Compression Model on a Clinically-Relevant In-Vitro Lactating Breast Model

by

Tiffany Xi

Submitted to the
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ABSTRACT

Breastfeeding is incredibly important in infant nutrition and can provide many health benefits for the lactating parent as well [1]. Breast pumps allow for the expression and feeding of breastmilk when natural breastfeeding cannot occur. However, breast pumps only use suction to express milk, and the mechanics that come from a baby's natural suckling [2] are ignored. The aim of the research in this thesis is to understand the capabilities of compression via soft robotics in assisting the expression of milk from a lactating breast. The work presented in this thesis is two-fold: (1) a clinically-relevant in-vitro model of the lactating breast is developed, and (2) a soft robotic compression model mimicking natural breastfeeding and hand expression is tested on the lactating breast model. Although the compression model alone was able to express liquid from the model, it was not as effective as suction alone, nor did it increase the efficacy of suction when used in conjunction.

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Table of Contents

List of Figures

List of Tables

1. Introduction

The aim of the research in this thesis is to understand the capabilities of compression via soft robotics in assisting the expression of milk from a lactating breast. Natural breastfeeding is incredibly beneficial to the parent and the baby, but for parents and babies who cannot naturally breastfeed, breast pumps can be used to assist in the expression and feeding of breastmilk. Most breast pumps that are currently on the market rely on suction to extract milk. A cone is aligned with the nipple to form a seal around it, and in an electric system, a pump creates a vacuum in the cone which draws the nipple forward to extract milk. While the use of breast pumps can be often be advantageous, their mechanical function isn't comprehensive as they don't involve the compressive motions of a baby's mouth that occur in natural breastfeeding [2].

Studies have shown that therapeutic breast massage in lactation can reduce breast pain by managing engorgement, plugged ducts, and mastitis [3], and adding hand techniques with electric pumping can increase production and the caloric content of breastmilk [4,5]. This thesis seeks to understand whether robotic actuation of soft materials can increase the efficiency of the expression of breastmilk by mimicking the compression that occurs in natural breastfeeding and in hand massaging techniques. In order to conduct experiments with the proposed compression model, a model of the lactating breast must be developed as well. Therefore, the work presented in this thesis is two-fold: (1) a clinically-relevant in-vitro model of the lactating breast is developed, and (2) a soft robotic compression model mimicking natural breastfeeding and hand expression is tested on the lactating breast model.

2. Background

2.1 Benefits of Breastmilk

Breastfeeding is incredibly important in infant nutrition and can provide many health benefits for the lactating parent as well. Breastmilk contains many complex proteins, lipids and carbohydrates, the concentrations of which alter dramatically over a single feed, as well as over lactation, to reflect the infant's needs [6,7]. Breastmilk also contains a myriad of biologically active components that help develop the infants immune system and microbiome [6]. Children who are breastfed for longer periods of time have lower infectious morbidity and mortality and higher intelligence than do those who are breastfed for shorter periods, or not breastfed. For mothers, breastfeeding can prevent breast cancer and reduce risk of diabetes and ovarian cancer [1].

Despite all the benefits, breastfeeding became less common in high-income countries during the 20th century [8], and even in low-income and middle-income countries, only 37% of infants younger than 6 months are exclusively breastfed [1]. Societal factors, health systems, workplace settings, and parent/infant attributes (such as cleft lip and palate or tongue tie) can all affect the ability to exclusively breastfeed, and thus breast pumps are often used to still encourage lactation and feeding of breastmilk.

2.2 Anatomy and Models of the Lactating Breast

The non-lactating female breast is composed primarily of adipose and collagenous tissue. The mammary glands are composed of lactiferous ducts, and during pregnancy, they expand and branch while clusters of alveoli bud and expand from the ducts. Breast alveoli are lined with lactocytes that secrete milk, which are surrounded by a net of contractile myoepithelial cells [9,10].

There has been little investigation of the lactating breast due to limitations of imaging techniques and risks of various diagnostic methods for healthy lactating women. Ramsay et al.

(2005) used ultrasound as a noninvasive approach to re-examine the gross anatomy (Figure 1) of the lactating breast and improved the standard model of the breast that originated from dissections of the breasts in lactating cadavers by Sir Astley Cooper in 1840 [9]. This study found that there was a wide distribution of adipose and glandular tissue between women: expressed as a percentage of the total amount of tissue measured, the glandular tissue represented 63 ± 9% (range 46-83%) and 65 ± 11% (range 45-83%) of the breast tissue for the left and right breast respectively. In the milk duct system, the mean number of main ducts was 9.6 ± 2.9 (range 6–18) and 9.2 ± 2.9 (range 4–14) for the left breast and right breast. While previous anatomical diagrams describe lactiferous sinuses as expansion of the ducts at the base of the nipple in which milk accumulates, Ramsay et al. did not observe these structures. The mean diameter of the milk ducts for both breasts was 2.0 ± 0.8 mm (range 1.0–4.4 mm).

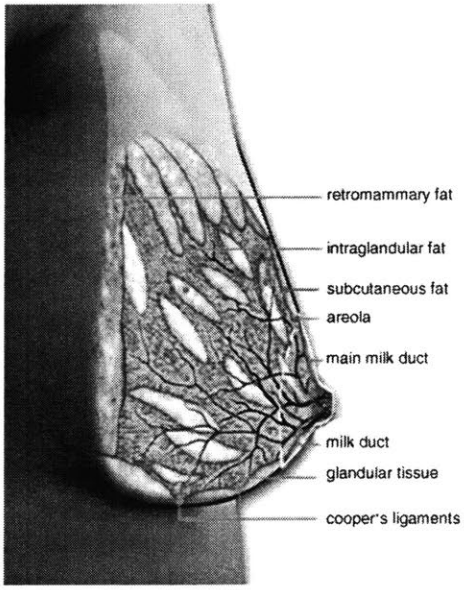

Figure 1: Drawing of the gross anatomy of the lactating breast based on ultrasound observations of the milk duct system and distribution of different tissues within the breast [9].

A more recent study [11] of a mathematical model of milk transport through lactating human breast ducts suggests that the completed milk flow system in a lactating breast looks like a tree. S. Negin Mortazavi et al. describe 20-40 lobules (clusters of alveoli) as a lobe and suggest only 5-9 active lobes are in each lactating breast. Figure 2 shows the anatomy from which this mathematical model is developed.

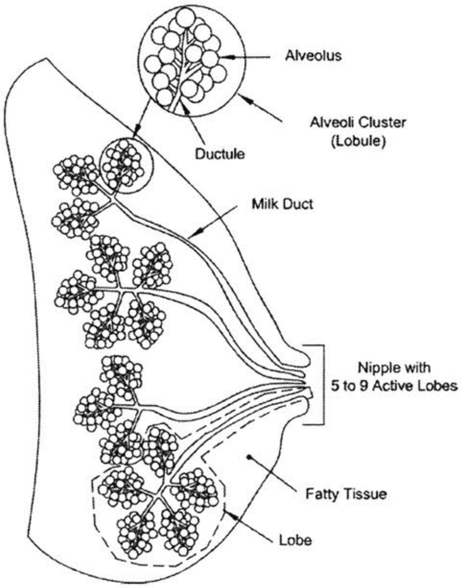

Figure 2: Anatomy of the lactating breast as the basis of a mathematical model describing only 5-9 active lobes [11].

2.3 Physiology of Breastfeeding [2]

The production of milk is primarily controlled by the hormones oxytocin and prolactin. When a baby suckles at the breast, sensory impulses from the nipple go to the brain to signal the release of oxytocin and prolactin. Oxytocin is produced more quickly than prolactin and makes the myoepithelial cells around the alveoli contract. This contraction allows the collected milk in the alveoli flow along and fill the ducts, helping the baby get the milk easily. The oxytocin reflex is also sometimes called the "letdown reflex," and occurs when a parent expects a feed as well as when the baby is suckling. This reflex becomes conditioned to sensations such as touching, smelling, hearing, or seeing the baby.

Prolactin allows for the secretion of milk by the cells of the alveoli. The prolactin level is highest about 30 minutes after the beginning of the feed, so its effect is to prepare milk for the next feed. During the first few weeks, the more a baby suckles and stimulates the nipple, the more prolactin is produced, and the more milk is produced.

In order to stimulate the nipple and trigger the release of these hormones for an adequate supply and flow of milk, the baby needs to be well attached so that he/she can suckle effectively. For good attachment, the baby should be suckling from the breast, not just from the nipple, since the areola and the tissues underneath it, including the larger ducts, are in the baby's mouth. The baby uses suction mainly to stretch out and hold the breast tissue in the mouth, and as the baby suckles, a wave passes along the tongue from the front to back to press milk out. The differences between good and poor attachment are shown in Figure 3.

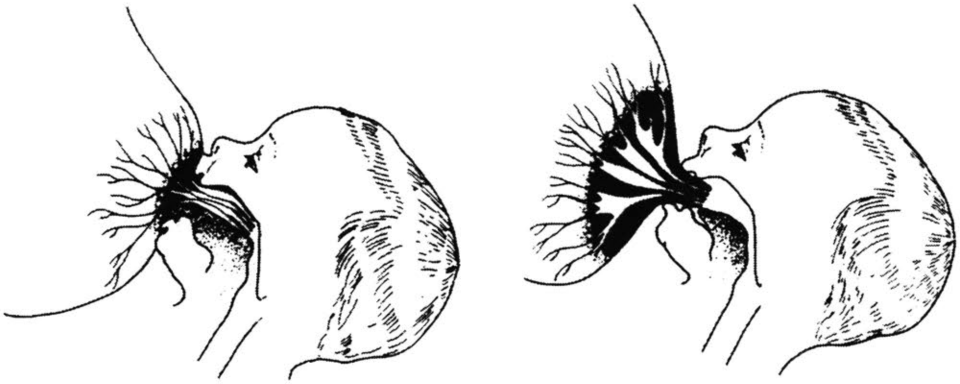

Figure 3: Good attachment (left) and poor attachment (right) inside the baby's mouth. The baby should be suckling from the breast, not just from the nipple [2].

3. Design of the In-Vitro Lactating Breast Model

In order to be able to test the efficacy of actuated compression on the lactating breast for expressing milk, a clinically-relevant lactating breast model was desired. Human breasts come in a large range of shapes and sizes, so the outer shape of the model in this thesis follows a previous lactating breast model that was attained for a related project with approximate dimensions of 170 mm long, 140 mm wide, and 45 mm from the base to the nipple. A negative mold of the previous model was created using a vacuum-former to capture the outer shape.

While the outside geometry was maintained, this previous model was improved upon for its inner geometry; the previous model only features one large reservoir for fluid right behind the nipple. For a clinically-relevant model, a similar rubber form was desired, but with multiple reservoirs representing the multiple lobes found in anatomical studies [9,11]. To create these lobes and the corresponding milk ducts, wax lobes were molded with silicone tubing embedded so that silicone rubber could be molded around lobes and tubing, and then the wax could be melted out and the silicone tubing removed after the silicone rubber cured. Silicone tubing with a 2 mm outer diameter was chosen for the negative space of the milk ducts based on the average milk duct diameter from the ultrasound-guided anatomical study (Ramsay et al) [9]. To create a clinically-relevant model that was also feasible in fabrication, the glandular tissue was simplified as 5 ellipsoid lobes. The number of lobes falls within the lower range determined by the ultrasound-guided anatomical study and the mathematical model study [9,11]. The shape and size allows for the arrangement of then lobes to fall within the range of percent glandular tissue determined by the aforementioned ultrasound-guided anatomical study [9]. The negative lobe molds were 3D-printed (Figure 4), and jeweler's water-soluble wax was crumbled, placed in the molds, and melted with a heat gun at 350°F to form the ellipsoid shape around the silicone tubes (Figure 5).

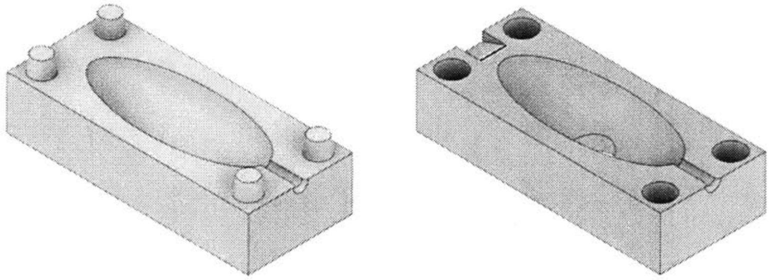

Figure 4: The bottom (left) and top (right) molds for creating the wax lobes.

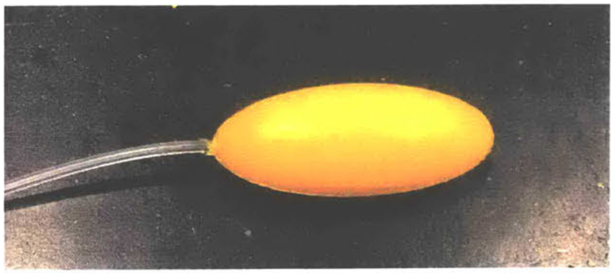

Figure 5: Finished wax lobe molded around silicone tubing.

Holes were drilled into the nipple of the vacuum-formed outer profile mold as the nipple orifices, and the silicone tubes that originated from the wax molds were pulled through these holes. Each wax lobe also had two pieces of string attached: one piece of string was melted into opposite end from the silicone tube, and a second piece of string was tied to where the silicone tube inserted intot he wax lobe. The opposite ends of these strings were tied to various fixtures above the mold in order to suspend the wax lobes within the vacuum-formed mold such that the lobes were not in contact with each other or the edges (Figure 6). Dragon Skin® 10 FAST (Smooth On, Inc.) silicone rubber was poured into the vacuum-formed mold with added Slacker® (Smooth On, Inc.) as a silicone tactile mutator in a 1:1:1 ratio of Part A Dragon Skin® : Part B Dragon Skin® : Slacker® for a short cure time and rebound properties similar to human tissue [12]. The three components were each weighed separately on a scale, then thoroughly combined to a mixture. The mixture was then carefully poured into the vacuum-formed mold to avoid disturbing the suspension of the wax lobes.

After the silicone rubber cured within the vacuum-formed mold, the model was removed from the mold with the wax lobes within. The strings and silicone tubes were removed before the model was placed in the oven to allow the wax lobes to soften and melt. Once the wax lobes were pliable, they were carefully extracted from the back of the model. Water was also injected into the model to wash out the wax (Figure 7). Lastly, the model was placed on a thin sheet of the same mixture of Dragon Skin® 10 FAST (Smooth On, Inc.) silicone rubber and Slacker® (Smooth On, Inc.) to plug the back of the lobes.

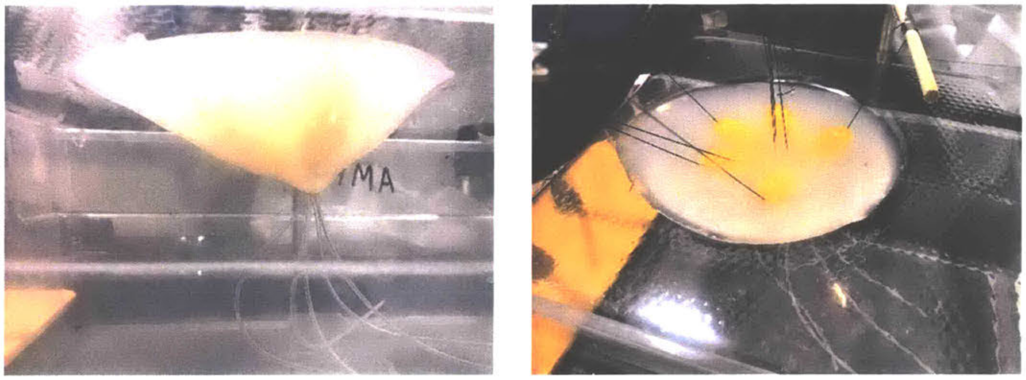

Figure 6: Wax lobules suspended in vacuum-formed mold filled with silicone rubber.

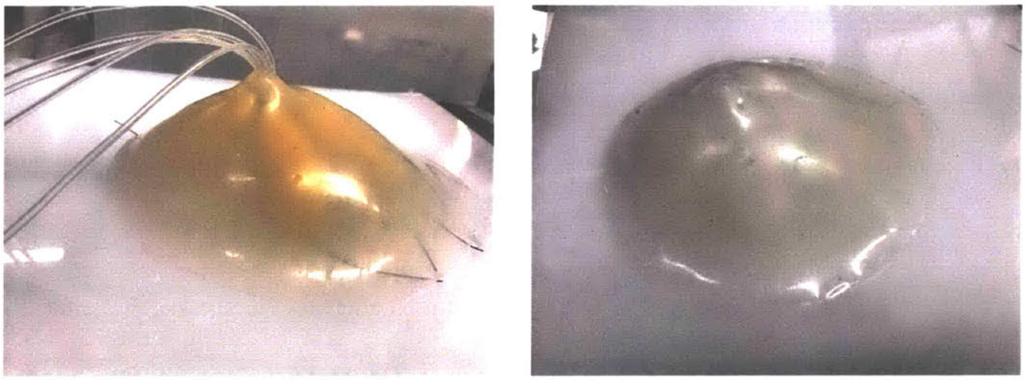

Figure 7: Lactating breast model before (left) and after (right) the silicone tubes, wax lobes, and strings were removed.

4. Design of the Compression Model

To mimic the use the hand expression, breast massage, and natural suckling, a soft-robotic compression model was designed to interface with the lactating breast model and assess the efficacy of compression for breastmilk extraction. The inspiration behind these soft actuators is a soft robotic sleeve that was designed to be implanted around the heart and assist contractile motions of the heart muscle with actuation from compressed air [13]. The soft material used in the heart sleeve allows the device to fit snuggly around the heart, and similarly, the use of fabric in the compression model allows it to conform to the shape of the breast. The soft-robotic bladders were made out of a flexible fabric lined with thermoplastic polyurethane (TPU). As hand breast compression techniques involve creating a C-shape with the hand to apply gentle pressure to the breast [14,15], the bladders were designed as rings around the areola. Additionally, breast massages involve applying pressure from the base of the breast towards the nipple [14], so the compression model included two concentric rings. The two ring bladders were individually actuated and inflated to 1 psi in a pattern from the outside in to mimic the movement of the baby's tongue during natural breastfeeding [2]. In a cycle of 2 seconds, the outer ring bladder was pressurized for 1 second, and the inner ring bladder was actuated .5 seconds later for a duration of 1 second as well, creating a wave motion from the outside of the breast towards the nipple.

The TPU fabric was cut into an ovular/fan shape with a slit so that sewn together, the bladders could create a three-dimensional shape and cup the breast model. The two-dimensional shapes of the concentric ring bladders were cut out of polyvinyl alcohol (PVA) sheets and placed between the TPU fabric as inserts. The materials were pressed together at 400°F for 180 seconds so that the TPU fabric fused in the absence of the PVA inserts. The PVA inserts were flushed with water to dissolve and remove the material, leaving behind air bladders (Figure 8). Polyurethane tubes were inserted into one side of each bladder and sealed to the fabric with fabric glue. A hole was cut in the center of rings to accommodate the nipple, and the slit was sewn together to form a cone shape.

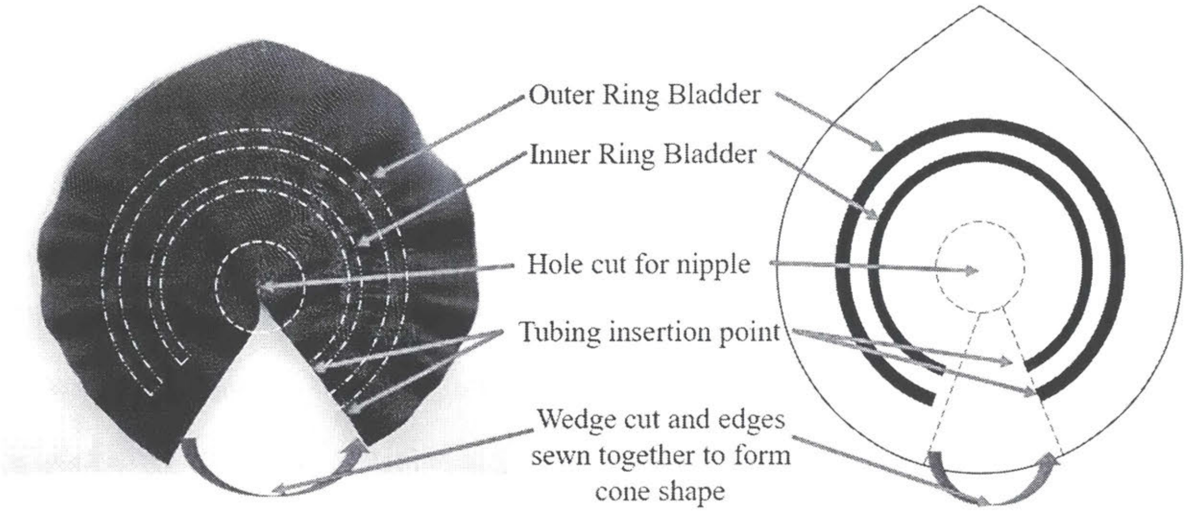

Figure 8: Concentric ring bladders for the soft-robotic compression model.

5. Experimental Results

5.1 Experimental Design

To assess the effect of compression on milk expression, 4 expression methods were employed on the lactating breast model with 3 trials each: suction (with cone), suction (with no cone), compression, and compression with suction (with no cone). Suction experiments were conducted with and without the cone (Figure 9) because the size of the cone did not allow for the compression to occur simultaneously with the suction as the hard cone was covering a lot of surface area on the model. Suction was applied using Medela's Pump in Style Advanced® breast pump on the lowest suction setting. A nursing bra was pinned to a Styrofoam block, and when used, the compression insert was placed inside the nursing bra. To secure the compression insert, the top corner and sides were gently sewn to the nursing bra, and the polyurethane tubes were securely sewn into the bra so that the weight of the tubes did not twist the compression insert. For each trial, the lactating breast model was filled with water (dyed blue) that was injected into each lobe using a syringe (Figure 10). The mass of the model before and after water was injected was recorded on a scale. The breast model was then placed into the nursing bra against the Styrofoam block (Figure 11). The expression technique would be active for 15 seconds, and the mass of the water expressed recorded afterwards.

Figure 9: Suction using the cone (left) and without the cone (right).

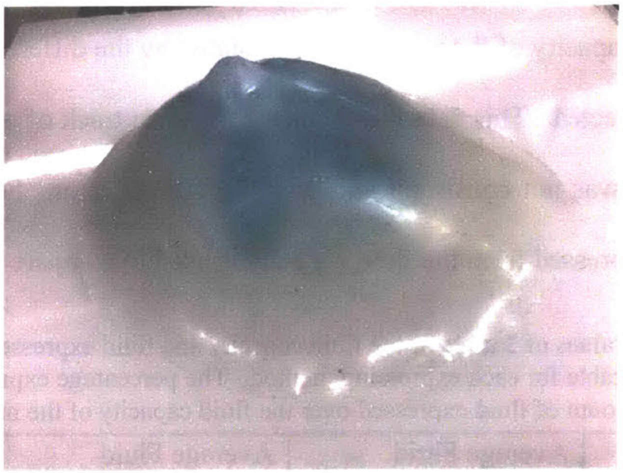

Figure 10: First-ever self-sealing breast model with water (dyed blue) injected into the lobes.

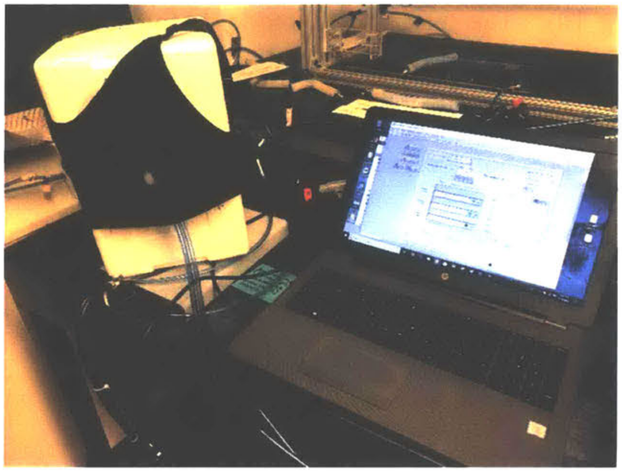

Figure 11: Lactating breast model placed in nursing bra with compression insert.

5.2 Results and Discussion

The efficacy of each expression method was determined by the ratio of the expressed water volume to the water volume capacity before the expression method was applied for 15 seconds (Table 1). The fluid capacity of the model was calculated by the difference in weight before and after the water was injected. This data was important to keep track of given that the injection of water into the model was not consistent and prone to human error. For the same reasons, the percentage of fluid expressed from the fluid capacity is used to compare the expression methods.

Table 1: Average data values of 3 trials of the fluid capacity and fluid expressed from the lactating breast model are listed in the table for each expression method. The percentage expressed is calculated by the amount of fluid expressed over the fluid capacity of the model.

	Average Fluid Capacity (mL)	Average Fluid Expressed (mL)	Average Percentage Expressed
Suction (with cone)	40.1	25.0	62.3%
Suction (without cone)	38.6	30.8	79.8%
Compression	38.6	5.3	13.8%
Compression and Suction (without cone)	37.8	30.1	79.5%

The compression model alone was able to express liquid from the lactating breast model, but only a small percentage of the fluid capacity. When comparing normal suction methods (suction with cone) to the compression model, the data suggests that the actuated compression alone cannot be as effective as normal suction, as the percent expressed due to normal suction is more than 4 times the percent expressed from compression alone. Additionally, the use of compression in conjunction with suction is not seen to increase the percentage of water expressed, as suction without the cone led to an average of 79.8% expression and compression and suction without the cone led to an average of 79.5% expression. The four different expression models suggest that even though soft-robotic compression is capable expressing water from the lactating breast model, compression alone is not comparable to suction alone in efficacy, and the use of compression along with suction does not increase expression efficacy when compared to suction alone.

Although previous research has shown that manual compression can increase the efficacy of milk expression when used in conjunction with breast pumps [4], the use of robot-actuated compression may be inconclusive within this thesis due to the differences of testing on real human subjects versus in-vitro models. The lactating breast model developed in this thesis may be an improvement on existing models in terms of anatomy, but it is still limited physiologically. The model does not restrict the flow of fluid well enough, nor does it follow the hormonal control in the production of milk. After 15 seconds, the suction methods tend to draw out most of the liquid from the model, which is must faster than the average breastfeeding session. Additionally, the compression model could have been too weak compared to the forces exerted in hand expression and natural breastfeeding. The bladders were only inflated to 1 psi, and higher pressures could have been tested for increased compressive forces. Even though the bladders were sewn into the maternity bra, it shifted in position at times and often seemed to undergo an expansion motion outward in addition to compression. To further develop the soft robotic actuation, the bladders could be fabricated with a stiffer material on the outside to favor the inflation and movement of fabric towards the breast.

6. Conclusions

A clinically-relevant lactating breast model was developed for the first time based on current anatomical research of the lactating breast. A soft robotic compression model was also designed and actuated to mimic the compressive forces in natural breast feeding and hand expression. The compression model was used on the lactating breast model within the context of suction expression methods. Although the compression model alone was able to express liquid from the model, it was not as effective as suction alone, nor did it increase the efficacy of suction when used in conjunction.

To further understand the methods of breastmilk expression with soft robotic compression techniques, multiple approaches can be taken to improve the breast model and the compression model. The lactating breast model can be more physiologically accurate. The resistance within the fluid ducts could be increased with more branching and more lobes. A fluid with a viscosity similar to that of milk could be used instead of water. Additionally, a pump could be used inject the fluid into the lobes over time to mimic the roles of hormones in the production of milk. The compression model could be better suited to use in conjunction with suction. The inflated bladders could be incorporated within the cone used for suction to interface with more surface area yet still provide adequate contact to create a vacuum. The actuation of the bladders and suction could be controlled from a single computer so that the patterns can be synchronized. Bladders with varying fabric stiffnesses could promote actuation so that the forces are more directed towards the breast. The future improvements of the lactating breast model and compression initially developed in this thesis can allow for more effective means of breastmilk expression and thus facilitate the benefits that breastfeeding and breastmilk provides for parents and babies.

7. References

[1] Victora, C. G., Bahl, R., Barros, A. J. D., França, G. V. A., Horton, S., Krasevec, J., Murch, S., Sankar, M. J., Walker, N., and Rollins, N. C., 2016, "Breastfeeding in the 21st Century: Epidemiology, Mechanisms, and Lifelong Effect," The Lancet, **387**(10017), pp. 475–490.

[2] Information, N. C. for B., Pike, U. S. N. L. of M. 8600 R., MD, B., and Usa, 20894, 2009, *The Physiological Basis of Breastfeeding*, World Health Organization.

[3] Witt, A. M., Bolman, M., Kredit, S., and Vanic, A., 2016, "Therapeutic Breast Massage in Lactation for the Management of Engorgement, Plugged Ducts, and Mastitis," J. Hum. Lact. Off. J. Int. Lact. Consult. Assoc., **32**(1), pp. 123–131.

[4] Morton, J., Hall, J. Y., Wong, R. J., Thairu, L., Benitz, W. E., and Rhine, W. D., 2009, "Combining Hand Techniques with Electric Pumping Increases Milk Production in Mothers of Preterm Infants," J. Perinatol. Off. J. Calif. Perinat. Assoc., **29**(11), pp. 757–764.

[5] Morton, J., Wong, R. J., Hall, J. Y., Pang, W. W., Lai, C. T., Lui, J., Hartmann, P. E., and Rhine, W. D., 2012, "Combining Hand Techniques with Electric Pumping Increases the Caloric Content of Milk in Mothers of Preterm Infants," J. Perinatol. Off. J. Calif. Perinat. Assoc., **32**(10), pp. 791–796.

[6] Andreas, N. J., Kampmann, B., and Mehring Le-Doare, K., 2015, "Human Breast Milk: A Review on Its Composition and Bioactivity," Early Hum. Dev., **91**(11), pp. 629–635.

[7] Zou, L., Pande, G., and Akoh, C. C., 2016, "Infant Formula Fat Analogs and Human Milk Fat: New Focus on Infant Developmental Needs," Annu. Rev. Food Sci. Technol., **7**, pp. 139–165.

[8] Rollins, N. C., Bhandari, N., Hajeebhoy, N., Horton, S., Lutter, C. K., Martines, J. C., Piwoz, E. G., Richter, L. M., and Victora, C. G., 2016, "Why Invest, and What It Will Take to Improve Breastfeeding Practices?," The Lancet, **387**(10017), pp. 491–504.

[9] Ramsay, D., Kent, J., Hartmann, R., and Hartman, P., 2005, "Anatomy of the Lactating Human Breast Redefined with Ultrasound Imaging," J. Anat., **206**(6), pp. 525–534.

[10] "28.6 Lactation | Anatomy & Physiology."

[11] Negin Mortazavi, S., Hassiotou, F., Geddes, D., and Hassanipour, F., 2015, "Mathematical Modeling of Mammary Ducts in Lactating Human Females," J. Biomech. Eng., **137**(7).

[12] "Slacker® Product Information," Smooth- Inc [Online]. Available: https://www.smooth-on.com/products/slacker/. [Accessed: 19-May-2019].

[13] Roche, E. T., Horvath, M. A., Wamala, I., Alazmani, A., Song, S.-E., Whyte, W., Machaidze, Z., Payne, C. J., Weaver, J. C., Fishbein, G., Kuebler, J., Vasilyev, N. V.,

Mooney, D. J., Pigula, F. A., and Walsh, C. J., 2017, “Soft Robotic Sleeve Supports Heart Function,” Sci. Transl. Med., **9**(373), p. eaaf3925.

[14] 2017, “Breast Compression and Massage While Pumping to Increase Milk Output,” Spectra Baby Aust. [Online]. Available: https://spectra-baby.com.au/breast-compressions-massage-pumping/. [Accessed: 19-May-2019].

[15] 2017, “Expressing and Storing Breast Milk,” nhs.uk [Online]. Available: https://www.nhs.uk/conditions/pregnancy-and-baby/expressing-storing-breast-milk/. [Accessed: 19-May-2019].