Linked Spatial and Temporal Normalization for Analysis of Cyclical 4D Skeletal Motion Data

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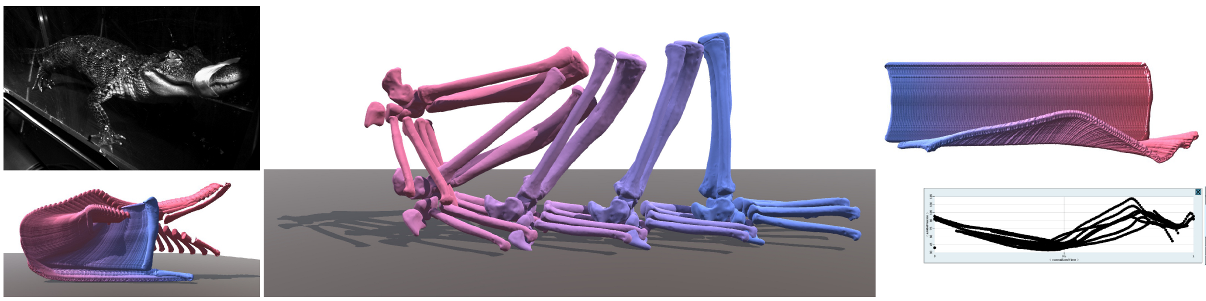

Figure 1: Visualizations of X-ray-based reconstructions of alligator hindlimb skeletal motion used for research on the evolution of locomotion in extinct animals [1]. The coordinated 3D spatial and 2D temporally normalized cycles (right) split walking data into homologous cycles of movement, which are challenging to analyze when viewed as continuous data without temporal context (bottom left), and in the coordinate space of the experimental recording environment (center and left).

Abstract

We introduce a new interactive visualization technique that links temporal and spatial perspectives of cyclical skeletal motion data to help evolutionary biologists relate bone form and function.

Index Terms: Human-centered computing—Visualization—Visualization techniques—Visualization systems and tools;

1 Introduction and Related Research

Visualizing and measuring skeletal motion from live animals is a key research pathway into understanding how extinct animals like dinosaurs once walked the earth. Our visualization research is motivated by a collection of skeletal motion data that is particularly challenging to acquire and analyze. The alligator foot motion dataset pictured here (Figs 1-2) represents some of the more complex data acquired using living animals with this method, including 11 bones, 14,032 frames of skeletal pose data, from both left and right sides of 3 animals, and spanning a diversity of behaviors [1]. These data were collected through a particular method of skeletal motion reconstruction, called XROMM (X-ray Reconstruction of Moving Morphology) [2], which enables researchers to look inside a living animal, accurately measure skeletal movement in six degrees of freedom, and study bone morphology from a kinematic (motion) data-based point of view. In the case of the alligator walk cycles, the evolutionary biologists studying the data hope to gain insight into the relationship between bone structure and motion, and how evolutionary changes in shapes of bones might relate to evolutionary shifts in extinct animal locomotion.

Unfortunately, distilling kinematic patterns from the wealth of multidimensional time-varying data generated from the XROMM method is complex, even just for a single toe tip or a relatively simple joint between two bones [3]. Patterns in the motion can be recognized by watching two animated bones interact, however, the high cognitive load on the user to retain and compare multiple, if not hundreds or thousands of motions is a major hurdle in the exploration and analysis of form-function relationships in such datasets. This problem is further amplified when confronted with multiple animated bones and degrees of freedom. While scientific motion ensembles [3, 4] have been developed to facilitate the exploration of this motion complexity, many of these lack visual and interactive coordination between spatial and temporal data that are key to understanding patterns in motion, particularly for their application to unlocking information about extinct motion from fossil bones.

To address this problem, we designed a novel interactive visualization technique that links temporal and spatial perspectives of the same data, based around cycles of motion. Patterns of motion historically are represented using temporal normalization. This technique uses key kinematic events, such as ‘heel-strike’ and ‘toe-off’ during walking to split motion into cycles and normalize time-based scalar variables within the defined cycle. While this method provides consistent context for analyzing patterns and variation in the motion, coordination of spatial relationships with this data has remained a key challenge in visualization research. The key creative advance in our approach is to combine traditional, temporal normalization with a new form of spatial normalization applied to the spatial skeletal pose data. Our design includes both visual and interactive methods for exploring the normalized views and relating one form of normalization to the other.

2 Motion Data Processing

Due to the cyclical nature of many animal movements, we divided the data into “Motion Clips” based on a table of observed key events, such as initial and last contact of a foot hitting the ground during a walk cycle. This technique of “clipping” consistent units of motion data from longer sequences of varied animal behavior permits analysis of patterns within the cycles of motion (Fig. 1, right).

3 Rendering Normalized Spatial and Temporal Views

The 3D bone renderings were implemented using the Unity-based Artifact-Based Rendering (ABR) technique [5] for both the spatial

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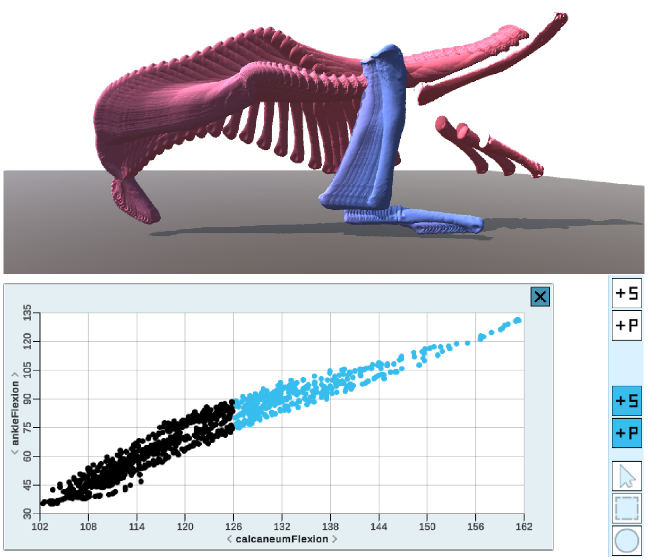

Figure 2: Linking multidimensional plots with skeletal poses.

and temporal view. High-resolution bone meshes were instance-rendered for each frame of transformation matrix data from the skeletal animation. In Fig. 1, a time-based color gradient was applied to the skeletal poses to correlate the start (blue) and end (pink) of a motion clip across the different views.

To create the temporally normalized views, the start and end frames of the motion cycles were used to normalize the time-based scalar data that occured during each cycle. These temporally normalized data were displayed using a scatter plot on a Unity canvas stacked vertically below the 3D bone view. To enable large point datasets like those produced by XROMM, an instanced particle system is used to render the scatter plots.

To create the spatially normalized views, the original transformation matrices from the experimental recordings were transformed. First, to view the motion relative to a static reference bone, the transformation matrices of a user-defined reference bone were applied to all elements within a given skeletal pose. The user may also apply a rotation to all skeletal poses about a pre-calculated reference bone pivot point to bring a region of interest into view. Lastly, the user defines a horizontal axis with endpoints that the motion cycle will register with. Transformations are calculated such that the reference bones and corresponding skeletal poses are equally spaced along this axis.

4 Linked Multidimensional Plots and Space-Time Views

Since the data analysis requires more than just understanding the spatial and temporal relationships, we designed the visualization to also incorporate several standard multidimensional data visualization techniques, such as scatter plots and parallel coordinates plots. These 2D plots appear in separate view windows adjacent with the normalized 3D views. To facilitate exploratory analysis, all of the views support linked brushing and highlighting. For example, in Figure 2, the user may brush over a particularly interesting set of data in the 2D plot (blue) and show only those corresponding skeletal poses in the 3D view.

5 Conclusions and Future Work

Our linked spatial and temporal visualization for 4D biomechanical skeletal motion data provides a new technique of analyzing complex experimental data. By linking 2D and 3D data and dividing cyclical motion into ‘motion clips’, our technique permits simultaneous temporal and spatial context, critical to understanding complex 4D motion. One immediate area of future work is addressing the problem of data occlusion. With hundreds of motion cycles in the alligator dataset, the density of skeletal geometry quickly occludes patterns and spatial relationships within the motion. This presents an exciting future visualization challenge for how to interact with temporal variables and/or spatial geometry to mask data in a way that enables domain researchers to quickly identify patterns among the entire dataset, without being inhibited by the large datasets themselves. For example, to best visualize how the alligator foot flexes and extends relative to the shin, only one foot bone is shown to move relative to a leg bone, as shown in Fig. 1 (right). The 9 remaining bones in the ankle are masked or hidden to not obscure this pattern. How might multiple spatial variables be encoded in the visualization to intuitively indicate how those ankle bones coordinate across walking cycles, without occluding a motion pattern of interest? Visualizations with this level of complexity are important for researchers to answer key biomechanical questions in investigating the evolution of dinosaur locomotion.

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