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Exploratory Visualization of Animal Kinematics Using Instantaneous Helical Axes

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Abstract

We present novel visual and interactive techniques for exploratory visualization of animal kinematics using instantaneous helical axes (IHAs). The helical axis has been used in orthopedics, biomechanics, and structural mechanics as a construct for describing rigid body motion. Within biomechanics, recent imaging advances have made possible accurate high-speed measurements of individual bone positions and orientations during experiments. From this high-speed data, instantaneous helical axes of motion may be calculated. We address questions of effective interactive, exploratory visualization of this high-speed 3D motion data. A 3D glyph that encodes all parameters of the IHA in visual form is presented. Interactive controls are used to examine the change in the IHA over time and relate the IHA to anatomical features of interest selected by a user. The techniques developed are applied to a stereoscopic, interactive visualization of the mechanics of pig chewing and assessed by a team of ecologists and evolutionary biologists.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism – Animation I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism – Virtual reality

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1. Introduction

Analysis of 3D motion plays an important role in many scientific processes. In biomechanics, analysis of the rigid body motion of bones is integral in the treatment of disease and injury [Win90] and in the study of animal behavior and evolution [Bie03]. Visual analysis tools have a long history of use in these fields, dating back to the pioneering work of Maray, Muybridge, and their contemporaries [Bra94]. Imaging capabilities have improved considerably, and scientists now benefit from a new ability to collect accurate high-speed motion data of internal anatomical structures, such as bones, during motion experiments [YSAT01]. In this paper, we examine novel visual and interactive techniques for analysis of this 3D kinematic data.

As a rigid body, such as a bone, moves through space, it undergoes both translation and rotation. This movement may be described in several ways. Translations are typically reported relative to three orthogonal axes, and rotations are often described with either Euler angles or quaternions. An alternative description of rigid body movement comes from screw theory and is called the helical axis or screw axis. (Woltring et al. provide an introduction to helical axes in the study of biomechanics [WHdL85, WLOF94].) The helical axis is the unique axis in space for which the movement of a rigid body from one pose to the next may be described entirely as a combination of rotation about the axis and translation along the axis. Figure 1 shows a graphical illustration of the concept. An instantaneous helical axis (IHA), or first order screw, is characterized by the four parameters shown in the Figure and listed in Table 1.

Several strategies exist for calculating helical axes from motion data, including methods appropriate for relatively large, finite displacements, leading to finite helical axes (FHAs) [WHdL85]. For high-speed data instantaneous helical axes may be calculated [AMd04, Som92, WLOF94].

The helical axis representation is advantageous for the study of motion in several domains, notably in biomechanics, where it has been applied to study of the hu-

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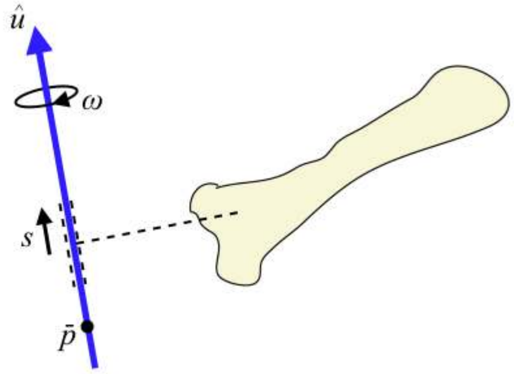

Figure 1: *Instantaneous helical axis (IHA) for a moving, rigid body.*

man carpus [CCM*05], finger [VCR98], arm [LMM00], neck [WLOF94], and jaw [GAAP97, GFP00]. Previous use of visualization in these contexts has been limited to relatively simple views of the axis and the ruled surface that is swept out as it advances through space during a motion sequence. This is sometimes coupled with statistical analysis of helical axis parameters to address specific hypotheses.

We focus our investigation on effective use of the helical axis in an interactive, exploratory visualization tool. We address two primary visualization challenges. First, there is a question of how to best visually represent the time-varying instantaneous helical axes, composed of two vector and two scalar quantities, within an animated stereoscopic visualization of 3D motion. Second, in visualization of kinematics in animals and humans, there is a need to relate the helical axis to the context of the anatomy in order to address the scientific questions driving the investigation. We introduce three interactive tools for visualization of the relation between the helical axis and surrounding anatomical context.

We present results from applying the visual and interactive techniques developed to the study of animal kinematics, specifically we work with a team of evolutionary biologists to visualize the movement of a pig's mandible during food gathering and chewing. We report technical details and user feedback from this case study.

We begin with a discussion of related work. Then, we introduce novel visual and interactive techniques for visualization of the IHA. Finally, we present the application to visualization of mastication in pigs.

2. Related Work

Table 1: *Parameters of the IHA.*

$\hat{u}$ = unit direction of IHA
ω = magnitude of angular velocity
s = magnitude of sliding velocity along IHA
$\bar{p}$ = a point coincident with IHA

The helical axis has application in many fields, from structural mechanics [Som92] to 3D modeling in computer graphics [LKG*03]. Most closely related to our work are applications in biomechanics, where both finite helical axes (FHAs) and instantaneous helical axes (IHAs) have been employed for the study of motion capture data.

Our tools produce an animated view of bones in motion along with a 3D presentation of helical axes. Bone surface information is obtained from CT scans which are registered with the motion data. We build upon previous contextualized 3D visualizations of helical axes [VCR98] by adding more sophisticated visual display features and interactive tools appropriate for high-speed IHA data.

For clinical application and functional descriptions of joints, it is often important to characterize the helical axis parameters via statistical measures that may be related to the anatomy. Several examples of this exist within the literature for use with FHAs. Common procedures include projecting the axis direction onto planes defined by anatomical landmarks, upon which 2D angle measurements may be made [CCM*05,GAAP97]. Distance measurements can also be useful. For example, the distance from a joint center to the closest point along the helical axis may be examined over the course of a motion sequence [GAAP97, GFP00]. These connections to anatomical structure are critical for addressing many scientific questions with helical axes. Our work makes it possible to relate axis parameters to the surrounding anatomical context within a user-driven exploratory environment.

The use of IHAs rather than FHAs in biomechanical experiments is governed largely by limitations and availability of appropriate motion sensing technologies. Woltring and colleagues explore the use of optical tracking technology with a capture rate of up to 5 Hz for diagnosis of whiplash based on neck kinematics and provide an overview of relevant data filtering and processing techniques for IHA analysis [WLOF94]. We visualize data from a new biplane fluoroscopy system, similar to that used for analysis of skeletal kinematics in the human knee [YSAT01]. With this system, six degree-of-freedom motion tracking information may be obtained for individual bones at more than 250 Hz. As these new technologies become more prevalent, data appropriate for robust calculation of IHAs will become increasingly available. Thus, we expect interactive strategies for exploring this data to be of great utility in the future.

3. Exploratory IHA Visualization

Our exploratory IHA visualization tools are implemented in the stereoscopic desktop viewing environment seen in Fig-

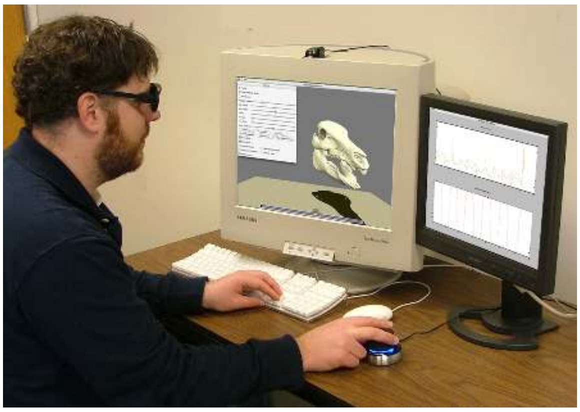

Figure 2: *Interactive, stereoscopic visualization environment.*

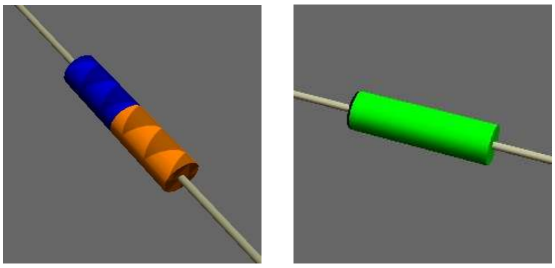

Figure 3: *Direction and magnitude of angular velocity* ω *are encoded using color and texture (left). Sliding velocity along the IHA is encoded by a green bar extending in the direction of sliding from a black center marker (right).*

ure 2. User interaction is performed using a mouse, keyboard, and a Space Navigator 6-DOF input device (3DConnexion Inc.) for adjusting the viewpoint. In this section, visual and interactive techniques appropriate for visualization within this user-driven environment are described.

3.1. Visualizing IHA Parameters

The IHA is displayed as an oriented line segment drawn relative to the anatomical data (bones) using a gray cylinder as seen in Figures 3 and 4. The cylinder is oriented to align with the direction $\hat{u}$ of the IHA. Additional IHA parameters are described with additional concentric cylinders that vary in length according to data values.

The angular velocity ω is represented as seen in the Figure 3 (left). A half blue, half orange cylinder is drawn on top of the gray one. The length varies linearly with ω. A gain factor for this mapping is adjustable by the user and set interactively to tune the display to the particular question under investigation. The direction of rotation is doubly coded on the axis. The blue and orange colors mark sides of the axis. Rotation always occurs in the same direction relative to these colors and follows the right hand rule with the thumb pointing in the direction of the orange side of the axis. For cyclic animations, this coding scheme makes direction reversals immediately obvious. (For example, during jaw opening and closing observed from a posterior view, we see blue on the right for the opening phase and blue on the left for the closing phase.) An arrow texture applied to the cylinder also encodes this directional information and is useful during static viewing.

The sliding velocity s along the IHA is represented similarly, as seen in Figure 3 (right). A thin black mark denotes the “center point” of the axis. A green cylinder of length proportional to s is drawn from the center point in the direction of sliding.

One interesting property of IHAs calculated from experimental data is that the estimation of $\hat{u}$ is generally less robust when ω is small. In fact, $\hat{u}$ is undefined when $\omega = 0$. This is an important consideration for the design of animated displays. If a strong visual depiction for the axis is displayed during times of low angular velocity, the result is a visually dominating, fast moving axis, which has the effect of visually highlighting this noisy portion of the data. To avoid this scenario, the orange/blue cylinder decreases length as described above with low values of ω and the gray extension of the axis (useful in general for identifying the intersection of the axis with surrounding anatomy) fades to a transparent value to be less apparent in the visual field during periods of low ω.

3.2. Visualizing Variation over Time

Animated views of the IHA and surrounding bones may be produced with the rate of playback and time window of interest controlled via on-screen sliders. Additionally, variation in the axis over time may be explored by displaying previous and future axes for each frame of the animation, as seen in Figure 4. The number to display in each direction is set interactively by the user, allowing for close inspection while stepping through frames of the animation. The effect produces the sense of a 3D ruled surface, which has been employed in previous analyses [LMM00, WLOF94], but the animated display is similar to a motion blurring effect, as is sometimes used in flow visualization [SFL*04].

3.3. Relating to Anatomical Contexts

In many applications, there is a need to relate the helical axis to an anatomical context. We explore methods of establishing a connection to the underlying anatomy within an interactive visualization.

3.3.1. Comparing Sliding and Rotation

When working with IHA data, it is important to understand the relative contributions of the two types of motion de-

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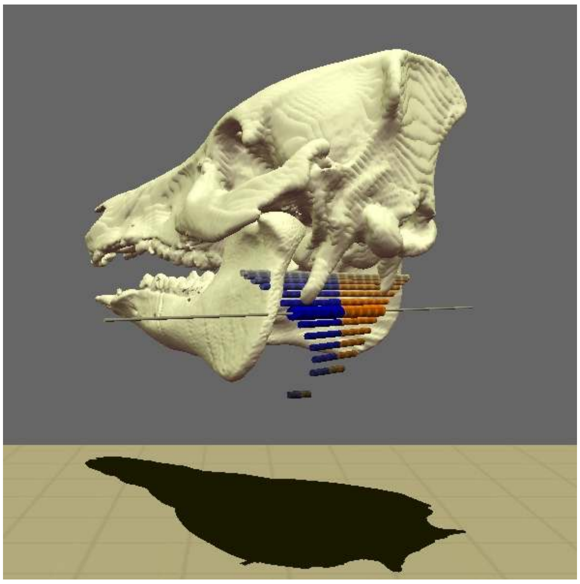


Figure 4: *Views of the IHA are extended interactively forward and backward in time to highlight change in IHA location and magnitude over time. Here, the location of the IHA moves up toward the condyles and angular velocity increases during this closing phase of chewing.*

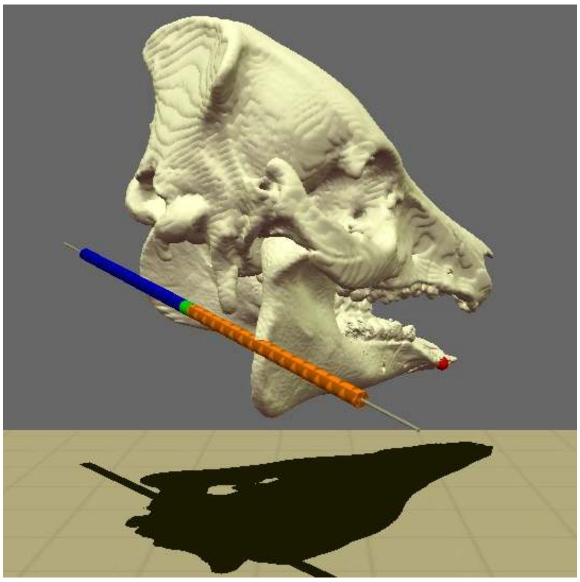


Figure 5: *After selecting a point of interest on the bone (marked with a small red sphere), the relative effect of IHA sliding and rotation parameters with respect to this point is visualized on the axis.*

scribed, rotation captured by the angular velocity ω (typical units are radians per second) and translation along the axis captured by the sliding velocity s (typical units are cm per second). Although the two quantities are measured in different units, their relative effects on the movement of a user-specified region of interest may be compared on a common scale.

In the comparison mode of our software, the user selects, via a mouse-controlled ray casting technique, an anatomical feature (point $\bar{q}$) on the surface of the bone. Given a time window Δt, the translation due to sliding of this point is

$$d_1 = s\Delta t, \tag{1}$$

while the effective translation of $\bar{q}$ as a result of the rotation around the IHA is

$$d_2 = R\bar{q} - \bar{q}, \tag{2}$$

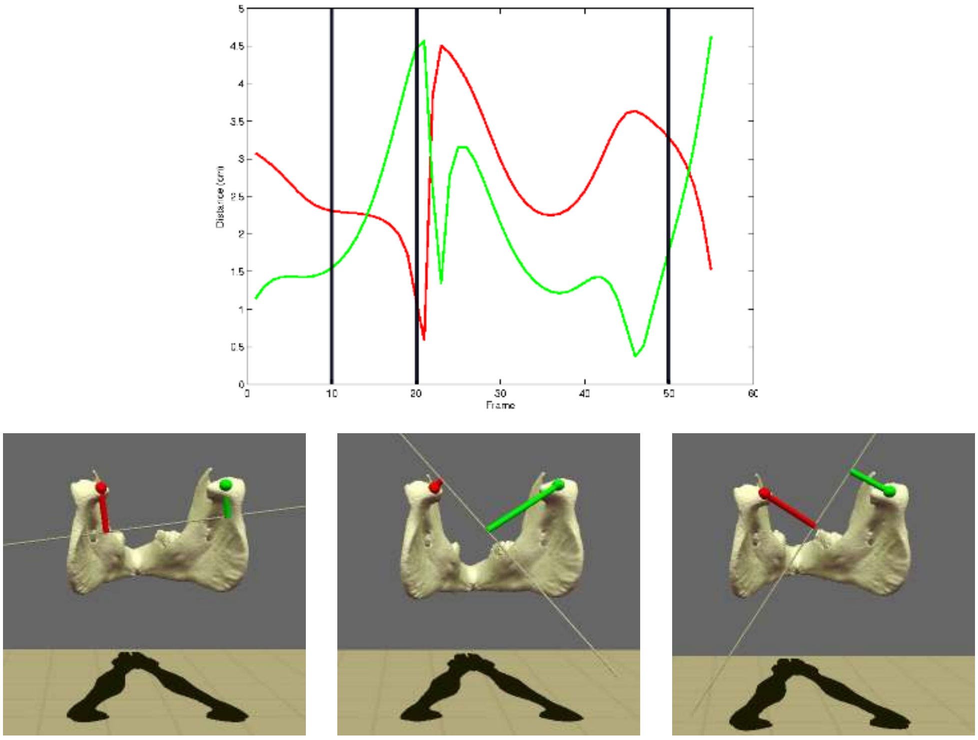
where R is the matrix that rotates $\bar{q}$ about the IHA by the angle $\omega\Delta t$. By visualizing the values d_1 and d_2, we are able to compare the contributions of the rotation and sliding components of the IHA to the movement of an anatomical region of interest. An example visual result is seen in Figure 5. In this case, a point of interest, marked with a small red sphere, was selected on a tooth of the pig. As before, the length of the cylinders surrounding the axis are mapped to sliding and rotation values, but now the two values are in the same units and magnitude comparisons may be made. Here, d_1 is mapped to the length of the green cylinder and d_2 is mapped to the length of the orange/blue cylinder. At this instant, we see that the angular velocity described by the IHA contributes to the motion of the point of interest far more than does the sliding velocity.

3.3.2. Anatomical Context and Axis Position

Points of interest interactively selected by the user may be used to examine the position of the axis in space relative to the anatomy. Figure 6 shows an example. For analysis of movement of the mandible, points on the condyles provide a useful context. These have been selected in the left image of Figure 6. The green and red line segments drawn mark the perpendicular distance from these points to the IHA. A plot of these distances over time (Figure 6 right) is updated interactively as users explore the dataset in this distance plotting mode.

3.3.3. Anatomical Context and Axis Orientation

A similar mode shown in Figure 7 plots the dot product of the IHA direction vector $\hat{u}$ with a vector specified by selecting anatomical features in the display. In Figure 7 an reference vector has been created between the two condyles. In the resulting plot to the right, a chewing cycle can be clearly seen. The dot product is close to negative one when the jaw is opening, close to positive one when closing, and undergoes a transition during a grinding phase.



Frame 10 Frame 20 Frame 50

Figure 6: *Plots of IHA distance to anatomical points of interest selected by the user. Here, the condyles are selected. At frame 10 of the motion, as the jaw is closing, the axis is roughly the same distance from each point. At frame 20, the axis moves close to the left condyle. This is during a food grinding phase, where the mandible undergoes lateral movement relative to the skull. Considerable lateral movement is also occurring at frame 50.*

4. Application to Pig Mastication

The data seen in Figures 4-7 come from an application that has driven the development of the tools described here. In collaboration with a research group of evolutionary biologists, we have been examining kinematic data from several animal species. Here we describe one project from this collaboration, exploration of the mechanics of pig mastication.

The motion data driving the visualization come from a biplane fluoroscopy system. High-speed (250 Hz) X-Ray movies are captured from two near-orthogonal angles. 3D reconstruction software is used to derive 3D positional information from the X-Ray imagery for radio-dense markers implanted within the bones of interest. When registered with CT scans, the 3D marker data may be used to drive animations of 3D bone geometries extracted from the CT scan. This is the source of the anatomical data in our examples.

In our implementation IHAs are calculated directly from these 3D marker coordinates. After removing high-frequency noise in the data and transforming coordinates to reflect the motion of the mandible relative to that of the skull, the algorithm described by Sommer [Som92] and Angeles [Ang86] is used to compute the IHA at each sample of the motion sequence.

5. User Evaluation

Three evolutionary biologists from our research team participated in a subjective evaluation of the IHA-based visualizations. The lead researcher had some previous experience with the visualization, having used a prototype of the system on her desktop for several weeks prior to the session. The other researchers had participated in discussion shaping the development of the visualization tool and were familiar, through these discussions and knowledge of related work in biomechanics, with the notion of helical axes of motion.

5.1. Hypotheses and Discussion

The session began by asking the scientists to review hypotheses they have regarding the study of pig mastication. Our intent was to begin to evaluate which of these candidate hypotheses might lend themselves to evaluation via helical axis techniques and which might not. A few specific hypotheses were mentioned during this discussion, but the

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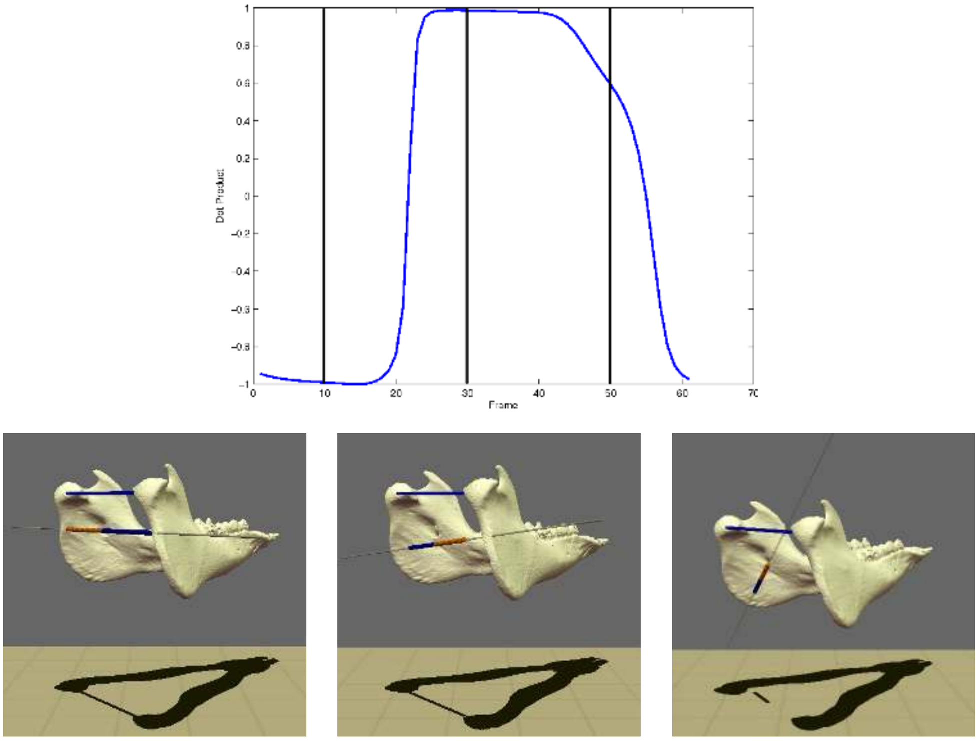

Frame 10 Frame 30 Frame 50

Figure 7: *The dot product of IHA direction* $\hat{u}$ *with a user-selected reference axis, placed here connecting the condyles of the mandible. At frame 10, the dot product is near negative one, as the jaw rotates open. At frame 30, the motion has reversed, the dot product is near positive one, and the jaw is now closing. Note the IHA has rotated and now the orange and blue sides point in opposite directions as compared to frame 10, visually indicating the change of direction. At frame 50, the mandible is in the middle of a gradual transition from opening to closing. The IHA is nearly perpendicular to the reference axis while the mandible undergoes lateral movement to grind the food.*

dominant theme expressed by our collaborators was the desire to broadly explore the collected motion data. One researcher explained his data analysis process as starting with a mental image of the mechanics of a joint, likely formed by years of observation and study of similar mechanisms. In examining experimental data, he is looking to see if the data captured match or differ from his mental model. More specific hypotheses are often formed during this broad, exploratory phase.

Initial discussion also focused on the mechanics of the IHA. It was pointed out that the use of helical axes requires a shift in the mindset of many researchers. Joints are typically thought of being capable of both rotation and translation, but these are talked about as being centered in or relative to the center of the joint. The helical axis presents an axis of rotation that, depending on the joint of study, may not fall within the area of the joint. A rotation around such an axis will produce a sliding effect in the joint, which is described using previous models as a combination of rotation and translation. In fact, helical axes may be extremely useful for describing such sliding joint motions, but there remains an issue in terms practical application with respect to adjusting to new terminology and new conceptions of motion.

5.2. Specific Findings

The participants commented specifically on the utility of stereoscopic viewing. The extension of the axis forward and backward in time as seen in Figure 4 was also singled out as particularly useful for understanding the progression of the motion, as was the comparison of the relative contributions of rotation and sliding to the movement of points of interest on the anatomy.

A specific hypothesis was investigated using the distance-to-axis tool described in Section 3.3.2. It has been proposed that the mandibular axis of rotation may be centered in close proximity to the tendon and nerve connections on the internal faces of the mandible. These attachment points are visible in the form of the bone and were able to be selected as points of interest for calculation of the distance to the helical axis. We confirmed that on average the distance from these insertion points to the IHA is shorter than the distance to points on the condyles. Similar IHA distance calculations have been applied in the study of human mastication [GAAP97, GFP00]. The difference in this example is the ability to perform these calculations interactively within a data exploration setting, and with reference to the anatomical structure.

5.3. Future Directions

Several suggestions were made regarding future additions to the tool that may be useful for biomechanical analysis. One is to trace the intersection of the IHA on the bone models. This suggestion is representative of a larger goal of this research, identifying mechanisms for relating the IHA to anatomical context during data exploration. This continues to be an important area for the development on new IHA techniques.

Several hypotheses presented by the group require comparison of multiple motion sequences. For example, the rate of transition from one phase of chewing to the next may change based on the amount of food in the mouth. Tools facilitating comparison of IHA parameters across multiple motion sequences are likely to be of great value in future analyses of experimental data in biomechanics.

6. Conclusions

High-speed motion data makes possible robust calculation of IHAs. We present an exploration of the design space of interactive, animated visual techniques for displaying this data. Feedback from the evaluation of the visualization reiterates the importance of exploratory tools for biomechanical analysis. Continued research in this area is warranted, particularly in developing tools targeting comparison of multiple motion sequences.

Data from this domain are 3D and capture complex spatial and motion relationships. Stereoscopic views and the ability to step slowly through motion datasets while viewing time-lapsed displays of the IHA are important for capturing this complexity. Also critical for biomechanical analysis using IHAs is relating the axis parameters to the surrounding anatomical context. Three interactive techniques (comparison of sliding and rotation IHA parameters given a feature of interest, plots of distance from the IHA to selected features, and plots of IHA orientation relative to selected features) were useful in this regard and helped with investigating specific hypotheses during the user evaluation.

Analysis using IHAs requires, in some cases, a shift in thinking from traditional approaches to biomechanical analysis. However, IHAs show great potential for forming understandings and providing descriptive accounts of complex motion patterns. The workings of the mandible and temporomandibular joint (TMJ) in pigs, provides a case study of a complex motion that is challenging to describe using more traditional rotation and translation parameters. We anticipate the visual and interactive tools presented to be applicable in many other instances as well.

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