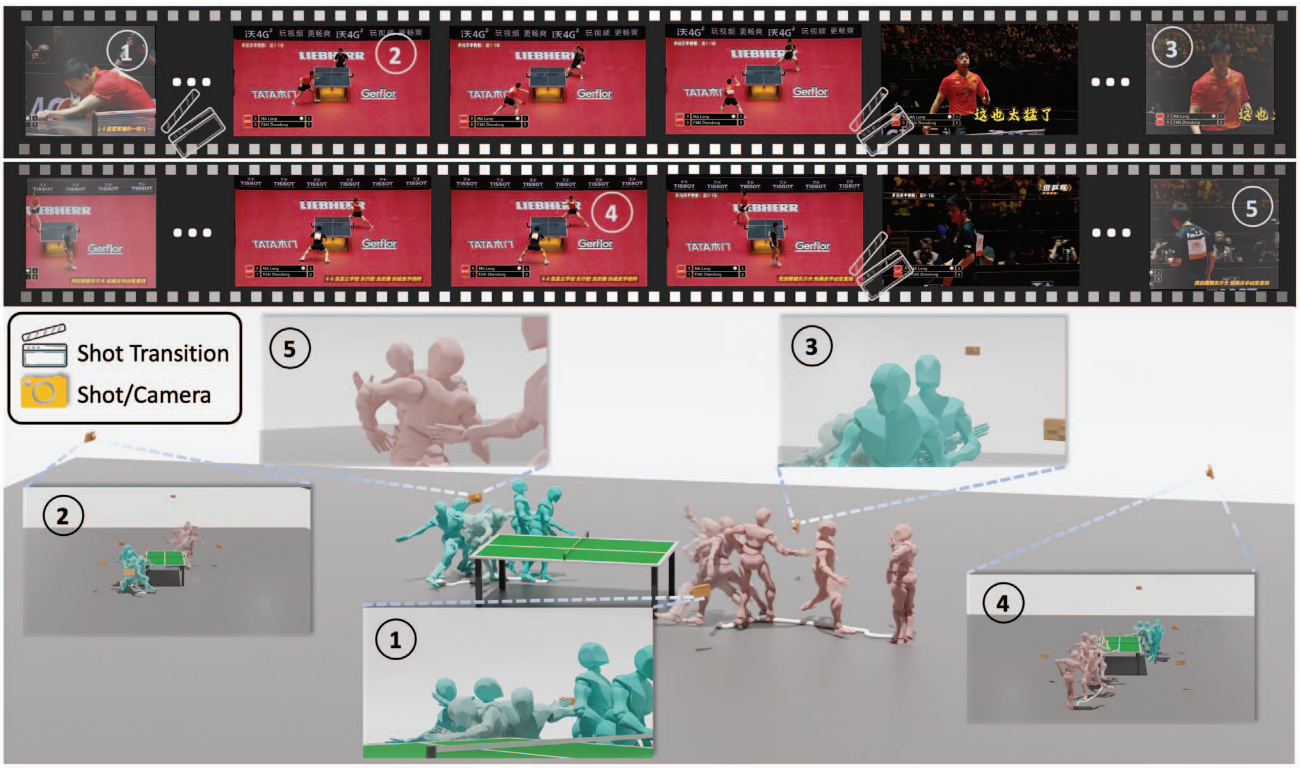

Figure 1. **Recovering a human motion from multi-shot videos.** **Top**: We take two multi-shot table tennis game videos with shot transitions as input. We aim to recover two motions of two athletes (Long MA and Zhendong FAN) from two videos, respectively. The first video is recorded by three shots ("①", "②", and "③"), and the second one is recovered by two shots ("④" and "⑤"). **Bottom**: We recover two motions (Long MA in green and Zhendong FAN in pink), different shots, and camera poses for each multi-shot video. The recovered motion is aligned with the motion in the videos.

Abstract

In this paper, we present a novel framework designed to reconstruct long-sequence 3D human motion in the world coordinates from in-the-wild videos with multiple shot transitions. Such long-sequence in-the-wild motions are highly valuable to applications such as motion generation and motion understanding, but are of great challenge to be recovered due to abrupt shot transitions, partial occlusions, and dynamic backgrounds presented in such videos. Existing methods primarily focus on single-shot videos, where continuity is maintained within a single camera view, or simplify multi-shot alignment in camera space only. In this work, we tackle the challenges by integrating an enhanced camera pose estimation with Human Motion Recovery (HMR) by incorporating a shot transition detector and a robust alignment module for accurate pose and orientation continuity across shots. By leveraging a custom motion integrator, we effectively mitigate the problem of foot sliding and ensure temporal consistency in human pose. Extensive evaluations on our created multi-shot dataset from public 3D human datasets demonstrate the robustness of our method in reconstructing realistic human motion in world coordinates.

*Equal contribution, ‡Core contributor, †Corresponding author. Work done by Yuhong Zhang, Guanlin Wu, Ling-Hao Chen, Jing Lin and Jiamin Wu during the internship at IDEA Research.

1. Introduction

In recent years, significant advances have been made in 3D human pose estimation, particularly in enhancing the accuracy of human motion recovery (HMR)[1] from monocular video sequences. HMR has demonstrated extensive applications in human-AI interaction [1, 2], human motion understanding [3–6], and motion generation [3, 7–24]. While existing methods [25] achieved relatively high performance in recovering human mesh in camera coordinates, estimating human motion in world coordinates remains challenging [26–29] due to inaccurate camera pose estimation and the complexity of reconstructing human motion spatially.

Most current progress in 3D human motion community mainly benefits from large scale data [25, 27–31], and long-sequence videos. These resources enhance estimation accuracy for HMR methods and improve the understanding and generation of longer motion sequences for tasks such as motion understanding [3, 32, 33] and generation [3, 7–20, 34–47], even when annotations are derived from markerless capturing methods like pseudo labels [48–51].

A promising approach to enlarge the scale of the motion databases is to estimate human motions from *unlimited* online videos in a *markerless* manner. However, many long-sequence online videos are recorded with multiple shots, referred to as multi-shot videos[2], especially prevalent in domains such as sports broadcasting, talk shows, and concerts. In filmmaking and television live show, a "shot" denotes an individual camera view capturing a specific moment or action from a particular vantage point [52].

Segmenting multi-shot videos into separate shots inevitably reduces the length of the video sequences, which can be detrimental to tasks that benefit from longer sequences, such as long motion generation [47, 53]. This limitation is highlighted in the existing datasets [54, 55], where the longest clip is less than 20 seconds after segmentation, as shown in Fig. 2. Moreover, focusing exclusively on online single-shot videos diminishes the utilization ratio of available online videos and may negatively impact the diversity of scenarios represented in the created datasets.

Therefore, *how to address the issue of discontinuities caused by shot transitions* is notoriously difficult in the community. To resolve this problem, previous works [56–59] have proposed algorithms to address human mesh recovery in a camera space from movies containing shot change between long shots and close-ups.

[1]In this paper, the "human mesh recovery" refers to recovery in the camera coordinates and the "human motion recovery" denotes recovery in the world coordinates. Unless specified otherwise, HMR refers to **human motion recovery**.

[2]In this paper, a **multi-shot video** refers to a long-sequence video containing multiple shot transitions. We assume that the camera intrinsics remain consistent across different shots within a multi-shot video.

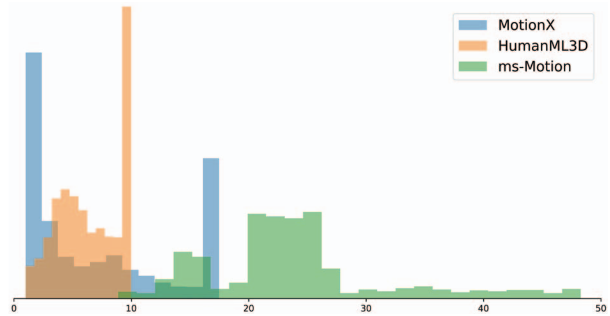

Figure 2. The comparison between the distribution of sequence lengths in different existing large-scale markerless motion datasets with ours. The x-axis and y-axis denote the duration time (s) and percentage of video number, respectively. Our dataset (in green) contains more portion of long-sequence videos in general.

However, recovering human motions in world coordinates from multi-shot videos presents two fundamental challenges that remain underexplored. 1) *How to align the human motion and orientation in the world coordinates during shot transitions?* Ensuring continuity of human orientation and pose across shots is complicated by factors such as partial visibility of human body (*e.g.* transitioning from long shot to close-up) and changes in human orientation (*e.g.* two long shots from different viewpoints). These issues, caused by abrupt changes in camera viewpoints, necessitate robust alignment mechanisms. 2) *How to reconstruct accurate human motion in world coordinates?* Existing approaches employ Simultaneous Localization and Mapping (SLAM) methods to estimate camera parameters, which are then used to project recovered human meshes from camera to world coordinates [26–29]. This process requires highly accurate camera estimation and must address motion consistency and foot sliding in the recovered human motion within the world space.

Despite these challenges, human motion in multi-shot videos often remain continuous across shots, even as camera viewpoints change. This observation suggests that with appropriate handling of shot transitions and camera motion, it is possible to reconstruct consistent and complete 3D human motions throughout multi-shot videos.

In this paper, we propose a novel framework *HumanMM*, Human Motion recovery from Multi-shot videos, to address these challenges. It integrates human pose estimation across shots with robust camera estimation in the world space. Firstly, we develop a shot transition detector to identify frames with shot transitions. To ensure a more robust camera pose estimation, we introduce an enhanced SLAM method incorporating long-term tracking of feature points and exclusion of moving human from bundle adjustment process. We utilize existing HMR method integrated with our enhanced camera estimation to get the initial human parameters for each separated shot. Subsequently, we implement an alignment module to align human orientation based on stereo calibration and smooth human poses through a trained multi-shot HMR encoder, which effectively captures the temporal context of human movements across different shots. Finally, after aligning human and camera parameters between shot transitions, we train a motion decoder and a trajectory refiner to smooth the human pose and mitigate issues such as foot sliding, thereby enhancing the overall motion consistency in the reconstructed 3D human motions.

Our contributions can be summarized as follows.

- We present the first approach to reconstruct human motion from multi-shot videos in world coordinates.
- We introduce *HumanMM*, a HMR framework for multi-shot videos. It includes an enhanced camera trajectory estimation method, a human motion alignment module and a motion integrator to ensure accurate and consistent recovery of human pose and orientation in world coordinates across different shots in the whole video.
- We develop a multi-shot video dataset *ms*-Motion to evaluate the performance of HMR from multi-shot videos, based on existing public datasets such as AIST [60] and Human3.6M [61]. Extensive experiments on related benchmarks verify the effectiveness of our method.

2. Related Work

2.1. HMR from One-shot Video

One-shot videos, captured with a single camera without shot transitions, has been extensively studied within the community for human mesh and motion recovery.

Human mesh recovery in camera coordinates can be broadly categorized into two approaches: optimization-based methods [62–66] and regression-based methods [30, 67–70]. With the significant advancements of transformer [71], HMR2.0 [25] has surpassed previous methods and benefits several downstream tasks related to HMR.

Although there are several previous works tried to recover motions in world coordinates with multi-camera capture system [60, 72] and IMU-based methods [73, 74] and enjoy relatively satisfying results, this setup limits their use for applications of *infinite* in-the-wild monocular videos. To address this limitation, several attempts [26–29] integrate SLAM into the HMR pipeline by first estimating the camera pose using SLAM methods, *e.g*. DROID-SLAM [75] or DPVO [76], and then project the recovered human motion from camera to world coordinates. To exclude the inconsistencies caused by dynamic objects, such as moving humans, TRAM [27] modifies DROID-SLAM by incorporating human masking and depth-based distance rescaling. However, DROID-SLAM performs dense bundle adjustment (DBA) on feature maps from downsampled images and selects features based only on two consecutive frames rather than long-term video sequences [75–77]. Consequently, masking significantly reduces the number of informative and consistent features, especially when humans occupy large portions of the image, leading to inaccuracies. Therefore, developing a SLAM method that retains sufficient and representative features for DBA after masking is important.

2.2. HMR from Multi-shot Video

Multiple shots are fundamental elements of cinematic storytelling and live performances, utilizing various camera positions and focal lengths to create immersive and detailed viewing experiences for audiences [52]. However, most marker-based motion capture (MoCap) datasets [60, 72, 73, 78, 79] consist single-shot videos only, resulting in limited research on HMR from multi-shot videos.

Recovering human motion from multi-shot videos in camera coordinates is already challenging. This is because treating each pose estimation result of each shot separately leads to inconsistencies when combining all estimations, caused by partially or fully invisible human bodies across shot transitions. Pavlakos *et al*. [56] addresses this issue by focusing on shot changes from long shots to close-ups, which are common in film. They develop smoothness constraints within a temporal Human Mesh and Motion Recovery (t-HMMR) model to infer motions during occlusions caused by shot transitions.

Advancements in HMR methods [29] for single-shot videos in world coordinates have paved the way for extending HMR to multi-shot videos with varying camera viewpoints. However, aligning human orientation, body pose, and translation continuously across multi-shot videos in world coordinates underexplored. Effective alignment is crucial to maintain motion continuity and coherence, especially when dealing with diverse camera perspectives and abrupt transitions between shots.

In summary, while substantial progress has been made in HMR from single-shot videos, extending these techniques to multi-shot videos requires addressing additional complexities related to camera pose alignment and motion consistency across shot transitions. We address this challenge by proposing a novel pipeline that ensures accurate and continuous 3D HMR from multi-shot monocular videos.

3. Method

In this section, we propose *HumanMM* to recover human motion from multi-shot videos. The system overview is shown in Fig. 3. Given an input video sequence $\mathbf{V} = \{I_t\}_{t=1}^{T}$ of length T, where I_t denotes the t-th frame, our objective is to recover human motion in world coordinates. We begin by detecting shot transition frames based on human bounding box (*a.k.a*. bbox) and 2D keypoints (*a.k.a*. KPTs) through a *shot transition detector* (Sec. 3.2). For each clipped shot, we initialize the camera pose (camera rotation and camera translation) and recover initial human motion in world coordinates (Sec. 3.3). The initialized SMPL parameters and camera poses are then fed into a *hu-*

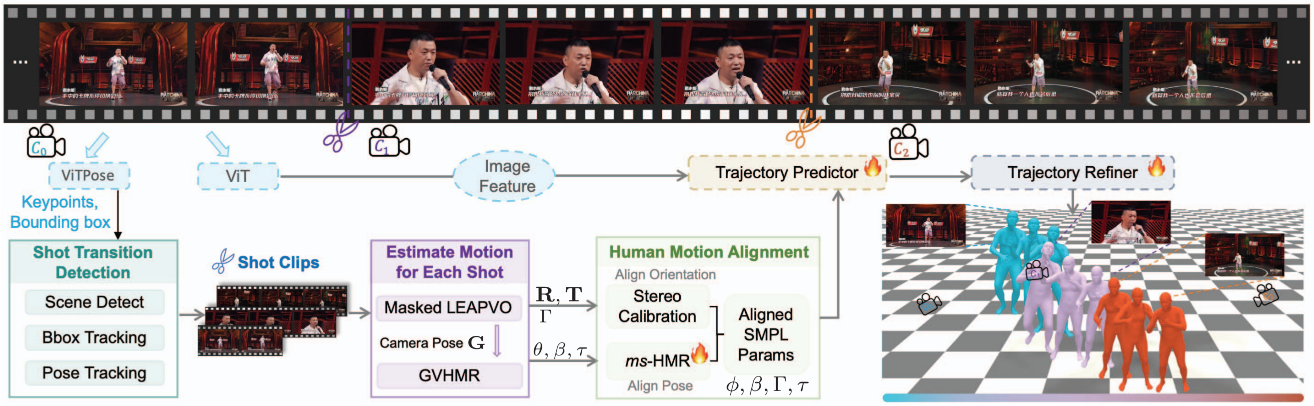

Figure 3. **The overview of *HumanMM*.** *HumanMM* processes multi-shot video sequences by first extracting motion feature such as keypoints and bounding boxes, using ViTPose [80] and image feature using ViT [81]. These features are then segmented into single-shot clips via *Shot Transition Detection* (Sec. 3.2). Initialized camera (camera rotation $\mathbf{R}$ and camera translation $\mathbf{T}$) and human (SMPL) parameters for each shot are estimated using *Masked LEAP-VO* (Sec. 3.3) and GVHMR [29]. Human orientation is aligned across shots through *camera calibration* (3.4.1), and *ms-HMR* (Sec. 3.4.2) ensures consistent pose alignment. Finally, a bi-directional *LSTM-based trajectory predictor* with *trajectory refiner* predicts trajectory based on aligned motion and mitigates foot sliding throughout the video.

man motion alignment module (Sec. 3.4), which aligns human orientations via camera calibration based on human 2D KPTs and smooth the human pose by incorporating pose information across different shots. Additionally, it refines the entire motion sequence through whole video using a temporal motion encoder *ms*-HMR. Finally, we introduce a post-processing module for motion integration (Sec. 3.5).

3.1. Preliminary: 3D Human Model

Our method aims to recover motions in world coordinates in the SMPL [82] format, whose pose at frame t can be represented as $\mathcal{M}_t(\theta_t, \beta_t, \Gamma_t, \tau_t) \in \mathbb{R}^{6890\times 3}$. Here, the body pose, body shape, root orientation, and translation are $\theta_t \in \mathbb{R}^{23\times 3}$, $\beta_t \in \mathbb{R}^{10}$, $\Gamma_t \in \mathbb{R}^3$, and $\tau_t \in \mathbb{R}^3$, respectively. We use $\mathbf{K}_t^{2D}$ to denote human 2D KPTs at each frame t.

3.2. Shot Transition Detector For Multi-shot Video

Our algorithm begins with shot transition detection in one video. As shown in Fig. 3, the *shot transition detector* has three key components, scene transition detector, bounding box (*a.k.a.* bbox) tracking, and human keypoints tracking. (1) *Scene change transition detector.* Initially, we employ the SceneDetect [83] algorithm to identify scene changes based on significant variations in the background. However, the SceneDetect fails to detect shot transitions when background changes are unnoticeable, illustrated in Fig. 4. Subsequently, we leverage the following modules to bridge the gap. (2) *Bbox tracking for shot transition.* As a shot change often accompanies with a sudden change of human subject size, we track humans in a video via mmtracking [84]. Consequently, we compute the Intersection over Union (IoU) between neighbor bboxes and identify a shot transition when the IoU falls smaller than a manually tuned threshold. (3) *Human pose tracking for shot transition detection.* To achieve a finer granularity, we additionally introduce human 2D KPTs to detect extreme corner shot changes in a video. By thresholding the IoU of corresponding keypoints between neighbor frames, we can accurately identify shot transitions even with subtle human movements.

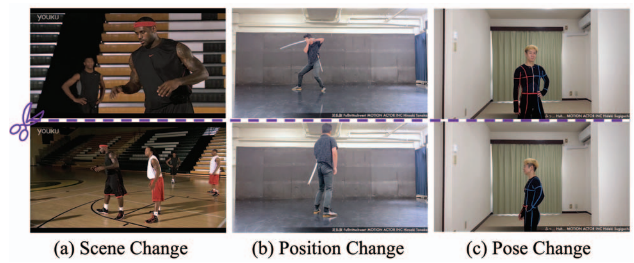

Figure 4. **Shot transition detection examples**. Examples (a), (b), and (c) illustrate multi-shot scenarios in online videos. (a) shows scene transitions detectable by SceneDetect. (b) illustrates significant position changes undetectable by SceneDetect but resolvable with bbox tracking-based method. (c) shows pose or orientation transition, requiring pose tracking-based methods as they cannot be addressed by either SceneDetect or bbox tracking.

As each separate module cannot identify all kinds of shot transitions, the three modules are jointly used to clip a video into several sub-sequences serially.

3.3. Human Motion and Camera Pose Estimation For Each Shot

After obtaining the clipped videos, our next goal is to estimate the camera pose and SMPL parameters in the world coordinates for each clipped video. The estimated camera pose and motions for each shot will be used to construct the whole motion sequence in the next stage (Sec. 3.4).

How to estimate the camera parameters accurately? Our approach for camera parameter calculation is based on a visual odometry (VO) estimation method, LEAP-VO [77]. Utilizing the CoTracker method [85], LEAP-VO estimates the visibility and trajectories of N selected points by analyzing image gradients across the video sequence. LEAP-VO subsequently computes confidence scores for each trajectory, retaining only those with high confidence while discarding trajectories shorter than a predefined threshold. The remaining trajectories undergo bundle adjustment (BA) within a fixed window size to estimate the camera poses.

However, simply applying LEAP-VO in the camera estimation process is still unsatisfactory in most human-centric scenarios. The primary limitation stems from the dynamic movements of human subjects, which typically occupy a substantial portion of each image in human-centric videos. This dynamic presence introduces noise into the camera pose estimation in world coordinates, as the estimation process relies heavily on the relationship between the camera and the static environment. To address this issue, we propose a Masked LEAP-VO algorithm. Our approach involves inputting the image I_t and the human bbox at frame t into SAM [86] to generate a human mask. We then assign a visibility value of zero to points within the human mask, effectively excluding these trajectories from the BA process. For clarity, we denote S_{BA} as the window size of BA, $\hat{n}$ denotes the number of filtered point trajectories, and $w_{ij,\hat{n}}$ as the normalized weight based on confidence score and visibility. For estimating the camera poses $\mathbf{G} = \{\mathbf{R}, \mathbf{T}\}$ of orientation and translation, the reprojection loss function for BA can then be formulated as follows,

$$\mathbf{G} = \arg\min_{\mathbf{G}, d_{i,\hat{n}}} \sum_i \sum_{j \in |i-j| \leq S_{BA}} \sum_{\hat{n}} w_{ij,\hat{n}} ||\mathcal{F}(\mathbf{G}_i, \mathbf{G}_j, d_{i,\hat{n}}) - \Pi_{ij}(\mathbf{p}_{i,\hat{n}})||,$$

where $\mathcal{F}(\mathbf{G}_i, \mathbf{G}_j, d_{i,\hat{n}})$ denotes the point positions calculated by camera pose $\mathbf{G}$ at frame i and j with depth $d_{i,\hat{n}}$. $\Pi_{ij}(\mathbf{p}_{i,\hat{n}})$ denotes the position for project position of $\mathbf{p}_{i,\hat{n}}$ from frame i to j. Consequently, we obtain the camera rotation $\mathbf{R}_t$ and translation $\mathbf{T}_t$ from camera pose $\mathbf{G}_t$ at t.

Recovering human motion in world coordinates with estimated camera parameters. Given an input video, we feed the estimated camera parameters ($\mathbf{R}_t$ and $\mathbf{T}_t$) into the state-of-the-art motion recovering model, GVHMR [29],

$$\theta_t^w, \beta_t^w, \Gamma_t^w, \tau_t^w = \texttt{GVHMR}(I_t, \mathbf{R}_t, \mathbf{T}_t). \quad (1)$$

Initialized human parameters $\theta_t^w, \beta_t^w, \Gamma_t^w, \tau_t^w$ and camera parameters $\mathbf{R}_t, \mathbf{T}_t$ will input to human motion alignment.

3.4. Aligning Human Motion Between Shots

Based on initialized world motion for each individual shot, the subsequent question is *how to merge discontinuous motions from different shots into a continuous motion sequence as a whole in world coordinates*. A straightforward solution is to align all motion sequences to the world coordinate system of the first shot. However, finding the correspondence between different shots is still under-explored and challenging. To resolve this issue, we decompose the motion parameters into camera-dependent and camera-independent ones. The former (Sec. 3.4.1) achieves alignment between shots

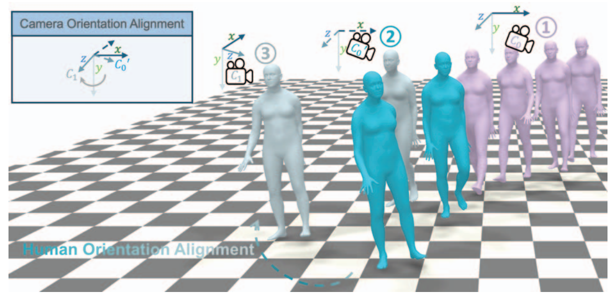

Figure 5. **Human orientation alignment module**. Following a shot transition after the foremost purple human mesh (shot ① captured by camera C_0), the unaligned (blue) and aligned (green) motions are captured as shot ② and shot "③" by camera C_0' and C_1, respectively. $C_0' = C_0$. To achieve human orientation alignment from shot "①" to "③", the camera rotation matrix from C_0' to C_1 is computed and applied as the offset of human orientation.

via human orientation alignment based on camera calibration, whereas the latter (Sec. 3.4.2) is a trainable module to enhance the continuity of human motion sequence. These two key designs ensure a consistent motion sequence between frames when encountering shot transitions.

3.4.1 Aligning Human Orientations Between Shots

After obtaining the initial SMPL and camera parameters $\{\theta_t^i, \beta_t^i, \Gamma_t^i, \tau_t^i, \mathbf{R}_t^i, \mathbf{T}_t^i\}$ for each shot, directly concatenating motions between shots result abrupt changes of human poses and orientations. To address this issue, we introduce the *Orientation Alignment Module* (OAM), as shown in Fig. 5, to align human orientations. As the whole motion sequence is continuous, we have the following assumption.

Assumption 1 *Human orientations and translations during the shot transition in world coordinates are continuous.*

To align the orientations between two frames with shot transition under Assumption 1, we decompose the human orientation with shot transitions in world coordinates as,

$$\mathtt{R}(\Gamma_{\text{world}}) = \mathbf{R}_{\delta_{\text{cam}}} \mathtt{R}(\Gamma_{\text{view}}), \quad (2)$$

where $\mathbf{R}_{\delta_{\text{cam}}}$ represents the camera rotation on the Y-axis between current t-th and previous $t-1$-th frame, Γ_{view} denotes the human orientation estimated by the current shot, and $\mathtt{R}(\cdot): \mathbb{R}^3 \rightarrow \mathbb{R}^9$ is the mapping from axis angle to rotation matrix. As Γ_{view} in current shot can be estimated independently, mentioned in Sec. 3.3, obtaining accurate Γ_{world} in Eq. (2) remains a key challenge to estimate the relative camera rotation $\mathbf{R}_{\delta_{\text{cam}}}$ between frames in shot transitions.

Estimating the relative camera pose $\mathbf{R}_{\delta_{\text{cam}}}$ between transition frames. Different from our approach of estimating camera pose in each shot (Sec. 3.3), we do not mask the human subject when estimating camera rotation $\mathbf{R}_{\delta_{\text{cam}}}$. Instead, we use human 2D KPTs as explicit feature matching. Specifically, we filter out unmatched keypoints based on their visibility and unaligned direction using RANSAC [87], effectively addressing camera pose estimation during shot transitions. This procedure is referred to as *Camera Calibration* (*a.k.a*. epipolar-geometry-based camera extrinsics estimation), and is detailed below.

In *Camera Calibration*, we assume that the human translations remain unchanged across the shot transition, implying that only the camera's orientation changes (*i.e*. Assumption 1). Consequently, we calculate the orientation offset by determining the change in camera orientation using camera calibration. We begin by extracting human 2D KPTs from two consecutive frames during the shot transition. Due to the shot transition, the visibility of 2D KPTs may vary, *e.g*. occlusion in some shots. Therefore, we employ ED-Pose [88] to filter out invisible 2D KPTs between shot transition frames. Subsequently, RANSAC identifies matching 2D KPTs corresponding to the most possible camera rotation direction. These matched 2D KPTs facilitate the estimation of the aligned camera rotation $\mathbf{R}_{\delta_{\text{cam}}}$. The detailed estimation process is as follows.

We denote the detected 2D KPTs of two frames in the shot transition as $\mathbf{S}_1 = [(x_1^{(1)}, y_1^{(1)}), (x_1^{(2)}, y_1^{(2)}), \cdots, (x_1^{(N)}, y_1^{(N)})]^\top \in \mathtt{R}^{2\times N}$ and $\mathbf{S}_2 = [(x_2^{(1)}, y_2^{(1)}), (x_2^{(2)}, y_2^{(2)}), \cdots, (x_2^{(N)}, y_2^{(N)})]^\top \in \mathtt{R}^{2\times N}$. The essential matrix $\mathbf{E} = [\mathbf{T}]_\times \mathbf{R}$ should satisfy the following orthogonal property such that,

$$\mathbf{S}_1^\top \mathbf{E} \mathbf{S}_2 = \mathbf{0}. \tag{3}$$

Once $\mathbf{E}$ is obtained by solving Eq. (3), we enforce the rank-2 constraint on $\mathbf{E}$ through SVD decomposition and subsequently derive the aligned camera rotation $\mathbf{R}_{\delta_{\text{cam}}}$ between two frames (*cf*. Hartley *et al*. [89] for more details).

In summary, we reformulate the alignment problem of human orientation in shot transitions as estimating the relative camera rotation $\mathbf{R}_{\delta_{\text{cam}}}$ between frames. Accordingly, we obtain the camera rotation $\mathbf{R}_{\delta_{\text{cam}}}$ via camera calibration.

3.4.2 Aligning Human Poses Between Shots

In shot transition, video sequences recorded by two shots are often with various occlusions. However, unoccluded body parts in two shots can be complementary to each other for motion alignment. Thus, we introduce the *multi-shot HMR* (*ms*-HMR, *i.e*. $\mathtt{E}_M(\cdot)$) module to refine the whole motion sequence. As shown in Fig. 6, the *ms*-HMR is a Transformer encoder-like architecture, whose input and output are the estimated global motion and the refined global motion, respectively. The process can be formulated as,

$$\phi_1, \phi_2, \cdots, \phi_T = \mathtt{E}_M(\theta_1, \theta_2, \cdots, \theta_T), \tag{4}$$

where ϕ_* denotes the refined motion of each frame. With this design, our method can adapt to diverse occlusions of human body brought by shot transitions.

3.5. Post-processing Module for Motion Integration

Trajectory Predictor and Trajectory Refiner. Based on the aligned human pose and orientation, we introduce a

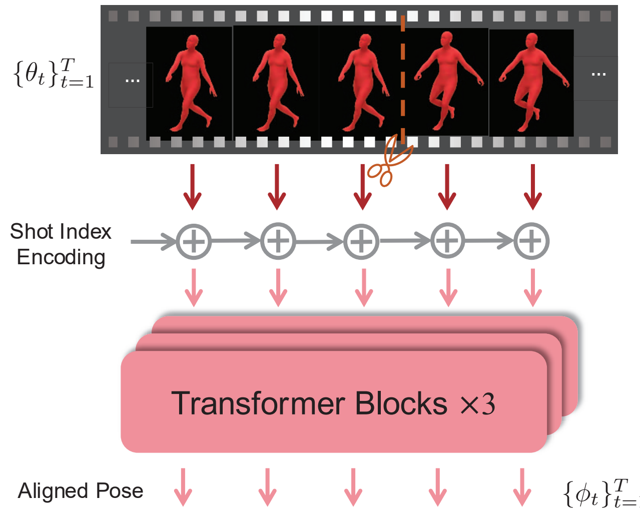

Figure 6. ***ms-HMR* Structure.** The initial human pose parameters θ across multiple video shots are input into a transformer with shot-index-based positional encoding. This enables *ms-HMR* to generate consistent human poses across all shots in the video.

bi-directional LSTM trajectory predictor to recover foot-ground contact probabilities p_t^c, and root velocity v_t as,

$$p_t^c, v_t = \mathtt{LSTM}(\phi_1^m, \Gamma_1, \mathtt{F}(I_1), \phi_2^m, \Gamma_2, \mathtt{F}(I_2), \cdots, \phi_T^m, \Gamma_T, \mathtt{F}(I_T)), \tag{5}$$

where $\mathtt{F}(\cdot)$ denotes the image feature of each frame extracted by ViT [81]. Accordingly, the contact probabilities p_t^c, and velocity v_t are supervised by the ground-truth labels with MSE loss and are used to reconstruct the trajectory. Besides, we extend the trajectory refiner in WHAM [28] to alleviate foot sliding problem in our estimated trajectory.

4. Benchmarking Multi-shot Motion Recovery

Dataset Construction. To create a multi-shot 3D human motion dataset, we introduce *ms*-Motion by processing existing public 3D human datasets with multiple camera settings and ground truth human and camera parameters, specifically AIST [60] and Human3.6M (H3.6M) [61]. In our construction pipeline, we randomly separate each original one-shot video into several clips. Then, we choose each clip from different shots and concatenate them together as one video recorded by multiple shots. For example, AIST provides each video with eight cameras `C0`, `C1`, ..., `C7` from different view point and we choose a video and split it into 5 clips at `t0`, `t1`, ..., `t4`. For frames in these separated clips, we choose frames shot by a random camera for each clip and combine five clips as one multi-shot video. Therefore, we construct a multi-shot version of AIST and H3.6M, which are named *ms*-AIST and *ms*-H3.6M subsets. Then we combine them and name this new dataset *ms*-Motion. The detailed statistics of *ms*-Motion are shown in Tab. 2. We do not compare with other existing 3D human datasets as they contain limited number of multi-shot videos.

Benchmark Evaluation Protocol. To evaluate the performance of our proposed methods on multi-shot videos, our

Dataset	Models	2-Shot						3-Shot						4-Shot					
		PA.↓	WA.↓	RTE↓	ROE↓	Jitter↓	F.S.↓	PA.↓	WA.↓	RTE↓	ROE↓	Jitter↓	F.S.↓	PA.↓	WA.↓	RTE↓	ROE↓	Jitter↓	F.S.↓
ms-AIST	SLAHMR [2023]	72.34	341.75	9.62	96.26	62.59	3.26	80.35	510.77	10.33	101.36	72.39	4.43	90.32	803.69	12.11	104.07	80.37	16.52
	WHAM [2024]	65.34	336.82	4.39	84.48	**25.24**	2.75	78.68	451.32	5.14	89.84	**24.06**	**2.99**	102.88	603.93	5.57	90.07	**26.29**	**3.62**
	GVHMR [2024]	60.72	231.36	6.20	96.58	34.87	7.65	70.33	357.16	7.55	99.69	34.46	9.42	83.77	563.17	8.96	104.53	35.67	9.78
	Ours	**36.82**	**121.35**	**2.56**	**69.23**	33.27	**2.66**	**38.52**	**141.38**	**3.64**	**67.71**	35.07	3.55	**39.63**	**161.52**	**4.55**	**70.31**	39.49	4.09
ms-H3.6M	SLAHMR [2023]	80.67	352.61	16.67	111.97	37.80	7.93	97.15	562.10	16.91	118.46	52.23	9.96	107.90	748.58	17.85	116.72	65.15	11.58
	WHAM [2024]	71.32	313.58	11.41	82.42	**18.40**	5.09	79.51	423.98	12.36	84.85	18.87	5.03	90.50	512.66	12.91	90.34	**18.40**	5.69
	GVHMR [2024]	64.63	254.30	6.94	81.93	18.45	8.80	80.79	296.74	85.25	58.26	18.36	10.62	85.19	471.53	9.12	91.63	19.47	10.65
	Ours	**40.52**	**132.13**	**3.65**	**53.39**	19.05	**4.17**	**45.35**	**145.36**	**5.33**	**58.26**	**17.35**	**4.62**	**50.59**	**147.62**	**6.20**	**61.22**	19.77	**5.12**

Table 1. **Quantitative comparison of different HMR methods on *ms*-Motion dataset.** We record the results for *ms*-AIST and *ms*-H3.6M separately. PA. and WA. means PA-MPJPE and WA-MPJPE respectively, while F.S. is Foot Sliding. Our proposed method has achieved the best performance in PA-MPJPE, WA-MPJPE, RTE and ROE across *ms*-Motion among these methods.

Dataset	Duration(s)	Videos	FPS	Max Length	Min Length	Shots
ms-Motion	23.7	600	30	1478	314	2, 3, 4

Table 2. Statistics of the *ms*-Motion dataset. By shots, we mean the number of shot transitions in a single video.

Methods	*ms*-Motion		
	Recall↑	Precision↑	F1 Score↑
Scenes Detect (SD) [83]	0.74	0.72	0.70
SD+Bbox Tracking (Bbox)	0.88	0.85	0.86
SD+Bbox+Pose Tracking	**0.96**	**0.88**	**0.92**

Table 3. **Comparison between difference shot detection algorithms.** We evaluate our shot transition detector on our proposed multi-shot video human motion dataset *ms*-Motion.

Methods	ATE↓	RPE Trans.↓	RPE Rot.↓
DPVO (w/o mask)	0.48	1.85	1.06
Masked DPVO	**0.48**	1.57	0.97
LEAP-VO (w/o mask)	0.50	0.93	0.97
Masked LEAP-VO	0.51	**0.92**	**0.95**

Table 4. **Camera tracking results on EMDB-1 [73].** Our method has achieved $\sim 50\% \downarrow$ on RPE trans. than that of the original DPVO and perform the best in RPE rot. metrics.

target is to evaluate metrics for accurately reflecting the performance on videos with shot transitions. To this end, we use Root Orientation Error (*a.k.a.* ROE in deg) to measure the performance of the proposed method on human orientation alignment across different shots. Besides, we use Root Translation Error (*a.k.a.* RTE in m) to assess the performance of the proposed method on global trajectory recovery. Jitter ($\frac{10m}{fps^3}$) is also used to evaluate the stability of recovered human pose from multi-shot videos. We also include foot sliding (cm), the averaged displacement of foot vertices during contact with the ground, to assess the precision of recovered motion in the world coordinates [28].

5. Experiment

5.1. Datasets and Metrics

Evaluation Datasets. To evaluate the performance of our proposed pipeline for multi-shot videos, we use *ms*-Motion dataset and EMDB-1 dataset [73] with self-added noise for the evaluation of ablation study. For camera trajectory estimation, we use EMDB-1 and EMDB-2 split [73] as they contain the GT moving camera trajectory. Our self-created dataset contains 600 multi-shot videos, 42.7K frames, totaling 237 minutes. EMDB-1 split contains 17 video sequences totaling 13.5 minutes and EMDB-2 split contains 25 sequences in a total of 24.0 minutes.

Evaluation Metrics. For shot detection we use *Recall*, *Precision* and *F1 Score* as evaluation metrics. For 3D human pose estimation-related tasks, we use ROE, RTE, jitter, and foot-sliding for evaluating the human motion recovery results on multi-shot videos. For the ablation study of our proposed pipeline, we evaluate the Procrustes-aligned Mean Per Joint Position Error (*a.k.a.* PA-MPJPE) and Per Vertex Error (*a.k.a.* PVE) as additional metrics besides previous mentioned ones. For camera pose estimation, we use absolute trajectory error (*a.k.a.* ATE) (m), Relative Pose Error (*a.k.a.* RPE) rotation (deg), and RPE translation (m).

5.2. Implementation Details

The *ms*-HMR, the trajectory, and foot sliding refiner are trained on the AMASS [78], 3DPW [79], Human3.6M [61], and BEDLAM [90] datasets, and evaluated on EMDB and our *ms*-Motion. During training, we introduce random rotational noise (ranging from 0 to 1 radian) along the y-axis to the root pose Γ and random noise to the body pose θ at random positions to simulate the inaccuracies of pre-estimated human motions caused by shot transitions in multi-shot videos. This strategy enables the network to robustly recover smooth and consistent human motion from noisy initial parameters. The benchmark test results were obtained after training for 80 epochs on one NVIDIA-A100 GPU.

5.3. Main Results: Comparison of Global Human Motion Recovery Results on the Benchmark

We compare our proposed method *HumanMM* with several state-of-the-art HMR methods (SLAHMR [26], WHAM [28] and GVHMR [29]) on our proposed benchmark *ms*-Motion. As illustrated in Tab. 1, our proposed method has achieved the best performance for PA&WA-MPJPE, RTE and ROE through videos with all numbers of shots across *ms*-AIST and *ms*-H3.6M, indicating that our method reconstructs both the global human motion and orientations in the world coordinates more accurately and robustly. For the foot sliding metric, our method also performs as the best on *ms*-H3.6M across all numbers of shots.

5.4. Ablation Studies

Human-centric Scene Shot Boundary Detection Evaluation. To evaluate the performance of our proposed *Shot Transition Detector*, we test the algorithm on our proposed multi-shot human motion recovery benchmark and compare the output frame list of shot transitions with the ground truth (GT) of our dataset. As shown in Tab. 3, by apply-

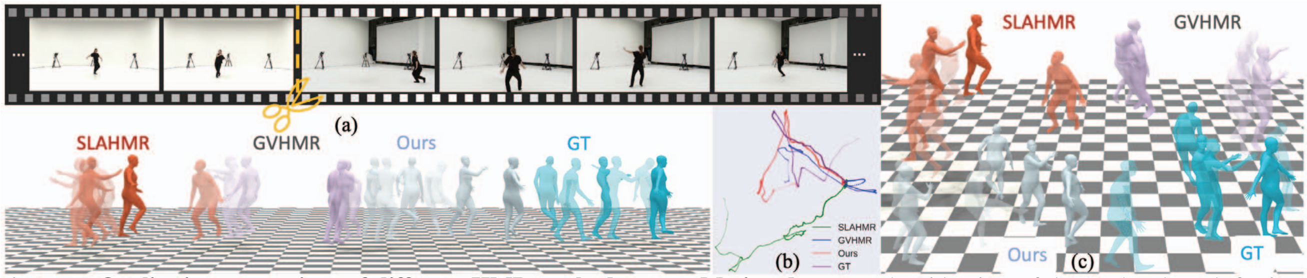

Figure 7. **Qualitative comparison of different HMR methods on *ms*-Motion dataset.** The side view of the rendered mesh for input mutli-shot video is shown in (a), while the top view is shown in (c). We also draw the comparison of the human trajectory as shown in (b). Our method is the most similar as GT in both rendered motion and trajectories among these methods.

Methods	PA-MPJPE↓	MPJPE↓	WA-MPJPE↓	W-MPJPE↓	PVE↓	ACCEL↓	RTE↓	ROE↓	F.S.↓
Baseline (Concat)	106.48	141.67	273.15	553.67	122.15	6.14	10.86	91.55	14.91
w/o *ms-HMR*	78.24	101.52	246.42	436.57	85.77	5.87	3.89	50.63	3.54
w/o OAM	73.56	92.13	243.65	425.18	79.64	5.67	6.61	76.74	4.45
w/o traj. pred.	50.49	83.68	231.75	432.17	75.77	5.75	5.52	47.68	4.96
w/o traj. ref.	50.49	83.68	198.58	397.65	75.77	5.23	4.06	47.68	7.84
***HumanMM* (Ours)**	50.49	83.68	194.77	393.21	75.77	5.16	3.54	47.68	3.28

Table 5. **Ablation studies on different combinations of *HumanMM* modules.** We evaluate the contributions of each key module on EMDB-1.

Methods	ATE↓	RPE Trans.↓	RPE Rot.↓
DPVO (w/o mask)	**0.48**	1.07	1.26
Masked DPVO	0.50	0.86	1.21
LEAP-VO (w/o mask)	0.50	0.83	1.21
Masked LEAP-VO	0.49	**0.83**	**1.19**

Table 6. **Camera tracking results on EMDB-2 [73].** Masked LEAP-VO performs better in both RPE Trans. and RPE Rot. metrics.

Methods	WA-MPJPE↓	W-MPJPE↓	RTE↓	Jitter↓	F.S.↓
DPVO	305.40	117.10	5.10	17.90	3.50
Masked DPVO	303.90	116.40	4.10	17.40	3.50
LEAP-VO	284.10	112.80	3.10	16.30	3.50
Masked LEAP-VO	**283.70**	**112.70**	**3.10**	**16.30**	**3.50**

Table 7. **Global motion recovery results on EMDB-2 [73].** We input estimated camera parameters from different methods into GVHMR for comparison on HMR.

ing the proposed finer granularity shot detection methods, the number of recall, precision, and F1 score all increases consistently. The combination of three steps (ScenesDetect, bbox tracking, and pose tracking) has achieved 0.96, 0.88, and 0.92 on the recall, precision, and F1 score, respectively, which indicates a comparable performance in shot boundary detection. Besides, as can be seen in the results, the latter two steps of shot detection contribute to the fine-grained final results significantly and jointly.

Key modules in the Proposed Method. We compare our methods with four variants on EMDB with noise dataset, as shown in Tab. 5, *ms*-HMR is the key component for the improvement in PA-MPJPE and PVE, which indicates a more accurate modeling of the whole motion sequence. This design serves as a recovery module to estimate some invisible body parts in some shots. Additionally, the orientation alignment module (*OAM*, in Sec. 3.4) is also a critical block for accurate human orientation estimation, indicated by the metric ROE. This module helps to model the global human motion between shots. For foot sliding, the results in Tab. 5 also show that the trajectory refiner (Sec. 3.5) in our method helps mitigate the foot sliding issue.

Comparison on Camera Trajectory Estimation. To evaluate the performance of our proposed camera trajectory estimation method **Masked LEAP-VO**, we evaluate the camera trajectory accuracy on EMDB-1 and EMDB-2. For more convenient comparison, we introduce two baselines, DPVO [76], which has been widely used in HMR methods such as WHAM [28] and GVHMR [29], and LEAP-VO [77]. To provide more intuition about the insights of masking dynamic humans in the video, we also implement a variant, Masked DPVO, by applying SAM at the patchify stage of DPVO to exclude patches containing human pixels. As shown in Tab. 4 and Tab. 6, compared with baseline methods, our key design of masking dynamic human subjects improves the result in both RPE Translation and RPE Rotation while maintaining competitive ATE. This result indicates the effectiveness of the design of masking dynamic human subjects in the process of camera trajectory estimation. Compared with the DPVO baseline, our method achieves $\sim 50\% \downarrow$ RPE translation on EMDB-1. In addition, we run GVHMR [29] on EMDB-2 with different estimated camera trajectories. The results is shown in Tab. 7, which further illustrates the effectiveness of our method.

6. Conclusion and Discussion

Conclusion. In this paper, we introduce *HumanMM*, the first framework designed for human motion recovery from multi-shot videos in world coordinates. *HumanMM* addresses the challenges inherent in multi-shot videos by incorporating three key components: an enhanced camera trajectory estimation method called masked LEAP-VO, a human motion alignment module that ensures consistency across different shots, and a post-processing module for seamless motion integration. Extensive experiments demonstrate that *HumanMM* outperforms existing human motion recovery methods across various benchmarks, achieving state-of-the-art accuracy on our newly created multi-shot human motion dataset, *ms*-Motion.

Limitations and Future Work. While *HumanMM* represents an dvancement in human motion recovery from multi-shot videos in world coordinates, its performance may decline when faced with an excessive number of shot transitions. Despite these challenges, *HumanMM* provides a solid baseline for human motion recovery from multi-shot videos and can be employed in annotating *markerless* human motion datasets. Our newly introduced dataset, *ms*-Motion, offers a valuable benchmark for evaluating general human motion recovery methods in world coordinates, especially regarding their performance on multi-shot videos. Based on the proposed method, our future work aims to enlarge the related datasets for larger-scale motion databases.

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