The Case for Physics Visualization in an Animator's Toolset

Ari Shapiro, Andrew W. Feng
Institute For Creative Technologies
University of Southern California
shapiro, feng@ict.usc.edu

Keywords: physical simulation, character animation

Abstract: By associating physical properties with a digital character's joint and bones, we are able to visualize explicitly a number of properties that can help animators develop high-quality animation. For example, proper ballistic arcs can be shown to demonstrate proper timing and location of a character during flight. In addition, a center of mass that accurately reflects the posture of the character can be shown to help with a balanced appearance during walking or running. In addition, motion properties not previously considered, such as angular momentum, can be easily identified when blatantly violated by an animator. However, very few in-house or commercial system employ such tools, despite their nearly transparent use in an animator's workflow and their utility in generating better-quality motion. In this paper, we argue the case for incorporating such toolset, describe an algorithm for implementing the tools, and detail that types of uses for such a tool.

1 MOTIVATION

Techniques for animating characters in both visual effects and fully digital features have seen only incremental improvement in the recent past. While high quality motion, such as that generated via motion capture, can be used under limited circumstances, much character animation is still created through hand-constuction by animators, often using video or motion capture as reference. The resulting motion quality of character animation varies greatly according to the skill of the artist; expert animators can produce high-quality motion, while novice animators often produce low-quality motion. The tools traditionally used for generating character animation have changed very little; curve editors, key-framing capabilities and inverse kinematics chains. Many animation passes are required in order to convincingly animate the proper parts of the character with increasing amounts of detail. These traditional tools are focussed on kinematic movement; movement of a character in space over time, and generally do not restrict the ability of the animator to create any arbitrary movement, even non-physical ones. The flexibility of these animation tools make it quite easy for even a non-skilled user to produce some kind of character movement, albeit low in quality. The high quality character animation seen in visual effects and 3D scenes is produced through painstaking efforts of coordinating movements of the character's joints by restricting such movements to those that appear natural or appropriate the scene. In fact, great efforts are spent to make characters appear balanced in their poses, fluid in their movements, and to demonstrate an implied sense of mass. Many seminal animation principles such as squash-and-stretch, anticipation and follow-through are intended to guide animators towards generating motion that loosely obeys the laws of physics, since doing so has been shown to produce more pleasing animation results. Oddly, very few of such tool sets have attempted to incorporate physical parameters explicitly, such as body masses, moments of inertia. By including these physical parameters into an animator's toolset, an animator can get explicit feedback towards generating motion that better adheres to the basic principles of animation. For example, consider the following exerpt from Richard Williams' "The Animator's Survival Kit" p. 36 (Williams, 2009)when explaining the principle of spacing by using a bouncing ball:

"The ball overlaps itself when it's at the slow part of the arc, but when it drops fast, it's spaced further apart. That's the spacing. The spacing is how close or far apart those clusters are. That's it. It's simple, but it's important. The spacing is the tricky part. Good animation spacing is a rare commodity."

Here Williams points out that it is difficult to do spacing well through traditional hand-drawing meth-

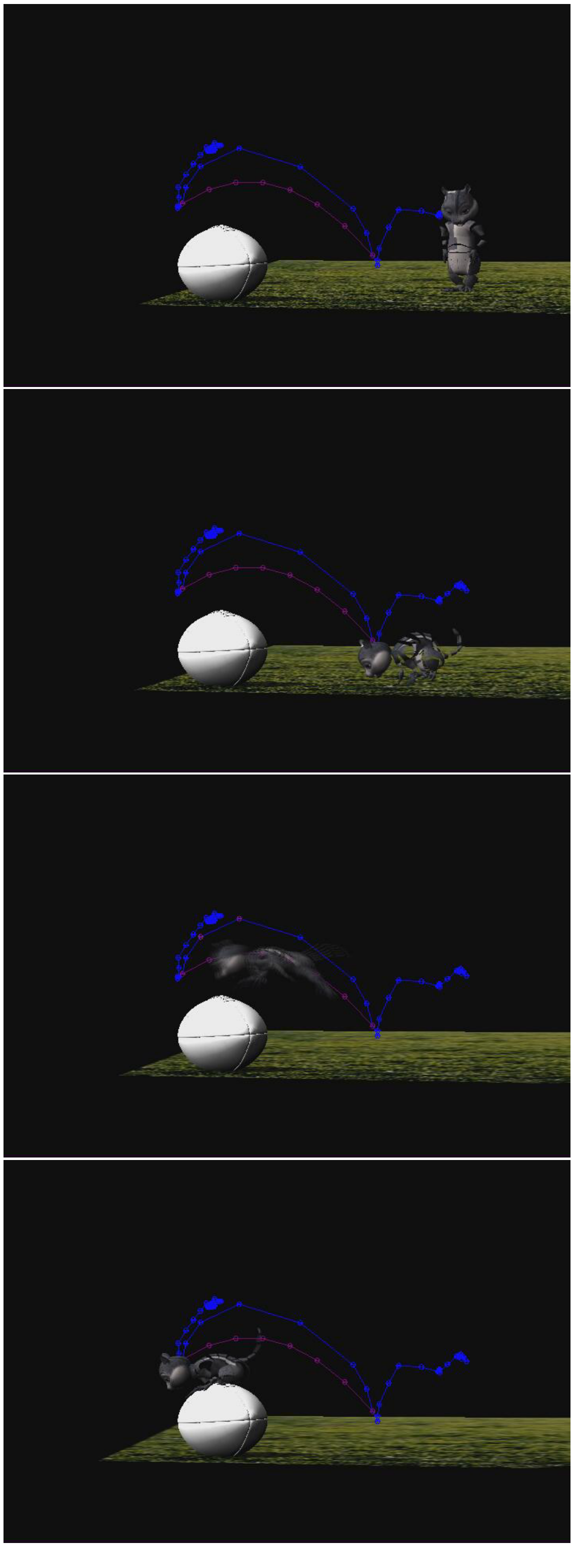

Figure 1: Visualization of physical properties of a digital character. Shown in blue is the original path generated by an animator. Shown in red is the path generated by the tools after consider the mass and moment of inertia of the character. Note that the timing (knots) and the path are visibly different from each other. By incoporating such visualization tools into an animator's workflow, better coherence between animations can be achieved, in addition to creating more plausible motions.

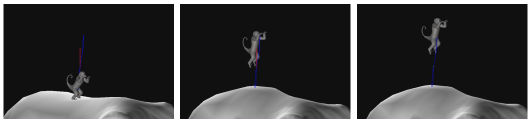

Figure 2: Timing during a jump. Here a monkey jumps up and down on a giant octopus. The blue line indicates the original path and timing from the animator. The red line indicates the proper timing according to physics. The middle image shows the maximum height of the monkey during the jump timed according to physics and gravity. The bottom image shows the maximum height of the monkey as determined by the animator. Note that the poses created by the animator remain intact and are not changed by the physics tools, thus preserving the level of control for the animator.

ods. Likewise, it is also difficult, although can be done more quickly with kinematic toolsets. Without incorporating dynamical information, the animator would not know either the exact center of mass, nor the effect of gravity on the ball. The absence of explicit physical parameters forces the animator to guess the effect of physics on a character.

2 BACKGROUND

Applying physics to synthesize character animation is an ongoing research area for computer graphics, and in recent years has achieved interesting results (Ye and Liu, 2012; Coros et al., 2011). These techniques vary from creating dynamic control mechanism (Wang et al., 2012; Mordatch et al., 2010), to using optimization (Liu, 2009; Mordatch et al., 2012; Jain et al., 2009; McCann et al., 2006), to machine learning (Levine et al., 2012; Wang et al., 2008) and even sketching interfaces (Popović et al., 2003). However, the overall motion quality of such techniques falls well below the threshold needed for visual effects or feature films. In fact, even motion capture data is frequently not used directly in feature films since the timing and positioning of each shot is specific and subject to the whim of the director or animation lead. Instead, such motion clips are used as a visual reference, then replicated by an animator digitally. In addition, generating physically valid character motion typically requires setting many unintuitive parameters, as the impact of such settings has a global effect on the final simulation.

In addition, the process of creating animation is a creative process with a history extending long before the advent of the digital pipeline. Animators are trained on a traditional 3D pipeline and toolset, and changes to such a workflow are not easily accepted. Even when a new method could be used in place of traditional animation method, there can be resistance from animators to changing their pipeline unless the results both clearly superior and simultaneously require little or no change in their workflow. Thus the integration into a production pipeline is as important a factor as is the method itself. An animator requires a non-invasive tool that does not change his creative process while providing him enough control over the final outcome. Tight communication between the tool creators and the users are essential for the tool to be useful for an animator's creative process.

Indeed, the animation phase typically runs in a contrary fashion to the other pipeline phases. For example, when lighting a scene, the normal lighting equations would be applied which are roughly based on physical phenomenae, then later altered to achieve specific lighting effects. Thus lighting starts from being realistic, then changes (perhaps becoming less realistic or less physically-based) to accommodate the needs of the scene. The same goes for other types of simulation; a rigid body simulation will be run using normal physical settings (such as earth-like gravity and non-penetration constraints) and then altered according to the needs of the scene, perhaps satisfying fewer physical phenomenae. Even modellers will start with a scan and texture of a real object, then alter that object for its specific use in the shot. By contrast, an animator will start from a non-moving character, then perform rough animation, then slowly refine the animation until it is acceptable for the shot. Thus, unlike the other pipeline steps, animation starts from an unrealistic form, and then is fashioned to become more realistic. The effect is that models, particle effects, lights, backgrounds and other static aspects of digital or digitally enhanced scenes can look highly realistic, yet cartoony, non-plausible animation is readily identified on the characters in the scene and a pervasive aspect of modern digitially produced results.

To our knowledge, very few efforts have been done to integrate simulation tools into an animator's pipeline to help an animator produce physically realistic motions.

3 IMPLEMENTATION OF PHYSICS VISUALIZATION INTO AN ANIMATOR'S WORKFLOW

To implement a physics-based visualization, each of the character's joints must be associated with three additional properties that are not typically present in most character rigs; mass, moment of inertia and density. Many character rigs include a rigid skinning, as opposed to a smooth skinning, where each joint is associated with a polygonal geometry. By using such a rig, the calculation of physical properties can be automated:

- Determine the volume of the polygonal shape
- Determine the mass of the joint/bone by multiplying the density by the volume calculated in Step 1
- Determine the moment of inertia by sampling the polygonal object

Note that while this automated method will generate values for each joint, some adjustments will need to be made, particularly if the size of the polygonal geometry associated with each joint is out of proportion with the character's true dimensions. For example, cartoon-like characters can often have large heads, and assuming that the entire polygonal structure is of uniform density can yield exagerated results. Such exaggerations can be determined by observing the final center of mass. A large head will cause the center of mass to be very high up the character's body. Similarly, misproportioned limbs can result in a wildly varying center of mass during movement. In most cases, adjusting the density of each joint can bring the relative values of each body part in better balance with each other.

Details of implementing visualizations of linear and angular momentum can be found in (Shapiro and Lee, 2011).

4 ADVANTAGES OF PHYSICS VISUALIZATION

By incorporating dynamics-based parameters into an animator's toolset, new insight is gained into proper ballistic arcs, conservation of angular momentum, balance and scaling. This is done by associating a joint in the skeleton hierarchy with both mass and moment of inertia. Once such parameters have been added to a character, the following visualizations can be seen explicitly by the animator:

1) *Proper arcs during flight.* The law of conservation of linear momentum implies that all objects moving through space will fall according to gravity and their initial velocities, assuming no other forces affect them in flight. Thus, accurate ballistic paths for both simple objects, such as balls, or complex objects such as characters, can be easily generated by an animator by specifying both a start and an end point. The

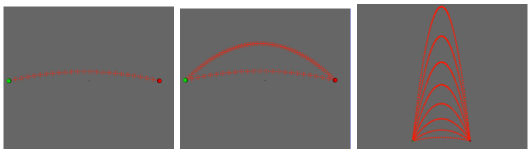

Figure 3: Proper paths as dictate by physics and gravity. (Left image) An object travels from the red sphere on the left side to the red sphere on the right side, with each circle represents the position of the center of mass of the object in 1/24 second increments. Note that there is only one proper path that travels the distance in exactly one second. (Middle image) A second path can be designed to move from the green ball to the red ball, but it will take more time to do so, since space and time are interconnected. (Right image) There are an infinite number of paths that can be taken, but each takes a different amount of time. It is not common knowlege in the animation community that there is only one valid time for each ballistic path.

tool can then produce physically correct ballistic trajectory through simple computation based on initial position **a**, initial velocity **b**, and gravity **g** using Eq. 1.Such a tool can be used to rough an animation of a character jumping or falling from a great height, or the calculation can be reversed in order to determine where a character originated from in order to land into the foreground of a scene.

$$\mathbf{r}(t) = \mathbf{a} + t\mathbf{b} + \frac{1}{2}Mt^2\mathbf{g} \tag{1}$$

2) *Proper timings during flight.* While the shape of a ballistic arc can be reasonably duplicated without physics-based tools, it is difficult to replicate proper timing of a character's movement along such a path. Thus, while an animator may create a proper path for a character to follow, the timing may be inconsistent, or overly slow or fast for the size of the object. In fact, the idea that space and time are interconnected, and thus, under realistic conditions, an object has only one time that is appropriate for a given path, is not widely known in the animation community, see Figure 3. The timing of a path contributes greatly to its plausible effect. Animators have a tendency to exaggerate the final phase of a jump or fall in order to demonstrate the increased energy of the character during this part of the movement. Proper timings along ballistic arcs can be generated that properly match the energy of the moving characters, while maintaining an energetic appearance.

3) *Proper center of mass.* Many animation rigs either implicitly or explicity contain a center point for the character, meant to indicate the center of mass, or balance point of the character. However, the true center of mass of a character varies according its instantaneous pose. For example, if a character is kneeling with his arms extended, the center of mass of such a character is in fact outside and in front of his body. Likewise, during some phases of a jump, a character's center of mass is behind the character (see Figure 5.) Thus, a proper center of mass varies from frame to frame, and cannot be considered to be a fixed point. Thus, showing the center of mass of a character on the ground in front of them can assist an animator with balance during high-energy activities, such as walking or running. In addition, characters can follow realistic-looking paths while doing flips in the air, see Figure 4. Without a dynamically-changing center-of-mass, a flipping character will not follow a proper path.

Figure 4: A character does a flip during a jump. Note that the original animated path (blue) shows inconsistent movements during the flipping motion. This is caused when the animator refers to a static center that doesn't adjust based on pose changes, rather than the true center of mass. The physics-based path produces a proper ballistic arc.

4) *Proper Rotations During Flight.* The law of conservation of angular momentum implies that the angular momentum of a rotating object will be preserved. Practically, this means that the sum of all rotations of a character need to remain constant during flight phases. Angular momentum can be visualized by a line segment derived from a vector, showing both direction and magnitude extending from the center of mass of the character (see Figure 6.) While there is no easy method to fix problems with angular momentum, severe violation of the law of conservation of angular momentum can be seen through sudden changes in the direction of the line segment, such as switching from one direction to the opposite one. Such violations frequently occur during character jumps for the following reason; animators are trained to bring the feet of their characters forward in preparation of a landing, but are not trained to counterbalance the forward movement of a character's legs with movement of the character's arms in the opposite direction. Thus, many hand-tuned animations of jumping character show reverses in the angular momentum of

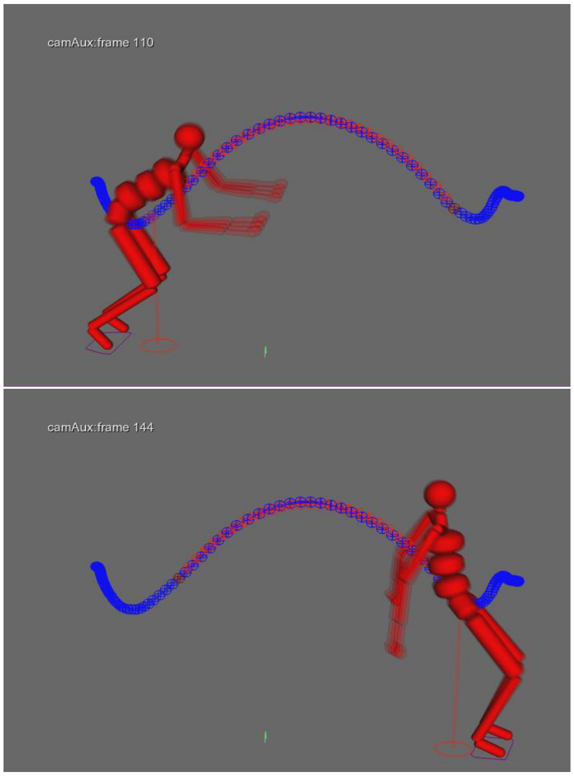

Figure 5: Visualization of a motion-captured jump. The blue arc indicates the actual path of the characer, while the red arc indicates the physics-based path according to the model. (Left image) The red line projecting the the ground represents the center of mass of the character. Notice that during the takeoff phase, the center of mass is in front of the character. (Right image) The character during the landing phase of the jump. Notices that the center of mass is now behind the character since most of the character's mass (arms, torso) are behind the character for a moment during the last phase of the jump for another frame. This demonstrates the dynamic nature of a character's center of mass that cannot be accurately represented as a fixed point on a character rig.

a character during flight (see Figure 7.). Such subtleties of animation are not easily discerned even by highly trained animators, since such rules of physics are not widely taught. A tool can correct the character's angular momentum $\mathbf{h}$ based on velocity $\mathbf{v_i}$, inertia $\mathbf{J_i}$ from each body part i, to the desired momentum h^* by adjusting character's global orientation at each key frame. However, proper correction of angular momentum requires a greater understanding of strategies that humans and other animals use to orient themselves during flight, such as windmilling arms or other appendages like tails.

5) *Proper treatment of character scale.* The size of a character affects the movement of character, and the speed of movement is used by the human mind to

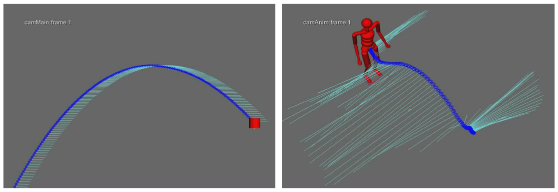

Figure 6: (Top image) Visualization of angular momentum for an object in flight that rotates counter clockwise. Angular momentum can be visualized as the blue line segment representing the axis of rotation extending from the center of mass of the object. Note that during the entire flight phase of the object, the momentum remains in the same direction and is the same length. This indicates that the axis of rotation is the same, and the momentum doesn't change. (Bottom image) Visualization of angular momentum of a motion-captured character during a jumping motion. Notice that during the flight phase, the axis of rotation is generally in the same direction. The magnitude (length) changes, but this is due to inaccuracies in the physical modeling, and noise during motion capture.

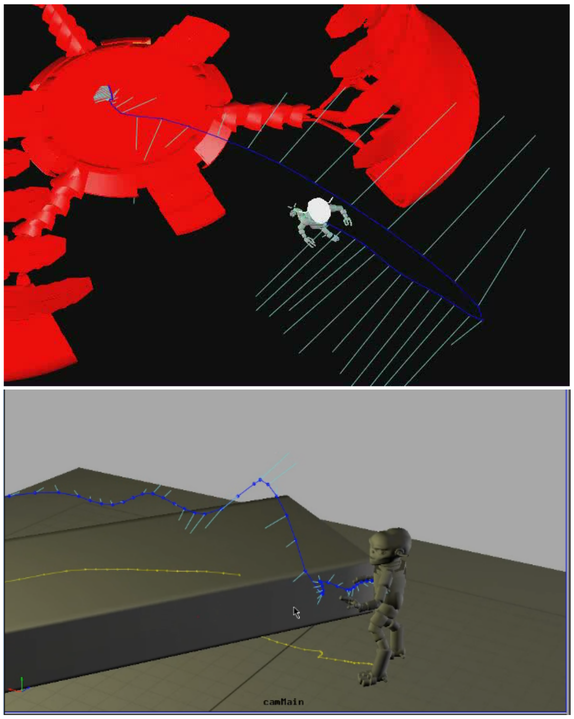

Figure 7: (Top image) A character is hit with a projectile and is throw backwards onto the red machine. Notice that near the end of the motion, the character's axis of rotation switches from one side to the other, indicating an impossible in-flight rotation. Subtleties like this momentum switch can be easily visualized by animators. (Bottom image) A character jumps onto a platform. Notice the switch in rotation direction during flight. This particular example is caused by failing to bring the arms down to counterbalance moving the legs forward.

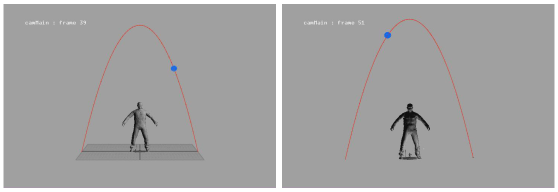

Figure 8: (Left image) A ball being thrown to the height of 15 feet above a normal-sized person's head, which takes slightly more than 2 seconds to complete (Right Image) A ball being thrown 150 feet above the head of a 60 foot giant, which takes slightly more than 6 seconds to complete. Note that we can determine the relative sizes of the characters by the speed of their motion.

determine the size of an object. Given two objects that occupy the same amount of visual space on a screen, we can determine which one is larger by the speed of its movement and the relative speed of movement of nearby objects. Since gravity affects objects in a nonlinear way, a simple heuristic can be determined that indicates how motion should be scaled according to its size: square root of scale factor. Specifically, we can determine the time t required for for an object to travel to height h using Eq. 2. In other words, objects that are four times as large should appear to move twice as slowly (Pollard, 1999). The correct treatment of the motion scale is a common pitfall for an animator. Since animators are most familiar with motion of a human scale, they usually produce physically incorrect motions for very large characters. The impact of this mismatch between size and speed can be readily seen in numerous feature films and clips that include giant-sized characters, often moving at the speed of normal-sized ones.

$$t = \sqrt{\frac{2h}{g}} \tag{2}$$

6) *Uniform treatment of characters by numerous animators*. Live-action films and animated movies often utilize dozens of animators in parallel who often work on the same digital characters in different shots in order to meet the deadline of the project. Thus, the movement of a single digital character can be interpreted differently by any number of animators designing their motion. While some processes are set up in order to reach uniformity, such as dailies sessions, these processes are often subjective. Physics-based tools allows each shot to be annotated with various physical paths, balance points, and momentum markers. Thus, it can become easier to evaluate the same character across multiple shots when constructed by different animators.

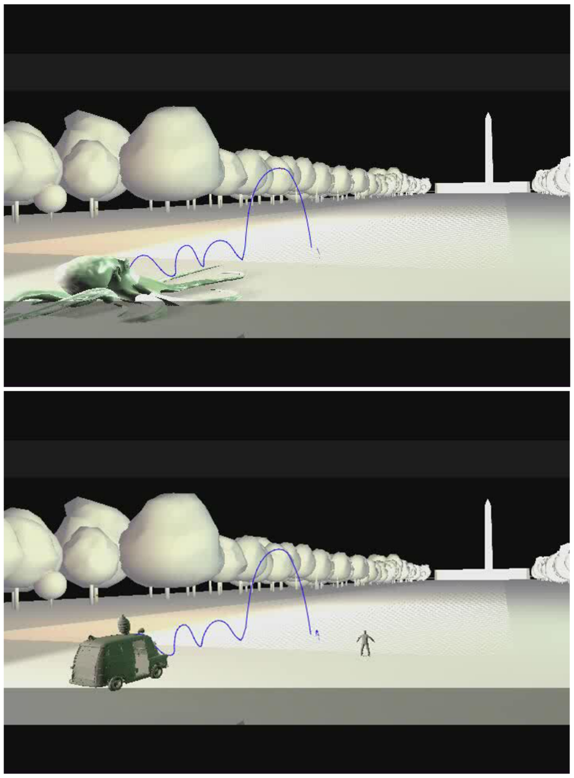

Figure 9: A large octopus jumping 25 feet across and 15 feet high into a pool of water. The octopus in this scene is very large, but is animated as if it is very small, thus violating physical plausibility. By replacing the giant octopus with a more familiar object of the same size, the discrepency between the size of the object and the motion becomes clear to the animator.

7) *Synchronization of Digital Character's With Live Actors and Physics-Based Effects* Often times, digital characters occupy the same scene as live actors. Thus, disparities between the quality of motion of a live actor and a digital actor can be obvious to the viewer. Thus it is to the animator's advantage to understand the impact of real world physics on a live actor, and thus on the digital character as well. In addition, many visual effects are generated from algorithms that incorporate rules about the physical world, such as rigid body simulations, water and particle effects, and so forth. Thus there are occassions where maintaining a character's physical validity is important to the shot when combined with such effects. For example, if a character and an object are both moving through the air, they should obey similar motion rules.

5 DISCUSSION

The inclusion of physical parameters, such as mass and moment of inertia into a rigged character can produce visualizations of the center of mass, linear and angular momentum and ballistic paths. While physically valid motion does not always appear more visually appealling than non-physically valid motion, there are many cases where it does improve the quality of perceived motion(Shapiro and Lee, 2011). In addition, the presence of changes in rotation during flight can be clearly seen only with the incorporation of such tools. We believe that increased awareness of problems with angular momentum will result in higher-quality animations once the animation community develops rules or guidelines for correcting such problems. In addition, the advent of such tools into an animator's pipeline can be done inobtrusively; a button can be pressed by the animator to render a non-destructive path against which the current animation is compared. The animator still retains control over all aspects of the animation.

One argument against the use of physics-based tools in character animation states that a film or movie is an artistic endeavor and the presence of physically-valid motion does not necessarily make the animation look more visually appealling. Indeed, it is sometimes desirable to exagerate motion in order to convey a particular character motion or storytelling idea. While this is true, the ability to compare an animation against the natural world can lead to better motion quality quickly under certain circumstances. So while physically realistic motion is not always needed, it is helpful to understand it for comparison. In addition, many classic animation texts refer heavily to physical phenomenae, and develop rules for mimicking them, such as squash-and-stretch, anticipation, spacing and so forth.

The authors have noticed that animators have expressed the greatest amount of trepidation about physics-based visualizations when discussing characters of large scale. Physics-based examples of large objects and creatures are generally at odds with an animators sense of space and time for large objects. The authors believe that this is due to a lack of familiarity with large creatures (such as fifty-foot tall characters) in the real world. We don't see giants in this world, and thus it is difficult to imagine what their movements look like. Thus, large creatures are often animated as if they are much smaller, often human-sized. While it is arguable what this motion should look like from an artistic standpoint, the application of physics reveals how such creatures would likely move were they to exist in our world. The authors believe that the use of such tools for large creatures will result in improved quality motion once these techniques become widespread.

REFERENCES

Coros, S., Karpathy, A., Jones, B., Reveret, L., and van de Panne, M. (2011). Locomotion skills for simulated quadrupeds. *ACM Trans. Graph.*, 30(4):59:1–59:12.

Jain, S., Ye, Y., and Liu, C. K. (2009). Optimization-based interactive motion synthesis. *ACM Transaction on Graphics*, 28(1):1–10.

Levine, S., Wang, J. M., Haraux, A., Popović, Z., and Koltun, V. (2012). Continuous character control with low-dimensional embeddings. *ACM Transactions on Graphics*, 31(4):28.

Liu, C. K. (2009). Dextrous manipulation from a grasping pose. *ACM Transactions on Graphics (SIGGRAPH)*, 28(3).

McCann, J., Pollard, N., and Srinivasa, S. (2006). Physics-based motion retiming. In *Proceedings of the 2006 ACM SIGGRAPH/Eurographics symposium on Computer animation*, pages 205–214. Eurographics Association.

Mordatch, I., de Lasa, M., and Hertzmann, A. (2010). Robust physics-based locomotion using low-dimensional planning. *ACM Trans. Graph.*, 29(4):71:1–71:8.

Mordatch, I., Todorov, E., and Popović, Z. (2012). Discovery of complex behaviors through contact-invariant optimization. *ACM Trans. Graph.*, 31(4):43:1–43:8.

Pollard, N. (1999). Simple machines for scaling human motion. In *In Proceedings of Computer Animation and Simulation '99*.

Popović, J., Seitz, S. M., and Erdmann, M. (2003). Motion sketching for control of rigid-body simulations. *ACM Trans. Graph.*, 22(4):1034–1054.

Shapiro, A. and Lee, S.-H. (2011). Practical character physics for animators. *Computer Graphics and Applications, IEEE*, 31(4):45 –55.

Wang, J. M., Fleet, D. J., and Hertzmann, A. (2008). Gaussian process dynamical models for human motion. *IEEE Trans. Pattern Anal. Mach. Intell.*, 30(2):283–298.

Wang, J. M., Hamner, S. R., Delp, S. L., and Koltun, V. (2012). Optimizing locomotion controllers using biologically-based actuators and objectives. *ACM Trans. Graph.*, 31(4):25:1–25:11.

Williams, R. (2009). *The Animator's Survival Kit–Revised Edition: A Manual of Methods, Principles and Formulas for Classical, Computer, Games, Stop Motion and Internet Animators*. Faber & Faber, Inc.

Ye, Y. and Liu, C. K. (2012). Synthesis of detailed hand manipulations using contact sampling. *ACM Trans. Graph.*, 31(4):41:1–41:10.