Perceived Naturalness of Interpolation Methods for Character Upper Body Animation

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Abstract. We compare the perceived naturalness of character animations generated using three interpolation methods: linear Euler, spherical linear quaternion, and spherical spline quaternion. While previous work focused on the mathematical description of these interpolation types, our work studies the perceptual evaluation of animated upper body character gestures generated using these interpolations. Ninety-seven participants watched 12 animation clips of a character performing four different upper body motions: a beat gesture, a deictic gesture, an iconic gesture, and a metaphoric gesture. Three animation clips were generated for each gesture using the three interpolation methods. The participants rated their naturalness on a 5-point Likert scale. The results showed that animations generated using spherical spline quaternion interpolation were perceived as significantly more natural than those generated using the other two interpolation methods. The findings held true for all subjects regardless of gender and animation experience and across all four gestures.

Keywords: Virtual characters · Procedural animation · Interpolation · Human motion · Gesture animation · Perception

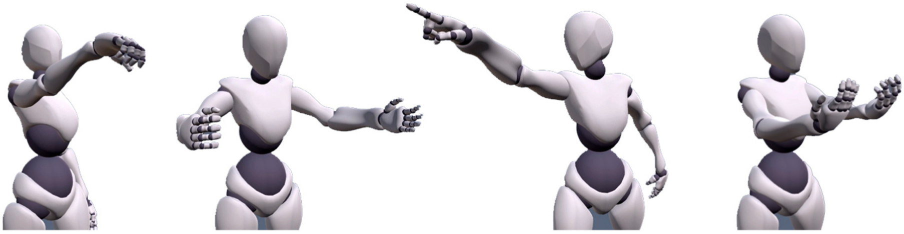

Fig. 1. Examples of four types of gestures (from left to right: metaphoric, iconic, deictic, and beat)

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1 Introduction

The ability to express and react to emotions is an essential element of human social interaction, and virtual characters in human-computer interaction (HCI) scenarios can enhance user experience [18]. Therefore, virtual characters must express and respond to emotions.

Creating believable character animation in real-time remains challenging. Keyframe animation is a traditional way to generate animation by defining extreme poses at crucial moments. However, the creation, assembly, and control of the animation is time-consuming, requires great expertise [9]. Motion capture has become affordable and accurate, with improvements in optical hardware and motion sensors. However, all of the actor's movements need to be pre-defined and cannot reflect real-time interaction. Dynamic simulations generate physically correct body reactions, but full-body dynamics are still complex to handle [19].

Animation applications increasingly require on-the-fly adaption [10,28]. Pre-recorded animation sequences can be blended together and mixed by using interpolation [19]. Interpolation algorithms are well-studied in computation complexity, error of the approximation, and the amount of missing information. However, only a handful of studies have examined the human perception of different interpolation methods in character animation [19].

Our work, aiming to study the effects of different interpolations on perceived naturalness of animated characters' upper body movements, has important practical implications. First, game studios would benefit from using a procedural way of identifying motion segments and applying effective interpolation [13], as it is expensive to create transition animations using keyframe and motion-capture techniques [10]. Second, this technique could enable artists to create animation prototypes faster, make motion more natural for background characters with fewer keyframes, and allow more time for other creative decisions. Third, animation interpolation can be used in state-machine, a common game mechanism in many HCI applications.

2 Prior Work

Animation Interpolation Methods: Dam et al. [6] introduced rotation represented by Euler angles, rotation matrices and quaternions. Euler angles are used by artists and supported in common content creation software, but they can lead to gimbal lock. Quaternions provide natural spherical interpolation, but they have a complicated mathematical model that is not intuitive to everyday users and are computationally demanding.

Traditional pose-to-pose animation is based on keyframes drawn by experienced artists. In-between frames can be interpolated by computers [6]. It has excellent applications not only in traditional 2D animation but also in modern 3D animation [15]. Key pose represents a "signature" motion that is unique and extreme [26]. Algorithms are effective in extracting critical motions. So and Baciu [26] measured the difference of poses in directional movements. The poses were ranked, with key poses having a more considerable difference.

The interpolation algorithm defines the smoothness of the transition. In the context of 3D character animation, motion is created by animating a character's major skeletal joints, which drive the character's skinned mesh. The interpolation of translation has been well studied in flat 3D Euclidean space. Character animation, however, is primarily achieved through joint rotation, and rotation lies in non-Euclidean space [1].

The interpolation path on a unit sphere can be translated into the orientation of a joint rotating from its base. Bloom et al. [3] identified three properties of the mechanical analysis of interpolation: the path, angular velocity, and commutativity. Similarly, Wang et al. [30] suggested dividing breaking down animation interpolation into three parts: blending time, path, and angular velocity.

Perception of Naturalness in Animation: Mezger et al. [19] mentioned that the study of interpolation methods for character animation "needs to be addressed by combining computer graphics and perception research" [19, p.1]. Moreover, they suggested that "psychophysical measures seemed to be more sensitive and appropriate for quantifying slight quality differences between animation techniques than the tested physical criterion" [19, p.8].

Interpolation of rotation is often analyzed at isolated joints, but full-body involvement is crucial for the naturalness of motion [12]. Even though user studies are invaluable for measuring motion naturalness, most naturalness metrics do not take into account human observation [27].

According to Blake and Shiffrar [2], both the form and the motion greatly influence the perception of human action. Motor learning (viewers' actions and experiences), social constraints and neural mechanisms, also play an essential role. Respectfully, Etemad et al. [7] studied two sets of themes representing different features of human motion: primary themes specifying actions and secondary themes specifying styles or characteristics.

People tend to make accurate judgments of simple, one-dimensional motion and make inaccurate judgments of complex, multi-dimensional motions [22]. According to Vicovaro et al. [29], people tend to rely on heuristic strategies rather than perceptual judgment. However, if more perceptual information is given, viewers will evaluate perceptually rather than heuristically.

The visual representation of the character can affect how viewers perceive the animation. Studies have found that robots designed to be highly human-like give viewers an eerie feeling [21]. Human traits in non-human objects known as anthropomorphism have been studied using virtual characters [4]. The more anthropomorphic the characters are, the more likely viewers are to report their motion as artificial, supported by fMRI examination [23].

Another important factor is the viewer's level of experience with animation. Those familiar with animation are very likely to spot errors in human motion than those who are new to animation [19]. The gender of the viewer and of the character influence human-computer interaction. Krämer et al. [14] found a difference concerning learning when viewers interacted with animated pedagogical agents of the same or opposite sex. For neutral motions such as walking or conversational gestures, viewers' judgments of male or female characters were similar; when certain emotions were involved, however, such as sadness or anger, gender bias appeared more prominently [31]. Emotional state of the animated character affects the viewer as shown in recent works [5,16,17].

Jansen and Van Welbergen [12] proposed three evaluation methods for naturalness in human motion: Two-alternative forced-choice (2AFC), Yes/No and Rating. Rating method could provide more valuable information on the naturalness of individual motion; Yes/No method and 2AFC are suitable for discriminating clips [12]. Hyde et al. [11] used a similar rating method to evaluate the naturalness of a character's facial expressions.

3 Methods

3.1 Studied Interpolations

Linear Euler Interpolation (LinEuler) is an interpolation between two tuples of Euler angles. Let a point in 3D space be represented as $P = [x, y, z] \in \mathbb{R}^3$; and a vector from the world's origin to that point is $v = (x, y, z)$ in the associated vector space $\mathbb{V}^3$. Consider a unit sphere, where a vector from the center to one point on the surface is represented as $v_0 = (x_0, y_0, z_0) \in \mathbb{R}^3$ and another as $v_1 = (x_1, y_1, z_1) \in \mathbb{R}^3$. Linear Euler interpolation between v_1 and v_2 is written as follow where $h \in [0, 1]$ is a blending parameter:

$$LinEuler(v_0, v_1, h) = (1 - h)v_0 + hv_1, \tag{1}$$

Spherical Linear Quaternion Interpolation (Slerp). A quaternion q consists of a scalar and a vector part: $q = s, x, y, z$ where $s, x, y, z \in \mathbb{R}^3$, also written as $q = s + ix + jy + kz$ where $s, x, y, z \in \mathbb{R}^3$ and $i^2 = j^2 = k^2 = ijk = -1$.

Slerp [24] interpolates the rotation along the shortest path on a unit sphere at a constant velocity, which causes a sudden change of angular direction when performing a series of rotations, making keyframes visible. Let H be a set of quaternions, where $p, q \in H$, $\cos \Omega = pq$ and $h \in [0, 1]$ is the interpolation parameter. Slerp is:

$$Slerp(p, q, h) = \frac{p \sin((1 - h)\Omega) + q \sin(h\Omega)}{\sin(\Omega)} \tag{2}$$

Spherical Spline Quaternion Interpolation (Spherical and Quadrangle, or Squad) is the spherical cubic equivalent of the Bézier cubic curve in the quaternion space. Shoemake [25] presented Squad and then proved the continuous differentiability of Squad at control points. Where $h \in [0, 1]$ and $s_i = q_i exp(-(log(q_i^{-1} q_{i+1}) + log(q_i^{-1} q_{i-1}))/4)$.

$$\begin{aligned} &Squad(q_i, q_{i+1}, s_i, s_{i+1}, h) \\ &\quad = Slerp(Slerp(q_i, q_{i+1}, h), Slerp(s_i, s_{i+1}, h), 2h(1 - h)) \end{aligned} \tag{3}$$

The three algorithms generate different interpolation paths as shown in Example: Fig. 2. Although algorithms for more complex interpolations exists [1, 6,8], they also require more complex parameters and were not considered in our study.

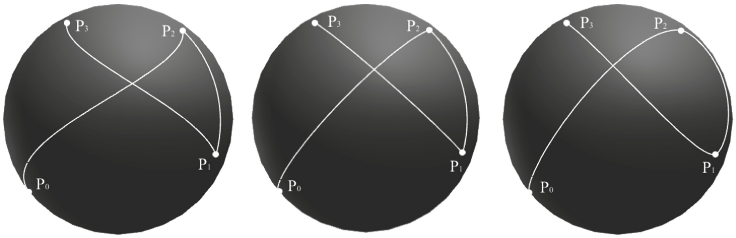

Fig. 2. Interpolation curve on a unit sphere using LinEuler (left), Slerp (middle), and Squad (right).

3.2 Study Design

This study aimed to examine the effects of the three interpolation methods: linear Euler (LinEuler; Eq. 1), spherical linear quaternion (Slerp; Eq. 2), and spherical spline quaternion (Squad; Eq. 3), on the perceived naturalness of four upper body character animations. The study included interpolation type, gesture type, participant's gender, and participant's level of animation experience as independent variables. The dependent variable of the experiment was the participant's perceived naturalness of each animation clip rated on a 5-point Likert scale (1 = not natural at all, 5 = very natural). Figure 1 shows the four gestures selected for this study: right arm throwing an object (metaphoric gesture); both arms moving outward, showing the size of an object (iconic gesture); right arm pointing to the sky (deictic gesture); both arms moving forwards in parallel (beat gesture).

The main null hypothesis of the study was that all the interpolation methods would be given the same naturalness ratings, meaning all three interpolation methods have equal effects on the viewer's perception of naturalness in character animation. The main alternative hypothesis was that at least one of the interpolation methods would be given a different rating; that is, the viewer would perceive some methods more or less natural than others.

Null Hypothesis 1 ($H1_0$). *The three interpolation methods are given equal ratings by the participants (i.e. $r_{LinEuler} = r_{Slerp} = r_{Squad}$)*

Alterative Hypothesis 1 ($H1_a$). *The three interpolations methods are given significantly different ratings by the participants*

The secondary hypotheses of the study were the following:

Null Hypothesis 2 ($H2_0$). *The three interpolation methods are given equal ratings regardless of the participants' animation experience (experts vs. novices)*

Alterative Hypothesis 2 ($H2_a$). *The three interpolations methods are given significantly different ratings based on the participants' animation experience*

Null Hypothesis 3 ($H3_0$). *The three interpolation methods are given equal ratings regardless of character's gesture type (beat, deictic, iconic, or metaphoric)*

Alterative Hypothesis 3 ($H3_a$). *The three interpolations methods are given significantly different ratings based on character's gesture type*

Null Hypothesis 4 ($H4_0$). *The three interpolation methods are given equal ratings regardless of the participants' gender*

Alterative Hypothesis 4 ($H4_a$). *The three interpolations methods are given significantly different ratings based on the participants' gender*

3.3 Experiment Design

Surveys were designed and hosted on Qualtrics and distributed through Prolific and Purdue University Computer Graphics Department's (CGT) email list. Four motion-captured recordings (duration ranged from 1.6 to 2.4 s) corresponded to four types of gesture. Four frames were identified to generate 12 stimuli clips using different interpolation methods. Figure 3 shows frames from the three different interpolation clips of metaphoric gesture.

Fig. 3. Metaphoric gesture: LinEuler a), Slerp b), and Squad c).

Motion data (.fbx file) were obtained from Motion-capture system Xsens and Motion-capture library Mixamo. They were then remapped to the character X Bot [20] through MotionBuilder's retarget feature. Minimum adjustments were applied for the motion to look correct. Next, the data were imported into Maya for clipping, and a custom script identified four frames and extracted rotation values along the joint hierarchy. It output XML files and passed to Unity, which performed the interpolation of rotation on individual joints.

3.4 Study Procedure

The study is divided into the pilot study and the main study. During each study, participants were first presented with an overview of the survey and asked to provide their demographic information, including age, gender, race, highest completed education, and experience in animation.

Second, they were asked to watch and evaluate different animation clips. This part consisted of 12 animations divided into four gesture groups. The gesture groups were presented in counter-balanced random order. Three animation clips of that gesture using different interpolation methods were presented in random order within each group. Each clip was looped and was shown along with a descriptive text (e.g. "The character is throwing an object"). After viewing each clip, the participants were asked to rate the clip on a 5-point Likert scale. A hidden timer was used to track the time spent on each clip. Rules were used to filter out participants who were potentially rushing through the survey by giving patterned or random responses.

3.5 Data Collection and Analysis

The analysis followed a three-step procedure. In the first step, the mean rating for each interpolation method was calculated using linear regression, with LinEuler as the baseline. In the second step, a one-way analysis of variance (ANOVA) test was conducted. Its outcome p-value was used to either reject or fail to reject the null hypothesis using an alpha value of 0.05. Tukey's honest significant difference test (Tukey's HSD) was performed for post-comparison if the null hypothesis was rejected. The outcome adjusted p-value from Tukey's HSD identifies which pairs of groups are different. The result further indicates which method is different compared to the others in terms of perceived naturalness using a confidence level of 95%.

A power analysis was performed based on the data collected from the pilot study to determine the ideal sample size; the power level was set at 80%.

The Pilot Study: A total of 18 responses were used for analysis. The mean values are reported in Table 1. The p-value obtained from the one-way ANOVA was 1.99e-12, far less than the alpha value.

In the Tukey HSD post-ANOVA comparison, the Squad-LinEuler pair and Squad-Slerp pair had a p-value <0.05, rejecting the null hypothesis that the two groups had identical ratings. Slerp-LinEuler pair had p-values >0.05, which failed to reject the null hypothesis that the two groups had equal ratings.

Table 1. Mean table for the pilot study

	LinEuler	Slerp	Squad
Mean	2.2500	2.0694	3.3611

The Main Study: A total of 97 responses were used for the analysis. The number of participants was far greater than the minimum of 48 (obtained using power analysis for ANOVA in the pilot study), which gave this study a power level of approximately 98%.

The mean rating values are reported in Table 2. The one-way ANOVA test yielded a p-value equal to 2e-16, which is <0.05.

The adjusted p-value from the Tukey HSD matched the result from the pilot study, with the Squad-LinEuler pair and the Squad-Slerp pair's p-values <0.05; thus, the null hypothesis that the two groups had identical ratings was rejected. The Slerp-LinEuler pair had a p-value >0.05 which failed to reject the null hypothesis that the two groups had equal ratings.

Table 2. Mean table for the combined main study

	LinEuler	Slerp	Squad
Mean	2.6598	2.7010	3.4948

The main study combined results from two platforms: Prolific and CGT. The latter was biased toward animation-major students; therefore, the analysis was also conducted on data collected solely from Prolific, with a total of 42 subjects.

The means are reported in Table 3. And the one-way ANOVA test yielded a p-value of 1.1e-6, which was still significantly <0.05. Therefore, there was significant evidence to reject the null hypothesis $H1_0$.

In the Tukey HSD, Squad-LinEuler pair and Squad-Slerp pair yielded p-values <0.05, thus rejecting the null hypothesis that these two groups had identical ratings. As for the Slerp-LinEuler pair, the p-value was >0.05, which failed to reject the null hypothesis that the two groups had equal ratings.

Table 3. Mean table for Prolific subjects in the main study

	LinEuler	Slerp	Squad
Mean	2.8333	2.8929	3.3929

Analysis based on Animation Experience: Seventy-two subjects were novice, and 25 had some animation experience. The means for both groups are reported in Table 4. The p-values for both groups were 2e-16, which is significantly <0.05. Therefore, there was significant evidence for both groups to reject the null hypothesis $H2_0$.

The Tukey HSD test results for the two groups showed that the Squad-LinEuler pair and Squad-Slerp pair p-values were <0.05, rejecting the null hypothesis. As for the Slerp-LinEuler pair, both groups' p-values were >0.05, which failed to reject the null hypothesis that the two groups have equal ratings.

Table 4. Mean table for different animation experience level

	Novice	Experienced
LinEuler	2.7778	2.3200
Slerp	2.8125	2.3800
Squad	3.4688	3.5700

Analysis based on Gesture Type: Some gestures showed more differences in perceived naturalness compared to others. A sample size of 97 was used for this analysis. The mean values for the linear regression model are reported in Table 5. The one-way ANOVA tests yielded p-values that were all significantly <0.05 (Beat gesture 3.76e-09; Deictic gesture 4.78e-05; Iconic gesture 2.8e-16; Metaphoric gesture 6.82e-08). Therefore, there was significant evidence to reject the null hypothesis $H3_0$.

The Tukey HSD showed all Squad-LinEuler pair and Squad-Slerp pairs had p-values <0.05, rejecting the hypothesis that these two groups were identical in all gesture groups. As for the Slerp-LinEuler pair, all the p-values were >0.05, which failed to reject the hypothesis that the two groups had equal ratings in all gesture groups.

Table 5. Mean table for different gesture types

	Beat	Deictic	Iconic	Metaphoric
LinEuler	2.5464	3.0825	2.5155	2.4948
Slerp	2.5567	3.0412	2.6082	2.5979
Squad	3.3814	3.6289	3.6701	3.2989

Analysis based on Gender: The pool of subjects included self-identified 43 males and 49 females. The means for the two gender groups are reported in Table 6. Results of the one-way ANOVA test showed that the male group had a p-value of 2e-16 and the female group a p-value of 1.13e-11, which were both significantly <0.05. Therefore, for both male and female viewers, there was significant evidence to reject the null hypothesis $H4_0$.

The Tukey HSD test for the two groups showed that the Squad-LinEuler pair and Squad-Slerp pair's p-values were <0.05, rejecting the null hypothesis that there are no significant differences based on gender. As for the Slerp-LinEuler pair, both groups' p-values were > 0.05, which fails to reject the hypothesis that the two groups gave equal ratings.

Table 6. Mean table for different gender

	Male	Female
LinEuler	2.6512	2.6888
Slerp	2.5581	2.8414
Squad	3.5872	3.4082

4 Discussion

The findings from the data analysis provide sufficient evidence to reject the null hypothesis that LinEuler, Slerp, and Squad would be given the same naturalness ratings. It was found that upper body animation generated by Squad interpolation was perceived as significantly more natural than that generated by LinEuler or Slerp. This conclusion holds not only for audiences with different levels of expertise in animation and different gender groups, but also for different gesture types.

Although LinEuler and Slerp use entirely different rotation models and interpolation calculations, there was insufficient evidence to reject the hypothesis that LinEuler and Slerp interpolation would be given the same naturalness rating. These two interpolation methods, therefore, had the same effect on the viewer's perception of naturalness. This finding was consistent across all the data subsets.

We believe Squad interpolation is superior to the other two linear models due to its algorithm, which generates a smoother path and continuous angular velocity. Our perceptual experiment has shown it to produce the most natural animations. The average naturalness rating for animations generated using Squad interpolation was between 3 ("neutral") and 4 ("somewhat natural"). In contrast, animations generated using LinEuler and Slerp were rated between 2 ("somewhat unnatural") and 3 ("neutral").

Findings also suggest that experienced viewers can distinguish interpolation methods more clearly than inexperienced viewers. Results of our study also showed there were no significant differences based on participants' gender. In regard to the perceived naturalness of different gesture types, findings show that the iconic gesture was rated the most different between interpolations, and the deictic gesture showed the least difference.

5 Conclusion and Future Work

The experiment reported in the paper investigated the effect of different animation interpolation methods on perceived naturalness of four types of animated body gestures. Findings showed that animations generated with Squad interpolation were perceived as significantly more natural than animations generated with the other two methods (i.e. LinEuler and Slerp). Findings held true across the four gesture types, and there were no significant differences in ratings based on participants' gender and animation experience.

The experiment had a few limitations that could be overcome in future work. First, given the wide range of possible upper body motions, more gesture types could be tested in the future to further support these findings. Second, other test paradigms proposed by Jansen and Van Welbergen [12], could also be used in future work aside from subjective rating. Post-experiment qualitative questions could also help explain why Squad is perceived as more natural than the other two methods. Different camera views could be explored in future studies.

Third, one of the essential elements of interpolation algorithms is the control points (translated by extracting key poses). This work used the researcher's judgment to identify the key poses of motion-captured clips; in future work it is possible to algorithmically determine the key pose to interpolate. This method could potentially be used for other purposes such as keyframe reduction. Furthermore, the number of control points and the frame interval between each point also play a considerable part in the animation's smoothness. Although there are usually no limits to the number of keyframes that can be added, fewer and pre-planned control points saves memory. When the motion range exceeds 180^o between two orientations, using quaternions will interpolate along the shortest path. Applying no-flip rules to the algorithm could avoid such an extreme case.

Lastly, the algorithms themselves have some limitations. All three methods interpolate along a perfectly planned path, but human motion is imperfect. Furthermore, the rotation starts and ends at the same time with no variation. Animation interpolation methods also fail to handle the collision of body parts, which could result in model clipping. Improvements could be implemented, such as adding random noise to avoid perfectly smooth curves. Interpolating with timed offsets based on joint hierarchy could add secondary motion and specifying rotation constraints for limbs could reduce the chance of model clipping.

Despite the limitations, our findings are important as they could benefit both real-time and non-real-time applications. The state-machine mechanism which utilizes interpolation is commonly used in games and other interactive applications. A more natural behavior of the virtual character enhances user experience. The implementation of a more natural animation can also reduce stress for developers: by saving time on repetitive tasks and allocating more resources for creative decisions. It also enables independent developers to create content more quickly, and larger studios to generate animation prototypes faster. Furthermore, this semi-procedural approach for creating human motion encourages people with little professional knowledge to take an interest in animation. Lastly, the work reported in the paper has created a basis for further research into the evaluation of animation techniques.

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