Animation Techniques in Human-Robot Interaction User Studies: A Systematic Literature Review

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There are many different ways a robot can move in Human-Robot Interaction. One way is to use techniques from film animation to instruct the robot to move. This article is a systematic literature review of human-robot trials, pilots, and evaluations that have applied techniques from animation to move a robot. Through 27 articles, we find that animation techniques improves an individual's interaction with robots, improving the individual's perception of qualities of a robot, understanding what a robot intends to do, and showing the robot's state or possible emotion. Animation techniques also help people relate to robots that do not resemble a human or robot. The studies in the articles show further areas for research, such as applying animation principles in other types of robots and situations, combining animation techniques with other modalities, and testing robots moving with animation techniques over the long term.

CCS Concepts: • **Computer systems organization → Robotic autonomy**; *Robotics*; • **Human-centered computing → *HCI design and evaluation methods***; *Interaction paradigms*;

Additional Key Words and Phrases: Robot, human-robot interaction, literature review, animation, motion

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1 INTRODUCTION

When the Kismet robot was introduced, individuals could interact with it via conversation or gestures as opposed to typing on a keyboard [18]. Human-robot interaction (HRI) requires the robot to also respond. A robot that gestures and moves can aid an individual in understanding what the robot is doing and aid in the interaction.

In movie production, we observed the phenomenon of *animation*—layering slightly different frames of an object to create the illusion of movement. Animators follow principles such that animations are believable and tell stories [85]. The principles are successfully used in computer graphics [49], and studies suggested that the principles should be considered for robots [68, 89]. However, what is the extent to which animation techniques are used with robots and how do animation techniques affect HRI?

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The present study maps the current knowledge by conducting a systematic literature review of evaluations using animation principles and techniques in HRI. First, we construct a foundation and context by examining movement, how movement affects an individual's interpretation of things, *animation* in the HRI context, and animation techniques (Section 2). Then, we present the method to perform a systematic review (Section 3). This is followed by the search results, where we provide a review of the articles that we examined (Section 4). We discuss the implications and potential areas for future research (Section 5) before providing a few concluding remarks (Section 6).

2 BACKGROUND: MOVEMENT, ANIMATION, AND ROBOTS

We first define types of movement. Then, we quickly review principles of animation as a way of looking at animation techniques for HRI and how they can be applied to robots. We briefly discuss other techniques for moving robots and conclude the section with an exploration of the concept of *animacy* and its relation to HRI and our study.

2.1 Movement and Animation

The phenomenon of *movement* is straightforward. In physical terms, movement is a *vector* with *speed* and *direction*. In robotics, movement that changes the position of the robot is called *locomotion* or *translation*. Robot movement that does not affect its position is called *configuration*. Locomotion and configuration can be combined. So, a robot can move toward a person (locomotion), wave at a person (configuration), and say "hi."

Animation in HRI uses techniques from animation in films or computer graphics (or inspiration from them) to specify how a robot moves. This movement should help a robot communicate with humans. This complements a suggestion by van Breemen [88] with using animation principles to help create "believable behavior" [88, p. 2873] in a robot. Ribeiro and Paiva [67] built on this definition and added that "…robot animation consists of all the processes that give a robot the ability of expressing identity, emotion and intention during autonomous interaction with human users" [67, p. 388].

Let us review some of these animation techniques, starting with the 12 principles of animation.

2.2 The 12 Principles of Animation and Other Animation Techniques

The idea behind traditional, hand-drawn animations for films corresponds to physics. That is, switch drawings sufficiently fast such that what is rendered appears to move. The idea also applies to computer animation or anything that is filmed. The actual drawing (or rendering) is considered as art. Thomas and Johnston [85] documented how animators at Walt Disney Studios practiced their methods of creating their animations until they obtained a few methods that "…seemed to produce a predictable result" [85, p. 47]. The artists termed these methods the *fundamental principles of animation*, and the principles were taught to new animators. Although the principles were not verified scientifically, they have been used in financially successful animated films and cartoons watched by millions. The 12 principles are as follows:

Squash and Stretch. Characters and objects should squash and stretch with their action, although they do not completely lose their shape.

Anticipation. Major action should be telegraphed such as reaching back before throwing an object.

Staging. An action should be clear to the audience. For example, the audience should understand the action by only viewing it in silhouette.

Straight Ahead Action and Pose to Pose. This principle describes how to draw an action. Drawing straight ahead involves starting to draw and simple continuing until the action is completed. Pose to pose implies that specific poses are desired in an action and are choreographed before the actual animation.

Follow Through and Overlapping Action. Actions are not performed in isolation. An animated character exhibits a plan and moves from one action to the next without stopping between.

Slow In and Slow Out. The speed of a motion is not the same during the time that it is performed. Action is slower at the beginning and end.

Arcs. Move limbs in arcs as opposed to of straight up-down and left-right motions.

Secondary Action. Create complementary actions that emphasize the main action. For example, a character puts on a coat while walking out the door.

Timing. Changes in number of frames that are between a start and stop determines the speed of the action, thereby increasing the number of frames and decreasing the speed of the action.

Exaggeration. Exaggerated action ensures that it is easier to understand the feelings of a character.

Solid Drawing. Drawings should look plausible and three-dimensional and *twins*—symmetrical limbs on a character—should be avoided, since it makes characters look stiff.

Appeal. All the characters should be appealing whether one is expected to sympathize with them or despise them.

A few of the principles are related to the craft of pen-and-paper animation and narrative of films, although they are shown as applicable to other areas, such as 3D computer-animated films [49].

The 12 principles are not the only methods to animate an object or produce cartoon-like movement; several other methods reflect aspects of the principles. For example, a common method involves the use of *key frames*, which are frames that define important (key) points in a movement. Then, the software or other animators interpolate the frames between the key frames. This is similar to the pose to pose part of the *Straight Ahead Action and Pose to Pose* principle.

A different way of animating movement involves an individual acting out the movement and transferring it to the animation media. One method is *rotoscoping* where animators trace individual frames of a filmed action to create a realistic and human-like animation. Another technique involves the use of *motion capture*, where sensors capture the movement and software translates the movement onto another model.

A field related to animation is *puppetry* and *animatronics* where a person controls how a puppet or other creation moves and reacts to a situation. This is a relevant method to consider for moving a robot, especially if the robot is teleoperated. Scherer [75] has argued that this is a fertile area to investigate for robot design.

Kinematics is a mathematical method to express movement and is used for robots that are composed of a chain of articulated nodes. *Inverse kinematics* is a method to solve for the different nodes (joints) to move to obtain a desired position by working backwards to its starting position. A common use of inverse kinematics is when a robot arm is picking or placing objects. In the real world, joints have limited degrees of movement, so not all solutions are valid. However, applying animation principles to the formulas (e.g., making movement follow arcs) can turn kinematics into an animation technique.

2.3 Other Techniques for Robot Communication Through Movement

Techniques for communicating through movement exist beyond those used in animation and film. These are not animation techniques, but were developed in other areas and have been applied to robots.

In the world of dance and acting, Laban created the *Laban Effort System* [48] that describes human motion in four effort factors: Space, Weight, Time, and Flow. Each factor has two elements (polarities) to adjust the factor's character. For example, Space has elements of direct versus indirect, and Time has elements of quick versus sustained. The system can be used by dancers and actors to better understand their own patterns and biases in movements and impart better quality on their movement. LaViers and Egerstedt [50] used Laban's work to make robots dance alongside other dancers using the robots' own style. The system was fully formalized for a humanoid robot [51]. Knight and her colleagues implemented a version of the Laban Effort System to express the internal state of robots with limited degrees of motion—such as only a head [45] or only a platform that can turn [44]. They investigated situations like sharing space in an office environment [47] and putting the Laban System on top of other tasks the robot was performing [46].

Other HRI studies have different solutions for robot motion and communication. Some studies have used colored lights flashing in different patterns to signify direction [81] for a flying drone and what a robot moving in the office is doing [3]. Citing an inspiration from animation, but not necessarily using animation techniques, Dragan and her colleagues have investigated the difference between what makes a robot's motion legible and what makes it predictable [26]. This tension between legible and predictable motion affects collaboration between a robot and a person [25]. They have also investigated how a person's familiarity with a robot affects how easily the person can predict the robot's motion [27].

2.4 Animacy

Animacy refers to an object moving as if it is alive (or that it "exhibits life"). The concept was traced back [6] to Piaget's study of children learning what is alive or not [63].

The motion that creates animacy is described as *animate motion*: "movement that is self-propelled but not necessarily created by other living creatures" [15, p. 837]. Even simple shapes can exhibit animacy. In a classic psychology study by Heider and Simmel [33], individuals watched a film of shapes moving around and then interpreted what happened. A majority of the individuals described the action in the film as a story and gave personality traits to the shapes. Subsequently, another study indicated that individuals perceive animacy in a particle if it moves on a path and speeds up [87].

Another set of studies examined how individuals perceived *contingency* [57]. Individuals watched films of objects moving and were asked to interpret them. In a few films, individuals said the movement of one object (X) was contingent on the movement of another object (Y). These aforementioned studies—and studies that built on the concepts—were reviewed by Scholl and Tremoulet [76]. Another study used simple films of objects depicting contingency and animacy to explore what parts of the brain were activated for each film [15].

Several HRI studies examined how individuals ascribe feelings and personalities to the way robots move, whether they look like a dog [8, 11], a vacuum cleaner [30, 73, 79], or simply an arm [100]. Other HRI animacy studies are based on Piaget and examine children's relationship to robots and other things that are alive [14, 56, 61]. Others have examined how individuals' interaction with a robot affects their willingness to end the robot's existence [4, 9, 10, 38].

Animacy references the original definition of animation (i.e., bringing an element to life) and the idea of an animate object—an object that moves on its own—versus an inanimate object—an object that does not move. Specifically, animation techniques in Section 2.2 and the other techniques mentioned in Section 2.3 can be used to create animacy. However, this study focuses on the use of animation techniques and not on animacy generally.

3 METHOD: LITERATURE REVIEW PROTOCOL

The systematic review followed a process outlined by Budgen and Brereton [19, p. 1052]. The process consists of five parts: (a) define a review protocol with research questions and methods employed for assessment, (b) define a search strategy, (c) document the search strategy, (d) specify explicit inclusion and exclusion criteria, and (e) specify the information that will be obtained from each item. We present each part as a subsection here.

3.1 Research Questions and Methods for Assessment

The goal of the review involved mapping the knowledge that exists for using animation techniques to move robots and see where further research can be directed. This resulted in several research questions: (a) What animation principles and techniques are used for moving robots? (b) What kind of studies are performed with animated robots and individuals? (c) How do animation techniques affect individual's interaction with a robot? (d) What data was collected in the aforementioned studies? (e) What robots are used in these studies? (f) What are the environments (lab or real world) in which the studies are conducted? (g) What was the modality for the study (e.g., a live evaluation or a video)?

Most of the answers are found in the study method, study results, and design of the robot. So, we can determine candidate articles by searching article metadata. Then, a reading the method and results section should determine if the study is relevant for the research questions.

3.2 Search Strategy Plan

We followed a similar search strategy employed by Riek [70]. We searched two databases, namley IEEExplore [40] and the ACM Digital Library [2], since they include many articles on HRI, HCI, and robotics. Neither databases index the HRI journal the *International Journal of Social Robotics* nor the HCI journal *Interaction Studies*, but it is necessary to balance the breadth of the search relative to the complexity of reproducing the method. The search was performed on 30 June 2018.

The search on IEEExplore only examined metadata, and the search string was as follows:

`((HRI OR "human-robot interaction") AND (experiment OR "user study" OR pilot OR evaluation) AND (animation OR animate OR cartoon)).`

The search of the ACM Digital library searched the *ACM Guide to Computing Literature* that includes additional items from other publishers. The search string for the ACM Digital Library was equivalent to the IEEExplore search string:

`+(+(HRI "human-robot interaction") +(experiment "user study" pilot evaluation) +(animation animate cartoon)).`

We included "cartoon" in the searches, since a few studies we were aware of did not mention animation techniques for movement, but they mentioned techniques for "cartoon-like movement."

3.3 Inclusion and Exclusion Criteria

Beyond the search string, the inclusion criteria corresponded to peer-reviewed conference and journal articles about robots that used one or more animation techniques to move and included a study with individuals. Therefore, a relevant paper included the following: (a) at least one robot, (b) at least one animation technique, and (c) at least one person that evaluated or interacted with the robot.

The goal involved mapping the use of animation techniques in HRI studies, and thus we were generous in what was considered a study and included pilot studies, informal studies, or critiques of a robot's movement.

Table 1. Number of Articles Found in Each Database

Database	Results
ACM Digital Library	68
IEEExplore	46
In both	(8)
Total	106

The review excluded posters, workshop announcements, and non-peer-reviewed books. We also excluded articles that: (a) only described a robot, (b) only described a tool or algorithm for a robot, (c) evaluated robot interaction with animals, (d) only studied animacy (as per Section 2.4), and (e) only evaluated interaction with virtual agents or virtual robots.

3.4 Information Obtained from Each Study

For each relevant article, we collected information about it for the review. The information was the following: (a) robot used, (b) embodiment of the robot, (c) animation technique that was used, (d) number of participants, (e) data that was collected, (f) whether the study was performed with a video or in real-life, (g) whether the robot was in a lab or not, and (h) what type of movement was involved (configuration, locomotion, or both).

4 RESULTS

The searches returned 68 items from the ACM Digital Library and 46 items from the IEEExplore database. The results from the searches were combined and controlled for entries that appeared in both the ACM Digital Library and IEEExplore. This resulted in a total of 106 items (Table 1). The searches produced a sufficient number of articles, although they were not overwhelming. We began reading the items to apply the inclusion and exclusion criteria.

For articles that matched our inclusion criteria, we wrote down information as outlined in Section 3.4. Articles that were missing this information or matched our exclusion criteria were excluded, and the reason for exclusion was documented.

The authors met to discuss the placement of the articles and agreed on a final list. We had initial disagreement on six articles [17, 28, 66, 86, 95, 99]. The final consensus was to exclude them as each lacked one of the inclusion criteria. This resulted in 79 articles that were excluded and 27 that matched the inclusion criteria.

There were three articles we expected to be in the search results, but they were not in the results due to missing information in the metadata. One article [68] was about applying animation principles to a robot for showing emotions. The article *does* include an evaluation, but it is *not* specified in the article metadata. The second article [80] used the animation principles of *Arcs*, *Anticipation*, and *Slow in and Slow out* for Assistive Free Flying robots, but there was no mention of animation in the metadata. The third article [54] documented the design process for an animated robot for the smart home but mentioned neither a user study nor animation in the metadata. On one hand, it is unfortunate that the databases missed these articles, and we chose to keep these specific articles out of the review to keep the method straightforward to replicate. On the other hand, several of these authors *are* included in our list of relevant articles. So, while a specific article may not be included, their research in this area is part of the relevant literature.

4.1 Paper Demographics

The majority of the 27 papers (20) were conference papers. Over three-quarters of the conference articles (15) were from HRI conferences (HRI, RO-MAN, and Humanoids). The other conferences

Table 2. Breakdown of Articles by Conference and Journal in Order of Number of Articles

Type	**Name**	**Articles**
Conference	ACM/IEEE Conference on Human-Robot Interaction (HRI)	8
Conference	IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)	4
Conference	IEEE-RAS International Conference on Humanoid Robots (Humanoids)	3
Journal	*ACM Transactions on Interactive and Intelligent Systems* (TiiS)	2
Journal	*Computers in Human Behavior*	2
Journal	*Autonomous Robots*	1
Conference	International Conference on Advances in Computer Entertainment Technology (ACE)	1
Conference	International Conference on Interaction Design and Children (IDC)	1
Conference	International Conference on Multimodal Interaction (ICMI)	1
Conference	IEEE Portuguese Meeting on Bioengineering (ENBENG)	1
Conference	Graphics Interface (GI)	1
Journal	*Journal of Intelligent Robotics Systems*	1
Journal	*Multimedia Tools and Applications*	1
	Total	27

articles were from conferences that focused on specialized HCI (ACE, IDC, ICMI), graphics (GI), and bioengineering (ENBENG). The remaining seven articles were from robotics, HRI, and HCI journals: two journal articles from *ACM Transactions on Interactive Intelligent Systems* (TiiS); two articles were from *Computers in Human Behavior*; and the last three articles were from *Autonomous Robots*, *Journal of Intelligent Robotic Systems*, and *Multimedia Tools and Applications*. The breakdown of articles from each venue is shown in Table 2.

4.2 Robots and Robot Types Used in the Studies

Although there are articles that examine the use of tools and frameworks that use techniques from animation for moving a robot [7, 69, 88, 90], the review examined the animation techniques with robots that are evaluated with participants, robots that are used in the evaluations. Table 3 sorts the studies by year and identifies the robot; type of robot (i.e., humanoid, animal, a head, or other); and animation technique used.

Twelve studies used a humanoid robot or a combination of a humanoid robot with an animal robot. Eight of the aforementioned studies used Nao [1, 12, 41, 52, 55, 58, 60, 84] one of the eight also used a Pepper robot [41]. These commercially available robots offer software to animate the robot using animation techniques and using key frames [65]. Robovie II is another commercially available robot that was used for two animation studies [5, 94]. Finally, SIMON and Alpha are custom humanoid robots that were used for one study each [13, 31].

Seven studies used robots that resembled an animal. Two of the studies used the iCat [5, 58], a cat robot that was designed using animation principles to have an expressive face [91]. The other robots are custom robots. One study [93] used Tofu, a fluffy, squash and stretch robot that resembles a bird. Another study [98] used a plush dog-like robot to dance. A study [97] used the Haptic Creature, which resembles a mouse. A study [96] used Probo, a robot that resembles a type of mammoth [74]. The final animal robot study [67] used Adelino, a custom robot that resembles a snake.

Four studies used a head to test animation principles. Each robot head was different. One study [24] used RAF, a robot that is a retro-projected face that is projected on a sphere. Another study

Table 3. Studies Sorted by Year Ascending, with Robot and Animation Technique

Year	Reference	Robot	Type of Robot	Animation Technique
2005	[13]	Alpha	P	Arcs
2005	[94]	Robovie II	P	Motion Capture
2007	[5]	iCat, Robovie II	A, P	Secondary Action
2010	[24]	RAF	H	Secondary Action
2010	[32]	Stem	O	Unspecified animation techniques
2011	[37]	Shinmon	O	Anticipation, Follow Through, Slow In, Slow Out
2011	[82]	PR2	O	Anticipation, Follow Through
2011	[93]	Tofu	A	Squash and Stretch
2011	[97]	Haptic Creature	A	Pose to Pose (Key Frame)
2012	[12]	Nao	P	Motion Capture, Pose to Pose (Key Frame)
2012	[31]	SIMON	P	Exaggeration
2012	[72]	Alphabot	O	Pose to Pose (Key Frame)
2013	[23]	DEVA	O	Squash and Stretch
2013	[77]	Parrot AR.Drone	O	Motion Capture
2014	[98]	Roomba, Reactor	O, A	Motion Capture, Puppetry
2015	[34]	Custom Head	H	Unspecified animation techniques
2015	[55]	Nao	P	Pose to Pose (Key Frame)
2015	[60]	Nao	P	Secondary Action
2015	[62]	Custom Head	H	Exaggeration, Secondary Action
2015	[96]	Probo	A	Secondary Action, Squash and Stretch
2016	[52]	Nao	P	Motion capture
2016	[58]	Nao, iCat	P, A	Secondary Action, Pose to Pose (Key Frame)
2017	[1]	Nao	P	Secondary Action
2017	[53]	ISR-RobotHead	H	Secondary Action
2017	[67]	Adelino	A	Inverse Kinematics using animation principles
2017	[41]	Pepper, Nao	P	Pose to Pose (Key Frame)
2017	[84]	Nao	P	Puppetry, “Animation Best Practices”

Type of Robot: A: Animal, H: Head, O: Other, P: Humanoid.

[53] used the ISR-RobotHead, a head with LCD screens for the eyes and mouth. Another study [34] used a computer monitor with animated eyes and neck that moved expressively so that it was possible to identify where the robot was looking. A robot head with expressive eyes and a creative use of tubing to make an expressive mouth was used for the remaining head animation study [62].

Seven studies used robots that did *not* resemble a animal, head, or humanoid. These studies represented a variety of robots. Robots had an appearance of a stick [32], a large alphabet block [72], or a smartphone [23]. Other forms included domestic robots like the Roomba [98], a quadcopter drone [77], a PR2 [82], or a custom, three-armed, marimba-playing robot [37].

4.3 Animation Principles and Techniques Used in the Articles

Eighteen studies used one or more animation principles. This includes counting key frames as a version of the *Pose-to-Pose* principle. Some studies explicitly name the principle. For others, we inferred the principle from the text, and have noted this below. Table 4 breaks down the number of studies for each principle.

The principle that is most frequently used (eight times) is the principle of *Secondary Action* where something else is animated in addition to the main action. The studies that use *Secondary*

Table 4. Breakdown of Animation Principle and the Number of Studies They Are Used in

Animation Principle	**Articles**
Secondary Action	8
Straight Ahead Action and Pose to Pose	6
Squash and Stretch	3
Anticipation	2
Exaggeration	2
Follow Through and Overlapping Action	2
Slow In and Slow Out	1
Arcs	1
Timing	0
Staging	0
Solid Drawing	0
Appeal	0

Ordered by number of articles; some articles use more than one principle.

Action make the robot react to a situation or show an "emotion" in the acting sense of showing an emotion as lifeless objects like robots do not have real emotions [1, 5, 24, 53, 58, 60, 62, 96]. In the aforementioned studies, one [62] names the principle explicitly and the others imply the principle's use as they either use a robot that uses this principle (iCat) [5, 58] or document that additional parts are animated during an action (e.g., eyes and eyebrows in addition to the mouth [24, 53, 96] or moving parts of the body while the robot is idle [1, 60]). These secondary actions aid in highlighting what is going on.

The next principle that was used six times corresponds to *Straight Ahead Action and Pose to Pose*. This principle is similar to the idea of key frames, since—in applying the pose-to-pose part of the principle—the animator is trying to create the key poses (i.e., frames) for the character in a situation. All the studies either explicitly name the method [55, 72, 97] or use software that uses key poses for driving the animation [12, 41, 58]. Studies that employ the principle examine synchronizing action to another event (e.g., entering or leaving the virtual world [72], dancing [55], or falling [58]), present the robot's emotional state [12, 97], or the impression a participant receives about the robot [41].

Although most individuals do not consider robots soft and squishy, the *Squash and Stretch* principle was used in three studies. In two studies [93, 96] the squash and stretch principle was used to make the robot more appealing to children. Another study used crawl, breathe, and curl gestures to create a smartphone that exhibits emotions and appears alive [23]. The study does not name the *Squash and Stretch* principle directly, but the resulting smartphone and the description of the gestures seem to evoke it.

The principle of *Exaggeration* was used in two studies such that it was easier for individuals to understand what the robot was doing. In one study [31], the SIMON robot related stories to participants and exaggerated certain gestures used in the story. The other study [62] combined *Exaggeration* with *Secondary Action* such that it was easier for participants to understand emotions.

The principles of *Anticipation* and *Follow Through and Overlapping Action* were used together in two separate studies to help a non-standard looking robots to express what it was doing. In one study [82], an animator was employed to design animations following these principles so it was easier to understand that the robot was delivering a drink, escorting a person, opening a door, or looking to recharge. One study [37] used the aforementioned principles along with the principle of *Slow in and Slow out* with the marimba-playing robot Shimon to improvise and signal to jazz musicians playing along with it.

One study had its museum guide robot, Alpha, use sine curves instead of straight lines to make the robot's arm movement seem more human-like [13]. Although it is not stated in the article, this is exactly the animation principle of *Arcs*. The robot's arms moving in arcs made it easier for individuals to understand what it was pointing toward.

Rounding out the review of animation principles, a few principles (*Timing*, *Staging*, *Solid Drawing*, and *Appeal*) are not mentioned in any studies. These principles have more to do with the craft of creating an animated film.

With respect to techniques beyond the principles, motion capture was the most popular other technique and was used in five studies. Two studies used motion capture of humans as an input to how the robot should react to it. One study [94] used motion capture to track the robot's and person's position. The robot itself used "nonlinear motion" [94, p. 408], which could be interpreted as the *Slow In and Slow Out* principle, but this is not explicitly specified. Another study [98] motion captured individual's movements and used pattern matching and frequency analysis to generate complimentary trajectories for a Roomba to follow along and act as the individual's partner.

The remaining studies used motion capture to capture humans moving and translate it to robot movement. In one of these studies [12], motion captured actors performing emotions and then used this to animate agents and a Nao. Another study [52] took videos of lecturers and converted them to as input for a Nao robot. The final study [77] motion captured actors using the Laban Effort System and used this motion to communicate affect to individuals using a Parrot AR.Drone.

Two studies used ideas from puppetry. Puppetry was used as an addition to motion capture as the second part of a study [98] to teach a robot dog how to dance by following the movements of a puppet cat. Puppeteers were consulted along with applying "animation best practices" [84, p. 61] to creating the Nao's body language.

One study [67] defined an inverse kinematics engine such that the Adelino snake robot moved in a word guessing game. The movements indicated to the human participant as to how close the participant's guess was to the correct word.

Finally, two studies used animation techniques, but the exact method was not documented. One of the studies [32] cited several animation techniques and animated movies as inspiration to creating a concept termed *emotive actuation* to move the STEM robot stick expressively. The other study [34] used animation sketches and tests to articulate a neck and head such that it appears to be watching participants.

4.4 Environments, Participants, Data Collected, Movement Types, and Modality

After examining the robots and animation techniques used, we examine other details of the studies. Table 5 shows the studies' environment (lab or real world), number of participants, whether the motion was configuration, locomotion, or both, the data collected, and the modality (video or live). Given the information, at least 1,180 participants were involved in HRI studies that used animation techniques.

4.5 Video or Live Modalities

Several HRI studies include individuals that interact with a robot in person, while other studies show a video of the robot performing. Since the animation techniques are derived from the movie world, it is potentially expected that most studies use video. However, the opposite was true, since 22 studies took place with the participant and the robot in the same setting, while only 6 studies

Table 5. Studies in Same Order as Table 3 with Environment, Number of Participants, Data Collected, Movement Type, and Modality

Reference	Setting	# Participants	Data Collected	Movement	Modality
[13]	Real	Not Listed	Questionnaire: Human-like	C	Live
[94]	Lab	23 & 23	Questionnaire on cognitive ability, intelligence, Lifelikeness	B	Live
[5]	Lab	62	Questionnaire: robot intelligence, animacy	C	Live
[24]	Lab	24	Where is the robot gazing	C	Live
[32]	Lab	Not Listed	Design critique, Interpret motion	C	Live
[37]	Real, Lab	6 & 21	Hypothesis test, embodiement and appreciation, audience appeal	C	Live
[82]	Lab	273	Qualitative and rating appeal, intelligence, competence, subordinate	B	Video
[93]	Lab	8	Observation of children	B	Live
[97]	Lab	32	Questionnaire: pick emotion, SAM, and confidence, plus open questions	C	Live
[12]	Lab	23	Questionnaire: identify emotion, valence, arousal	C	Live
[31]	Lab	54 & 68	Test memory of story, test where robot is gazing	C	Live, Video
[72]	Lab	34	Qualitative measure for continuity	L	Live
[23]	Lab	6 & 10	Arousal, valence, other things	C	Live
[77]	Lab	18	Questionnaire: SAM + interview	L	Live
[98]	Lab	20, 38, 11	Observation, Interview	L, C	Live
[34]	Lab	60	Authority, Monitoring, and Guilt	C	Live
[55]	Real	Not listed	Interest in the set up	C	Live
[60]	Lab	48	Questionnaire: TA-EG, Competence and enthusiasm, Hypothesis testing	C	Live
[62]	Lab	25 & 20	Compare emotions	C	Video
[96]	Lab	35	Identify emotion	C	Video
[52]	Lab	40	Questionnaire: Knowledge recall and attitude, Presentation and enthusiasm	C	Video
[58]	Real	22	Questionnaire: Godspeed likability, Big Five Inventory	B	Live
[1]	Lab	26	Questionnaire: Godspeed: Perceived Anthropomorphism and Proficiency, Task Performance, and attention	C	Live
[53]	Lab	9	Questionnaire: Identify emotion	C	Video
[67]	Lab	42	Hypothesis testing: Performance, Animation, and Intention	C	Live
[41]	Lab	3	Questionnaire: CH33 (Impression of Robot)	C	Live
[84]	Lab	96	Questionnaire: SAM, robot familiarity	C	Live/VR

Movement Type: C: Configuration, L: Locomotion, B: Configuration and Locomotion.

used video. Although only 6 studies used video, it is possible to recruit many more individuals to look at videos instead of synchronize a time to meet a robot. They did provide over one-third of the participants in the studies: 402 participants in video studies versus 778 participants that interacted with the robot in person. Most of these 402 participants come from one study [82] that used Amazon's Mechanical Turk to recruit 273 participants. However, with respect to the median number of participants for video and live (30 and 23, respectively), the number of participants for each study are much closer.

Table 6. Breakdown of Articles Versus What They are Studying

Study Examined	Articles
Robot emotions	9
Robot characteristics	9
Specific study hypothesis	8
Pilot study	3
Robot gaze	2

Some articles appear in multiple categories.

4.6 Study Environments

One reason for the literature review was to see how many studies were done in a lab setting versus studies that were done in a real-world setting. Most of the studies (24) took place in a lab environment (video modality was counted as a lab environment). There were four studies that used an environment outside of the lab (one article [37] had a study in a lab and real-world setting for the robot). Two of the studies in the real-world environment [13, 55] did not have a count on the participants or were only a pilot. This was the case for only one lab study.

4.7 Studies with Locomotion and Configuration

Given the different kinds of movement from Section 2.1, we wondered what the articles would say about the movement used in them. Surprisingly, most of the studies (25) focused on configuration. That is, the robot only moved parts of its body and did not change its location. Seven studies focused on locomotion. However, four of the locomotion studies also had the robot do some sort of configuration (whether it was to shake the person's hand [94], squash and stretch [93], communicate the robots intention [82], or as part of a humor skit [58]). Only one study [98] used two different robots for testing locomotion and configuration.

4.8 Data Collected and the Affect of Animation Techniques

The studies fall into groups about what researchers were studying: (a) studies where participant should identify the emotion shown by the robot, (b) studies interested in participants' opinion of a robot's characteristics, (c) studies asking participants where the robot is looking, (d) studies examining a specific hypothesis for a robot or situation, and (e) pilot studies. The breakdown for the articles is shown in Table 6. Let us examine these groups closer.

Nine articles looked at interpreting the "emotion" or disposition of the robot either through the robot's face or its body language. Of course, a robot does not have emotions, but it can display expressions that indicate an emotion. In the studies presented here, there are two main methods used for assessment. One method has participants rate the valence (the level of pleasure) and arousal (the level of enthusiasm) of a robot to create a two-dimensional field of emotion. The other method asks the participant to identify the robot's expression as one of the five universal, basic human emotions as defined by Ekman [29]. These basic emotions (happiness, sadness, fear, surprise, anger, and disgust) have corresponding levels of valence and arousal, but may be easier for individuals to relate to.

Two studies [12, 23] asked participant to rate the valence and arousal using Likert scales to show that the robots' movements indicate certain emotions as interpreted by the studies' participants. The self-assessment mannequin (SAM) [16] offers a alternative method using only pictures for identifying arousal and valence, and creates similar results. The SAM was used in three articles in the review [77, 84, 97]. One study used the SAM with the Haptic Creature [97] and found that the robot's motion communicated four of the nine conditions correctly to participants, and participants had correctly identified arousal correctly, but less well the valence. The second study [77] had statistically significant results for valence and arousal in the Laban Effort System factors of Space, Weight, and Time, but only for arousal for the factor of Flow. The third study using SAM [84] showed that the valence and arousal of the robot's movements were reduced when the person was under a stressful condition.

The method for using Ekman's basic emotions is to ask participants to look at the robot and pick the corresponding emotion. The final results are then compared against the chance of someone randomly picking emotions. Some articles that were excluded had participants match the facial expression using static pictures of robots (e.g., References [17, 21, 78]), but four articles in the review [53, 62, 96, 97] ran the evaluation with robots that were animated and used secondary action. Regardless of if the robot was animated or not, the selections of the participants matched the shown emotion well above chance, especially for happiness or sadness. But participants showed confusion between some other emotions (e.g., disgust was often misidentified as anger).

The nine articles evaluating characteristics of the robot were concerned with the participants' opinion about the robots motion or other qualities. The earliest study [13] asked individuals visiting their stand how human-like the robot's arcing arm motions were, with the arcs generally making the motion appear to be similar to humans. One of the questions in another study [31] was for individuals to classify how different amounts of exaggeration in the robot's motion yielded more cartoon-like or human-like movement. A different study [94] looked at lifelikeness but also asked about the robot's cognitive ability and intelligence. The robot scored higher when its motions were reactive of the person interacting with it, than if the motions were simply static. This measurement was further developed in a later study [5] to include animacy, where participants worked with either a Robovie II or an iCat to play a game. Though participants found Robovie II to be more intelligent than the iCat despite them both giving similar advice, participants spent more time looking at the iCat's animated face than they did the Robovie. A different study [82] had participants rate the robot's appeal, intelligence, competence, and how subordinate it was on a Likert scale along with describing what was happening in the scene. Here, the robot that was animated to show forethought before it did a task increased its appeal. Similarly, a robot that reacted to succeeding or failing a task made participants feel that the robot had intelligence and competence. As part of another study [52], participants were asked to rate a lecturer's likability and attitude for delivering a video presentation with most participants preferring the human form or an animation using the same voice over a robot or an animation of a robot.

The Godspeed Questionnaire [6] was created as a standard way to evaluate participants' perceptions of different aspects of a robot interaction. The questionnaire consists of scales for Anthropomorphism, Animacy, Likeability, Perceived Intelligence, and Perceived Safety. Each scale is independent, so HRI researchers can choose the relevant scales that work for them. The questionnaire shows up in two articles in this review [1, 58]. One article [58] looked at Likability between two robots and showed how a robot could improve its likability by laughing at itself after it fell over. The other study [1] used the Anthropomorphism and Proficiency scales to compare two robots, one moving only for static situations and one moving when it was idle, the idle action robot attracted more attention and scored higher on the anthropomorphism scale. A separate method for evaluating safety and performance qualities of robots, the CH33, was developed in Japan [43] and was used in one study in this review [41] to examine how well a model of motion perception matched to the perception of individuals watching different types of robot motion.

Eight articles had a specific hypothesis that was being tested. One article [37] investigated the musicians' appreciation for seeing the robot's motions when they improvised with it and how much having the robot and musician on stage appealed to the audience watching. A different study [34] examined the feelings of a person doing a task with an animated robot watching. Though participants could cheat for a better result in their task, they tended to be more honest with the robot watching with possible negative attitudes toward the robot. Another study [31] found that the exaggerated motions of the robot storyteller made those parts of the story more memorable. Another study [60] used animation techniques to simulate competence and enthusiasm in a robot playing the ultimatum game with a participant. Ribeiro and Paiva [67] had participants rate the performance of the robot, its animation, and its intention. A different study [52] looked at how much each student remembered from each lecture from a human, an animated human using the lecturer's voice, a robot, and an animation of the robot. The human lecturer followed by the animation of the robot resulted in the best scores for the participants' knowledge.

Two studies used only qualitative methods. One study [72] asked qualitative question about what children thought of the Alphabot and how the children understood the robot entering and leaving the virtual world. The other study [98] used observation and interviews to find out which methods worked best for teaching robots new ways to move.

There were two studies that used animation techniques and investigated where participants thought the robot was looking. One study [24] compared gaze direction with a spherical robot head versus a flat screen monitor. The spherical shape of the head and its use of secondary action in its eyes made it easier to see what was being looked at than the flat screen monitor. The other study [31] showed that the exaggerated motion of the robot made it easier for participants to predict the direction of the eye gaze than if the robot's motion wasn't exaggerated.

Finally, there were three studies that tested an animation technique with some participants to see if a concept could be further developed. Two studies [55, 93] involved testing if a specific set up would work with children, with general success. The other study in this group [32] was a design critique of a stick robot and how it moved.

5 DISCUSSION

This systematic review has looked at HRI studies done with robots that move using techniques from animation. What do these articles say about this area of research and what are future directions for research?

5.1 The Articles as a Whole

Table 3 shows that there have been some HRI studies using animation techniques back in the mid-2000s and at least one article about animation techniques in an HRI study every year since 2010. So, researchers are interested in researching animation techniques and robots and see how it affects individual's interaction with the robot.

Animation techniques help a robot communicating with a person, either directly or indirectly. Motion from animated techniques can make it easier to express some emotions. Animation techniques also help making a robot appear more appealing to the individuals who are either watching the robot or interacting with it. It can make the robot easier to relate to, approachable, or to have more intelligence.

The studies also show that animation techniques help beyond communicating an emotion. Motion from animation techniques can draw individual's attention to the robot. It can aid in understanding where a robot is looking, what it is planning on doing, or going to do next. This makes it easier to cooperate for human and robots to work together on a shared task.

The studies also indicate that animation techniques are useful for robots that do not have a standard animal or humanoid form. Hoffman and Ju [35] suggest that robot forms that are different from animals and humanoids may need to move in ways that are familiar to individuals to help individuals understand the robot. Animation techniques provide a method of movement that is familiar to individuals and easy to relate to based on the nearly a century of animation techniques in other media.

Looking at Table 5, we can see there are good measurement tools available for looking at aspects of using animation techniques with robots and comparing with other studies. This can help connect new research in animation techniques to the already existing research. If using an animation technique is to make the robot appear more likeable, safe, alive, or intelligent, then the Godspeed questionnaire is a readily available measure that has been used by studies using animation and other studies [92]. It can be a useful tool to compare new research with past results. If the goal of a study with animation techniques is to convey emotions, then using the basic emotions of Ekman [29], SAM, or rating valence and arousal provide a way of comparing results with past studies using other movement techniques. Of course, other qualitative and quantitative methods can be applied to look at new areas.

In general, the studies seem to indicate that using animation techniques is overall a positive experience for the individuals interacting with the robot. Returning to Ribeiro and Paiva's definition [67] from Section 2.1, animation techniques can certainly help make robots' behavior believable and allow robots to express identity, emotion, and intention. This suggests that spending time thinking about how a robot's motion will be perceived by others should aid in creating better robots to interact with, especially if robots may be part of what we see in our future everyday lives. Designers and engineers can enlist the support of animators, puppeteers, and others for determining how a robot should move (e.g., References [36, 54, 75]).

5.2 Future Research Directions

This literature review also points to different areas where further research in using animation techniques with HRI studies. These are some possibilities.

The 12 principles of animation are an area that can be further explored. Table 4 shows that four of the 12 had no study related to them. Some of these principles, like *Staging* and *Timing*, may seem to apply only for framing and directing a movie, but even bits of these principles may still be applicable to robots. For example, the principle of *Staging* states that action should be understandable only by watching the silhouette, and this could aid individuals checking the robots action from a distance. Even the principles that are about aesthetics (*Solid Drawing* and *Appeal*) are useful for creating motion for robots (avoiding symmetrical motion or stopping of limbs) or designing a robot (making the robot appealing to individuals who will be interacting with it).

Secondary Action is used in several articles to add a small animation to help convey another action. But it was mostly used for humanoid or head robots, and the one animal robot, Probo, has a more human-like face. It would be interesting if this could also be applied to the non-human, non-animal robots. For example, a part on the non-humanoid, non-animal robot on could be animated to have an analog of a blink.

Other principles can also be investigated on other types of robots. For example, the principle of *Slow in and Slow out* is only used in one study here, but it could likely be employed in many situations of different types of robot motion. The principle of *Arcs* could also be used for other types of robot motion. The *Squash and Stretch* principle can pose an interesting challenge to individual's assumptions of a robot made of hard materials.

Another principle that could be looked at is the principle of *Follow Through and Overlapping Action*. One obvious place is the transition from configuration to locomotion or when locomotion and configuration are combined. This would also be an opportunity to examine more of the animation principles using locomotion.

Since animation techniques have been adapted in computer animation [49], they have also shown up in graphical user interfaces on computers [20, 39]. So, some of these techniques have already been formalized. This is another area where tools used for creating computer animation and games can be adjusted to work with robots [7].

Using formalization from animation techniques to computer algorithms from above, animation techniques may also be a way of achieving motion that is defined in other ways. For example, LaViers, Teague, and Egerstedt [51] and Knight and Simmons [46] worked on formalizing the Laban Effort System for different robots. One study in the review [77] provides an example of using the animation techniques of motion capture to demonstrate how to move a drone as expressed via the Laban Effort System.

Animation techniques could also aid in the combating the *uncanny valley* (re-translated to English as Mori, MacDorman, and Kageki [59]). The uncanny valley is the idea that there exists a curve representing an individual's affinity toward a robot versus how human-like the robot looks. As the robot looks more human-like, the individual's affinity grows until it peaks and suddenly the looks are *not good enough* (i.e., uncanny) and the individual's affinity for the robot wanes. Continuing through the valley, at some point the robot's looks near that of a human and the individual's affinity for it rises again.

Although the uncanny valley is focused on the robot's looks, Mori et al. posited that more machine-like movement than organic movement makes the slopes in the valley even steeper. That is, if something *looks* more like a human, but does not *move* like a human, then it is difficult for us to have affinity for it. Takayuki, Kanda, and Ishiguro claimed that a robot that resembles a human, but does not move like one is "unnatural" [83, p. 101]. Since animation techniques affect how things move, they could also help in addressing this. Some articles in the review [53, 58] mention the uncanny valley explicitly as a motivation for their research.

Note that animation techniques do not solve all problems. Animation that is created to be shown on a screen is free of limitations of the physical world. Servos and other methods for movement have limitations in strength, friction, flexibility in movement, and other issues. These limitations need to be considered if an animation technique will move from the screen to a robot. But this is another area that could be explored: the quality of the animation created by the animation techniques and how this affects interaction. That is, what separates good animation from bad animation in robots? This may be useful if other considerations such as limited movement or energy conservation must be balanced against interaction with the robot.

Future research could look at the combination of animation techniques with the other modalities like sound or smell. This may result in a stronger or weaker effect than just the animation technique alone. Combining modalities also makes the robot more universally designed and accessible to more individuals. A robot moving its limbs to communicate its intention is useless if the individuals it is interacting with cannot see it.

Most of the studies in this review took place in a lab setting with one-on-one interaction. Even though a lab provides an environment to ensure a robot works well, others have advocated that it is important to try to get HRI studies out into real-world settings and test interaction over a longer term [22, 42]. Testing robots in the real world will help determine how well motion using animation techniques works when competing or cooperating with other elements in the environment and if the animation is effective or annoying over long term exposure. This may also mean not using video recordings of the robot and instead focus on individuals working with the robot live.

Having studies that take place outside of the lab also allows the introduction of non-lab contexts. One psychology study shows that context can affect how individuals perceive human faces [71]. Further research is needed to see if context has an effect on how individuals perceive robots' faces and actions.

Although there were some methods that showed up multiple times (e.g., the Godspeed Questionnaire, SAM, and choosing from Ekman's basic emotion), future researchers should not feel that these are the only methods that can work for evaluating animation techniques in HRI. Other methods also exist for evaluating the emotion a robot is displaying, such as the circumplex model of affect [64]. Quantitative methods testing a hypothesis were used in several studies and may fit for certain studies. Furthermore, in some situations, such as working with children or looking for a deeper understanding of a phenomenon, qualitative observations and interviews are necessary.

Finally, this review has focused on the use of animation techniques. As mentioned in Section 2.4, animacy is a closely related concept and animation techniques can certainly lead to the perception of animacy in a robot, though it is not the only way this can be done. There was some effort involved in separating articles out about animation technique and the concept of animacy. With this review of animation techniques in HRI studies completed, it makes the task of looking at animacy in HRI studies more straight forward.

6 CONCLUSION

We have run a systematic review of animation techniques from movies and computer animation in user studies and evaluations in HRI. This resulted in 27 out of a total of 106 articles that were returned from the ACM Digital Library and IEEEXplore. There have been several animation techniques that have been adapted to work with HRI; this includes researchers using the 12 principles of animation (Section 2.2) and other techniques like motion capture. The studies in the articles show that motion created through animation techniques affect an individual's impression of the robot, help the robot express intention, or help individuals understand an expression a robot is showing. Having a better understanding of a robot can make it easier to interact with a robot, and it can also make it easier for the robot to interact with individuals.

The literature has shown that animation techniques can help in HRI and is an area that can be further researched. Given that animation techniques help in the motion of a robot, they are applicable in different types of HRI studies. If a researcher is interested in making a robot move distinctively to help interaction, then animation techniques are good places to investigate.

There is much to discover about animation techniques, robots, and HRI. Future researchers have a fertile frontier to explore in helping humans and robots interact better together.

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