Perceptual Metrics for Character Animation: Sensitivity to Errors in Ballistic Motion

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Abstract

Motion capture data and techniques for blending, editing, and sequencing that data can produce rich, realistic character animation; however, the output of these motion processing techniques sometimes appears unnatural. For example, the motion may violate physical laws or reflect unreasonable forces from the character or the environment. While problems such as these can be fixed, doing so is not yet feasible in real time environments. We are interested in developing ways to estimate perceived error in animated human motion so that the output quality of motion processing techniques can be better controlled to meet user goals.

This paper presents results of a study of user sensitivity to errors in animated human motion. Errors were systematically added to human jumping motion, and the ability of subjects to detect these errors was measured. We found that users were able to detect motion with errors, and noted some interesting trends: errors in horizontal velocity were easier to detect than errors in vertical velocity, and added accelerations were easier to detect than added decelerations. On the basis of our results, we propose a perceptually based metric for measuring errors in ballistic human motion.

CR Categories: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Animation

Keywords: animation, motion capture, evaluation, perceptual metrics

1 Introduction

Realistic animation of human characters is important for applications ranging from entertainment and training to communication across a distance. For full-body motions, a high level of realism can be obtained from motion capture data. However, techniques that are used to process this data, such as blending, warping, and splicing, can sometimes produce unrealistic results.

Artifacts such as foot sliding and interbody penetration are well known. Other artifacts, however, are less frequently considered. For example, many types of processing can result in motion that violates the laws of physics. Changing the height of a jump, for example, changes the effective gravitational constant.

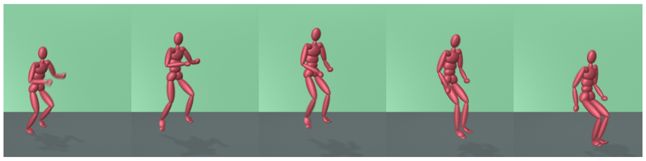

Figure 1: Example of a motion used in our study.

Many such errors may go unnoticed by the average viewer. A mechanism for estimating perceived error would be useful for evaluating processing techniques, constructing motion graphs, and managing time spent refining animations to make them optimal or physically correct. In addition, good perceptual metrics could allow automatic motion generation to be used in applications where high confidence in the quality of output is required, such as a training simulation.

This paper presents the results of a study of user sensitivity to errors in the ballistic phase of human jumping motion. Errors were added to motion captured jumps by manipulating the translational velocity of the center of mass in a systematic way, and user sensitivity to these errors was measured. We found that sensitivity varied with the level and variety of error added and that a significant level of error may be acceptable for many applications. Our specific results are subject to many factors, such as the complexity of the geometric model we used for testing [Hodgins et al. 1998]. However, for the specific circumstances of our test, we define a perceptual metric for evaluating translational errors in animated ballistic human motion.

2 Background

Prior work on perception of human motion in a computer graphics context has focused on the effect of animation quality on user perception. Hodgins and her colleagues [1998] added anomalies to a running motion and were able to show that for the types of anomalies tested—variations in torso rotation, arm swing magnitude, or additive noise—subjects were more sensitive to these variations when the character was rendered using a polygonal model than when a stick figure was used for rendering. Oesker et al. [2000] showed that perceived skill level of animated soccer players increased when more detailed and realistic motion was used for the players.

Perception of physically unrealistic motions has been studied for rigid bodies and simple mechanisms. It is generally acknowledged that people perform poorly on abstract physical reasoning tasks [Proffitt 1999]. Animation has been shown to improve performance [Kaiser et al. 1992] [Hecht and Bertamini 2000], but good performance is observed only for simple motions. In the study of Kaiser et al., for example, animation improved performance for discriminating correct and incorrect ballistic motion of a spherical body, but anomalies in a spinning motion that involved changing inertia (a satellite with extending and retracting solar panels) were not identified unless the spinning motion completely stopped or re-

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versed direction. Degradation of performance with complexity was also noted by O'Sullivan and Dingliana [2001], who showed that anomalies in collisions between complex objects were more difficult to detect than anomalies in collisions with spherical objects.

Point light experiments are also relevant. Researchers have found that observers can make very fine discriminations when presented with a sparse representation of actual human motion, for example accurately estimating lifted weight [Runeson and Frykholm 1981] and pulled weight [Michaels and de Vries 1998] from point light displays. It is argued that a high level of performance is possible because the relevant complexity of the motion is small; the weight of the manipulated object correlates well with observable parameters such as elbow velocity [Bingham 1987] or center of mass position and velocity [Michaels and de Vries 1998].

Our goal was to measure sensitivity to errors in animated human ballistic motions and to develop an error metric based on our results. Looking at results of previous perceptual experiments, we were uncertain how well subjects would perform. In some sense this task is simple; observation of center of mass velocity over time is sufficient to identify errors, and it seemed intuitive that user sensitivity might be high, as it is for estimating lifted weight and for simple physical reasoning problems. However, it seemed equally plausible that people would be forgiving of human motion with significant errors in center of mass behavior (i.e., incorrect overall physics) if the details of the motion were sufficiently realistic.

3 Experiment: Errors in Ballistic Motion

We chose to study motion containing a flight phase because error in ballistic motion can be controlled easily and anomalies in ballistic motion are a common result of motion processing techniques. Once the character has left the ground, the trajectory of the center of mass is fully determined. Any changes to that trajectory violate the laws of physics. Such changes can result, however, when motions with differing root velocities are spliced together, creating an anomalous acceleration, or when the effective gravitational constant changes as the result of an editing operation. An incorrect gravitational constant arises, for example, when the height of a jump is changed while timing remains the same. Scaling motion to characters of different sizes can also change the effective gravitational constant.

3.1 Method

Two studies were performed, the first to test perception of anomalous accelerations and decelerations and the second to test perception of errors in effective gravity.

3.1.1 Study 1: Acceleration

Participants. Participants were obtained by university-wide advertising. Five women and seven men ranging in age from 18 to 42 participated in the study.[1]

Stimuli. Animations of human jumping motions were created as stimuli. All animations were shown in the same rendering style, with the same (fixed) camera configuration (Figure 1), with the character beginning the motion at the same position and jumping in the same direction. Shadows were rendered, and a small amount of motion blur was added.

Errors were created by modifying human jumping motion obtained from optical motion capture. Seven different source motions were used. These source motions were performed by the same actor and were similar in overall character, although they varied in distance and height. Error variables were as follows:

- *Error level.* Small, medium, or large.
- *Error variety.* Horizontal or vertical.
- *Error direction.* Acceleration or deceleration.

To generate a horizontal acceleration error, for example, a fixed change in velocity was applied to the character root in the direction of horizontal motion. This change in velocity was added smoothly over a small window of time early in the flight phase of the motion. Details on how errors were created can be found in the Appendix.

Procedure. Participants were told that they would see a sequence of animated human jumping motions created from motion capture data. They were given some background information on how motion capture data is created and told that some of the motions they would see would contain errors. They were also told that all motions are jumps, slightly less than half have no error, and all errors would appear during the flight phase of the motion. Participants were then shown 12 representative motions. They were told that half contained errors but were not told which specific motions in this training set contained errors.

Tests were prepared by placing motions on video tape in random order. Two tapes were used. Tape order differed for different subjects, and no order effects were observed. Motions included each combination of error variables presented 3 times; an equal number of original motions; and 12 motions with composite errors. Composite errors included both horizontal and vertical acceleration and were introduced to test our intuitions about these interactions. Stimuli were presented on a projection screen in a small conference room. Participants were instructed to categorize each motion as either "no error (unchanged)" or "error" and mark their level of confidence in their answer using a rating scale that ranged from 0 (most confident an error is present) through 9 (most confident an error is not present).

At the end of the study, participants were asked to describe their experience in the study of motion, including involvement in sports, dance, video games, etc. No significant effect of level of experience was noted in the study. We also noted no significant effect due to gender.

3.1.2 Study 2: Gravity

Participants. Participants were obtained by university-wide advertising. Nine women and two men ranging in age from 19 to 29 participated in the study.[2]

Stimuli. Stimuli were prepared in the same manner as in the first study, with error varieties including increased and decreased gravity.

Procedure. The procedure was identical to that of the first study, except that all participants were shown one tape consisting of 60 motions, including 18 motions with gravity errors, 6 with vertical errors, 6 with horizontal errors, 4 with composite errors, and 26 with no errors. Motions with vertical, horizontal, and composite errors were included to test the validity of comparing data across studies, and performance was consistent with that observed in the first study.

3.2 Results

Figure 2 shows mean ratings for horizontal errors (top), vertical errors (middle), and gravity errors (bottom). Blue lines are acceleration (or decreased gravity) and green lines are deceleration (or increased gravity). Results are broken out by small, medium, and

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[1] One additional subject did not follow instructions and was excluded from the analysis.

[2] Three additional subjects did not follow instructions and were excluded from the analysis.

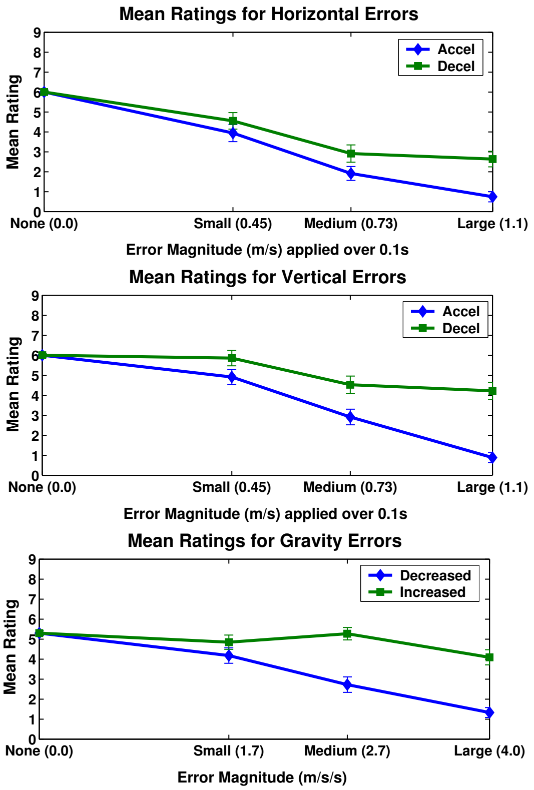

Figure 2: Mean ratings of motions with horizontal, vertical, and gravity errors. The mean rating for unchanged motions is plotted for reference. Each plot is broken out by error direction and error magnitude. Error bars show standard error of the mean.

large error levels. The plots show the mean ratings of motions at each magnitude of added error, including unchanged motions.

A repeated measures analysis of variance (ANOVA) was run for study 1 with 3 error levels x 2 error varieties (horizontal and vertical) x 2 error directions. All error treatments could be detected at $p < 0.01$ except for small vertical decelerations. A second ANOVA was run for study 2 with 3 error levels x 2 error directions. All error treatments could be detected at $p < 0.01$ except for small and medium levels of increased gravity.

No significant interactions were observed between error variety and error direction in study 1 or error variety and error level in either study. There was an interaction between error direction and error level (study 1: $F(2,426) = 5.7, p = 0.003$; study 2: $F(2,192) = 5.5, p = 0.005$). This interaction can be seen in Figure 2: added acceleration or decreased gravity is proportionately easier to detect for large errors. In addition, we found three main effects:

(1) Subjects found added acceleration easier to detect than added deceleration ($F(1,430) = 38.2, P < 0.001$). Mean ratings, (with standard error of the mean in parentheses) were 2.6(0.2) and 4.1(0.2) respectively.

(2) Subjects found low gravity easier to detect than high gravity ($F(1,196) = 41.9, P < 0.001$). Mean ratings were 2.7(0.2) and 4.7(0.2).

(3) Subjects found errors in horizontal velocities easier to detect than errors in vertical velocities ($F(1,430) = 18.1, P < 0.001$). Mean ratings were 2.8(0.2) and 3.9(0.2).

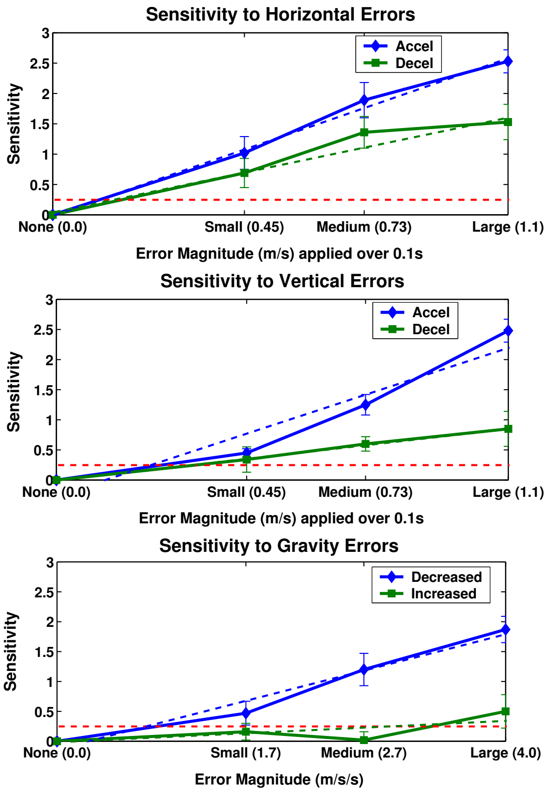

Figure 3: Mean sensitivities for all errors, with best-fit linear approximation.

4 Estimating Acceptable Error

From our results, we can form an estimate of a level of error that should be acceptable. We propose a method for calculating error thresholds based on detection theory [Macmillan and Creelman 1991]. The ratings given by a subject to unchanged motions form an approximately normal distribution, and the ratings given to motions containing errors form a second, also approximately normal distribution. The subject's sensitivity is the distance between the means of these two distributions, in units of standard deviation. For a simple yes/no classification, sensitivity d is easily calculated from the hit rate (H), the fraction of motions containing errors that are correctly judged to contain errors, and false alarm rate (F), the fraction of original motions that are incorrectly judged to contain errors:

$$d = z(H) - z(F) \qquad (1)$$

where z is the inverse of the normal distribution function. (See [Macmillan and Creelman 1991] for details.) For example, a hit rate of 69% with a false alarm rate of 31% gives a sensitivity of 1.0. Sensitivity does not reflect the biases of the subject, so a hit rate of 26% and a false alarm rate of 5% also represents a sensitivity of 1.0. As a result, sensitivities determined with one set of biases (such as a test setting) may be applied to a situation with different biases (such as playing a game). We computed sensitivities from subjects' ratings using the method in Macmillan and Creelman [1991]. In cases where the sparse data led to a degenerate distribution (e.g., if a participant marked only zeroes and nines), we calculated sensitivity using the participant's classification of the motion as "no error (unchanged)" vs. "error" rather than using the numerical ratings.

Sensitivity levels are plotted in Figure 3 and listed for all error treatments in Table 1, along with regression lines fit to these values plus the origin (zero sensitivity at zero error). As an example

	Small	Medium	Large	Regression Line
H Accel	1.02 (0.27)	1.89 (0.29)	2.53 (0.19)	$0.00 + 2.44E$
H Decel	0.69 (0.24)	1.36 (0.26)	1.53 (0.29)	$0.05 + 1.52E$
V Accel	0.45 (0.07)	1.25 (0.17)	2.48 (0.19)	$-0.25 + 2.32E$
V Decel	0.34 (0.21)	0.60 (0.12)	0.85 (0.29)	$0.00 + 0.81E$
G Decr	0.47 (0.20)	1.20 (0.27)	1.87 (0.22)	$-0.12 + 0.48E$
G Incr	0.16 (0.14)	0.02 (0.14)	0.50 (0.28)	$-0.05 + 0.10E$

Table 1: Mean sensitivity levels (and standard error of the mean) for horizontal (H), vertical (V), and gravity (G) errors. A sensitivity of zero means that participants cannot detect errors. The last column contains lines fit to the sensitivity data, also including the point $(0,0)$. **E** is the magnitude of the error, in m/s for horizontal or vertical errors and in m/s^2 for gravity errors.

Variety	Threshold
Horizontal error over $0.1s$ interval	$[-0.13m/s,\ 0.10m/s]$
Vertical error over $0.1s$ interval	$[-0.32m/s,\ 0.22m/s]$
Gravitational constant	$[-12.7m/s^2,\ -9.0m/s^2]$

Table 2: Error thresholds resulting from a desired sensitivity level of 0.25 or less. For reference, average initial velocities in the original jumps were approximately $2m/s$ in the vertical direction and $1.5m/s$ in the horizontal direction.

of how error thresholds can be set from these values, consider a hypothetical application. Suppose that for unmodified motion capture data we expect users to think that the motion looks incorrect 10% of the time (a false alarm rate of 10%). Then suppose that for motions containing error, we are willing to tolerate users thinking that the motion looks incorrect half again as often, or 15% of the time (a hit rate of 15%). The resulting sensitivity would be 0.25. Estimating acceptable errors at this sensitivity level results in the threshold values shown in Table 2. We emphasize that this is just an example. The actual desired sensitivity (and resulting threshold values estimated from our data) would depend on the application.

Composite Errors. Composite errors—those with both horizontal and vertical components—did not produce any surprises. Figure 4 plots mean ratings for vertical, horizontal, and composite errors. Results for composite errors fall approximately within the bounds of those for the two types of errors from which they are derived.

5 A Ballistic Error Metric

We briefly describe how an error metric for ballistic motion might be designed based on our results.

First, consider errors in gravity. Gravity is an average effect, and a metric designed to detect incorrect gravity captures errors where the motion is well behaved throughout the flight phase, but the timing of the motion is wrong. From the vertical takeoff velocity of the center of mass $v_v(t_i)$, the vertical landing velocity of the center of mass $v_v(t_f)$, and elapsed time $(t_f - t_i)$, we can compute the effective gravity represented by a motion:

$$g_{eff} = \frac{v_v(t_f) - v_v(t_i)}{(t_f - t_i)} \tag{2}$$

Results from our study suggest that under circumstances similar to this study, values for g_{eff} between $-12.7m/s^2$ and $-9.0m/s^2$ should lead to sensitivity levels below 0.25, resulting in the following constraint:

$$-12.7m/s^2 < g_{eff} < -9.0m/s^2 \tag{3}$$

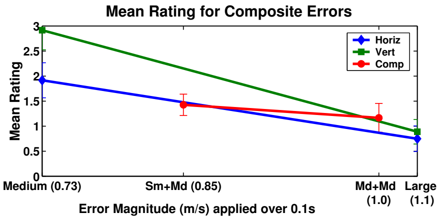

Figure 4: Results for composite errors are approximately bounded by results for the types of errors from which they are derived.

Anomalous accelerations and decelerations are shorter term phenomena, where the motion during the flight phase is not well-behaved over some window in time. One strategy for measuring errors of this type would be to compute error in horizontal or vertical velocity over a sliding time window, checking this error against the given thresholds. For example, horizontal velocity should be constant during flight, and so any change in horizontal velocity during flight is an error.

$$v_{h,err}(t) = v_h(t + 0.1s) - v_h(t) \tag{4}$$

$$-0.13m/s < v_{h,err}(t) < 0.10m/s \tag{5}$$

where $v_h(t)$ is the horizontal velocity measured at time t, and $v_{h,err}(t)$ is the horizontal velocity error for the time window of $0.1s$ starting at t. Changes in velocity outside this range would flag potentially anomalous motion. The time window of $0.1s$ is chosen because our study results are based on this value.

The metric for vertical velocity is similar, but must accommodate expected change in velocity due to gravity. For a time window of $0.1s$:

$$v_{v,err}(t) = v_v(t + 0.1s) - v_v(t) + 0.98m/s \tag{6}$$

$$-0.32m/s < v_{v,err}(t) < 0.22m/s \tag{7}$$

where $v_v(t)$ is the vertical velocity measured at time t and $v_{v,err}(t)$ is the vertical velocity error for the time window of $0.1s$ starting at t. When measuring errors against a gravitational constant different from $-9.8m/s^2$, the equation for $v_{v,err}(t)$ should be adjusted for the new value.

Our composite results suggest that vertical and horizontal velocity errors may combine in a straightforward way. The following metric would place limits on combinations of horizontal and vertical errors, which should be an improvement over treating them separately. One possibility is to work with the sum of squares of normalized error values. For example, if the error at time t is a horizontal acceleration (with threshold $0.10m/s$) and a vertical deceleration (with threshold $-0.32m/s$), the appropriate constraint would be:

$$\left[\left(\frac{v_{h,err}(t)}{0.10m/s}\right)^2 + \left(\frac{v_{v,err}(t)}{0.32m/s}\right)^2\right] < 1 \tag{8}$$

The expression on the left hand side of this equation is a squared distance in velocity space, with horizontal and vertical velocities weighted differently. Values in the denominators would change when the direction of the corresponding error changed.

6 Discussion

In this study, we measured sensitivity of human subjects to errors in animated ballistic human motion. We found that sensitivity was correlated with the level of added error, errors in the horizontal component of the motion were easier to detect than errors in the vertical component, and added accelerations were easier to detect than added decelerations.

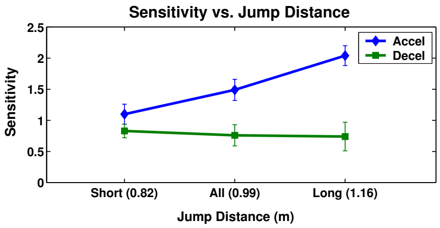

Figure 5: Mean sensitivity for study 1 for all seven source motions (middle), the three shortest jumps (left), and the three longest jumps (right). Accelerations are comparatively easier to detect for longer jumps.

Why might it be easier to hide errors in the vertical component of the motion than in the horizontal component? One possible explanation is that horizontal velocity during flight, which should be constant, behaves in a simpler manner than vertical velocity, which should have a constant derivative (gravitational acceleration). This difference may make anomalies in horizontal velocity more visually salient.

The acceleration / deceleration discrepancy seemed to us to be less intuitive. One possible explanation is that it may be easier to detect errors when distance or total time of the jump is increased and more difficult when one or both of these parameters are decreased.

It is important to point out that jump heights and distances alone could not have accounted for the effects we observed. 69% of the motions containing errors were within 10% of the range of heights and distances spanned by unchanged motions. In addition, although 4 subjects in study 1 mentioned making use of jump distance, timing, or similar indirect observations of error, 11 of the 12 subjects mentioned direct observation of errors, such as changes in jump trajectory. However, overall jump distance does appear to have been a contributing factor in participant ratings. Our study was not designed to test the effect of source motion—source motion was not fully crossed with other error variables. However, we did check for interactions between source motion and other variables considered individually. The only significant interaction found was between source motion and error direction in study 1 ($F(6,418) = 4.5, p < 0.001$). Examination of the data (shown in Figure 5) suggests that added accelerations are proportionately easier to detect for jumps that cover a longer distance. However, it is interesting to note that sensitivity for accelerations is higher than for decelerations even for the shortest jumps, which would not be the case if jump distance were the primary factor used to detect errors. Because we did not fully cross source motions with all other variables in the study, however, further investigation is required to verify this trend and to understand its implication for designing error metrics.

Many parameters can be expected to affect perception of anomalies in animated human motion. There is some evidence that improved graphical quality of animations, for example, may increase the ability of users to detect anomalous motions [Hodgins et al. 1998] [Oesker et al. 2000] [Hecht and Bertamini 2000] [Stappers and Waller 1993]. We focused on errors added to the character's root motion in hopes that the results would be robust with respect to detail in the rest of the animation, but this assumption remains to be tested.

Perception of anomalies also varies with task [Oesker et al. 2000] [Watson et al. 2001]. The task presented to subjects in our study was simply to observe the motion and indicate whether it appeared to be incorrect. We would expect that sensitivity to errors might be higher if the character was a target in a game environment, for example, and lower if the character was not the focus of attention (e.g. a background character in a virtual environment). More research is required to understand how sensitivity to error in the physics of human motion varies with task.

In our study, we showed the same motions to all participants and obtained sensitivities based on their numerical ratings of these motions. An alternative design is to use a staircase procedure (e.g. [Levitt 1971]), which can provide faster convergence to a desired sensitivity level by dynamically adapting the stimulus to the performance of each participant. We are interested in exploring this alternative in future work.

One specific area of future work is to test the predictive power of our ballistic error metric on motion that has been generated using standard motion processing techniques. Physically incorrect ballistic motion can be generated by scaling a given motion in time, which will result in gravity errors, or splicing one motion to another during the flight phase, which will lead to unnatural accelerations and decelerations. If results are promising, next steps would be to address additional types of physics errors that may be present in processed motion. In probable order of complexity, these are implausible changes in angular acceleration during flight; implausible forces when the character is in contact with the environment; and implausible joint torques.

It would be also interesting to examine whether people are more or less sensitive to errors in animated human ballistic motion than to identical errors in simpler motion, such as a ball fired out of a cannon. Such a test would be very easy to perform—the translational motions of the character center of mass from our study could be used to animate a spherical rigid body instead of the human character. We are excited to run this experiment to see whether the presence of the human model and the motion of the limbs during flight degrade ability to perceive errors in ballistic motion.

Acknowledgments

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Appendix: Error Generation

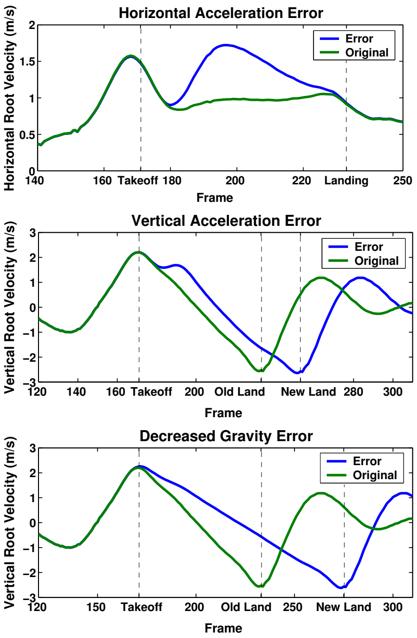
To create a motion with error, we must add the required error velocity or acceleration to the flight phase while minimizing undesirable artifacts. Our primary goals were to ensure that character motion before and after the flight phase was unchanged (except for horizontal landing position) and that the resulting motion had continuous second derivatives (smooth velocities). Achieving these goals required different processing for each error type. Assume a motion M whose flight phase starts at frame T and ends at frame L, sampled at FPS frames per second. Procedures with names in italics are described at the end of the section. All processing is performed on the translational parameters of the character root. Examples of velocity curves with and without errors are shown in Figure 6.

Horizontal Errors. Assume motion M sampled at 120Hz, with horizontal direction H. Use routine *AddError(E,H,M,T+12,T+24)* to add a horizontal velocity error with magnitude E to the motion from 0.1s to 0.2s after the start of the flight phase. To prevent a velocity discontinuity at landing, remove this error velocity over the remainder of the motion with *AddError(-E,H,M,T+25,L)*.

Gravity Errors. Compute new duration t_n = *Duration(M,G′,0)* for the new gravity level, and *Timewarp(M,N,t_m,t_n)* M to create a new motion N. Finally, *Deseam(N,dY,dV)* to remove position discontinuity dY and velocity discontinuity dV at landing. These discontinuities should be quite small and result from discretization errors, motion capture data errors, and differences between takeoff and landing height of the center of mass. Note that preserving average horizontal velocity and initial vertical velocity leads to jumps that cover a shorter horizontal distance in higher gravity cases and a longer distance in lower gravity cases.

Vertical Errors. Compute new duration t_n = *Duration(M,G,E)* for the vertical velocity error E, and *Timewarp(M,N,t_m,t_n)* M to create a new motion N. *AddError(E,V,N,T+12,T+24)* to add a vertical velocity error of magnitude E to the motion over the period from 0.1s to 0.2s after the jump starts. Finally, *Deseam(N,dY,dV)* according to the position discontinuity dY and velocity discontinuity dV at landing. As with gravity errors, preserving the horizontal velocity and gravity and applying these effects over the new duration of the flight phase leads to jumps that travel greater or lesser horizontal distances.

General Processing and Procedure Definitions. Errors were added to the motions at 120Hz, and the motions were downsampled to 30Hz for display. All motions were translated to align the root positions of their first frames and rotated to align their jump direction. The flight phase of a jump was defined as the first frame where the lowest joint was above 7cm from the ground plane through the first frame where the lowest joint was below 7cm. For all motions, the position change of the last frame of the flight phase was added to all subsequent frames to align the landing with the end of the jump. Procedure definitions follow.


Horizontal Acceleration Error

Vertical Acceleration Error

Decreased Gravity Error

Figure 6: Examples of velocities with and without errors. (Top) Horizontal velocities with and without added acceleration in the horizontal direction. (Middle) Vertical velocities with and without added acceleration in the vertical direction. (Bottom) Vertical velocities with and without decreased gravity.

AddError(E,D,M,a,b): Add an error velocity of magnitude E along direction D to the root translation of motion M. *Rampin(E,U,a,b)*, then *GetPosition(U,V)*, then simply add the motions: $M[i] = M[i] + V[i] * D$.

Duration(M,G,E): Compute the new flight time for root motion M given gravity G, vertical velocity error E, and initial vertical velocity V_i using basic kinematics. $t' = \lfloor(\frac{1}{G}(-(V_i+E) - \sqrt{(V_i+E)^2 + 2G(\frac{E}{20} + \frac{E*FPS}{L-T-0.2*FPS})})\rfloor$.

Timewarp(M,N,t_m,t_n): Timewarp the flight phase of M from t_m to t_n seconds in an ease-in/ease-out manner so as not to cause discontinuities in joint velocities, and place the result in N. First, remove gravity and average horizontal velocity from root translation of M, resulting in M'. Perform the timewarp. Add back in the average horizontal velocity and gravity removed earlier but applied over the whole of the new motion, resulting in N.

Deseam(M,dY,dV): Some error types lead to a vertical velocity discontinuity at landing, which is fixed in this postprocessing step. For a given required position correction dY and a given required velocity correction dV, let $D[T + 0.2 * FPS + i] = (-2dY + 0.1 * dV)t^3 + (3dY - 0.1 * dV)t^2$ where $t = \frac{i+1}{L-T-0.2*FPS}$ for $0 \le i < L - T - 0.2 * FPS$. D is then added to root translation M to make the corrections specified by dY and dV: $M[i] = M[i] + D[i]$.

Rampin(E,U,a,b): Using the spline $-2x^3 + 3x^2$, smoothly transition from 0 at frame a to E at frame b, and place the result in array U.

GetPosition(U,V): Integrate a velocity error in array U up into a change in position in array V.