ABSTRACT

PORTERFIELD, JANE ANNE. Exploring 3D Garment Simulation as a Prototype Validation Tool for Costume Design. (Under the direction of Dr. Traci A. M. Lamar).

This research examines the potential of 3D garment simulation technology in the context of costume design and production, specifically as a prototype validation tool for costume designers and makers. Three-dimensional garment simulation, though still a relatively new technology, has potential to be a time and resource-saving device in the apparel industry. In the performing arts, where time and resources are often scarce, costume designers and makers often choose to fall back on familiar but time-intensive methods. This research asked costume designers and makers to consider whether the quality of their product and the efficiency of their process can be enhanced by introducing 3D garment visualization technology into the prototype validation phase of costume design. This research employed a qualitative approach in which costume designers and makers were asked to participate in and respond to “virtual fitting sessions.” Research subjects were solicited from among professional costume designers who were asked to submit a costume sketch of a woman’s dress that was made-to-order for a recent production. Patterns for these garments were also obtained, and these were scanned using the N-Scan Pattern Digitizing System that allowed the two dimensional pattern data to be used in Lectra Modaris to create three simulated fittings of the costume. Both the designer and maker for each costume were asked to participate in a Web-based interaction (via WebEx) in which they were able to view the 3D simulation and assess the experience of participating in a simulated fitting. At the same time experts in the field of costume design and production were interviewed to obtain information about the costume design process, and about the experts’ awareness of the use of digital
technology in costume design and production. Interview responses were used to create a preliminary framework describing the essential elements of the collaborative process of costume fitting and production. These elements were divided into early mid, and late stage design communication. Each of these stages was characterized by interactive fit and design decisions, and interactive design communication. The majority of participants felt that early stage design decisions could be accommodated with a virtual fitting. Participants were divided on the potential of virtual fitting to accommodate interactive fit and design decisions. This was due in part to limitations of the currently available software, but also in part to the lack of involvement from a key stakeholder in the process, the performer. All participants felt that virtual fittings could contribute in some way to interactive design communication, either at early or mid-stages of the design and production process. These results were used to revise the preliminary framework to show potential for incorporation of 3D apparel simulation technology into the costume design and production process. It is expected that this framework will benefit both costume designers and makers, as well as those involved in development and implementation of 3D apparel CAD software. Additional benefit may be found in applicability to the apparel design process, particularly in areas of mass customization and made to order garments.
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Exploring 3D Garment Simulation as a Prototype Validation Tool for Costume Design

by
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A dissertation submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

Textile Technology Management

Raleigh, North Carolina

2015

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BIOGRAPHY

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ACKNOWLEDGMENTS

I would like to acknowledge the time and support of many individuals who have encouraged, supported, and inspired me in this work. First I would like to express my thanks to my committee chair, Dr. Traci Lamar who has patiently guided me through this process. I would also like to thank my other committee members, Dr. A. Blanton Godfrey, Dr. Kate Annett-Hitchcock, and Dr. Sharon Joines. Your enthusiastic support and advice on this project has been invaluable.

The experience that formed the foundation of this project would not have existed without the teaching and example of many individuals. I would like to especially thank Susan Tsu, Judy Adamson, and Jan Chambers for their support and advice, and Robert Weiss for the opportunity that led me to the College of Textiles in the first place.

I would like to express my appreciation for the opportunities I have had to work and teach in the College of Textiles. My studies here would not have been possible without that support. I would like in particular to thank Dr. Godfrey, Dr. Nancy Cassill, and Dr. Karen Leonas for those opportunities.

Finally I would like to express sincere appreciation for my parents, Charles and Becky, my sisters Mary Lee and Ellin, and the many friends and neighbors who have offered support and encouragement throughout this process.
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1. Introduction

The costume design and production process is an iterative, hands-on, collaborative one that involves input from several stakeholders at multiple stages. It is a time-delimited project-specific activity that results in apparel and apparel-related items that are not considered “products” in and of themselves, but rather are contributing components of a performance event that will be experienced from different points of view by performers, audience members, directors, producers and designers. Costumes can give the audience clues as to the time period and location of the play, opera or ballet. They can help to visually establish the age, economic background, and personality of a character. At the same time they must satisfy the director’s vision for the piece, and they must give the performer a sense of their character while enabling that performer to move in certain prescribed ways. They must be made within a certain window of time according to restrictions of budget, availability of materials, and abilities of the team of makers. The work of the costume designer is defined by all of these factors in addition to other aesthetic considerations, and he or she must satisfy these needs in collaboration with the team of directors, performers, producers, and makers involved in the production.

![Diagram](image)

Figure 1. The costume design and production process (synthesized from Anderson & Anderson, 1984; Cunningham, 2009; Ingham & Covey, 1992a and b).
The iterative nature of the costume design process is outlined in Figure 1, synthesized from several works on the subject. Each of these steps can be further broken down into detailed processes that involve a number of participants. In steps one and two, the definition of needs for a particular play or production involves input from the director or choreographer, analysis of the script, and input from the actor or performer. The costume designer manages the needs and opinions of all these stakeholders alongside his or her own vision to create designs that will be presented for approval by the director and producers in stage three of the process. In stage four the costume designer works closely with the makers and artisans who will build the costumes through a series of discussions and fittings. This stage typically involves one or more iterations of costume prototypes crafted by costume makers. These prototypes are presented in fittings with the performer in which costume makers, designers, and assistants examine the fit, line, color, and wearability of the costume. Stage four in this model, prototyping and design validation, is the focus of this research, which will examine how digital technology might play a role in this stage of the costume design and production process.

**Making Costumes**

Costume designers and makers in the performing arts rely on draping and flat pattern-making methods to create patterns for costumes (Cunningham, 2009; Ingham & Covey, 1992b). Their choice of methods is influenced somewhat by tradition; however this model of hands-on design and production makes some practical sense as well. In the United States, many if not most professional theaters are operated as not-for-profit or educational institutions (Theatrefacts, 2012). Typically those theaters produce a season of several
different plays that run for a period of weeks or months but are not repeated. The training that costume designers and makers receive focuses on creating one-of-a-kind garments that may or may not be used again, rather than on designing garments for mass production. Because of these factors, and because of an industry preference for traditional methods, it appears that the majority of costume designers and builders in the US have not adopted computer aided design (CAD) and computer aided manufacturing (CAM) systems into their costume development and production processes.

3D Apparel CAD

The term Computer Aided Design (CAD) for apparel covers a range of apparel design processes that can be accomplished using software from the design stage through product development and manufacturing. In the pattern development phase, two dimensional (2D) apparel CAD software such as Gerber Accumark and Lectra Modaris was developed to complement computer aided manufacturing (CAM) systems that increase productivity and efficiency in the industry (Collier & Collier, 1990). Prior to the adoption of CAD/CAM processes in early manufacturing systems, patterns were drafted and graded by hand. Automated cutting systems sped up the production process, but necessitated a means by which markers could be sent digitally to a cutter. Systems for digitally drafting and grading patterns and creating markers for efficient cutting were developed in the 1970’s and 1980’s and were broadly adopted in the apparel industry (Collier & Collier, 1990; Hardaker & Fozzard, 1997). In recent years three-dimensional (3D) simulation technology designed specifically to enable 3D simulation of apparel patterns for fit evaluation has been developed. This technology, which is typically linked with 2D pattern development software systems,
is intended to assist apparel product developers in the late stage design process when fit and design of their products must be evaluated prior to manufacturing. In addition to allowing quick viewing of garment shapes and features, 3D simulation has the potential to allow design consultation over long distance through virtual prototyping and fit sessions.

**Purpose of the Study**

This research examines the potential of 3D garment simulation technology in the context of costume design, specifically as a prototype validation tool for costume designers and makers. Three-dimensional garment simulation, though still a relatively new technology, has potential to be a time and resource-saving device in the apparel industry. In the performing arts, where time and resources are often scarce, costume designers and makers often choose to fall back on familiar but time-intensive methods. This research asks costume designers and makers to consider whether the quality of their product and the efficiency of their process can be enhanced by introducing 3D garment visualization technology into the prototype validation phase of costume design. The resulting framework will inform the incorporation of this technology into the costume design process. Because this research is exploratory in nature this framework speaks to the most basic features of what is required both of this technology to satisfy the needs of the user (in this case the costume designer and the costume maker) and of the user to effectively approach the technology. It is expected that this framework will benefit both costume designers and makers, as well as those involved in development and implementation of 3D apparel CAD software. Some additional benefit may be found in applicability to the apparel design process particularly in areas of mass customization and made to order garments.
2. Literature Review

Costume Design

It is difficult to separate the task of designing a costume from the overall process of creating a work of theatre, dance, or opera. Although a costume designer’s work often begins with a script or libretto, the involvement of the director, the design team, and the performers influences the costume designer’s work from an early stage. The director provides an overarching concept or “direction” for the piece, and the costume, set and lighting designers follow that concept in their work. At the same time this team of designers works closely with one another to ensure that all the elements function as a whole. It could be stated that there are many stakeholders in the costume design process. For the director the costume must support his or her vision of how the piece should be presented. For the actor the costume helps to establish a sense of character, both physically and aesthetically. Finally, for the audience, the costume helps to tell the story by representing the age, social standing, historical period, and personality of the character. In their still widely referenced 1984 book on costume design, Anderson and Anderson state that a costume must “…produce a result that is at once visually creative and integrated so firmly into a whole that it cannot be extracted as a separate entity” (Anderson & Anderson, 1984, p.29). The costume designer must attempt to satisfy all of the stakeholders in the project while contributing his or her own creative vision to the final product. For this reason the process of costume prototyping and design validation is particularly involved and complex.

The role of the costume designer. Working within the vision established by the director or choreographer, the costume designer determines what each performer will wear
from head to toe in each scene. This information is communicated to the director through design drawings, which are also used to communicate with the team of costume makers who will work to make the desired costumes. The available literature on this topic describes a process that most costume designers follow: read and analyze the script, discuss the overall concept with the director, make a list of the costume needs for each character, then begin drawing sketches of possible looks for each performer (Anderson & Anderson, 1984; Cunningham, 2009; DiBenedetto, 2012; Pectal, 1999). Figure 2 shows how the next steps in the design process may vary among designers, or according to the nature of the production.

Figure 2. Detailed components in stages 2 and 3 of the costume design and production process (synthesized from Anderson & Anderson, 1984; Cunningham, 2009; Ingham & Covey, 1992a and b).
In stage two, research and inspiration, a designer may pull images from all the sources listed, or may use a combination of these types of sources for their research. Similarly in stage 3, a designer may choose one or more methods of presenting his or her ideas to the director.

While there is no agreement as to the “best” way of approaching these stages, costume design experts agree that the final sketch should be a balanced presentation of the designer’s artistic interpretation of the costume and the information needed by the director, actor and costume maker (Ingham & Covey, 1992a). These drawings, with the accompanying notes and fabric swatches, help to establish the working relationship between the costume designer and the rest of the production team, including the director and the team of costume makers. It is important to note that while the costume sketch becomes a kind of blueprint for the finished costume, it is not itself an end point. Discoveries are often made in rehearsal and fittings that require changes to the finished design (Cunningham, 2009). The amount of information contained in the costume sketch can communicate to the costume maker the extent to which their input will be required and serves as a jumping off point for the creative give-and-take that characterizes the collaboration between a costume designer and a costume maker.

**The role of the costume maker.** The costume maker’s role is to interpret the work of the costume designer. Typically the person who is responsible for all aspects of making the costume, including development of patterns, creation and fit of prototypes, and creation and fit of final costumes is referred to as the draper (for women’s costumes) or the tailor (for menswear). In this study that individual will be referred to as the costume maker in recognition of the scope of their responsibility. They may themselves participate in cutting and sewing the costume, or they may have a staff of workers who help them perform those
tasks, but it is their job to see that those things are done to the satisfaction of the costume designer and performer, and according to the standards established by their costume shop manager. The titles and responsibilities of typical costume production team members are listed in Table 1. Not every production is staffed by this many people and in some cases one person may take on several or even all these roles.

Table 1

| Costume production personnel (adapted from Ingham & Covey, 1992b) |
|-----------------------------|------------------------------------------------------------------|
| Title | Primary Responsibilities |
| Costumer or costume shop supervisor | Oversees the work of the costume production team; manages the resources of the production (time, money, personnel, etc.) |
| Draper/Cutter or Tailor | Develops garment patterns based on the information provided by the costume designer; supervises creation and fitting of prototypes and final costumes |
| First Hand | Cuts prototypes and final costumes based on patterns developed by the Draper/Cutter; supervises the sewing of costume pieces |
| Stitcher | Sews the prototype and final costume pieces |
| Costume Painter/Dyer | Dyes or otherwise modifies fabric for costume according to the designs |

The costume fitting process. Figure 3 shows the steps in stage 4 (prototype validation) of a typical costume production process for a made to order costume. The muslin prototype typically represents the basic shell of a costume without its fastenings, interfacings and linings. Components such as sleeves, collars, and pockets may be unattached for this fitting, to be pinned on in the course of the fitting according to the fit of the garment and the
judgment of the designer. Features such as lapel roll lines, button placement, and trim may be shown by marking in stitched lines called “thread marking” so that they may be easily altered if not correct.

Figure 3. Detailed components in stage 4 of the costume design and production process (synthesized from Anderson & Anderson, 1984; Cunningham, 2009; Ingham & Covey, 1992a and b).

In the costume fitting, the costume designer gives detailed feedback to the costume maker on all of the features of the costume as they are presented. Alterations to the prototype are marked with pins or drawn with pencil so that they can be transferred to the final pattern.
The performer may be asked to show the range of motion required for the performance to ensure that the costume will accommodate what is needed.

In stage 5 of the above model (Production) the costumes are altered and finished based on the fitting notes. Further adjustment often takes place during the dress rehearsal period, in which the costumes are worn on stage for the first time. At this stage movement issues may be discovered or design decisions may be reconsidered. Once the show opens for an audience the costumes are typically considered finished and no further design and fit adjustments are made.

**Digital technology in the performing arts costume shop.** While there is very little formal research in this field anecdotal evidence suggests that costume designers can be resistant to incorporating digital technology in some aspects of their work (Cunningham, 2009). Costume designer Judith Dolan, when discussing the process of preparing a costume plot says:

> The computer isn’t just a tool; you have to be aware that it alters your perceptions. Doing plots by hand with pencils and rulers and pasting together papers slows the designer and the director down, allows them to think about the play more carefully and thoughtfully, instills pride of ownership, and gives them a strong handle on the piece (Judith Dolan in Cunningham, 2009, p.141).

Similar resistance has been recorded in other branches of fine art based on lack of access to technology, lack of training, and a belief that use of computers diminishes the quality of artistic output (Mak & Degennaro, 1990). Despite this idea of resistance to technology, there is evidence that at least some CAD capabilities are currently utilized by costume designers
and costume makers. Costume designers report use of software such as Adobe Photoshop and Adobe Illustrator for creating costume drawings and collages (Bradley, 2009; Cunningham, 2009). Additionally costume designers have embraced the use of computer software to create textile patterns for digital fabric printing (Pollock, 2014). These digital technologies that have been embraced by costume designers and makers add both efficiency and scope to the process of costume design. Sourcing fabrics is one of the primary functions of a costume designer. When a fabric can be created with little effort and printed quickly and easily it makes the task of sourcing easier and opens up opportunities for enhanced creative output. Similarly the use of digital technology to create and enhance costume sketches may offer opportunities for quicker communication between the costume designer and the costume production team. The supposed resistance felt by costume designers against computer technology may be swept away as other apparel CAD software becomes more accessible.

3D Apparel Visualization Technology

Computer aided 3D visualization technology for apparel has undergone tremendous development in the past twenty years. Selecting from a broad range of apparel pattern-making software today’s apparel designer can virtually “sew” and “model” two dimensional (2D) garment patterns in a three-dimensional (3D) environment. (Lectra, Modaris; Optitex, 3D Suite; Gerber Accumark, Vstitcher; Tukatech, Tuka3D; Assyst Bullmer, 3D Design; PAD System, Haute Couture 3D). At the time of its initial development and early adoption it was assumed that this capability would eliminate the need for manufacturing multiple prototypes and would facilitate decision making and communication at various stages in the apparel
design and production process (Collier & Collier, 1990; Hardaker & Fozzard, 1998). Three-dimensional visualization technology has, in effect, revolutionized other industries, enabling automotive and engineering product developers to design, view, modify, and validate product specifications in 3D simulation (Kim & Park, 2007). It is unclear at this time to what extent the current garment simulation technology has been adopted by the apparel industry. Review of the available literature on this topic reveals that questions remain about whether the complex process of apparel design can be supported by garment simulation software. The integration of this 3D component in apparel CAD will be the focus of the next section.

Unlike 3D simulation for machinery and durable goods, 3D simulation for apparel presents special challenges that initially slowed its adoption in industry. One is the problem of translating complex flat pattern data into a 3D shape that takes into account the varying and unpredictable nature of cloth as well as the force exerted by the body model underneath the garment (Magnenat-Thalman & Volino, 2005). Another issue arises due to the fact that garment assembly steps differ depending on the garment type and components involved; therefore the assembly phase of garment simulation cannot be based on a standardized model (Liu, Zhang, & Yuen, 2010). Research that incorporates 3D simulation into apparel CAD has made progress in addressing these issues, as discussed in the next section.

Translating the pattern into a 3D shape. Making 3D objects presents certain challenges in any material. Three-dimensional objects can contain complex curves, and in some types of materials, force must be applied to maintain those curves (Hinds, McCartney & Woods, 1991; Magnenat-Thalman & Volino, 2005). In garments this 3D shaping is accomplished through the shaping of seams and implementation of pleating, gathers, and
other methods of manipulating fabric to fit the desired form. Garment patterns are essentially polygons made up of straight and curved lines. In apparel CAD software pattern technicians input line lengths and curve shapes to create pieces that can be sewn together as garments. Points can be moved to alter line lengths and curve shapes that influence both the size of the garment piece and the style. For example, a sleeve may be made fuller by deepening the curve at the sleeve cap where it will be sewn to the armseye. These shaping features and others such as pleats, darts, and gathers can be specified by the pattern designer in 2D pattern-making software such as Lectra’s Modaris, Gerber Accumark, and Optitex (Gerber, 2014; Lectra, 2014; Optitex, 2014).

To develop 2D patterns with all of their features into a 3D simulation there must be some way of relating the data contained in those 2D pieces to the data that represents the 3D body form. This is most frequently done by creating a triangular mesh to represent each piece. A triangular mesh structure, in computing terms, is a list of triangles containing information about the number and relationships of vertices, edges, and faces (Dunn & Parberry, 2002). To create a 3D view of the garment piece each triangle can be moved in relation to the others within the defined coordinates of 3D space (x, y, and z) of the software. A 3D mesh can be made up of any type of polygon; however in many cases a triangular mesh presents more efficient opportunities for operations such as moving and scaling of 3D mesh form (Dunn & Parberry, 2002).

**Simulation methods.** Early fabric simulation methods, such as that developed by Weil (1986) were based primarily on geometry. A purely geometric approach to fabric simulation can represent the curves, darts, and seams of a garment by manipulating triangular
mesh elements, but this will not present an accurate visual picture of how fabric behaves under forces of drape, stretch, and shear (Bao, Ni, Wang, & Zhu, 2011; Fontana, Rizzi, & Cugini, 2005; Volino, Cordier & Magnenat-Thalman, 2005). Simulation methods that take into account these mechanical properties of fabric are much more computationally complex but can give the designer more visual information about how the garment looks and interacts with the body in terms of mechanical forces (Fontana et al., 2005; Yang & Magnenat-Thalman, 1992).

**Physically based simulation.** Both geometric and physical data are used for a physically based simulation. A physically based simulation adds data based on the mechanical properties of fabric and the forces operating on it. Fontana et al. (2006) described two types of physically based simulations; continuous and discrete. Discrete formulations “…describe cloth by a finite number of consecutive mechanical entities” (Fontatna et al., 2006, p.391). They can be thought of in very simple terms as corresponding to the warp and weft interactions of woven cloth. Breen (1992) worked on a particle model of physically based simulation in which each warp/weft intersection was represented as a separate particle. This method was computationally expensive and not very accurate (Bao et al., 2011). Provot (1994) proposed a method of representing the forces that stretch and repel the fibers at these intersections. In these discrete interactions the forces of stretching, bending, and shear can be represented. This method, having been improved and refined since its introduction (Maguenat-Thalmann & Volino, 2005) is currently the most widely used method of fabric simulation in apparel pattern software (Bao et al., 2011).
Collision detection and tension mapping. Garments in 3D simulation must be prevented from appearing to fall through the underlying body model as they are simulated. This problem calls for a method of detecting collision between the fabric and the body, or between individual fabric layers (as in folded collars, cuffs, pockets, etc.), and creating a repelling effect between those layers. One method for handling this issue is called the bounding box method. In this method boxes are drawn around units of the objects in question (fabric mesh units and body model units). Where these boxes are intersecting, correction is made to repel the colliding objects (Bao et al., 2011). Related to this issue, a key offering in most of the current apparel CAD software systems is the ability to view a “tension map” that displays the amount of strain on the simulated fabric based on interaction with the underlying body model. In some software the tension map can be used to indicate the distance between the garment and the body (ease) as well as the amount of physical tension in the cloth in either the warp or weft direction. Figure 4 shows amount of ease present in a garment simulated using Lectra Modaris 3D Fit software. In this system, areas of ease are shown in blue, with darker blue signifying greater ease, while yellow to red shades show degrees of tightening. In this figure the fabric around the 3D model’s waist is fairly loose, while some tightening is present in the hip and thigh area. This type of information may enhance the ability of the apparel pattern developer to make judgments about the fit of the garment in question; however fit test investigations show that such ease measurements also vary according to the type of fabric simulated (Ancutienea, Strazdiene, & Lekeckas, 2013; Lim, 2009; Lim & Istook, 2011). The need for multiple fit trials may not be completely eliminated by the presence of this technology.
Figure 4. Simulated garment on a 3D avatar in Lectra Modaris 3D Fit showing tension map.

**Garment assembly in 3D.** For an expert in apparel production, seaming the edges of garment pieces together is a fairly intuitive process. Seaming 2D garment pieces together into a 3D simulated garment is a much more complex process that involves defining the data contained in those edges so that they may be associated with each other in the visual 3D display. Yang and Magnenat-Thalman (1992) presented a data structure that included the underlying mesh of a 3D garment, the physical data needed for fabric simulation, the order in which piece edges would be seamed together, and the points at which the garment would be joined to the body. In the assembly process for a simulated garment, seam lines that are to be joined together are divided into corresponding mesh units and those units are joined in a one-to-one assembly process. Okabe et al. (1992) showed that seam lines of varying lengths might be divided proportionally into the same number of mesh units to simulate gathering or ease in a garment. This complex data is needed for basic simulation of a garment on a 3D
form; however it is not sufficient for the visualization of garment with layers, folds, and gathers.

Fontana et al. (2006) built on the idea of adding complexity to the 3D simulation. They proposed a method of describing the relationships between pieces as they are sewn together that would allow the simulation to show features such as seaming, layering, pleating, fastening, cutting, and reinforcement. They divided these relationships into “panel” features (pleating, cutting, reinforcement) and “assembly” features (seaming and fastening). Both types of relationships were represented as functions:

- Panel Features: \( fd: P \rightarrow P^* \) where \( P \) is the main panel and \( P^* \) is the modified panel
- Assembly features: \( fa: PxQ \rightarrow R \) where \( P \) and \( Q \) are two main panels, or disjoint sub-regions of the same panel, and \( R \) is the resulting assembled panel or region (Fontana et al., 2006, p. 395)

In developing these functions they considered what must be calculated for the different listed features for the operation to take place. For example the data needed for a pleat feature would include the panel to be pleated as well as the angle, orientation, and depth of the pleat.

While this type of approach contributes to the capabilities of 3D simulation it is not clear that the complexity desired in this experiment has been achieved. Accurate representation of layers and folds in fabric remains one of the primary challenges of 3D simulation, yet due to the complexity of most garments 3D simulation will not adequately replace a physical prototype unless layers and folds can be represented. Tests of garment fit in 3D simulation have shown that when features such as the folding over of a waistband are not accurately represented the fit of the garment is also not accurately represented (Lim, 2009).
Sul (2012) proposed a method of making garment pieces interchangeable by creating name-based sewing rules. In this system pattern pieces are grouped according to their position on the garment. Sleeves, for example, would be grouped together, and each seam edge would be given an identifying number and position, describing its placement and direction. It is not clear if this method is currently in use by any commercially available software. While this method was developed to give the pattern developer options for interchanging garment pieces to create new styles, the user input involved in defining each seam edge may cancel out any time and productivity benefits. Current software systems such as Lectra Modaris already require extensive user input in defining seams, ordering pieces to be sewn, and defining connection points from the garment to the body model (Figure 5).

Figure 5. Pattern pieces sewn together in Lectra Modaris,
Testing the accuracy of 3D simulation. Software developers rather than apparel experts have driven much of the research in 3D apparel CAD. As a result, meaningful assessment of 3D simulation as an accurate tool for validating garment fit has been limited. Pioneers in this area have demonstrated valid methodologies for approaching such research. Apparel design is a complex and iterative process, and it is simply not sufficient to say that a particular software can produce 3D garment simulations. Apparel design and development experts who have contributed to research in the area of testing the capabilities of apparel simulation software bring an important user perspective resulting in an understanding of not only what the software can do but also what the user needs from the technology in terms of both results and interaction.

Otieno and Apeagyei (2006) compared the fit of real garments with virtual ones using Gerber Garment Technology software. They created patterns for two jacket and skirt sets, which they cut and sewed in fabric and modeled in 3D. The garments were sewn in two different sizes and tried on nine human models. From this test two human models were selected and their measurements were used to test the garments in 3D simulation. Examination of virtual model cross sections showed similarities between the real and virtual garment fit; however their study had some limitations. The virtual model they used had no arms, so they were not able to make a comparison between the real and virtual fit of their jacket sleeves. Additionally these researchers did not report consideration of fabric properties in their simulation. Other research has shown that fabric properties strongly impact the fit of virtual garments (Ancutienea et al., 2013; Lim, 2009; Lim & Istook, 2011).
Lim (2009) also compared fit and appearance of real and simulated garments. Among other contributions this study shed light on the issue presented by garment simulations in which the appearance of the virtual fabric does not match that of the real fabric. This issue has implications not only for garment developers but also for marketers who wish to accurately represent their apparel products in a virtual try-on setting. Lim tested the mechanical properties of the two fabrics used in the study using the Fabric Analysis by Simple Testing (FAST) system. These properties were input into the apparel simulation software used in the experiment (Optitex and V-Stitcher). The importance of fabric simulation accuracy was shown in one key finding of this study. Because the two systems allowed different fabric properties to be input, both appearance and fit differences were shown between garment simulations of the same fabric obtained in the different systems used. Garments simulated in Optitex showed both fit and appearance close to the fit and appearance of the live garment, while garments simulated in V-Stitcher showed excessive wrinkling. Optitex allowed the input of extensibility, bending rigidity, surface thickness, and weight, while V-Stitcher allowed for input of relaxation shrinkage, extensibility, bending rigidity, shear rigidity, thickness, and weight. The differences obtained in findings between the two systems suggest that user input is still necessary to ensure that the fabric simulation satisfies the necessary parameters for accurate visualization and fit.

This study also showed that the selection of virtual avatar could impact the success of virtual garment fitting. Lim used 3D body scans of her subjects to create direct avatars in Optitex, while in V-Stitcher standard avatars with manually manipulated measurements were used. Lim compared fit on both the direct and standard avatars to live fittings with research
subjects. In this comparison Lim found greater similarity between the fit of virtual garments on the direct avatar and the live fitting. Lim attributed this difference to the realistic posture achieved in the direct avatars based on 3D scan data. Lim’s research is important because it showed the influence of multiple elements on the success of the virtual fitting. Further study on the accuracy of fabric simulation and on the best method of avatar development is indicated in these results.

Wu et al. (2011) examined quantitative comparisons between real and simulated garments through a slightly different method. They took photographs of their actual garments on a dress form, and using a technique that translated pixels into inches (based on the resolution of the photograph), derived measurements for a skirt in specific areas. They compared these to garment measurements obtained using tools in the 3D simulation software. Their results showed similarities between the real and simulated garments; however their study was limited in their use of a simple skirt as their study garment. Wu et al. (2011) also used measures of the mechanical properties of fabrics to enhance their study. Of twenty fabrics they measured using the FAST system, they discarded several due to the inability of the software to accurately simulate them. While they did not provide detailed information about these discarded fabrics, this result shows that further research is needed in the accuracy of fabric simulation for 3D garment visualization.

Kim and Labat (2012) framed their comparison of real and simulated garments around the idea of measuring accuracy and fidelity of 3D garment simulation. They created an experiment in which they asked research subjects to evaluate the fit of both virtual (3D simulated) garments and real ones. They based their research on Ferwerda’s (2003)
framework of functional realism in computer graphics. Ferwerda (2003) argued that when the viewer needs to be able to perform a task using or based on a given computer graphic, neither physical realism nor photo-realism provide the most useful visual information. Functional realism, in Ferwerda’s (2003) definition, captures the elements of the visual presentation that allow the user to perform tasks with the computer graphic as efficiently as they would be able to perform them with the real object. The measures of functional realism, according to Ferwerda are accuracy, based on physical measures, and fidelity, based on the viewer’s ability to perform specific tasks with the graphic.

In their comparison of the virtual (3D simulated) and live fit evaluations, Kim and Labat used qualitative and quantitative data to measure the fidelity of their computer simulations. They recruited research subjects who were used as fit models, and who also contributed feedback on the real and simulated garments. They first took measurements of their research subjects using 3D body scanning technology and developed a pattern for a pair of pants based on each subject’s measurements. Real samples of pants were sewn from these patterns, and virtual simulations of the pants were developed using 3D apparel simulation technology. Subjects were asked to view several sizes of pants on a virtual avatar based on their 3D body scan (parallel to direct avatars used by Lim, 2009) and asked to make intent to purchase decisions based on those virtual representations. They were also asked to try on real pants in the same range of sizes, and again asked to make intent to purchase decisions based on the real fittings. Through comparison of these intent to purchase decisions, Kim and Labat concluded that the 3D simulation used in their study did not provide sufficient fidelity for an accurate evaluation of fit. Many of the subjects chose the size pant in the
virtual fitting that they judged to fit badly in the actual fitting. Kim and Labat attributed this partly to the visual appearance of the simulated fabric, which did not accurately represent visible folds and wrinkles in the simulated garment as shown in figure 6.

Figure 6. Comparison of virtual (left) and real (right) pants fit, (Kim & Labat 2012, p.178).

This is a critical finding, because like Lim (2009) their methodology involved measuring the mechanical properties of their fabrics and applying those properties in the simulation software. Kim and Labat (2012) do not mention the type of software used in this experiment; however their results reinforce the idea that fabric simulation for 3D garment visualization, even with user input, continues to show inconsistent results across different types of apparel visualization software. Their approach did present a useful framework for
analyzing a 3D apparel prototype in comparison with a live garment fitting, and it is clear that more such studies are needed.

Another approach to fit evaluation using 3D technology is not directly related to 3D garment simulation, but offers some useful insights. Several research teams have explored the use of 3D scanning technology as a fit evaluation tool (Ashdown, Slocum, & Lee, 2005; Bye and McKinney, 2010; Loker, Ashdown, & Carnrite, 2008). This research involves dressing a live model in a prototype garment; scanning the model in a 3D body scanner; then using images from the 3D scan to assess the fit of the garment. Researchers in this area have discovered issues with this process, among them the inability of evaluators to view design details such as darts in the 3D scanned images (Bye & McKinney, 2010). Loker et al. (2008) pointed out a feature of this method that by itself changes the perception of the research participant. Many apparel design experts are accustomed to viewing 2D images of people on a computer screen. The very act of viewing a 3D image and the ability to view that image from different angles will alter what the evaluator can determine from the fit session. When this is compounded by issues in accuracy and fabric simulation, the need for further research in the use of 3D garment simulation technology for fit evaluation is further reinforced.

**Acceptance of CAD technology in the apparel industry.** Some of the resistance to CAD that is demonstrated in the artistic community has also been observed in the apparel industry. Studies of CAD acceptance in apparel companies have shown that several factors influence the attitudes taken by workers toward using and adopting CAD, including managerial approach, training offered, and type of work assigned (Bertolotti, Macri, & Tagliaventi, 2004). Time-intensive training required for the use of CAD may interfere with
production efficiency, and management attempts to streamline production through the use of CAD may result in worker dissatisfaction (Bertolotti et al., 2004). Many researchers claim that the training required to efficiently use the 2D CAD interface in currently available garment pattern development software is too complex and time consuming (Decaudin et al., 2006; Li et al., 2010; Wang, Wang, & Yuen, 2002; Liu, Zhang & Yuen, 2010). Some feel the need for even more rapid “prototyping” in the apparel design process. Others have concerns about the accuracy of 3D simulation engines in representing the fit of a garment that was created from 2D pattern pieces (Huang et al., 2010; Huang, 2011). One approach to addressing complexity, training, and speed concerns is exemplified by attempts to develop software that allows a user to create garment designs directly in a simulated 3D environment.

**Research in creating patterns directly in a 3D environment.** The direct to 3D method employed traditionally by apparel pattern developers involves draping fabric on a dress form or mannequin to achieve the desired shape of a garment. In the draping process fabric is pinned into pleats, darts, and folds, then pattern pieces are derived from the marked fabric. Rather than mimicking this method, researchers in 3D pattern development software have focused on the idea of drawing garment features onto a 3D body model (Choi et al., 2007; Kang & Kim, 2000; Kim & Park, 2007; Wang et al., 2007; Wang et al., 2004). Huang (2011) pointed out that most approaches in direct to 3D garment generation share common limitations. They are primarily based on geometric fabric modeling techniques and so do not present an accurate representation of the 3D garment, and they can only produce very simple tight-fitting garments of one layer. Another issue arises after creation of patterns on a 3D form. To be produced, garment patterns must be flattened without distortion so they can be
cut from fabric and sewn together into an actual garment (Huang, 2011). It is unclear at this time whether an accurate method of flattening 3D garment patterns has been developed. Most of the direct-to-3D garment development methods follow one of two directions; they either involve drawing points directly no a 3D body form or defining garments based on segmented features of the 3D body form.

Wang et al (2002 and 2004), Wang et al (2007) and Zhong (2011) all developed methods for drawing 3D garments based on identification of feature points on a 3D body model. This process involves establishing points in key areas that could be connected to serve as boundary lines for garment pieces. These methods all relied on geometric methods of fabric simulation and produced very simple fitted garments. While feature based drawing methods may allow for establishment of fitting ease in the garment through the relationship of feature points on the body and on the garment, design ease and fullness could not be shown through these methods. Additionally, Wang et al. (2004) and Zhong (2011) reported that extensive user input and expertise were required for the creation of even a single garment, showing that these researchers were not able to eliminate the need for training in garment pattern development.

Daanen and Hong (2007) compared two methods of creating a skirt pattern using 3D body scan data. They focused on the area between the waist and the widest part of the hip. From their scan data, triangles were derived from points and then combined to form a shape using the smallest possible number of triangles (Figure 7). These triangles became the pattern pieces of the skirt, which resembled a patchwork formation.
Using live models, they compared the fit of this skirt with the fit of a skirt pattern derived from circumference measurements at key points in the lower torso and found their triangulated method to be the more successful of the two in terms of fit. While this method does create easily flattenable pattern “pieces”, the resulting multi-piece garment is not typical of apparel that is produced and worn.

Figure 7. Back view of skirt created from triangulated 3D body scan data. (Daanen & Hong, 2007, p.19).

In one stage of their research, Daanen and Hong compared their triangulated skirt pattern to their skirts derived from measurements by superimposing the two. Perhaps at this stage an expert user could analyze the fit information derived from the triangulated pieces to improve the fit of a skirt pattern derived from more traditional methods, however this approach does not seem to offer increased productivity or efficiency.

Huang (2011) proposed a method of creating 3D garments through a method of parameterizing body models developed from 3D scan data. A 3D body scan results in huge
amounts of data, but does not automatically recognize body features. Such recognition must be programmed into the software that translates the points found by the body scanner into a recognizable model. To develop a measurable 3D body model, Huang first used a smoothing process on the 3D point cloud to remove redundant points. A triangulation method was then applied to the remaining points to derive a mesh structure in which was recorded the indices of all the triangle vertices. To segment the mesh body model into measurable features, Huang then divided the body into horizontal cross sections, and created B-Spline curves from the resulting points. B-Spline curves are poly-lines whose points control the degree of curve through their relative positions. Surfaces made up of B-Spline curves (either non-uniform, or as in this model, horizontal) are often used in modeling hard structures, such as automobiles or furniture. Using recognized industry standards; Huang then defined and measured key areas of the body model, including bust, waist, and hip. These features were recorded as an interdependent hierarchy. Huang used these features to divide the body model into bounded segments, (Figure 8) which then essentially became pattern pieces (Figure 9).

Figure 8. Segmentation of body model, (Huang 2011, p. 179).
Huang used the B-spline curve structure of his body model to distribute ease throughout his garment. He compared garment prototypes based on his 3D developed patterns with garments developed from traditional flat patterning methods using live fit models.

The results of this testing were mixed. While some test models preferred the garment developed by Huang’s method, others had issues with the amount of ease in the garment. Huang’s parameterization method may enable distribution of ease throughout a garment, however ease is a subjective requirement, and must be adjusted according to many factors, including wearer preference, fabric type, and garment style. Huang’s contribution also requires further testing with different types of garments to see how much detail and complexity may be achieved.

**The problem of pattern modification.** Drapers and flat pattern makers can easily alter the style of a garment by changing seam placement or altering the shape of a curve in a pattern piece. This can also be done easily and quickly in 2D pattern making software.
Researchers in direct-to-3D garment systems have looked at different ways of approaching this task. Geng et al. (2008) presented a method for sketching a sleeve onto a 3D garment design, and reusing that sleeve in multiple garments. They identified feature points on the arm based on 3D body scan data. They started by drawing the armscye, and from there drew lines to the elbow and wrist. These three points became the location for cross-sections in the 3D mesh “sleeve” (Figure 10). By rotating the cross section to appear “flat” on the screen, they were able to modify the sleeve shape by moving control points on each cross section (Figure 11).

Figure 10. Arm feature points and contour sketches, (Geng et al 2008 p. 712).

Figure 11. Sleeve modification through cross section, (Geng et al. 2008 p. 713).
The researchers used intersection points in their different bodice patterns that corresponded to points on each sleeve. When a sleeve was attached to a different bodice, the points were modified according to corresponding points on the new bodice. This method seemed to offer possibilities for creation of different garment styles; however since the fabric simulation method is purely geometric the resulting physical garments would be vastly different from their 3D representations. For example, the sleeve alteration pictured here did not show how the fabric would drape or fall under this amount of alteration.

**Incorporating user input.** While some of the research into creating garments directly in 3D is driven by the perception that the 2D to 3D process requires too much expertise, some of the interesting research in creating 3D garment patterns actually incorporates expert user involvement at key points during the process. Griffey and Ashdown (2006) used 3D body scan data to create a topographic map of the lower torso of a human body. They identified landmarks on the body to create side seams and darts for a skirt pattern. This operation required expert knowledge of the typical placement of seams on a skirt. Griffey and Ashdown reported that their fit results were mostly satisfactory. Their goal was to create a skirt “block”, a basic pattern that can be manipulated and altered to create many different styles. They acknowledge that the manipulation of the pattern block may be beyond the capabilities of 3D pattern development technology, yet the ability to create a block to fit a specific body form in 3D may prove beneficial to flat pattern developers.

Kim, Yeong, Lee and Hong (2010) used a similar method starting out with data from a 3D body scan of an asymmetrical female body. They traced design lines for a dress on the 3D scan image, creating boundary lines where they determined there was “abrupt curvature
change” (Kim et al., 2010, p.143). Using this method, they created a fitted bodice with 22 separate pieces. While this method may not be appropriate for all types of garments, it may hold possibilities for development of a system that is closer to the activity of physically draping fabric and pinning curved seams. Also, because they were working with specific body scans; their work may have implications for customization of garments using 3D pattern development technology.

At present, 3D to 2D pattern development technology is not ready for use by either trained or untrained practitioners in garment development applications. Limitations are also present in the available 2D to 3D garment visualization software; however the commercial availability of this software presents possibilities for testing by apparel product development experts. Existing studies have focused on the accuracy of these products. Three-dimensional simulation of garments that are developed from 2D patterns is still a relatively new technology; however it is presently offered in most of the available software systems for creating apparel patterns (Browzwear, 2014; Gerber, 2014; Lectra, 2014; Optitex, 2014; Tukatech, 2014). Research comparing the fit of real and simulated garments has shown that this technology has limitations in terms of accurate fit and visualization (Ancutienea et al, 2013; Otieno & Apeagyei, 2006; Kim & Labat, 2012; Lim, 2009; Lim & Istook, 2011). Further research is needed in this area to determine the best way of using 3D garment simulation in the apparel production process. Testing this question in the context of the costume design process with users who are not accustomed to using garment visualization technology will require an exploratory approach to specifically highlight the fundamental requirements of design decision-making that may or may not be met in the software.
3. Methodology

Research Questions

As demonstrated from the review of literature, the field of 3D garment simulation is relatively new, and approaches to using it continue to emerge. The potential effectiveness of 3D garment simulation as a tool for use by costume designers and makers relates to a basic design concept. As noted by Wang and Zhang (2007) in their exploration of a new approach to garment visualization, a garment simulation needs to work “interactively, intuitively, realistically, and efficiently” (p. 363). These four qualities could be stated as requirements for either a live or virtual garment fitting system, and they have informed the examination of this technology in the context of costume design and production. Specifically the Research Question guiding this investigation was:

RQ: Can a 3D simulated costume fitting replace one or more components of the prototyping and validation stages of the costume design process?

The research approach followed on Kim and Labat’s (2012) use of Ferwerda’s (2003) framework that informed analysis of functional realism in computer graphics. Functional realism is defined by how well a graphic representation enables the user to perform needed tasks or make required judgments. To address the Research Question three key strategies were employed:

1. Costume design and production experts were interviewed to obtain current perspectives on the costume design and production process and on the uses of digital technology in costume design and production. These interviews were used to establish an understanding
of the tasks and judgments costume designers and makers need to be able to carry out during the fitting process.

2. Virtual fittings were conducted with costume designers and costume makers, and their assessments related to the experience of a virtual fitting session using a 3D simulation were obtained. These interviews were used to gauge the effectiveness of virtual fitting in the context of the functional realism criteria generated by the expert interviews.

3. The process of working from an existing paper pattern to develop a 3D garment simulation and prepare for each virtual fitting session was documented. This data facilitated understanding of issues that are specific to the process of costume simulation in the context of Wang and Zhang’s (2007) statement that a garment simulation should work “interactively, intuitively, realistically, and efficiently” (p. 363).

Implementation of these strategies is discussed in detail in the following section.

**Overview**

This research employed a qualitative approach in two concurrent phases. Experts in the field of costume design and production were interviewed to obtain information about the costume design process, and about the experts’ awareness of the use of digital technology in costume design and production. Information from these interviews was used to create a framework describing the types of activities that contribute to the costume fitting process, and the participants in those activities. In parallel, costume designers and costume makers participated in and responded to three “virtual fitting sessions.” The framework developed from expert interviews was used to evaluate the “functional realism” offered by a virtual fitting, as it showed what participants should be able to do in a fitting, and how they should
be able to use the results of a fitting in later steps in the costume design and production process.

Research subjects for the virtual fitting phase of the research were solicited from among professional costume designers who were asked to submit a costume sketch of a woman’s dress that was made-to-order for a recent production. Patterns for these costumes were also requested, and these were scanned using the N-Scan Pattern Digitizing System. Scanning allowed the two dimensional pattern data to be translated to data usable in Lectra Modaris to create three simulated fittings of each costume. One simulated fitting showed the costume on an avatar that had been modified according to the measurements of the actress for whom the costume had originally been made. The other two fittings showed the same costume on the same avatar with altered shoulder posture as discussed in detail in the posture modification section. The goal of the virtual fitting was to elicit descriptive comments from both designers and makers in the nature of fit and design notes, such as would be given in a live fitting (the sleeve needs to be lengthened; the neckline is too low; the dress is puckering along the shoulder, etc.).

Both the designer and maker for each costume were asked to participate in a Web-based interaction (via WebEx) in which they were able to view the 3D simulation and participate in a simulated fitting. Scripted questionnaires for these interviews are included in Appendices B and C. A pilot study was conducted initially to confirm the viability of the process. In this pilot study, one costume was simulated and a virtual fitting interview was conducted with the costume maker. This interview demonstrated that the virtual fitting
format allowed the interviewee to make observations about fit and design features of a virtually simulated costume.

**Qualitative Approach**

A qualitative approach was selected for this research for multiple reasons. While it is understood by many practitioners, very little formal study has been made of the costume design process. It was anticipated, therefore that issues would emerge from this examination of technology in the context of costume design that could not be predicted. A qualitative approach is thought to be an effective method of teasing out emerging issues while thoroughly examining a complex problem or activity (Creswell, 2013; Tracy, 2012). Qualitative study provides opportunities for gathering rich insights through open-ended questions and in-depth interviews. Such insights are particularly necessary for understanding previously unexamined processes (Creswell, 2013).

**Role of the Researcher**

The researcher in this project has worked in the field of performing arts costuming as both a costume designer and a costume maker. The insight gained from this experience has informed the scope and focus of this project, as the researcher has explored incorporating digital technology in her own work (Porterfield and Lamar, 2012; Porterfield, Chapman, and Aframian, 2010). Further, this experience formed the basis of purposeful sampling in this research project, as the researcher was able to make informed judgment on inclusion of expert subjects. Researcher involvement is a critical component of qualitative research as the researcher is required to serve, in essence, as a data collection mechanism (Tracy, 2012).
is especially important for the researcher to have an understanding of the issues or activities being studied for effective research design and interpretation (Creswell, 2013; Tracy, 2012).

Sample Selection

A purposeful sampling approach was used in this study. Purposeful sampling is frequently used in qualitative enquiry, as it allows the researcher to select subjects whose expert knowledge and experience can offer useful insights into an area of specialized activity (Creswell, 2013). For this reason professional experience was a key criterion in sample selection for both phases of this research. Participants in the expert interview phase of the project were initially solicited from among researcher contacts at professional theaters and theater training programs. Additional participants in this phase were added based on suggestions obtained during interviews, and from a call made using the social media platform Facebook among a closed group called “Costume People”. Table 2 lists details about the experts who participated in this research.

Table 2

<table>
<thead>
<tr>
<th>Expert interview subjects</th>
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<tbody>
<tr>
<td>E1. A costume shop manager at a university theater department in the northeastern US</td>
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<tr>
<td>E2. An owner/manager of an independent for-profit costume shop in the northeastern US</td>
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<tr>
<td>E3. A costume shop manager at a professional not-for-profit regional theater in the southwestern US</td>
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<tr>
<td>E4. A costume shop employee at a large for-profit performing arts company in the southwestern US</td>
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<tr>
<td>E5. A costume department manager at a large for-profit performing arts company in the southwestern US</td>
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<tr>
<td>E6. The head of a costume production M.F.A. program at a university in the northeastern US (also a working costume maker)</td>
</tr>
<tr>
<td>E7. The head of a costume design M.F.A. program at a university in the southwestern US (also an award-winning costume designer)</td>
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</table>
Sample selection for the virtual fitting phase of the research project was based on four criteria: professional experience, participation in a recent applicable project, availability, and willingness to participate in a ninety minute virtual fitting/interview. Potential subjects were solicited from among contacts at professional theaters and among recent graduates of theater training (M.F.A.) programs. The goal in selecting the sample was to identify professional costume designers and makers who could participate in virtual fittings. While comparison between live and simulated fittings would be desirable following Ferwerda’s (2003) framework as used in Kim and Labat (2012), limitations of time and resources precluded working with costume designs that were in production at the time of the study. A costume shop may have as few as three weeks to pattern, fit and produce costumes for a production. It would be impractical to try to gain access to garment patterns during that short window of time since they are typically not completed until midway through that production period, and scheduling virtual fitting sessions with the busy designer and maker would be very challenging. Instead, by working with costumes that were previously produced, the researcher was able to draw on the experience of the research subjects with the actual fitting of the costumes to assess the usefulness of the simulated fitting in relation to the needs of the designers and makers.

For applicability to the project, it was necessary to select designers and makers who had in common a recently produced costume. To reduce variability among the simulations, the criterion of recently produced costume was narrowed to recently produced woman’s dress. Patterns for nine dresses were received from the five makers recruited for this study. Five garments were selected as being suitable for simulation based on their relative
simplicity. Of the four rejected garments, three involved complex layered components such as a jacket, cape, or apron, while the fourth contained irregular draped elements and openings. While it is possible to simulate layered pieces, the process is complicated and does not always produce satisfactory results. Garment openings are key in creating a 3D simulation, because points on the avatar must be identified for association with these openings. Garments with irregular openings present a challenge in simulation because the options for creating these point associations are limited to some standard body reference points (neck, arm, ankle, etc). For these reasons, the four rejected garments were determined to be too complex for the simulation software to handle efficiently. The final participants in the virtual fitting phase of the research and their associated garments are listed in Table 3.

Table 3

<table>
<thead>
<tr>
<th>Costume</th>
<th>Designer (# years experience)</th>
<th>Maker (# years experience)</th>
<th>Brief description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10</td>
<td>3</td>
<td>1930’s evening gown</td>
</tr>
<tr>
<td>B</td>
<td>20+</td>
<td>3</td>
<td>1960’s day dress</td>
</tr>
<tr>
<td>C</td>
<td>20+</td>
<td>20+</td>
<td>1910’s day dress</td>
</tr>
<tr>
<td>D</td>
<td>3</td>
<td>3</td>
<td>1930’s evening gown</td>
</tr>
<tr>
<td>E</td>
<td>3</td>
<td>3</td>
<td>Dress of unspecified era</td>
</tr>
</tbody>
</table>

**Pattern Digitization and Simulation**

The paper pattern pieces of the five selected garments were scanned using the N-Scan Pattern Digitizing System. This system required some user input to insure that the lines and points captured in the scan were correct, as illustrated in Figure 12. In this example, the scan
software did not distinguish between the outer edges of the piece and the internal markings (examples highlighted with green arrows). Extraneous marks were deleted and the perimeter of the piece was identified manually. In some cases pattern pieces were copied onto clean white paper so that the scanner could record the pattern piece outline cleanly and clearly. Oversized pieces presented a challenge, due to a tendency of the scanner to warp or skew them. Figure 13 shows a long skirt piece from Garment 3 that was distorted by the scanner (warped area circled in green). Long, narrow pattern pieces such as this one were attached to larger pieces of paper to feed through the scanner to eliminate warping.

![Pattern scan showing extraneous lines and points.](image)

Figure 12. Pattern scan showing extraneous lines and points.
Manual measurements of each piece were taken prior to scanning, and pieces were measured again using the Length Measure function in Lectra Modaris. Manual and digital measurements were compared and digital points adjusted using tools in the software where they did not agree within a tenth of an inch of the manual measurements.

**Measurement manipulation.** Measurements for the actress who wore each costume were received along with the paper patterns. These measurements were taken according to standards set in the costume shop at the theater where the play was produced. Several avatars with varying and adjustable body shapes are available in the software used for this study. The avatar with the closest measurements to the actress was selected for each garment simulation. Avatar measurements are adjustable only to a certain extent within the 3D simulation software. Certain measurements are linked, therefore changing one changes the other. Table 4 shows some of the standard measurements of the base avatar used to develop actress avatars 1, 3, 4, and 5. Also shown are the measurements of each actresses.
The basic measurements of the actress who wore Garment 2 required the use of a different
base avatar, however similar differences occurred between her measurements and the base
avatar measurements. Manipulation of height, bust, underbust, waist, hip, and pelvis
measurements was fairly straightforward. Other measurements proved more challenging to
approximate. Figure 14 shows a base avatar with bust, waist, hip, back and shoulder
measurements modified to match those given for the actress who wore Garment 4.

<table>
<thead>
<tr>
<th></th>
<th>Avatar</th>
<th>Actress 1</th>
<th>Actress 3</th>
<th>Actress 4</th>
<th>Actress 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>66.632</td>
<td>64</td>
<td>66.5</td>
<td>66.5</td>
<td>66</td>
</tr>
<tr>
<td>Head</td>
<td>21.824</td>
<td>22.75</td>
<td>22.25</td>
<td>22.25</td>
<td>22.5</td>
</tr>
<tr>
<td>Neck</td>
<td>12.129</td>
<td>12.75</td>
<td>12.5</td>
<td>12.5</td>
<td>12.5</td>
</tr>
<tr>
<td>Across back</td>
<td>12.182</td>
<td>13.75</td>
<td>14.5</td>
<td>13</td>
<td>13.5</td>
</tr>
<tr>
<td>Across front</td>
<td>12.163</td>
<td>13.5</td>
<td>14.5</td>
<td>11.75</td>
<td>12.25</td>
</tr>
<tr>
<td>Shoulder length</td>
<td>4.356</td>
<td>5</td>
<td>not given</td>
<td>5.75</td>
<td>5.5</td>
</tr>
<tr>
<td>Bust</td>
<td>36.106</td>
<td>37</td>
<td>34</td>
<td>33.5</td>
<td>36.5</td>
</tr>
<tr>
<td>under bust</td>
<td>30.292</td>
<td>31</td>
<td>30</td>
<td>29.25</td>
<td>31.75</td>
</tr>
<tr>
<td>waist</td>
<td>27.589</td>
<td>29</td>
<td>29</td>
<td>27</td>
<td>28</td>
</tr>
<tr>
<td>mid hip</td>
<td>33.489</td>
<td>36.5</td>
<td>37</td>
<td>34.75</td>
<td>35.5</td>
</tr>
<tr>
<td>pelvis</td>
<td>40.682</td>
<td>39</td>
<td>37.5</td>
<td>36.75</td>
<td>39</td>
</tr>
<tr>
<td>thigh</td>
<td>23.617</td>
<td>25</td>
<td>20</td>
<td>21</td>
<td>24.25</td>
</tr>
</tbody>
</table>
Figure 14. Virtual avatar showing modified shoulder, across back, and across front measurements for Actress 4.

The adjustments of across front and across back caused distortion in the avatar, therefore these adjustments were not used to create avatars for each actress. Instead, adjustments of height, bust, waist, mid hip, pelvis, and thigh were made. There were limitations, therefore, in the accuracy of the avatars used for the 3D simulation. Figure 15 shows the avatar adjusted with these basic measurements for Actress 4.

Figure 15. Virtual avatar showing modified basic measurements for Actress 4.
Figure 16. Posture modifications on the 3D avatar: a. neutral; b. posture adjustments +1; c. posture adjustments -.5.

**Posture adjustments.** Figure 16 shows the posture modifications created once the actress’s measurements had been established as closely as possible on the avatar. Posture modifications were made to create visible differences between the fit of the garments in the three virtual fittings. Shoulder posture was altered because often the first point of focus in a fitting is how a garment, especially a dress, hangs from the shoulder. Modifications were made based on two capabilities of the software. One, referred to in the software as “posture” affects the alignment of the upper torso in relation to the hips. Manipulating the “posture” in a positive direction brought the torso forward from the rib cage. The other, referred to in the software as “shoulders posture” positioned the shoulders either forward or back from their
neutral position. Figure 15b shows the avatar with a “shoulders posture” and “posture” adjustment of +1. Figure 15c shows the same avatar with a “shoulders posture” and “posture” adjustment of -.5.

3D Fit simulations. Simulations were developed for each interview showing the costume on each of the three posture variants of the avatar. These simulations were labeled Fitting A, B, or C. For four of the five garments, adjustments had to be made to either the pattern pieces or the number of components shown in the simulation. These adjustments will be discussed in greater detail in the results section. They are summarized in Table 5, which also shows the number of simulation attempts that were made before the final simulation was achieved.

Table 5

<table>
<thead>
<tr>
<th>Garment</th>
<th>Simulation Attempts</th>
<th>Modifications made to achieve final simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>Number of flounces reduced from 8 to 2</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>Sleeve cuffs not shown</td>
</tr>
<tr>
<td>3</td>
<td>23</td>
<td>Belt not shown, marked with stitching</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>Fabric was changed to achieve fit of bias cut dress</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>No modifications</td>
</tr>
</tbody>
</table>

Research Interviews

Expert interviews. Expert interviews focused on the participants’ process for costume design and production to establish the types of activities that contribute to the costume fitting process, and the participants in those activities. Experts were also asked to describe their training and experience, and their awareness of and attitudes toward computers.
in the costume industry. These interviews did not involve demonstrations of the 3D simulation software. Questions were general and open-ended, and the researcher was able to prompt for more detail where needed according to the interview instrument found in Appendix A.

**Virtual fitting interviews.** Virtual fitting interviews were conducted according to a script based on the costume fitting process (see Appendices B and C). The goal of the interview was to elicit the types of responses participants would give in an actual fitting. Virtual fitting interviews were divided into five sections:

- **Participant Information**: questions on the participant’s training and experience
- **Virtual Fitting Demonstration**: in which participants were shown a generic 3D simulated costume that the researcher used to describe the capabilities of the software, including the ability to rotate the virtual model, mark the garment, highlight seams, and view a tension map showing areas of ease and tightness.
- **Virtual Fittings**: in which the participant was asked to evaluate the fit and design features of their costume on avatars with three different posture variations.
- **Comparison**: in which the participant was asked to identify the variation (fitting A, B, or C) that showed the best overall fit.
- **Yes/No questions**: in which participants were asked “Based on this virtual fitting session, can you make fit decisions/design decisions in a virtual fitting?”
- **General Impressions**: in which the participant was asked to evaluate the experience of the virtual fitting, relate this experience to their own preferred fitting process, suggest
improvements to and uses for the technology, and describe their experience with computers in the costume industry.

During the virtual fitting section, the researcher prompted subjects for feedback on 3D simulations of their costumes, both in terms of fit and design. At the beginning of this part of each interview the researcher asked the designers to “Please respond as you would to the draper or tailor who would be making this costume” and the makers to “Please respond as you would if this “virtual fitting session” was going to be presented to the costume designer.” This part of the interview was interactive; the researcher responded to participant’s fitting and design feedback by rotating the model, zooming in and out on specific areas, and marking the virtual costume using tools in the software. Each of the three “virtual fittings” in the interview was dealt with in the same manner.

Coding and Analysis

**Expert Interviews.** Expert interviews were examined for recurring concepts and patterns. These transcripts were coded for responses relating to:

- Design development
- Early stage design communication
- Mockup development
- Fitting process
- Fitting communication
- Mockup description, and
- Performer involvement
Additional insights into novel practices in the fitting process, use of computers in the costume production process, and attitudes towards computers in the industry were also noted. In some instances these observations were single instances based on the unique experience of the interviewee. Some of these observations on computer use in the costume industry are discussed in the conclusions and inform suggestions on future research.

**Virtual Fitting Interviews.** Interviews were also transcribed, coded, and analyzed for patterns and themes. First the virtual fitting portions of each interview were coded for responses showing:

- Fit evaluation,
- Design evaluation, and
- Costume fitting process steps

After the initial marking of transcripts, recurring themes suggested additional categories for coding, and the interviews were read again for comments on:

- Measurement issues,
- Fabric type,
- Fabric appearance, and
- Software issues

In the general impressions section of the interview, questions in the script provided a natural system for separating out responses into categories.
4. Results and Discussion

Overview

Results are reported in three general areas, including expert interviews, the preliminary framework, and virtual fitting interviews. The seven costume design and production experts who participated in the Expert Interview phase of the research were asked to describe their process for costume design and production. Their responses helped to define what designers and makers should be able to do in a fitting, and how they should be able to use the results of a fitting in later steps in the costume design and production process. Together, these elements were used to create a framework for a more thorough and comprehensive understanding of what participants require from the costume fitting and production process. The framework informs the analysis of responses from the virtual fitting phase of the research, which focused on evaluating the “functional realism” of a virtual fitting, or the extent to which a virtual fitting enables the user to perform needed tasks or make required judgments.

Following details regarding framework development, the virtual fitting phase of the research will be discussed. First, issues encountered during the pre-fitting stages of the research are described. Next, fit and design feedback given during the virtual fitting sessions are examined. Responses to specific questions that show participant opinions about the virtual fitting experience are detailed in three sections, moving from more specific feedback about their confidence in the process to more general suggestions about use of and possible improvements to the virtual fitting. Finally, participants’ attitudes toward computer use in the costume design and production process are discussed. Themes found in responses from all of
these sections were synthesized to create a revised Costume Design and Production Framework that illustrates how virtual fitting could be incorporated into the costume design and production process.

**The Preliminary Costume Design and Production Process Framework**

The steps in the costume design and production process were listed in Figure 1, (page 1) and discussed in some detail in the literature review. This research focused on stage four in that diagram, prototyping and design validation. The purpose of the expert interviews was to further explore this stage to discern what is essential about it. Seven costume design and production experts were interviewed (Table 2). Quotations reference this table; for example E6 refers to expert number six as listed in Table 2. Experts were asked to describe their training, range of experience, and their process for costume design and production. Themes discovered in their responses suggested that one of the primary activities in costume design and production is communication. Three major interactive communication phases were identified. They are:

1. Early stage design communication, which involves exchange of ideas through consultation and the sharing of research and drawings
2. Mid-stage design communication in which design concepts are translated into three dimensional garments through a process of patternning, prototyping, and fitting
3. Late stage design communication in which design decisions are confirmed through final fittings and rehearsals

While mid-stage design communication relates more closely to the prototyping and design validation stage of the earlier model, it became clear in these interviews that costume experts
do not separate the stages in a linear fashion, and that the communication in each stage influences the success of the next.

**Early stage design communication.** As described in the literature review, early stage design decisions are influenced by the director, the script, and the performer’s requirements. While the costume designer is the primary agent in this stage, research interview responses suggested that the collaborative relationship between the designer and maker is established through early stage design communication, which involves both visual information given in sketches and research, and verbal or written information given in meetings and conversations. Both designer and maker take part in this exchange. The designer may select from a variety of methods for communicating design concepts visually, including drawings, painted renderings, and collage. The costume maker draws on his or her expertise in construction techniques, historical garments, and fabric properties to offer advice and suggestions, and to ask for clarification on design and construction details. Design decisions may be clarified, refined, or altered during those initial conversations. One expert described the training costume designers and makers go through to learn that collaborative process:

> We are training the designers to understand what they have drawn and to really think about the options, and I'm training makers to illuminate the possibilities for those designers (E6).

Both parties have a responsibility to contribute to the dialogue that will help the designer solidify design details as they work through the early stages of the production process. Another expert, a costume maker, described the preparation and work that allows him to actively participate in these early conversations.
I’ll take that [the costume sketch] and I’ll pair it with some of my own research so if it’s of a specific period I’ll do some research on the trends of fashion for that time and sewing techniques for that time just to inform myself so I have a good sense of how things were done at that time. (E1)

At the same time he acknowledged the importance of sharing that research interactively with the designer:

…sometimes while I've done historical research that may or may not be where the design has come from…And sometimes that conversation will give me information that I didn’t know, so for instance if I'm not familiar with the play or I'm not familiar with whatever the costume is for, there may be functional requirements, that I can’t tell from the rendering, that the costume needs to do (E1).

Another expert costume maker discussed her contribution to the process of interpreting a designer’s vision. In her work she feels responsible for making sure the materials the designer has chosen will perform in the desired ways. This involves detailed conversations centered on the drawings the designer has presented:

Sometimes things are drawn that you are not able to do, so you have to figure out a way to get close to their vision or a way around it. That usually comes in a long conversation (E4).

Finally, an expert who is a professional costume designer described her expectations for the collaborative relationship with costume makers and technicians.

You have a design, and it’s a blueprint, and then you develop it collaboratively. I really look at everybody as full partners…To me ultimately it’s not about your
design, it’s about the work, and the work involves so many different people, and you just want the best ideas, don’t you? I really like engaging them as artists. (E7)

To summarize, in early stage design communication, both costume designer and costume maker take an active role. Decisions are made in the course of these early conversations that may be related to smaller details of a costume, but they may also initiate larger changes in fabrication, seam placement, understructure, or finishing.

**Mid-stage design communication.** Moving into mid-stage design communication, this collaboration is carried on into the development of the muslin mockup, which may involve another intermediate step of showing the designer an initial drape or half drape (showing one side of the garment only) on a dress form. At this stage proportions and style lines are again discussed and may be modified. As one expert said, “It’s all part of a beginning conversation with the designer where you’re trying to help them understand this thing that they’ve drawn two-dimensionally in three dimensions” (E6). At this stage design communication is still very much integrated with design decision making.

Mid-stage design communication also encompasses the creation of a full prototype and the initial prototype fitting. Here the focus is on validating the decisions made by the designer in costume drawings, and in those early conversations between designer and maker. Experts described this garment as being “pretty much a replica of the final garment” (E4) with details such as style lines, trim, pockets, and hems clearly indicated. A medium weight cotton woven fabric is typically used to create this garment. In the initial fitting of the prototype, the designer and maker continue to collaborate. Typically the costume maker begins by setting the garment on the performer, and addressing any obvious fit issues.
Sometimes this is carried out before the designer is even invited into the fitting room. This allows the designer to focus on style lines and design details. Experts emphasized the importance of this stage of the process. “That first fitting is the most important time. It’s so important that you see everything in muslin and that the fit is right and the style is right. By the time you get into real fabric it’s too late to go back” (E4). In the fitting room where several people are present, non-verbal communication can become very important.

You get used to the designer’s face when they don’t like something and you can immediately try to figure out what they’re not happy about… There’s also a nonverbal communication between when the performer puts on that garment and you can see that they are either happy or they are… some people could care less. Some people are extremely happy. The worst is when they put it on and you can see they hate it. And that can be nonverbal. Not everybody’s going to say I hate this color, I don’t feel good in this…You need to be sensitive to that (E6).

Other experts also noted the importance of involving the performer in the fitting process. “At the very least you are making sure that they can move” (E6). Typically the performer is asked if he or she has specific movement or functionality requirements that may influence the design of the costume. For example a pocket may need to be a particular size to accommodate a specific action in the performance. From the remarks of these experts it becomes clear that this middle stage is still very much about interaction and decision-making, however communication in this stage focuses on finalizing decisions with a view to facilitating final production of the costume in the chosen fabric.
**Late stage design communication.** Some experts suggested that a second fitting of the garment in the actual fabric is a necessary step, providing a setting in which when trim and decoration decisions can be made. Others stated that as many decisions as possible should have been made before the second fitting so that it can be used simply to verify that decisions made in previous fittings and consultations were correct and have been appropriately carried out. Late stage design communication may involve a second costume fitting, but in general refers to communication involving any changes that might be made once the garment is in rehearsal. Experts suggested that these changes are influenced by differences in perception that take place once the garment is viewed from a distance, differences between the prototype fabric and the actual fabric, emerging exigencies of the onstage action, and aesthetic requirements of the director. Costume makers employ certain strategies to anticipate these issues. One expert described the use of the mirror in a fitting room to add distance to the view of the performer in the costume. The same expert described costume makers’ ability to anticipate differences between the cotton fabric used in the prototype and the final fabric used to make the costume, and reported that the costume maker will adjust the prototype according to their predictions about the fabric behavior. The expectation is that the communication and observations that takes place in early and mid-stages allow the costume maker to avoid unnecessary last minute changes to the garments.

These observations from costume experts contributed to a preliminary visual framework (Figure 17) that describes the iterative, interactive nature of the communication that drives the costume design and production process. The framework derived from these expert interviews suggested that the validation of a costume design does not happen in a
singular instance, nor is it the act of a sole individual. This framework lists the primary goals of each of the three stages of communication in the costume design and production process, as well as the key participants in each stage (in green). Tools used in the process are shown in blue, and actions and processes in yellow. This framework shows a flow of information, ideas, decisions, and interactions in which several participants have a significant amount of input at various stages.

In this framework, the early stage communication goal of establishing collaborative relationships between designer and director and between designer and maker is accomplished through interactive communication, which also contributes to the second goal of refining design decisions. This interaction also allows the designer to confirm that both director and maker understand the design decisions so that the team can move forward to the next stage with director approval. To accomplish mid-stage goals of validating design and fit of a costume, more active, process-oriented steps are carried out as the maker uses patterns and fabric to interpret the design in three-dimensional form. Design decisions are still being refined at this stage, and the performer plays a key role in that process. Equally important at this stage is establishing the functionality of a costume through watching the performer move and noting the range of motion allowed by the garments. The costume fitting gives the designer and costume maker an opportunity to anticipate design, fit, and wearability issues that might arise during the rehearsal and performance stage of the process. Late-stage goals in this framework involve re-confirming the decisions that were made at earlier stages. There are through-lines in this framework both in participants and in tools used. The director’s influence remains consistent even when that individual is not actively involved in
the process steps. Research, drawings, and notes from conversations are kept at hand during the entire process for reference, and this set of tools may be supplemented at any point. They represent the core of communication that fuels the costume design and production process.

This research investigated whether a 3D simulated costume fitting can replace one or more components of the prototyping and validation stages of the costume design process. The goals in these three stages contribute to an understanding of what a costume designer and costume maker might require from a virtual fitting to perform needed tasks or make required judgments in their work. The following sections will discuss analysis of data from the virtual fitting phase of the research in the context of this framework. The analysis examined at what point and to what extent a virtual fitting might offer functionality in the complex process of costume design and production.
Figure 17. Preliminary costume design and production framework
Preparation of Virtual Fittings

Preparing costumes for 3D simulation involved several process steps. The following section will describe those processes in the context of Wang and Zhang’s (2007) suggestion that a garment simulation should work “interactively, intuitively, realistically, and efficiently” (p. 363). Next, results from the virtual fitting interviews will be discussed.

Digitization and Simulation Process. For each virtual fitting, the researcher obtained paper patterns for the selected costume, as well as measurements for the actress who originally wore it. Patterns were scanned using an N-Scan device, then they were imported into Lectra Modaris where they were prepared for virtual seaming, which required adding seam allowances and defining overlaps and folds. To prepare for simulation, the measurements of a standard avatar in the software were modified to match those of each actress. Issues encountered in the simulation process included representation of layers, representation of folds, selection of virtual fabric, and manipulation of the avatar measurements.

Measurement issues. One challenge was present in the measurement manipulation step of this study. The measurements received for the actresses in question were presented in standardized charts generated by each theater according to standards set by their costume shop manager or costume director. For Garments 1, 2, 3, and 5, it was unclear how much time had elapsed between the taking of measurements and the production of the costumes used in this study. M3 explained that an actress might be measured for one production, then her measurements may not be updated for several years. This is due to lack of availability on the part of the actress or performer. M2 explained that performers must be scheduled for
fittings within the rehearsal day, which is very limiting. It is impossible to determine whether the measurements used for this study matched the sizes of the five actresses when they wore these costumes.

**Fabric selection.** Further limitations may have been presented in the fabric used. The initial simulations of Garments 1 and 4 showed poor fit through the hip and midriff area which may have been due to the tight weave of the virtual fabric chosen (medium weight cotton). Garments 1 and 4 were designed and patterned to be made out of silk fabric, and they were both cut to maximize the stretch of the bias direction of the fabric weave. While the virtual garments were “cut” in the same bias direction, the virtual fabric with properties of medium weight cotton could not be expected to show the same stretch in the bias direction as silk fabric. Figure 18 shows how this poor fit was manifested in Garment 1, through unexpected fullness in the midriff area. Figure 19 shows the initial simulation of Garment 4, with holes in the simulated fabric (indicated by arrows) where the garment was tight. After conducting virtual fit interviews for Garment 1 in which this tightening was remarked upon by participants as a negative feature of the virtual fitting, a silk fabric was selected for the final simulation of Garment 4 (shown in Figure 20). This change allowed the garment to appear to fit more smoothly on the avatar. It is unclear, however whether this change completely eliminated any fit issues. D4 and M4 both noted incorrect placement of style lines in Garment 4 that may have been due to persistent tightening in the hip area, which would prevent the garment from sitting correctly on the virtual body. Because the goal of the study was to elicit fit and design notes in the virtual fitting process, these simulation issues were determined to be acceptable for the virtual fitting sessions.
Figure 18. Simulation of Garment 1 showing poor fit through midriff and hips.

Figure 19. Unsuccessful simulation of Garment 4 using standard fabric.
Figure 20. Final simulation of Garment 4 in alternate fabric.

Figure 21. Simulation of Garment 3 showing poor fit through hip and midriff.
The fit issues in Garments 1 and 3 may also have been due to differences made by shaping undergarments worn by the actresses. Measurements provided were for the body in typical undergarments, but it was reported during the virtual fitting interviews that shaping undergarments were worn with the costumes. D3 and M3 both noticed that the bust on the avatar in Garment 3 appeared to be low, and they both reported that the undergarment worn by the actress pulled her bust up so that her figure resembled a corseted figure from the early 20th century. This information was not accommodated in the measurements because it is uncommon for measurements to be updated from production to production. M3 reported that he relies on his expertise to make the adjustments required when the performer’s body is modified by undergarments. Figure 21 shows poor fit in the midriff area of Garment 3 exemplified by wrinkles in the garment that may have been due to measurement differences created by the shaping undergarment worn by the actress.

**Representation of layers.** Layers must be clearly defined in the garment simulation process. Three of the five garments used in this study involved simple layers, either in flounces, a collar and overlapping closure, sleeve cuffs, or a fabric belt. While commands for creating layers exist in the software, results of using these commands can differ from garment to garment, and even from simulation to simulation with the same garment. Tools for manual manipulation of layers during the simulation process also exist, however these are also not consistent. The simplest and most successful layers to represent in this set of garments was the collar and overlapping closure on Garment 2. This was a matter of defining the roll line as a fold, defining the order of overlapping closure layers, and “pulling” the fabric using manual tools during the simulation process to place the layers correctly.
Using the same commands, the sleeve cuffs were also attempted, however these were not successfully simulated.

Figure 22. Successful simulation of collar and placket opening on Garment 2.

Figure 23. Unsuccessful simulation of sleeve cuffs on Garment 2.
In some attempts, the effect of simulating gravity on the virtual fabric caused the sleeve cuffs to fall rather than maintaining their folds. In other attempts the cuffs remained folded but appeared to sit inside the sleeve rather than outside. In the final version of this simulation the cuffs were not included.

The flounces on Garment 1 were also challenging. The original design contained eight flounces, placed in seams with four on either side of the skirt center front. Repeated attempts to simulate all eight flounces resulted in a simulation that showed at most seven, with the eighth clearly sitting “underneath” the dress layer (circled in red).

![Simulation showing only seven of eight flounces on Garment 1.](image)

The solution chosen for this problem was to show the dress with only two flounces, one on either side of the center front.
Garment 3 included a belt that also presented a problem. Several attempts to show this piece on top of the skirt were unsuccessful. This was partly due to the ease built into the belt. It was designed to sit easily on top of the dress, rather than being stitched tightly to it. For this reason, it was impossible to virtually “stitch” the belt to either the bodice or skirt, and without being stitched to the garment the belt had no association for the software to place it in the simulation. The solution to this difficulty was to use tools in the software to create lines showing the upper and lower boundaries of the belt on the garment and to digitize those lines to mark where the belt would sit.
These issues all relate to Wang and Zhang’s (2007) suggestion that a garment simulation needs to work “interactively, intuitively, realistically, and efficiently” (p.363). These conditions are not met if whole pieces of a garment cannot be represented, or if the user has to carry out repeated simulation attempts to represent simple features such as a placket overlap. Implications of these issues for this and future research are discussed in the conclusions.
Virtual Fitting Interviews

The ten virtual fitting sessions were held via WebEx. In each session, the participant was able to see the 3D Fit software on their computer screen. The researcher briefly demonstrated the capabilities of the software using one of the costume simulations from the pilot study. Then each virtual fitting (A, B, and C) was shown and the participant was asked to give notes on fit and design features of the virtual garments. Where possible, the researcher marked the virtual garment according to instructions from the participant to show how fit and design issues might be resolved. In each virtual fitting session, fit differences were perceived between the three virtual models that were related to the posture of the avatar. For example, Garment 1 showed some gapping in the center back neckline in Fitting C due to the shoulders back posture of the avatar. This was remarked on by both D1 and M1.

![Figure 27. Garment 1, fittings A, B, and C (left to right).](image-url)
In general the conversations with costume makers focused more on fit than on design issues. In some cases designers and makers showed disagreement about fit and/or design features. D1 stated that the hem length in Garment 1 was fine across all three fittings, while M1 declared the dress was too short in all three. D2 and M2 both remarked that in fitting B of Garment 2 there were some points of stress along the bust darts. Where M2 wanted to mark an alteration to fix this issue, D2 felt that the character did not require a perfectly fitted costume and she was satisfied with the fit. For Garment 3, D3 and M3 appeared to have differing memories of certain design and fit details. Where D3 wanted to modify the sleeve cuffs, M3 declared that the cuff detail was exactly as D3 had requested. Similarly, M3 noted that the belt on Garment 3 was perfectly placed, while D3 felt its shape needed to be refined. Figure 28 shows original and marked lines indicating belt placement on the simulated garment.

Figure 28. Garment 3 showing belt alteration as directed by D3. Top arrow indicates original belt line. Bottom arrow indicates alteration.
In other areas, M3 and D3 were in agreement. Both noticed the poor fit through the midriff on all three models of Garment 3. D4 and M4 were also mostly in agreement regarding fit and design issues on Garment 4. Both noticed that bodice panels in this garment were not sitting in the correct position. Again, M4 had more fitting related notes than D4. For garment 5, the designer reacted to both fit and design issues related to the character. D5 noted that the shoulders appeared broad and the waist high in Fitting A of Garment 5. M5 also noted these areas, but stated she would typically defer to the designer before making any alteration to these areas. M5 was more focused on areas of fit, noting apparent tightness at the back of the skirt.

Where possible the researcher marked alterations as directed by the participant. Figure 28 shows marking for a design note that simply involved drawing a new style line on the garment. Marking fit notes proved more challenging. Figure 29a shows the tension map that demonstrated where extra fullness was exhibited in the midriff area of Garment 1. Figure 29b shows the marking requested by M1 to show how much fullness would need to be taken out of this area. Figure 30 shows a marking on the sleeve of Garment 2 where M2 suggested slashing and spreading that sleeve to add fullness. Both M1 and M2 noted that the nature of the virtual fitting required them to think differently about how they would handle those fit notes. Overall participants expressed satisfaction with alteration marks as they were being made; however they also expressed frustration at their inability to participate hands-on in the marking of alterations. More importantly, each participant expressed a desire to be able to pinch and feel the amount of fabric being manipulated in alterations.
Figure 29a. Tension map on Garment 1 demonstrating excess fullness, b. showing marking of alteration.

Figure 30. Garment 2 showing slash lines for adding fullness to sleeve.
**Best representation of fit.** A comparison of designer and maker responses to the question, “which virtual fitting shows the best overall fit” shows similarities and differences in their observations regarding the virtual fitting. The questions “which of the three [virtual fittings] do you think shows the best overall fit?” and “what differences can you perceive between the three fittings?” provided one opportunity for this comparison. Table 6 shows the designer and maker selections for best overall fit in relation to the posture variations of +1 or -.5.

Table 6

<table>
<thead>
<tr>
<th>Garment</th>
<th>Posture/Fitting selected as best overall fit</th>
<th>Designer Pick</th>
<th>Maker Pick</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+1, Fitting B</td>
<td>Neutral, Fitting A</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Neutral, Fitting A</td>
<td>-0.5, Fitting C</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Neutral, Fitting A</td>
<td>Neutral, Fitting A</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-0.5, Fitting C</td>
<td>+1, Fitting B</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Neutral, Fitting A</td>
<td>+1, Fitting C</td>
<td></td>
</tr>
</tbody>
</table>

The reasons participants gave for their selections fell into one of three categories, fit, avatar appearance, and fabric rendering. D1 and M1 reported that all three variants had fit issues. M1 specified that fitting A (neutral) had the best fit from the front, while fitting C (-0.5) had the best fit from the back. When pressed she selected the variant with the neutral posture. M2 based her response on her perception that the avatar in fitting C (-0.5) showed a posture that was closer to her recollection of the performer’s posture, while D2 reported that the fit in garment 2, fitting A (neutral) showed better overall fit. D3’s response to this question was based on the modifications made to the model during the virtual fitting. At his request the
bust on the virtual avatar (Garment 3, fitting A) was raised. This gave the avatar a silhouette that more closely resembled the look he had designed for this character. D3 also stated that establishing the correct actor silhouette is an important part of his design process. M3 reported that all three versions showed issues with fit, but he felt that the sleeves in version A (neutral) were more accurately rendered, showing fullness and gathers in the fabric.

D4 also based her assessment on the way the garment was rendered. She reported that the skirt fullness in fitting C (-0.5) looked more like what she intended for the costume. She felt the fabric in C looked like it was falling more naturally. D4 based her response on the fit and proportions of the garment, stating that in fitting B (+1) she perceived that key design elements were better placed than in the other two versions. M5 reported that fitting C (+1) of garment 5 looked more like the rendering, which she said showed a looser, more easy-fitting dress. D5 selected fitting A (neutral) of that costume, because of her perceptions of the skirt width. These selections show differences in priorities of the participants, but they also raise questions about the consistency and usability of 3D simulation software that will be discussed in the section on suggested improvements.

**Participant Evaluation of Virtual Fitting Experience**

**Making design decisions.** Two of the five designers in the sample responded with a definite yes to the question can you make design decisions based on this virtual fitting. Two responded with a qualified positive, and one replied no (Table 7).
Costume maker responses to this question were mostly positive. One maker (M1) declined to give an opinion based on her conviction that design decisions are a designer’s purview. The other four makers each suggested that a virtual fitting could provide an opportunity to communicate with a designer about design details. Of these one specified that the benefit to such use would occur in the early to mid-stages of the process (i.e., before the live prototype fitting). One suggested in the context of design decisions and judgments that beginning makers without the experience of translating two-dimensional drawings into three-dimensional garments would benefit from a virtual fitting.

**Making fit decisions.** Two of the five designers expressed a qualified positive response to the question “Can you make fit decisions based on this virtual fitting” (Table 8). Two appeared slightly more hesitant, and one, again gave a negative response. Costume makers were also hesitant in their responses to the question, “can you make fit decisions based on this virtual fitting” (Table 9). Two implied a willingness to consider making fit decisions in the virtual fitting, while at the same time expressing concern about the accuracy of such decisions. The other three stated that without being able to put their hands on the garment they were unwilling to make fit decisions. They explained that they typically make fit decision by pinching, folding, pulling, or otherwise manipulating the fabric on the
performer’s body, so without that ability to interact with the fabric they could not make accurate judgments on what needed to be altered.

Table 8

<table>
<thead>
<tr>
<th>Designer responses to the question “Can you make fit decisions based on this virtual fitting?”</th>
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</thead>
<tbody>
<tr>
<td>(D1) I do in theory, of course I have no idea of what it would become in practice in terms of when it becomes a real garment, but in theory it makes a lot of sense.</td>
</tr>
<tr>
<td>(D5) Yes, I think it’s difficult to completely know, but I think it’s as much as any initial fitting.</td>
</tr>
<tr>
<td>(D2) In terms of fit decisions I would be uncomfortable doing it without the body, without me and the body together.</td>
</tr>
<tr>
<td>(D4) I don’t know, because I trust that this is her measurements but it’s more difficult to see… There’s something perhaps in seeing it in the material and seeing it here is not the same</td>
</tr>
<tr>
<td>(D3) Well today we didn’t address the fit really.</td>
</tr>
</tbody>
</table>

Table 9

<table>
<thead>
<tr>
<th>Maker responses to the question “Can you make fit decisions based on this virtual fitting?”</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M5) I think to an extent.</td>
</tr>
<tr>
<td>(M3) Yes and no.</td>
</tr>
<tr>
<td>(M4) It’s really hard in regards to the fit.</td>
</tr>
<tr>
<td>(M1) That’s something that I feel like I should really have to have my hands on it to fix. To see what the best solution is.</td>
</tr>
<tr>
<td>(M2) I think since I can’t actually physically pinch out or take out the extra fullness like in that one where we’re taking out a ton I would be worried that I might have over pinched things or not taken out enough,</td>
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**Designer’s intention for the costume.** For the most part participants answered yes to the question, “Do you feel that the fitting session materials convey a sense of the designer’s intention for the costume?” Where responses to this question were negative or uncertain, participant comments clarified that some of the issues encountered in the simulation process
impacted perceptions of the virtual fitting. In response to the question M1 reported that the absence of six of the eight flounces in Garment 1 diminished the effectiveness of the simulation in her view. D3 reported that the fit issues present in the simulation of Garment 3 made it difficult for him to feel that his intentions were represented in the simulation. He reiterated the idea that in a fitting it is typical practice for the costume maker to address fit issues in the prototype costume before the designer is invited to look at it. He also asserted that for him, establishing the silhouette of the performer’s body is part of the design decision making process, further reinforcing the notion of costume design as a non-linear activity.

**How a virtual fitting might be used.** The responses described in the preceding sections can be better understood through examination of participant responses to the question “Can you talk about how this virtual fitting session relates (or does not relate) to your costume design process.” Four of the five designers responded that a virtual fitting would be useful in the early stages of collaboration. One suggested that complex garment details such as seam placement, proportions, and lengths could be worked out more easily in a virtual fitting. Another responded in a similar vein,

> I think it’s great as a very initial fitting. Its similar but even better version of when you can go up to the draper and see what’s on the mannequin and check it out. It seems like it’s just a better way to get a grasp on things and kind of cut out the initial steps. (D5)

Two other designers had ideas for how to incorporate a virtual fitting into communication with other members of the production team at early stages. One suggested using a 3D costume simulation in conjunction with models of scenic elements to understand how they
would work together visually. The other suggested using 3D simulation to facilitate conversations with the director about design details and options. One costume maker also suggested using the technology to communicate design ideas to a director, stating that “sometimes people have trouble visualizing …the three dimensional and how it will look in real life” (M5).

Other suggestions involved mid to later stage design communication. One costume maker suggested that the virtual fitting would be helpful in situations where “because the actor or actress is there, there are certain things we can’t say because we might hurt their body image or feelings” (M4), and cited ease of marking the virtual garment as a positive feature. At the same time she wondered if communication protocols in the virtual fitting would be ignored if the performer was not present. Her concern stemmed from the need as a costume maker to have some control over the flow of communication in the fitting “I need to interact with the designer and tell them things when I need to tell them things, and let them discover things when it’s their turn to look at the dress” (M4). She felt that the rhythm of exchange between designer and maker might be lost without the performer present, citing instances of chaotic interchanges between designer, design assistants, shop managers, and herself outside of the fitting room. A slightly different perspective on that issue was voiced by another maker, who said “The beauty of this is the designer can be as far away as you are” suggesting that the technology could facilitate long-distance design communication.

The responses discussed so far indicate that the virtual fitting might be appropriate for early to mid-stage design decisions and communication. Designers and makers were able to identify fit issues and design issues in each virtual fitting session, however these results
indicate more positive responses among these research subjects to the idea of making design decisions within the virtual fitting.

**Suggestions for improvements to the virtual fitting.** Participant suggestions for improvements to the virtual fitting experience reflected ways in which the fitting session fell short of the requirements illustrated in the preliminary framework shown in figure 17. These suggestions either involved features that might increase participant confidence in the current virtual fitting, or changes that would make the virtual fitting more usable in their process. Five participants suggested that more accurate representation of a performer’s actual body shape would increase their confidence in the existing software. This was related to issues with body measurements that impacted the fit of virtual garments. M1 stated that she was not confident that the simulation was accurately representing the behavior of the silk fabric used to create Garment 1. Notably two other participants (D4 and D5) perceived differences in virtual fabric appearance and behavior between their respective fittings, even though the virtual fabric was consistent across all three variants of these costumes. D4 reported that one fitting showed Garment 4 in a heavier, more luxurious fabric, while D5 reported that one fitting of Garment 5 showed more fullness in the skirt. While the issues in Garment 1 were quite possibly linked to the differences between the ways the virtual fabric (medium weight cotton) and the actual fabric (silk chiffon) behave in a bias cut dress, the other two instances of fabric behavior could simply be due to the differences that can occur between multiple simulations of the same garment.

Five participants suggested that adding movement to the avatar would be helpful. This would allow the user to establish range of motion allowed by the garment, and help to
anticipate how the garment would look in action. Two participants suggested that adding some level of transparency to the simulation so that the position of the body could be viewed relative to the garment, would help them to make fit decisions. A related suggestion involved adding a function that could show the position of certain reference points, such as the bust line, waist, or hip line. One designer suggested that rendering facial features of the performer would be useful. She reported that she makes design decisions based on how garment features interact with facial features and proportions. Another designer suggested that the ability to quickly change out garment features would be helpful. For example, she might like to look at a garment with several different types of sleeves or collars.

One designer suggested that she would like to be able to draw a costume and have the 3D simulation and costume pattern derived from her drawing. Another designer mentioned a practice of drawing on pictures of costume mockups using programs such as Photoshop. He gave as an example an instance in which he was working with a costume maker over long distance. Working from his original sketches the costume maker made muslin prototypes of costumes that she then photographed. The designer used drawing tools in Photoshop to indicate changes in design and style lines on the digital images of the prototypes. In some cases he indicated on these drawings areas to take away fullness in the 3-dimensional form, while in other areas he has indicated adding fullness. He expressed frustration that he was not able to draw in this manner on the costume in the virtual fitting. While marks can be made on the virtual garment, this designer wished to also be able to mark in the space around the avatar to show where fullness or layers might be added, and to vary the line weight of this drawing to indicate volume and shape.
Suggestions for use of the virtual fitting. Participants were asked to suggest types of
costumes or productions that would be appropriate for use with a virtual fitting. Four
participants reported that a virtual fitting would be useful for a situation requiring multiples
of the same costume, as in a chorus of a musical. One participant suggested the software
would be useful in a situation where a repeat of a costume was needed for a new performer
entering a long-running show. Three participants thought the software would be useful for
fitting stretch dancewear. One of these reported that a virtual fitting could be used for fitting
stretch garments on different bodies where the fit of a base size was already known. Another
thought it would be a useful tool for testing the performance of different stretch fabrics, again
where the fit of a base garment in a particular fabric was already established. The same
participant also suggested that simulating stretch garments for the purpose of establishing a
surface design would be useful. Another participant thought stretch garments would not be
appropriate for use of a virtual fitting, because range of motion is extremely important in
fitting dancewear. Simple, tailored garments were considered by one participant as
potentially more appropriate than complex, organic ones. Finally, two participants suggested
that a virtual fitting would be useful for working out early stage design details in a full body
walk around costume. These costumes are typically built out from the body using reticulated
foam, and involve an outsized head that is attached to a helmet, with mesh eye openings.
One of the two emphasized that early stage work only could be carried out with this
technology, due to the range of motion and safety concerns inherent in such costumes. Live
fittings must be conducted with this type of garment so that the performer’s ability to see and
move safely may be evaluated.
These suggestions reinforce the positive responses of participants to the idea of using a virtual fitting to facilitate design decisions rather than fit decisions. In the instance of garment multiples, whether stretch or not, typically the fit for one average model would be established, so virtual fittings could be used to confirm design details on several performers within a narrow range of sizes. In the instance of a walkaround full body costume, safety issues would preclude relying on the software to establish fit.
5. Conclusions

Revised Costume Design and Production Framework

This research asked, can a 3D simulated costume fitting replace one or more components of the prototyping and validation stages of the costume design process. The Costume Design and Production Framework (Figure 17) showed goals of the major stages of the process, participants in these stages, actions toward meeting goals, and tools available for carrying out these actions. The virtual fitting sessions conducted in this study were most closely related to the mid-stage communication goal of confirming fit and design decisions, and to the action of a muslin mockup fitting. While responses in these sessions spoke to the use of virtual fitting in the context of these goals and actions, they also reinforced the idea that each stage builds upon the other in this process. During the interviews, participants referenced earlier and later stage communication goals as well, which suggests that costume design and production professionals think about their work in iterative steps and that evaluation of costume fitting independently of other, supporting steps may not produce usable insights.

Responses in the virtual fitting interviews suggested that virtual fitting technology could contribute most readily to the early stages of the costume design process that involve consultation with other members of the production team, and refinement and understanding of design features pre-fitting. Responses also suggested that lack of performer input, lack of tactile involvement with fabric, uncertainty about the reliability of fabric simulation, and inability to satisfactorily represent the actor’s body shape all detract from the functional realism of a virtual fitting, because without those tools, costume designers and makers cannot
perform the tasks and make the judgments required. It appears that, for now at least, virtual fitting cannot completely replace a live fitting.

For this reason, the final Costume Design and Production Framework (Figure 31) shows potential uses of virtual fitting without removing any of the established actions or participants. The different possible uses of virtual fitting in the costume design and production process are derived from the virtual fitting interviews, and are categorized as either alternate or supplementary actions (in pink), or as potential disruptions (in blue). Using virtual fitting as a tool to facilitate early stage design communication between designer and maker is an example of a potential supplementary action, which could enhance the quality and efficiency of these conversations. Virtual fitting as a tool to facilitate production of costume multiples could potentially eliminate some, but not all live fittings and so serve as an alternate process. Two other possible uses may represent potential disruptions to the current workflow of costume design and production. Respondents suggested using virtual fitting in early conversations with directors, and in design presentations to star performers (particularly in film). This idea requires some consideration of the processes involved in creating a virtual fitting. Garment simulation in this type of software requires development of a garment pattern, and as demonstrated in the digitization phase of this project, moving from a two-dimensional pattern to a three-dimensional simulation can involve several intermediate steps that require planning. If this technology is to be used in the early stages of the costume design and production process, some modification to the traditional workflow might be required. In a typical process as reported by respondents, designers and directors meet and discuss design concepts prior to the designer meeting with the costume maker. To
facilitate use of a 3D simulation in a designer/director consultation, patterns for costume garments would have to be developed prior to those initial design meetings. This may be best suited to situations in which advance planning is possible. Certain types of performance such as opera and film frequently have a longer production lead time that could accommodate advance work on costumes. Perhaps what is called for instead is a re-definition of the functional realism requirements of the virtual fitting in terms of what it can add to the current process. This idea is discussed in the following section, which examines some of the ways that computer technology is currently being used in costume production.
Figure 31. Costume design and production process framework.
Computers in Performing Arts Costuming

The participants in the virtual fitting phase of this research were almost overwhelmingly enthusiastic about being introduced to this software and curious about its potential and future development. Except for Designer 3, participants in the virtual fitting phase of this study appeared eager to explore the possibility of using 3D simulation for early communication and validation of design ideas. Despite their enthusiasm for this project, most participants acknowledged that computer-aided pattern making has not been widely adopted in costume production because performing arts costume making typically involves creation of one-of-a-kind garments fitted to a specific person. The economies of scale that make investment of time and money in computer systems for apparel manufacturing do not exist in theater, dance and opera. The difficulty in implementing the use of such equipment arises with the current state of the art in 3D garment simulation software. It is not possible to divorce the 3D simulation function from the apparel pattern-making software, and to make use of that tool requires involvement of the costume maker, which in turn requires an investment in training and equipment. Programs do exist for simply drawing in 3D, however such programs still require development of a garment pattern, and so do not offer any increased efficiency in design or fit validation. Three ideas that were presented during the expert interview phase of this study offer some interesting insight into how a path to using 3D garment simulation in costume design and production might be forged.

E2 described a recent investment in apparel CAD software for her costume-making business. Her intention at the time of the interview was to test this software on an upcoming project involving making simple stretch costumes for 20 dancers ages 10-13. Her software
investment did not involve a 3D simulation component, however she is moving a step
towards using apparel CAD in the production process. She reported that this project seemed
like an ideal one to test the effectiveness of CAD in her business model, as it involved
multiples of the same simple garment. Her plan was to fit one sample costume on an
average-size fit model, then grade the pattern up and down to fit the range of sizes required in
the order. Grading involves identification of key points on a pattern piece that are used to
scale a pattern up or down while maintaining basic proportions. Because she frequently gets
orders for multiples of the same costume, this costume maker perceived a need for quick
grading and efficient cutting, which a CAD program would offer. She is interested in
increasing and maintaining efficiency in her business, but she is also aware that
implementing apparel CAD will require ongoing analysis of how implementation of this
technology impacts her workers and their product.

Are you going to retrain your drapers? Do you bring in people who are already
trained? …Then I think it’s really unclear at this point, if you’re doing one of the lead
costumes in Sweeney Todd and you’re just doing one of them, you know, one
costume one person, and your draper can just drape it and pattern it in a couple of
hours, is there a benefit to doing it with a computer? I think there’s a big question in
the industry about that. (E2)

E2 is looking at this from a business perspective, but the questions she must answer about the
balance of projects that lend themselves to using CAD and the potential re-training of
employees are ones that could point to new definitions of what costume designers and
makers need. Maybe in order to have time to focus on that one costume for the lead in
Sweeney Todd her shop needs to be able to quickly produce 30 dance costumes using apparel CAD to speed up the process.

E5 reported that the company he works for does employ apparel CAD to manufacture the hundreds of costumes made every year at their headquarters. He described a system of storing pattern data along with manufacturing process steps and standards that ensures the efficiency of this for-profit company. While this company does have access to 3D simulation, E5 reported that at the present time they are using it as an early stage design validation tool. He reported seeing 3D simulation used to determine placement of a custom digital print on a costume, but further stated that the costume in question was one for which the pattern was known to fit, therefore fit issues were not being examined using 3D simulation. E5 suggested that the performance requirements of this company preclude relying on virtual fitting at present, because range of motion is of paramount importance for their performers, however he suggested that the culture of innovation in his company combined with their focus on efficiency may lead them to explore virtual fitting in the future, especially since they frequently work with stock patterns.

If we could send somebody who is in China to get their body scanned…put them in the computer…and try the patterns from the artists that we currently have on these other bodies, and that way when they get here I would know who fits best into what, and then I put them in that and there’s no guessing. (E3)

Such an implementation of virtual fitting would still involve preparation and data from prior fittings, but in the case of this company which may produce 100 costumes for one performer in a year, it might make sense to make use of this technology.
Both of these examples show use of apparel CAD for situations where a performing arts costume shop is approaching the “economy of scale” that drives adoption of CAD in the apparel industry, but there is still another idea that came out of those interviews that might help form a bridge between the scale of a large performing arts company and a small theater. E4 described a situation in which she had been employed to make costumes for a performer of some renown who did not care for fittings. E4 obtained a custom mannequin with this performer’s measurements and described having “virtual” fittings with the mannequin that allowed her to refine costumes to the point that she did not need to hold live fittings with this performer. E4 suggested that this model is one that had been in place in couture houses with frequent repeat customers who preferred not to endure long fittings. 3D apparel CAD and virtual fitting might offer the same kind of opportunity for custom fitting in a theater with resident performers where time is precious and fittings are hard to schedule. D5, who has worked in film, reported a similar opportunity in that arena, where a starring performer’s time is both expensive and hard to schedule. She also likened the world of film production to high-end apparel production, and suggested that interest in rapid prototyping and other CAD applications is growing in the film industry.

These three examples suggest that it may not be enough to evaluate virtual fitting in terms of the functional realism definitions in the earlier costume design and production framework. Asking what designers and makers need to accomplish in a virtual fitting may be a good first step, but questions about efficiency, culture, and work styles within the costume shop also need to be defined and addressed.
6. Suggestions for Future Research

Future research in this area could fall into three different categories: further definition of the functional requirements of a virtual fitting for costume design and production, exploration of the impact of virtual fitting on the culture and work flow within a costume shop, and examination of the efficiency and accuracy of the current virtual simulation technology. Small sample size limits generalizability of the findings from this study, however themes, suggestions, and concerns voiced by research subjects point to some avenues for more thorough examination of this technology in the context of costume design and production. This is in keeping with the purpose of qualitative enquiry, to define emerging issues relating to a complex activity (Creswell, 2013; Tracy, 2012)

This study asked “can a simulated fitting replace one or more components of the prototyping and validation stages of the costume design process.” Results suggested that this technology could supplement one or more activities in the process but could not realistically substitute for any of them. Replicating this study over a larger sample could confirm those results; however issues encountered in this research point to some potential ways in which such a study could be more focused. With some advance planning, more accurate and up-to-date measurements for performers referenced in a virtual fitting study could be obtained, either through a standardized method of manual measuring or through 3D body scanning. Fabric data for actual costumes could also be obtained and used in the simulation process. These steps might help to eliminate some of the issues connected to fit that were encountered in this study.
Evaluating the impact of virtual fitting on the costume design and production workflow will be more complicated. Inserting a virtual fitting study into the production process would be very challenging, both in terms of time and logistics. E2, when describing her incorporation of CAD using the test case of multiple dance costumes, stated that if the CAD process did not appear to be efficient she intended to go back to her usual methods of patterning and grading by hand. She does not have time built into her production calendar for her employees to study and test this new technology extensively. The most important thing to her is still producing those 20 costumes. Implementation of a fit study in a producing costume shop will require time built into the production calendar, and cooperation of the production team. One possible strategy would be to look for opportunities to incorporate virtual fitting into situations where pre-defined needs exist, such as the fitting of international performers described by E5. It will also be important to examine potential value added, costs and benefits within budget constraints to implementing this technology in a costume shop. Value added is itself a construct that needs examination in the context of the costume shop, involving not only costs and benefits but factors such as time, usability, and design priorities. Research in this area will continue to be exploratory in nature as the technology and understanding of it develops, however it is worth thinking about incorporating virtual fitting into an actual production. Allowing costume professionals to study the software’s capabilities in their own dynamic and creative environment may bring opportunities for them to further define their requirements for virtual fitting, and demonstrate hitherto unanticipated uses for it.
Evaluating this study in the context of Wang and Zhang’s (2007) recommendation that garment simulation should work “interactively, intuitively, realistically, and efficiently” (p. 363) also points to areas for future research. Twenty attempts at simulating one costume does not seem efficient, however one researcher’s efforts do not form a basis for generalization. A study that examines the ability of multiple users to simulate the same garment given the same information and tools might shed some light on the types of training and data required for an efficient and effective garment simulation, and inform strategies for implementation and adoption of this technology.

Research has already been conducted on the accuracy of garment simulation through comparison of virtual and actual garments (Ancutiene et al., 2013; Kim & Labat, 2012; Lim, 2009; Lim & Istook, 2011; Otieno & Apeagyei, 2006; Wu et al, 2011); however more such research is needed. A one to one comparison of virtual and actual costumes could contribute specific data about fit accuracy to this field. Studies by Kim and Labat (2012) and Lim (2009) incorporated fit models as research subjects and obtained their feedback on the real and simulated garments; however they worked with typical clothing. Because a costume often requires such specific fit, a study that involved costumes could produce valuable insights into the accuracy of complex garment features in simulation. Using costume designers, costume makers, and performers as evaluators in such a comparison would also be valuable, as they each may have different requirements and standards for evaluation.
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Appendix A, Expert Interview Script

These questions will be asked by the researcher during a recorded, interactive Web-based meeting in which the subject will be able to view from his or her computer screen the “virtual fitting” that will take place using Lectra Modaris 3D Fit software. The research subject will not have access to the questions prior to the session.

Thank you for participating in this research project. I’m going to start by asking a little about you and your work…

1. How long have you been a (costume designer or costume maker)?
2. Describe your training.
3. What type of production do you primarily work on? (plays/musicals/dance pieces/opera?)
4. Tell me about your process for costume design/costume making.
5. Describe the network of costume professionals that you work with. (costume makers, dyers, artisans, vendors)
6. How often do you use a computer in your work, other than for email and web browsing? Describe the types of programs you use and what you do with them
7. When you have work that needs to be jobbed out, how often do you work with artisans or vendors who use computers extensively in their day-to-day operations (i.e. digital print services, pattern making, etc.)
8. Do you have any other thoughts about computers in the costume industry?
Appendix B, Costume Designer Interview Script

These questions will be asked by the researcher during a recorded, interactive Web-based meeting in which the subject will be able to view from his or her computer screen the “virtual fitting” that will take place using Lectra Modaris 3D Fit software. The research subject will not have access to the questions prior to the session.

PARTICIPANT INFORMATION
Thank you for participating in this research project. I’m going to start by asking a little about your background…

1. What was your role in this production? _________________ (costume designer or costume maker)
2. How long have you worked as a (see above)?
3. Have you also worked as a _________________ (answer not chosen for 1)?
   If yes prompt for details (duration, level, how long ago…)
4. Can you briefly describe your education and training? (if necessary prompt “did you train exclusively as a ____ or was your training more general?”)

VIRTUAL FITTING DEMONSTRATION:
Now I’m going to show you a short clip that will demonstrate the capabilities of this software. (Showing clip of costume simulation from pilot study) This is another costume that I have simulated. As you can see I can rotate the virtual model, or zoom in and out. (demonstrating these capabilities while describing them). I can also show you a view of this costume that will tell us how much ease is present in the garment (showing tension map), and I can mark design lines or alterations as we talk.

VIRTUAL FITTINGS
Now we are going to look at your costume. I am going to show you three different versions. I will show you rotating views of the virtual model so that you can see it from all available angles, and ask for your feedback on the costume itself. As we go through the questions I can manipulate the virtual actor (zooming in or out, changing the angle of the view, or showing the ease etc) as needed. Please respond as you would to the draper or tailor who would be making this costume. These fittings are in no particular order, but I can tell you there are slight differences between them:

Fitting A

5. What are your impressions of the fit of the garment? Do you have any specific fitting notes? (if necessary prompt for feedback on specific features of the garment(s), “let’s start by looking at the bodice… what do you think of the sleeve length… how is the fit over the hips, etc”)
6. Do you have any specific design notes? (if necessary prompt for specific design features of the garment “how is the collar width…what do you think of the skirt fullness, etc”)

Fitting B

7. What are your impressions of the fit of the garment? Do you have any specific fitting notes? (if necessary prompt for feedback on specific features of the garment(s), “let’s start by looking at the bodice…what do you think of the sleeve length…how is the fit over the hips, etc”)

8. Do you have any specific design notes? (if necessary prompt for specific design features of the garment “how is the collar width…what do you think of the skirt fullness, etc”)

Fitting C

9. What are your impressions of the fit of the garment? Do you have any specific fitting notes? (if necessary prompt for feedback on specific features of the garment(s), “let’s start by looking at the bodice…what do you think of the sleeve length…how is the fit over the hips, etc”)

10. Do you have any specific design notes? (if necessary prompt for specific design features of the garment “how is the collar width…what do you think of the skirt fullness, etc”)

COMPARISON
Now I will show you all three fittings and I’m going to ask you to compare their effectiveness:

11. Which of the three do you think shows the best overall fit and design?
12. What differences can you perceive between the three fittings?

GENERAL IMPRESSIONS
Now I’m going to ask you some questions specifically related to the experience of the virtual fitting session. You may have already covered these topics in our conversation, but I have a list of standardized questions that I am asking all of the participants in the project, and these may prompt you to give me more detailed information about things we have already talked about.

13. Tell me about your first impressions of the virtual fitting session materials.
14. Do you feel that the fitting session materials convey a sense of the costume you designed?
15. Based on these examples, can you make design decisions based on a virtual fitting?
   a. If needed prompt for impressions of specific garment features
16. Based on these examples, can you make judgments regarding the fit in a virtual fitting?
   a. Again if needed, prompt for impressions of specific features
17. Can you tell me about your typical process as it relates to costume fitting. (if necessary prompt for “how do you approach communicating with the costume maker, what do you like to see in a prototype?...
18. Can you talk about how this virtual fitting session relates (or does not relate) to your costume design process.
19. Can you suggest any improvements or amendments to this fitting session that would make it more productive for you as a designer?
20. Can you think of other ways you can envision this technology being useful in other stages of the design process, or specific settings in which it would be preferable to use this type of “virtual fitting”?

Thank you for your time today! Are there any other thoughts you would like to share before we wrap up?
Appendix C, Costume Maker Interview Script

These questions will be asked by the researcher during a recorded, interactive Web-based meeting in which the subject will be able to view from his or her computer screen the “virtual fitting” that will take place using Lectra Modaris 3D Fit software. The research subject will not have access to the questions prior to the session.

PARTICIPANT INFORMATION
Thank you for participating in this research project. I’m going to start by asking a little about your background…

1. What was your role in this production? _____________ (costume designer or costume maker)
2. How long have you worked as a (see above)?
3. Have you also worked as a _____________ (answer not chosen for 1)?
   If yes prompt for details (duration, level, how long ago…)
4. Can you briefly describe your education and training? (if necessary prompt “did you train exclusively as a ____ or was your training more general?”)

VIRTUAL FITTING DEMONSTRATION:
Now I’m going to show you a short clip that will demonstrate the capabilities of this software. (Showing clip of costume simulation from pilot study) This is another costume that I have simulated. As you can see I can rotate the virtual model, or zoom in and out. (demonstrating these capabilities while describing them). I can also show you a view of this costume that will tell us how much ease is present in the garment (showing tension map), and I can mark design lines or alterations as we talk.

VIRTUAL FITTINGS
Now we are going to look at your costume. I am going to show you three different versions. I will show you rotating views of the virtual model so that you can see it from all available angles, and ask for your feedback on the costume itself. As we go through the questions I can manipulate the virtual actor (zooming in or out, changing the angle of the view, or showing you the ease etc) as needed. Please respond as you would if this “virtual fitting session” was going to be presented to the costume designer. These fittings are in no particular order, but I can tell you there are slight differences between them:

Fitting A

5. What are your impressions of the fit of the garment? Do you have any specific fitting notes? (if necessary prompt for feedback on specific features of the garment(s), “let’s start by looking at the bodice… what do you think of the sleeve length… how is the fit over the hips, etc”)

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6. Do you have any specific design notes? (if necessary prompt for specific design features of the garment “how is the collar width…what do you think of the skirt fullness, etc”)

Fitting B
7. What are your impressions of the fit of the garment? Do you have any specific fitting notes? (if necessary prompt for feedback on specific features of the garment(s), “let’s start by looking at the bodice…what do you think of the sleeve length…how is the fit over the hips, etc”)

8. Do you have any specific design notes? (if necessary prompt for specific design features of the garment “how is the collar width…what do you think of the skirt fullness, etc”)

Fitting C
9. What are your impressions of the fit of the garment? Do you have any specific fitting notes? (if necessary prompt for feedback on specific features of the garment(s), “let’s start by looking at the bodice…what do you think of the sleeve length…how is the fit over the hips, etc”)

10. Do you have any specific design notes? (if necessary prompt for specific design features of the garment “how is the collar width…what do you think of the skirt fullness, etc”)

COMPARISON
Now I will show you all three fittings and I’m going to ask you to compare their effectiveness:
11. Which of the three do you think shows the best overall fit?
12. What differences can you perceive between the three fittings?

GENERAL IMPRESSIONS
Now I’m going to ask you some questions specifically related to the experience of the virtual fitting session. You may have already covered these topics in our conversation, but I have a list of standardized questions that I am asking all of the participants in the project, and these may prompt you to give me more detailed information about things we have already talked about.

13. Talk a little about your first impressions of the virtual fitting session materials.
14. Do you feel that the fitting session materials convey a sense of the designer’s intention for the costume?
15. Can you make design decisions based on this virtual fitting?
   a. If needed prompt for impressions of specific garment features
16. Can you make judgments regarding the fit in this virtual fitting?
a. Again if needed, prompt for impressions of specific features

17. Can you tell me about your typical process as it relates to costume fitting. (if necessary prompt for “how do you approach communicating with the costume maker, what do you like to see in a prototype?...)

18. Can you talk about how this virtual fitting session relates (or does not relate) to your costume design process.

19. Can you suggest any improvements or amendments to this fitting session that would make it more productive for you as a designer?

20. Can you think of other ways you can envision this technology being useful in other stages of the design process, or specific settings in which it would be preferable to use this type of “virtual fitting”?

Thank you for your time today! Are there any other thoughts you would like to share before we wrap up?