The EMOTE Model for Effort and Shape

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ABSTRACT

Human movements include limb gestures and postural attitude. Although many computer animation researchers have studied these classes of movements, procedurally generated movements still lack naturalness. We argue that looking only at the psychological notion of gesture is insufficient to capture movement qualities needed by animated characters. We advocate that the domain of movement observation science, specifically Laban Movement Analysis (LMA) and its Effort and Shape components, provides us with valuable parameters for the form and execution of qualitative aspects of movements. Inspired by some tenets shared among LMA proponents, we also point out that Effort and Shape phrasing across movements and the engagement of the whole body are essential aspects to be considered in the search for naturalness in procedurally generated gestures. Finally, we present EMOTE (Expressive MOTion Engine), a 3D character animation system that applies Effort and Shape qualities to independently defined underlying movements and thereby generates more natural synthetic gestures.

Keywords

Animation systems, human body simulation, gestures, procedural modeling, expression

1. INTRODUCTION

Human movement ranges from voluntary, goal-oriented movements to involuntary, subconscious movements. Voluntary movements include task-driven actions, such as walking to get somewhere or speaking. Involuntary movements occur for physiological or biological purposes; for instance, blinking, balancing, and breathing. A wide class of movement falls in between these two. In general, this class is characterized as consisting of movements which occur in concert and perhaps unconsciously with other activities. We note two interesting subclasses of this class of movements. One subclass consists of low-level motor controls that assist the accomplishment of a larger coordinated task. For instance, unconscious finger controls form grasps, leg and foot coordination enable walking or running, and lip movements generate speech. Another interesting subclass is the set of movements that accompany communicative acts: facial expressions, limb gestures, and postural attitude. While computer animation researchers have actively studied all these classes of human movements, it remains difficult to procedurally generate convincing, “natural” limb and postural movements .

We pose the problem as follows: What parameters characterize body or limb motions in real people performing communicative acts? The foremost computational approach to this issue has been through the gesture models proposed by McNeil [27], and elaborated with computer implementations primarily by groups led by Cassell [14,39,13], Badler [2,3], and Thalmann [8,12]. McNeil’s approach is to characterize communicative arm gestures into several categories:

- **Iconics** represent some feature of the subject matter, such as the shape or spatial extent of an object.
- **Metaphorics** represent an abstract feature of the subject matter, such as exchange, emergence, or use.
- **Deictics** indicate a point in space that may refer to people or spatializable things.
- **Beats** are hand movements that occur with accented spoken words and speaker turn-taking.
- **Emblems** are stereotypical patterns with understood semantics, such as a good-bye wave, the OK-sign, or thumbs-up.

Such an approach has served to make conversational characters appear to gesture more-or-less appropriately while they speak and interact with each other or actual people. The impression that one gets when watching even the most recent efforts in making convincing conversational characters is that the synthetic movements still lack some qualities that make them look “right”. Indeed, the characters seem to be doing the right things, but with a kind of robotic awkwardness that quickly marks the performance as synthetic. It is not a computer animation problem *per se* — conventional but skilled key-pose animators are able to produce excellent gestures in 3D characters. So there is some gap between what such an animator intuits in a character (and is therefore able to animate) and what happens in a procedurally synthesized movement. Key pose animators have managed to bridge the technology gap by careful application of classic rules for conventional animation [35,25].

The McNeil/Cassell approach to gesture is rooted in psychology and experimental procedures that use human observers to manually note and characterize a subject’s gestures during a story-telling or conversational situation. The difficulty in this approach is *hidden within the decision to call something a gesture*. That is, the observer notes the occurrence of a gesture and then records its type. This kind of recording fails to capture the parameters of movement that makes one particular gesture appear over another, as well as what makes the gesture appear at all. This issue is crucial in the studies of Kendon [19], who tries to understand the deeper question: What makes a movement a gesture or not? In his work, a gesture is a particular act that appears in the arms or body during discourse. *There may be movements that are not gestures and there may be movements that are perceived as gestures in some cultures but not in others*. So clearly, the notion of “gesture” as a driver for computer-generated characters cannot be − in itself − the primary motivator of natural movements. Further, we note that these approaches are limited by their basis in linguistics.

To address this, we look toward movement representations outside the constraints of communicative acts. We find that the

Effort and Shape components of Laban Movement Analysis (LMA) [22,23,17,7,28] provide us with a more comprehensive set of parameters for describing the form and execution of the qualitative aspects of movements. Our approach to gesture augments the McNeil/Cassell approach by addressing a missing dimension: movement exists not just because it has underlying linguistic relationships *but also because it has some distinctiveness in its Effort and Shape parameters.* Effort and Shape provide a means to describe the aspect of human movement that relates to individual character, cultural norms and distinctions. Our approach meshes perfectly with the perspective offered by the LMA proponents: "Gesture ... is any movement of any body part in which Effort or Shape elements or combinations can be observed" [7].

Our approach to gesture also complies with two other important LMA concepts. The first one is synthesized by Bartenieff when she observes that it is not just the main movement actions that let us identify behavior but it is the sequence and phrasing of Effort and Shape components that express and reinforce content [7]. The other concept is best expressed by Lamb: a gesture localized in the limbs alone lacks impact, but when its Effort and Shape characteristics spread to the whole body, a person appears to project full involvement, conviction, and sincerity [24].

We present EMOTE (Expressive MOTion Engine), a 3D character animation system that allows the specification of Effort and Shape parameters to modify independently defined arm and torso movements. The underlying movements of the arms and torso are specified through key time and pose information much like conventional computer animation. However, rather than performing a simple linear interpolation, we apply Effort and Shape parameters to these motion templates to create expressive movements. Our approach allows users to specify separate parameter values for different body parts, as well as phrasing parameter values across the key poses. We note that the key pose values may be generated synthetically, by inverse kinematics, motion capture, or otherwise pre-stored movement patterns.

In the next section, we present related work, followed by a brief overview of the Effort and Shape components of LMA. Then, we present the EMOTE model for Effort and Shape. Next, we discuss several animations that were created to demonstrate the power of our approach. Finally, we point to some directions that guide our future investigations and conclude with the main contributions of our work.

2. RELATED WORK

In addition to the use of computational implementations of gesture models to animate synthetic humans during communicative acts [14,39,13,3,8,12], many researchers have addressed the issue of generating more natural movements in broader contexts. Several researchers have suggested methods of adding expressiveness to animated motions using such methods as stochastic noise functions [31], Fourier function models [38], or emotional transforms [1]. Such methods require an off-line modeling process for each different type of expression. Others have implemented tools that modify or interpolate existing motions to display different expressions or fit other constraints [10,40,33]. Various researchers have developed behavioral animation systems to generate animations of multiple creatures with varying personalities and/or goals [32,36,5,8]. Although creatures in behavioral animation systems display different high-level behaviors, their low-level movements are often very simple, non-expressive, or drawn from a small library of movements. A task-level animation system that generates arm motions of a human figure moving an object to a goal location has been developed using an inverse kinematics algorithm based on neurophysiological studies [21]. The focus of this system is on the "intention" of moving an object from one location to another and not on the underlying movement qualities of the character. The use of secondary motions has been proposed as a way to enliven computer generated animations. One approach adds secondary movements to walking characters based on user-specified personality and mood [29]. Another approach focuses on passive motions like the movement of clothing and hair, generated in response to environmental forces or the movements of characters and other objects [30].

Badler originally proposed (but did not implement) the use of Effort to provide users with expressive movement control of articulated figures [2]. Bishko suggested analogies between the "Twelve Principles of Animation" [35] and Laban Movement Analysis [8]. She shows that there is an abstract relationship between LMA and traditional animation techniques, but does not provide a computational means of exploiting this relationship. Others have done work with computerizing Labanotation (a notation, primarily used for recording dance, based on Laban's work that focuses on the structural aspects of movement) [4,11], but are only beginning to address the more qualitative aspects of movement provided by the Effort and Shape components.

3. BACKGROUND

Rudolf Laban (1879-1958) made significant contributions to the study of movement, bringing together his experiences as a dancer, choreographer, architect, painter, scientist, notator, philosopher, and educator. He observed the movement of people performing all types of tasks: from dancers to factory workers, fencers to people performing cultural ceremonies, mental patients to managers and company executives. His theories on movement, which were significantly extended and applied by his students and colleagues have resulted in a rich vocabulary for describing and analyzing movement, leading to the development of Laban Movement Analysis[1] [7,28,17,26]. LMA has evolved into a comprehensive system that has been used in dance, drama, nonverbal research, psychology, anthropology, ergonomics, physical therapy, and many other movement-related fields [6,15].

Laban Movement Analysis has five major components: Body, Space, Shape, Effort, and Relationship. Together these components constitute a textual and symbolic language for describing movement. Body deals with the parts of the body that are used and the initiation and sequencing of a motion. Space describes the locale, directions, and paths of a movement. Shape involves the changing forms that the body makes in space. Effort describes how the body concentrates its exertion while performing movements. Effort is often compared to dynamic musical terms such as legato, forte, dolce, etc., which give information on how a piece of music should be performed. Relationship describes modes of interaction with oneself, others, and the environment.

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[1] LMA is promoted by the Laban/Bartenieff Institute of Movement Studies (LIMS), 234 Fifth Avenue, Room 203, New York, NY 10001; (212)477-4299; www.limsonline.org.

Relationship examples include facings, contact, and group forms. As part of our approach to gesture, we developed a computational model of the Effort and Shape components of LMA.

Effort comprises four motion factors: Space, Weight, Time, and Flow. Each motion factor is a continuum between two extremes: (1) *indulging* in the quality and (2) *fighting* against the quality. In LMA these extreme Effort Elements are seen as basic, "irreducible" qualities, meaning they are the smallest units needed in describing an observed movement. The eight Effort Elements are: Indirect/Direct, Light/Strong, Sustained/Sudden, and Free/Bound. The eight Elements can be combined and sequenced for innumerable variations of phrasings and expressions. Table 1 illustrates the motion factors, listing their opposing Effort Elements with textual descriptions and examples.

Space: attention to the surroundings	
Indirect:	flexible, meandering, wandering, multi-focus
Examples:	waving away bugs, slashing through plant growth
Direct:	single focus, channeled, undeviating
Examples:	pointing to a particular spot, threading a needle
Weight: sense of the impact of one's movement	
Light:	buoyant, delicate, easily overcoming gravity, marked by decreasing pressure
Examples:	dabbing paint on a canvas, describing the movement of a feather
Strong:	powerful, having an impact, increasing pressure into the movement
Examples:	punching, pushing a heavy object, expressing a firmly held opinion
Time: lack or sense of urgency	
Sustained:	lingering, leisurely, indulging in time
Examples:	stretching to yawn, stroking a pet
Sudden:	hurried, urgent
Examples:	swatting a fly, grabbing a child from the path of danger
Flow: attitude towards bodily tension and control	
Free:	uncontrolled, abandoned, unable to stop in the course of the movement
Examples:	waving wildly, shaking off water
Bound:	controlled, restrained, able to stop
Examples:	moving in slow motion, tai chi, carefully carrying a cup of hot liquid

Table 1: Motion Factors and Effort Elements

The Shape component involves three distinct qualities of change in the form of movement: Shape Flow, Directional Movement, and Shaping. A Shape Flow attitude primarily reflects the mover's concern with the changing relationship among body parts. These changes can be sensed as the increasing or decreasing volume of the body's form or a moving toward or away from the body center. Shape Flow can be seen from these two different perspectives. The first one emphasizes the torso, which can be said to Grow or Shrink. A continuous breathing pattern reveals changes in Shape Flow as seen from the torso perspective. The other perspective emphasizes the limbs, which are said to be Opening or Closing with respect to the longitudinal axis. Shrinking from the cold or stretching to wake up would be characterized as having a Shape Flow quality.

While Shape Flow is mainly concerned with sensing the body's shape changes within itself, Directional Movement describes the mover's intent to bridge the action to a point in the environment. These movements can be simple spoke-like or arc-like actions to reach a direction or object, such as a reach to shake a hand or to touch an object or to move to a specific location.

Shaping Movement depicts the changes in movement form that demonstrate a carving or molding attitude as the body interacts with the environment. This form can be dictated by objects in space or simply created by the mover. An active adapting of the body shape in order to move through a crowd, or a gesture describing an elaborately carved sculpture might illustrate a Shaping mode.

Shape changes in movement can be described in terms of three dimensions: Horizontal, Vertical and Sagittal. Each one of these dimensions is in fact associated with one of the three main dimensions (Width, Length, and Depth) as well as one of the three planes (Horizontal, Vertical, and Sagittal) related to the human body. Changes in Shape in the Horizontal dimension occur mainly in the side-open and side-across directions; as the movement becomes planar there would be more of a forward-backward component added to the primary side component. Changes in the Vertical dimension are manifested primarily in the upward-downward directions; the plane would add more sideward component to the up-down. Finally, changes in the Sagittal dimension are more evident in the body's depth or the forward-backward direction; planar movement would add an upward-downward component.

Horizontal	
Spreading:	affinity with Indirect
Examples:	opening arms to embrace, sprawling in a chair
Enclosing:	affinity with Direct
Examples:	clasping someone in a hug, huddling in the cold
Vertical	
Rising:	affinity with Light
Examples:	reaching for something in a high shelf
Sinking:	affinity with Strong
Examples:	stamping the floor with indignation
Sagittal	
Advancing:	affinity with Sustained
Examples:	reaching out to shake hands
Retreating:	affinity with Sudden
Examples:	avoiding a punch

Table 2: Shaping Dimensions and Affinities

We note that while there is distinct vocabulary for each quality – Shape Flow, Directional Movement, and Shaping – in the various dimensions, we have merged these three concepts (using them interchangeably) and chosen to use the Shaping terminology. The terms we are using to describe the opposing changes in these dimensions are Spreading and Enclosing, Rising and Sinking, Advancing and Retreating. It is important to point out that limbs and torso movements are not required to involve the same Shape qualities at a given time. In this way, Shape Flow functions as a breathing baseline to support Directional and Shaping movement of the limbs. In another example, a traffic officer might hold up one arm with a Directional reach, while the other arm gestures in a circular Shaping mode, and the head does small tilting Shape Flow actions to accompany the Shaping arm.

Another LMA concept is Reach Space in the Kinesphere (near, middle, and far). Our current approach regards Reach Space only from the perspective of the limbs in relation to the distance from the body center. Though this is a simplified view, it adds an important feature to the limb range of movement.

Shape changes can occur in affinity with corresponding Effort Elements. Table 2 shows the opposing attitudes towards Shape, some examples, and their affinities with Effort Elements.

4. THE EMOTE APPROACH TO GESTURE

Our current implementation of EMOTE uses a commercially available, fully articulated, human model [18]. At this point, we focus on expressive gestures involving arm and torso movements.

EMOTE has four features which we believe are essential for creating gestures that convey naturalness and expressiveness:

1. A given movement may have Effort and Shape parameters applied to it independent of its geometrical definition.
2. A movement's Effort and Shape parameters may be varied along distinct numerical scales.
3. Different Effort and Shape parameters may be specified for different parts of the body involved in the same movement.
4. The Effort and Shape parameters may be phrased (coordinated) across a set of movements.

The underlying movements of a gesture are specified through key time and pose information defined for the arms and the torso. An external process, such as using a specific gesture stored in a motion library, a procedurally generated motion, or motion captured from live performance, could be used to generate these underlying movements. Key pose information could be extracted from these movements and used as input into EMOTE. With the key pose information, the EMOTE parameters could then be applied to vary the original performance (property 1).

Effort and Shape qualities are expressed using numeric parameters that can vary along distinct scales (property 2). Each Effort and Shape factor is associated with a scale ranging from -1 to +1. The extreme values in these scales correspond to the extreme attitudes of the corresponding factors. For example: a +1 value in Effort's Weight factor corresponds to a very Strong movement; a -1 value in Shape's Vertical dimension corresponds to a Rising movement. Effort parameters are translated into low-level movement parameters, while Shape parameters are used to modify key pose information. By interactively using one or many of the Effort and Shape dimensions, we can search for the desired quality of a particular movement. During procedural synthesis, EMOTE parameters can be applied directly based on parameter values dependent on a character's particular utterance, reactions, or personality.

EMOTE permits independent specification of Effort and Shape parameters for each part of the body (property 3). In its current implementation however, Effort parameters do not apply to torso movements. Although Shape parameters have proven to be effective in the specification of expressive torso movements, further investigation should be carried out to identify how Effort qualities are manifested in the torso. Moreover, the Shape parameters are mainly applied to torso movement. The general Space concept of Kinespheric Reach Space is used in the arms. Table 3 summarizes which dimensions of Effort and Shape can be used to modify the movements of the different parts of the human body.

Allowing the definition of expressive gestures that include the legs can be similarly done, however, additional constraints need to be carefully considered in order to provide static and dynamic balance and stability. Moreover, using Effort and Shape parameters to modify locomotion is a more complex task and involves the identification of a different set of low-level movement parameters, including an exploration of the pelvic-femoral movement rhythm. Furthermore, including the legs may also affect the movement of the torso and arms, because changing the qualities in the legs may result in a reworking of the posture. For instance, the additional effort in the legs is reflected and reinforced by the exertion of the torso and placement of the arms.

		Right Arm	**Left Arm**	**Torso**
Effort	Space	yes	yes	no
	Weight	yes	yes	no
	Time	yes	yes	no
	Flow	yes	yes	no
Shape	Horizontal	yes	yes	yes
	Vertical	yes	yes	yes
	Sagittal	yes	yes	yes
	Reach Spc	yes	yes	no

Table 3: Body Parts and Effort and Shape Dimensions

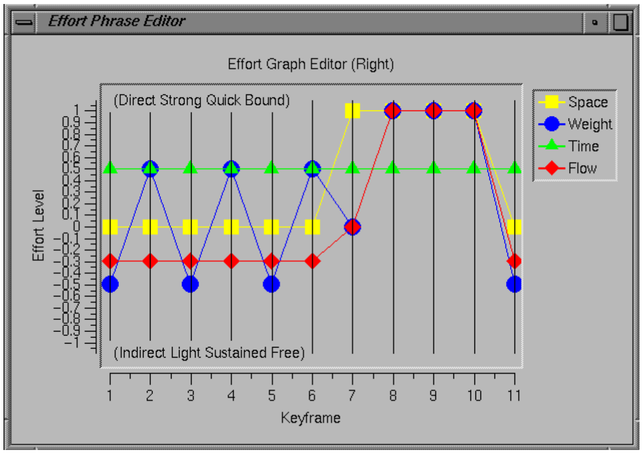

Figure 1: Effort Phrase Editor

Finally, our approach allows the specification of different sets of values for the Effort and Shape parameters across any series of keys that define the underlying motions (property 4). By property (3), this can be done separately for each part of the body.

Figure 1 depicts a graph editor used to specify Effort parameters across a series of keyframes defined for the arms.

4.1 Expressive Arms

The underlying key poses of the arms are defined as end-effector positions (keypoints). Keypoints can be defined as being global or local. Local keypoints are defined relative to the human's shoulders. Global keypoints, on the other hand, establish a constraint relative to the environment. Keypoints can also be classified into *Goal* or *Via* points. *Goal* points define a general movement path; the hand follows this path, stopping at each *Goal* point. *Via* points direct the motion between keyframes without pausing. For instance, a *Via* point might be used to generate a semi-circular path between two *Goal* points.

EMOTE uses an arm model with a 1 degree-of-freedom (DOF) elbow joint and spherical (3 DOF) shoulder and wrist joints. An analytical inverse kinematics algorithm (IKAN) computes the shoulder and elbow rotations, given a goal specified by three-dimensional position coordinates and an elbow swivel angle [36]. Wrist rotations are determined according to Effort settings (as described below).

Reflecting Effort and Shape definitions provided by the LMA system, Shape parameters are used to modify the keypoints that specify arm movements, while Effort parameters affect the execution of those movements resulting from the modified keypoints.

4.1.1 Applying Shape to Arm Movements

Let us first consider the Horizontal, Vertical and Sagittal dimensions of Shape and show how the parameters associated with them are used to modify the keypoints. Because we are striving to simulate volume-like changes in the movement we are associating the Shape changes more with planar action than with strictly dimensional movement.

For a particular keypoint, let the variables *hor*, *ver* and *sag* in the interval [-1, +1] represent the parameters corresponding to the Horizontal, Vertical and Sagittal dimensions, respectively. We define two constants $abratio > 1$ and $maxd\theta$. For each one of the above dimensions, we find an ellipse containing the keypoint and lying in a plane parallel to the plane associated with that dimension (as described in Section 3). The center of the ellipse is the projection of the shoulder joint position on that plane. The major axis of the ellipse is parallel to the direction mostly affected by changes in that dimension and its minor axis is parallel to the other direction affected by such changes. The quotient between its major radius *a* and its minor radius *b* is *abratio*. We calculate the angle $\theta \in [0, 2\pi)$ formed by the major axis of the ellipse and the segment whose endpoints are the center of the ellipse and the keypoint. We find the contributions of that dimension to the modified keypoint by rotating the keypoint by $d\theta$, a fraction of $maxd\theta$ determined by the numeric parameter associated with the dimension being considered. Figure 2 illustrates how we calculate *vdy* and *vdz*, the contributions of the Vertical parameter *ver* to a particular keypoint.

Let *x*, *y* and *z* be the coordinates of the keypoint in Figure 2. We find θ such that

$$\begin{cases} \theta = atan(\frac{y}{-z} * abratio) \\ 0 \le \theta < 2\pi \end{cases} \quad (1)$$

The major radius *a* of the ellipse is calculated by the following equation:

$$a = \frac{-z}{cos(\theta)} \quad (2)$$

The angle formed by the rotated keypoint and the major axis of the ellipse is given by the function *rot* defined as follows:

$$rot(\theta) = \begin{cases} 0 & ver = 0 \\ min(\theta - ver * maxd\theta, 2\pi) & ver < 0, \theta \ge \pi \\ max(\theta + ver * maxd\theta, 0) & ver < 0, \theta < \pi \\ max(\theta - ver * maxd\theta, \pi) & ver > 0, \theta \ge \pi \\ min(\theta + ver * maxd\theta, \pi) & ver > 0, \theta < \pi \end{cases} \quad (3)$$

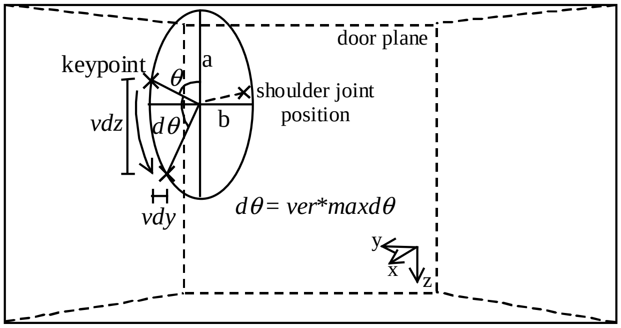

Figure 2: A Keypoint Modified by theVertical Parameter

Finally, the contributions *vdy* and *vdz* are calculated as follows:

$$vdz = -(a * \cos(rot(\theta))) - z \quad (4)$$

$$vdy = (a * \frac{1}{abratio} * sin(rot(\theta))) - y \quad (5)$$

We use the same model as described above to determine the contributions of the Horizontal (*hdy*, *hdx*) and Sagittal (*sdx*, *sdz*) parameters to the modified keypoint. We find the *x'*, *y'* and *z'* coordinates of the modified keypoint by adding the appropriate contributions to the coordinates of the original keypoint. Then,

$$x' = x + hdx + sdx \quad (6)$$

$$y' = y + hdy + vdy \quad (7)$$

$$z' = z + vdz + sdz \quad (8)$$

Let us now consider how the Kinespheric Reach Space parameter affects a particular keypoint. When considered from the perspective of the arms, Reach Space design describes the limb relationship with the body as it moves toward or away from the body center. Therefore, our Shape model modifies a particular keypoint by moving it along the direction that passes through the keypoint and the center of mass of the human figure. We use the Reach Space parameter *rs* to calculate the amount by which the keypoint is moved toward or away from the center of mass. This Reach Space modifier is considered after the keypoint has been modified according to its Horizontal, Vertical and Sagittal parameters. When the achievement of the modified keypoint requires shoulder angles outside the human body limits, stored joint limits avoid unattainable configurations of the body. As they establish a constraint relative to the environment, *Global* keypoints are not affected by the Shape parameters.

4.1.2 Applying Effort to Arm Movements

The translation of the qualitative Effort Elements into quantitative, low-level movement parameters was the key task in defining a computational model of the Effort component of LMA. Initially, we tried to deduce movement characteristics from motion capture data. We collected 3D motion capture data of a Certified Movement Analyst (CMA) trained in LMA performing numerous examples of combinations of Effort Elements. Analysis of the motion capture data led to only the most obvious conclusions; i.e.: Sudden is short in duration, Sustained is longer in duration, and Strong tends to have large accelerations. The inability to deduce the more subtle characteristic qualities of Effort arose from several factors. First, Effort reflects complex inner physiological processes that are related to a being's inner drive to respond to the physical forces in nature. Thus, Effort is embodied in the whole person and manifested in *all* body parts, whereas we were interested solely in the physical embodiment and visual result of inner attitudes on *movement*, particularly that of the arms. Furthermore, numerous other movements such as visual attention, changes in muscular tension, facial expressions, and breath patterns are not adequately captured by current motion capture technology. As a result, we turned to other methods for deducing the low-level movement parameters and corresponding settings for Effort. We defined underlying quantitative structures that model each Effort Element. Visual analysis of the motion capture data played an important role in extracting other manifestations of Effort and focusing our attention solely on the influence of Effort on arm movements. Other methods we used to derive an empirical model of Effort included descriptions of Effort from the literature [7,17,26,28], application of traditional animation principles [25,35], and much experimentation with feedback from a CMA.

First, we describe the set of low-level, quantitative movement parameters. Then, we show how these parameters are set based on the settings for the Effort parameters.

There are three types of low-level movement parameters: those that affect the arm trajectory, those that affect timing, and flourishes that add to the expressiveness of the movement.

4.1.2.1 Trajectory Definition

We define the arm trajectory for a given animation with two parameters:

- **Path curvature**: determines the straightness or roundness of the path segments between keypoints. We control the path curvature using the tension parameter introduced by Kochanek and Bartels for interpolating splines [20]. The tension parameter *Tval* ranges from -1 to +1.
- The **interpolation space**: defines the space in which the interpolation is performed: end-effector position, joint angle, or elbow position.

For end-effector interpolation, we use the end-effector position and swivel angle stored for each keypoint. We define an interpolating spline between the positions at keypoints using the tension parameter to determine the curvature of the path. We also interpolate between swivel angle values with an interpolating spline. For joint angle interpolation, we compute and store the shoulder and elbow rotations at keypoints. We then generate an interpolating spline between the elbow angle values at keypoints and perform spherical linear interpolation to determine the shoulder rotations. For interpolation in elbow position space, we compute and store the elbow position at keypoints using the posture defined by the end-effector position and swivel angle. We then define an interpolating spline between these positions, which are later used to set the shoulder rotations. The elbow rotations for elbow position interpolation are the same as those for end-effector interpolation. Interpolation in elbow position space gives smooth elbow motions, but a less path-driven movement than interpolation in end-effector position space.

The Effort settings determine which interpolation space is used. The default interpolation space uses end-effector position. Free movements use angular interpolation to achieve a less path-driven and less controlled movement. Our empirical studies show that Indirect movements tend to be driven by the elbow, and thus use interpolation in elbow position space.

4.1.2.2 Parameterized Timing Control

We separate timing control from trajectory definition by using a variation of the double interpolant method introduced by Steketee and Badler [34]. The interpolating splines that define the trajectory (described in the preceding section) compute values between keypoints using an interpolation parameter *s* that varies from 0 to 1 over the interval from keypoint *i* to keypoint $i+1$ [20]. Let the trajectory be defined by some function *P*(*s*,*i*). We now need a method of translating frame numbers into *s* and *i*. At the *i*th keypoint, $s = 0$. For in-between frames, we define a variable $t' \in [0,1]$, a frame's relative time between the previous and following keypoints. Let *prev* equal the frame number of the previous keypoint, *next* equal the frame number of the next keypoint, and *curr* equal the current frame number. Then,

$$t' = \frac{curr - prev}{next - prev} \qquad (9)$$

We define a frame number-to-time function $Q(t', I) = s$, parameterized by a set of variables *I* to achieve various timing effects (described further below). For each in-between frame, we normalize the frame number to produce *t*', use function *Q* to compute *s*, and then input *s* and the corresponding keypoint number *i* into function *P* to compute the position values (or joint angle values for angular interpolation) for the given frame.

We provide several parameters for timing control:

- The **number of frames between keypoints** is initially set according to the user's specified key times, but these values get adjusted according to the Effort settings.
- **Input variables to the keyframe-to-time function** (*I*) include inflection time t_i, time exponent *texp*, start velocity v_0, and end velocity v_1.

Our parameterized frame number-to-time function *Q* assumes every movement (from one *Goal* keypoint to the next) starts and ends at rest. Also, every movement has a constant acceleration *a* until time t_i, followed by a constant deceleration. We introduce velocities v_0 at time t_0 and v_1 at time t_1 to achieve the traditional animation effects of anticipation and overshoot [25].

This model gives us the following velocity function (Figure 3):

$$v(t'') = \begin{cases} \dfrac{-v_0}{t_0} t'' & [0, t_0) \\ \dfrac{-(v_0 + t_i)t'' + v_0 t_i + t_0 t_i}{t_0 - t_i} & [t_0, t_i) \\ \dfrac{-(v_0 + t_i)t'' + v_1 t_i + t_1 t_i}{t_1 - t_i} & [t_i, t_1) \\ \dfrac{-v_1 t'' + v_1}{t_1 - 1} & [t_1, 1] \end{cases} \qquad (10)$$

where

$$t'' = (t')^{t\exp} . \qquad (11)$$

The function *Q* is the integral of Equation (10).

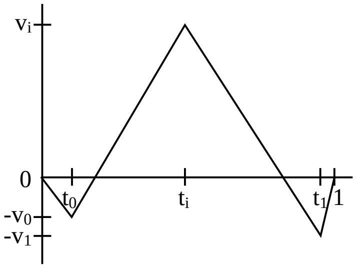

Figure 3: Velocity Function

The set of input variables I to the frame number-to-time function Q provides control to the acceleration/deceleration pattern of the movement, as well as allowing for anticipation and overshoot. The inflection point t_i represents the point (between 0 and 1) where the movement changes from accelerating to decelerating. A value of 0.5 gives a basic ease-in/ease-out curve. A value greater than 0.5 corresponds to a primarily accelerating motion, while a value less than 0.5 gives a decelerating motion. The default time exponent (*texp*) value of 1.0 does not affect the velocity curve; however, values greater than 1.0 magnify an acceleration, while values less than 1.0 exaggerate a deceleration. The start (v_0) and end (v_1) velocities[2] default to 0. Increasing v_0 generates movements with anticipation, where the hand pulls back before extending in preparation for a Strong movement. Decreasing v_1 generates movements with overshoot, such as in Free movements where an indulgence in flow causes one to swing out past a target before hitting it. We set t_0 to 0.01 and t_1 to 0.99, which gives us natural-looking anticipation and overshoot effects; however, these values can easily be included in I as variable low-level movement parameters.

4.1.2.3 Flourishes

Flourishes are miscellaneous parameters that add to the expressiveness of the movements. These are listed below:

- Wrist bend is determined by the wrist bend multiplier *wbmag* and the wrist extension magnitude *wxmag*. The *wbmag* parameter is a multiplier that represents the magnitude of the wrist bend. If the *wbmag* is set for a flexed wrist, the wrist bend is set to 0.6 radians about the x-axis. Otherwise, the wrist bend is set using

$$wrist\_bend = wbmag * sin(2\pi(t'+0.75)) + 1 - wxmag) \quad (12)$$

  where $t' \in [0,1]$ and represents the normalized time between two keypoints. This results in a wrist that gradually bends inwards and back out. The value of *wxmag* shifts the sinusoidal graph, setting the beginning wrist extension to be positive (outward) or negative (inward).

- Arm twist is parameterized by wrist twist magnitude *wtmag*, wrist frequency *wfmag*, elbow twist magnitude *etmag*, and elbow frequency *efmag*. The wrist twist is measured in radians about the z-axis and is determined by:

$$wrist\_twist = wtmag * sin(wfmag * \pi t') \, . \quad (13)$$

  Elbow twist is set using a similar equation, replacing *wtmag* and *wfmag* with *etmag* and *efmag*, respectively.

- Displacement magnitude is a multiplier *dmag* that adds a sinusoidal displacement to the elbow angle

$$elbow\_angle = elbow\_angle * (1 + dmag * sin(2\pi t')) \quad (14)$$

  where t' is the normalized time between two keypoints.

4.1.2.4 Parameter Settings

To determine the mapping of the four Effort Elements into our low-level movement parameters, we first determined the default settings for each of the eight Effort Elements by trial and error using visual analysis and testing by a CMA. For example, the default interpolation space is set to elbow position for Indirect, joint angle for Free, and end-effector for the other Effort Elements. The default tension of the path curvature *Tval* is set to -1 for Indirect, +1 for Direct, and 0 for the other Effort Elements.

Once we had the default settings for the individual Effort Elements, we generated the range between opposing Effort Elements by interpolating continuous variables and using the nearest value for discrete variables such as the interpolation space. We note that these may lead to discontinuities in the animation if Space, Weight, or Flow cross zero when they are phrased across the keyframes. In [15], we show that such discontinuities occur only if the zero crossings occur at points that are *not Goal* keypoints, which is fairly uncommon in real human movements. In general, combinations of Effort Elements are achieved in a straightforward manner. The magnitude of an Effort Element is used to weight its contribution for a parameter setting. If more than one Effort Element contributes to a parameter setting, we take the maximum value of the weighted contributions. Several parameters undergo minor adjustments when combining Effort Elements from different motion factors.

Finally, we express our Effort model as a set of equations. Let the variables *ind*, *dir*, *lgt*, *str*, *sus*, *sud*, *fre*, and *bnd* represent the magnitudes for Indirect, Direct, Light, Strong, Sustained, Sudden, Free, and Bound, respectively. Each of these variables is in [0,1]. Variables within the same motion factor are related as such: if one Effort Element variable is positive, then its opposing Effort Element variable is zero. To adjust parameters for combined Effort settings, we use the function *f*:

$$f(a,b) = \begin{cases} a & a \le b \\ b & otherwise \end{cases} \quad (15)$$

Our model for translating Effort into low-level movement parameters is given by the following equations:

$$Tval = (-1 * ind + 1 * f(ind, fre)) + dir \quad (16)$$

$$wbmag = max(0.6 * ind, 0.5 * lgt, 0.4 * fre) \quad (17)$$

$$wxmag = -0.3 * \mathrm{lgt} + (0.3 * fre - 0.9 * f(str, fre)) \quad (18)$$

$$dmag = etmag = wtmag = 0.4 * ind \quad (19)$$

$$efmag = wfmag = 2 * ind \quad (20)$$

$$\begin{aligned} t_i = {} & 0.5 + 0.4 * max(str, sud) \\ & - 0.4 * max(lgt, sus) + 0.8 * f(bnd, lgt) \end{aligned} \quad (21)$$

$$v_0 = 0.1 * str - max(0.06 * f(sus, str), 0.1 * f(fre, str)) \quad (22)$$

$$v_1 = max(0.03 * max(lgt, sus), 0.2 * fre - 0.1 * f(ind, fre)) \quad (23)$$

---

[2] As mentioned, each movement begins and ends at rest. The start and end velocities represent shortly after the beginning or shortly before the end of a movement, respectively. They are so named to emphasize that they are not initial and final velocities, which remain 0.

$$\begin{aligned} texp = {} & 1 + 2*sud + (0.2*f(str, sud) - f(fre, sud)) \\ & - 0.2*max(str, f(dir, sus)) \\ & - 0.4*fre - 0.5*f(ind, fre) \end{aligned} \tag{24}$$

4.2 Expressive Torso

The underlying key poses of the torso involve, in fact, the neck joint, the spine, the pelvis and the two clavicle joints. The neck has 3 DOF, the spine has 17 joints with 3 DOF each, the pelvis has 3 DOF and each clavicle has 2 DOF. A key pose consists of angles for the neck, the pelvis, and the clavicles, in addition to the configuration of the spine [18]. When, for a particular keyframe, no pose information is provided, the system assumes a neutral posture, where all the angles are 0. We use an ease-in/ease-out curve to interpolate the angles in the keyframes and hence calculate the angles in the in-between frames. In summary, Shape changes essentially provide “squash and stretch” within the limits of a fixed segment length articulated skeleton.

4.2.1 Applying Shape to Torso Movements

As seen before, EMOTE allows the definition of Shape parameters for the torso corresponding to the Horizontal, Vertical and Sagittal dimensions, which are used to modify the key poses. Each parameter lies in a scale ranging from -1 to +1.

Our Shape model for the torso associates each main body dimension (upward/downward, sideward-open/sideward-across, and forward/backward) with specific parts of the body. We note that our Shape model was designed considering the available controls in our selected articulated figure model [18]. In particular, the torso could not be expanded and contracted for breath and other volume-changing movements. We based our Shape to body part associations on the suitability of each body part in producing changes in the form of the body in given directions. Thus, we associate the upward-downward direction with the neck and the spine; the sideward direction with the clavicles, and the forward-backward direction with the pelvis. Therefore, changes in the Horizontal dimension, which occur mainly in the sideward direction but also have a forward-backward component as the movement becomes planar, affect mostly the angles of the clavicles but also slightly alter pelvis rotations. Changes in the Vertical dimension, which are manifested primarily in the upward-downward direction but also have a sideward component in planar movement, affect mostly the angles of the neck and the spine but also change clavicle angles. Finally, changes in the Sagittal dimension, which are more evident in the forward-backward direction but also involve an upward-downward component in planar movement, mainly affect pelvis rotations but also change the angles of the neck and spine.

For each opposing attitude associated with the above dimensions (Spreading, Enclosing, Rising, Sinking, Advancing, and Retreating), we define maximum displacement angles for all the body parts that are affected by changes in that dimension. For instance, for the opposing attitudes in the Horizontal dimension, we define the following constants: *spreading_clavicle_angle*, *enclosing_clavicle_angle*, *spreading_pelvis_angle*, and *enclosing_pelvis_angle*. The first two angles represent clavicle rotations about the z-axis and the latter represent pelvis rotations about the y-axis.

For a particular keyframe, let the variables *spr*, *enc*, *ris*, *sin*, *adv*, and *ret* represent the magnitudes for Spreading, Enclosing, Rising, Sinking, Advancing, and Retreating, respectively. Each of these variables is in [0,1]. Variables referencing the same dimension are related such that if one variable is positive, then its opposing variable is zero. We modify the angles in the key pose by adding the weighted contribution of all the dimensions that affect the particular body part being considered. For instance, if the clavicle rotation about the z-axis is represented by the variable *clavicle_angle* and the pelvis rotation about the y-axis is represented by the variable *pelvis_angle*, then we modify those angles as follows:

$$\begin{aligned} clavicle\_angle = {} & clavicle\_angle \\ & + ris*rising\_clavicle\_angle \\ & + sin*sinking\_clavicle\_angle \\ & + spr*spreading\_clavicle\_angle \\ & + enc*enclosing\_clavicle\_angle \end{aligned} \tag{25}$$

$$\begin{aligned} pelvis\_angle = {} & pelvis\_angle \\ & + spr*spreading\_pelvis\_angle \\ & + enc*enclosing\_pelvis\_angle \\ & + adv*advancing\_pelvis\_angle \\ & + ret*retreating\_pelvis\_angle \end{aligned} \tag{26}$$

where *rising_clavicle_angle* and *sinking_clavicle_angle* are the maximum displacement angles of the clavicles corresponding to the opposing attitudes towards the Vertical dimension, and *advancing_pelvis_angle* and *retreating_pelvis_angle* are the maximum displacement rotations of the pelvis corresponding to the opposing attitudes towards the Sagittal dimension.

5. EXAMPLES

To demonstrate the power of our approach to gesture we have created a series of animations shown on the accompanying video. All the examples were generated in real-time. The first series of animations are all generated from the same set of key poses and try to mimic an actor during an actual performance. We vary the values of the Effort and Shape parameters across the animations and show how these variations can completely alter the meaning of the dramatization enacted by the synthetic actor. By suppressing its Shape parameters, we also show the important role that the torso plays in gesture and in the depiction of a convincing character.

The second video series emphasizes the slight differences in dynamic qualities of movements superimposed on American Sign Language phrases (from an ASL sign library) and tries to capture the nuances of meaning represented by these differences.

The movement of the hands in the video is implemented using forward kinematics and linear interpolations.

6. DISCUSSION

Our EMOTE computational model of Effort and Shape components allows the animation of characters with natural-looking gestures through the usage of high-level parameters that represent qualitative aspects of movements. By using EMOTE interactively we hope to avoid the hassle that the animator goes through while working with a large number of low-level parameters. In order to further assess the advantages of using Effort and Shape parameters from the perspective of user interaction, formal methods of evaluation of our approach should be devised.

We did a preliminary evaluation of the Effort Elements of EMOTE [15]. Using a stylized character with head, arms, and hands, we created a 16-minute video of randomly selected Effort Elements. In the first part of the tape, Effort gestures with 16 two-keypoint and 16 five-keypoints were paired with a neutral (no Effort Element) animation. The second part of the tape consisted of 30 long (5 keypoint) animations with various Effort combinations. The tape was given to 3 CMAs and the project consultant CMA. They were asked to view it once to get a feeling for the presentation and then a second time while marking a coding sheet. They were asked to mark the primary overall Effort Element(s) they observed as present (-1 or 1) or neutral (0).

The results are presented in Table 4. The first row indicates the percentage of correct responses – where the CMA either marked the Effort that we were trying to display in the animation or marked neutral when we were trying to display neutrality along a given motion factor. The second row indicates the percentage of neutral responses – where the CMA marked neutral when we were trying to display an Effort or where the CMA marked an Effort when we were trying to display neutral along a give motion factor range. The third row indicates the percentage of opposite responses – where the CMA marked the Effort opposite from the one we were trying to portray. The low but significant percentage of neutral responses is partially attributed to the fact that most of the animation segments on our video showed *combinations* of the Effort Elements – thus, a more prominent Effort may have masked other displayed Effort Elements.

One consequence of this experiment for us was to increase the maximum movement rate for the limbs. For example, the Sudden movements did not appear fast enough to trained observers. Also, the Shape elements were not included in this experiment. Note that the normal CMA observer situation is to watch motions repeatedly; by limiting their samples to two we were forcing them to pick distinctive Effort features in a slightly unnatural setting. The results were encouraging enough, however, for us to proceed with refinements to the Effort Elements and the incorporation of the torso and Shape components.

	Consultant	**CMA 1**	**CMA 2**	**CMA 3**
Correct	76.6	55.6	53.2	60.1
Neutral	22.6	38.7	39.1	37.1
Opposite	0.81	5.6	7.7	2.8

Table 4: Overall Percentages for Effort Element Evaluation

Our attempt to bridge the gap between characters manually animated and characters animated by procedures establishes a new layer in the motion control process in which expressiveness is represented by a small number of parameters. We expect that this layer of control will give rise to yet another layer, where characters controlled by natural language commands show different performances according to adverbs that convey manner. These adverbs should be automatically mapped into Effort and Shape parameters. For example, "carefully" might translate into Light and slightly Sustained Effort portrayed during arm movements and a little Retreating Shape displayed by the torso; "proudly" might translate into a Rising posture. Furthermore, we expect to find connections between emotions and personality and our high-level parameters and so be able to synthesize movements that reflect these inner states.

7. CONCLUSIONS

We have introduced a new approach to procedural human animation that tries to close the gap between characters animated by the use of manual techniques and characters animated procedurally. This approach goes beyond the realm of psychology of gestures and linguistic-based approaches by exploring the domain of movement observation. This approach uncovers the movement qualities, which can be combined together to reveal different manners, inner states, personalities and emotions. The EMOTE approach to gesture proposes a computational model of the Effort and Shape components of Laban Movement Analysis and associates with each one of their dimensions numerical parameters that modify pre-defined movements.

Two other important aspects of EMOTE are inspired by the tenets of movement observation. The first is the ability to phrase Effort and Shape parameters across a set of movements. We believe that a character's gestures should be phrased similarly to communicative phrasing with an expressive content consonant with the principal utterance; for example, a strong accent in speech should be correlated by a strong Effort in gesture. Since Effort plays a key role in the interpretation of a character's action, a gesture must display Effort qualities that match his/her intentions, motivations, and mood. Otherwise, the character's message appears conflicted and confused. Furthermore, EMOTE reflects our belief that, even if a character moves its arms with appropriate gestures, it will lack conviction and naturalness if the rest of the body is not appropriately engaged. If the empirical principles of movement science hold up when transformed into computer code implementations, we should be able to animate engaging, committed, expressive, and believable characters consistently and automatically.

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