Toward Engineering Biological Tissues by Directed Assembly and Origami Folding

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1. Introduction

Human tissue engineering can save lives by providing donor tissues and organs, and by acting as a tool for screening new medical therapies before any human testing takes place. Tissue engineering has proven successful for certain types of tissue (e.g., skin [Wood et al. 07] and bladder [Atala et al. 06]) that have a more planar, sheet-like structure rather than a fully three-dimensional (3D) structure. The creation of more complex, fully 3D tissues has proven more challenging because of the need to create a functional (typically biomimetic) structure that is supported by appropriate vascular networks. Although some techniques have been demonstrated (e.g., bioprinting [Jakab et al. 10]), the current state of the art faces challenges in producing human tissue fast enough (i.e., with sufficient throughput), with complex human tissue structures suitable for transplantation or medical therapy testing (i.e., with sufficient control), and in a way that can be done to meet demand (i.e., with sufficient scalability). Origami offers potential to obtain well-controlled 3D structures for tissue engineering. Manual folding [Kuribayashi-Shigetomi and Takeuchi 11] and cell traction forces [Kuribayashi-Shigetomi et al. 12] have been used to fold nonbiodegradable parylene for tissue engineering. Nonbiodegradable polymeric microcontainers are folded to encapsulate biological specimens by a self-actuation process in [Azam et al. 11]. Patterned poly(ethylene glycol) (PEG) hydrogels are self-actuated and folded into structures with uniform radii of curvature for biological applications in [Jamal et al. 13]. In contrast to the previous demonstrations, the present work simulates and experimentally demonstrates actuated self-folding of biodegradable polymeric structures for tissue engineering in which well-defined hinges localize folding between the more rigid plates.

The present concept for tissue engineering combines the previously demonstrated ability to organize cells of different sizes (e.g., of different cell types) into hemispherical wells on a two-dimensional (2D) sheet [Agarwal and Livermore 11] with origami folding. In this approach, spherical cells suspended in a liquid medium are assembled onto a polymer surface; the surface may be precoated with collagen to better promote the survival and correct function of the cells. Although cells can adhere anywhere on the surface, external fluid forces ensure that they ultimately assemble only in wells that match the cells' diameters. The new element in this approach, and the focus of the present work, is the origami folding of the cell-seeded sheet to form the desired 3D tissue structure. The origami-folded structure will permit not only cell culture in static medium [Freshney 05] but also cell culture in a medium that flows through the folded origami channels. The scaffold material biodegrades through a process of surface erosion [Wang et al. 03], leaving behind the cells that have been organized through directed assembly and origami folding. The present results focus on the creation of potential origami-based folding architectures that mimic the structure of real human tissues and on the development of self-actuated polymer folding scaffolds for their implementation. Requirements for potential folding designs, material selection for polymer scaffolds, potential origami architectures, finite-element simulations, and experiments are demonstrated.

2. Requirements for Origami-Based Tissue Engineering

Each tissue in the human body has its own unique structure. Origami is a promising method for structuring tissues because of the wide diversity of forms that can be folded. An added layer of complexity may be introduced by controlling the pattern of cells on the 2D scaffold sheets. Despite origami's potentially broad applicability for tissue engineering, it is worthwhile to focus on a particular tissue structure for the original demonstrations. In this case, the chosen demonstration system is the liver. Although liver's macroscale structure appears complex, with four lobes, connective tissue, vasculature, etc., functional liver tissue comprises approximately 100,000 repeating units called liver lobules. Each liver lobule is about 1–2 mm in size and has an irregular hexagonal cross section with approximately sixfold symmetry; diagrams may be found in [Ho et al. 13]. Perpendicular to the cross section, each lobule is extruded to form a roughly hexagonal prism with nonplanar caps. Blood enters each lobule through six inlets organized around the lobule's periphery and fed by the portal vein and hepatic artery. Blood flows radially to the center of the lobule and exits through the central vein. Lobules are arranged in a rough array and are connected to common vascular inlets and outlets. The goal of this research is to replicate the structure and function of liver lobules in a modular origami system and to tile the repeated units together to form functional tissue.

For most tissues, including liver tissue, appropriate vasculature is one of the most challenging features to engineer. Not only must the network of blood vessels reach all of the parts of the tissue to supply nutrients and oxygen and to remove metabolic byproducts, but it must also meet requirements for vessel size, branching geometry, etc. In the origami tissue approach, the vascular architecture may be created in either of two main ways. If the folding sheets are pre-formed with holes in the appropriate locations, the vascular channels may cross folded sheets, with blood flowing through the holes. Alternatively, the fold pattern may be designed so that blood flows parallel to the sheets, in channels formed between adjacent folded plates (Figure 1). Liver lobules are well suited to the second approach, in which flow travels between radially oriented or partially radially oriented folds.

The design of the folds must meet additional requirements beyond achieving an (ideally hexagonal) radial fold structure. Because biological tissues are sensitive to contamination, it is important that the folding be achieved with a minimum of contact between the cell-seeded folding sheet and the outside world. An ideal fold design should therefore have one degree of freedom (1DOF), enabling the fold to be implemented with a minimum number of contacts with sterile actuators. Finally, the detailed design of the structure should be

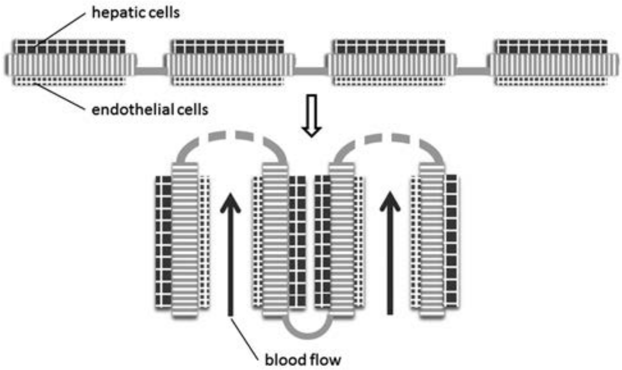

FIGURE 1. Conceptual design of a scaffold, showing a planar scaffold before folding (top) and after folding into three dimensions (bottom). The hinges may be made of the same material as the plates as long as each hinge's thickness and length are chosen to enable the desired folding architecture.

compatible with self-folding, in which biodegradable, biocompatible actuators integrated into the scaffold sheet itself drive the 1DOF folding with no contact with external actuators at all.

The research takes a multi-pronged approach to meeting the challenges of origami-based tissue engineering. Section 3 describes the design of candidate fold patterns that replicate the hexagonal structure of a liver lobule while maintaining few DOFs. Section 4 presents the concept and initial demonstrations of the proposed self-actuating polymer system for origami-based tissue engineering. Section 5 presents finite element analysis of the proposed polymer actuator system for a simple, well-controlled model system (the Miura fold). The Miura fold's well-understood architecture enables these models to highlight the mechanisms by which self-actuated folding can deviate from the design intent. Finally, Section 6 shows results to date on self-folded systems implemented in the target biocompatible polymer material system.

3. Candidate Fold Architectures

Figure 2 illustrates one candidate crease pattern for a group of lobules, as well as a photograph of the resulting folded structure implemented in paper. The pattern offers a hexagonal symmetry in each repeating unit, as well as the ability to tile multiple units together in a single sheet. The resulting folds form an approximately spiral structure, in which a radial inflow pattern is combined with a circumferential element. The hexagonal-spiral design is not a single-DOF structure like the idealized Miura-ori, but when facet bending and other real-world nonidealities are considered, it does have a single well-defined low-energy path in phase space from the unfolded to the folded state, which gives the same behavior as a single DOF: it folds easily in a single smooth motion. The proposed pattern deviates from biomimetic liver lobule structure in several ways. First, the spiral channels result in a longer flow length from the peripheral entry vessels to the central exit vessels. Second, the spiral folds are naturally wider at the periphery than near the center, unlike the more uniform dimensions of the vasculature in liver lobules. Third, liver lobules achieve these more uniform dimensions by increasing the number of vessels at larger distances from the

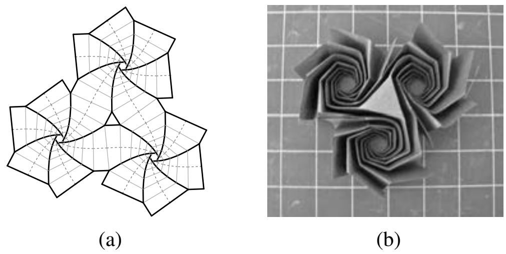

FIGURE 2. (a) Crease pattern and (b) paper demonstration of the hexagonal-spiral fold architecture.

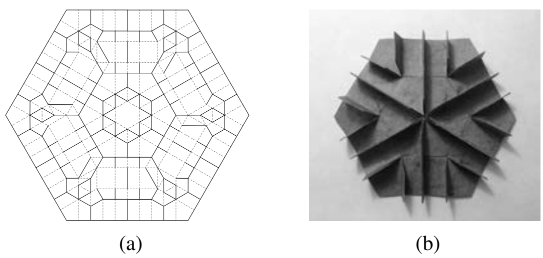

FIGURE 3. (a) Crease pattern and (b) paper demonstration of the hexagonal-radial fold architecture.

lobule's center; the multiplication of vessels at larger radii is not included in the present fold pattern.

Figure 3 illustrates a second candidate crease pattern that allows radial flow through fixed-size channels, so that both the flow and sidewalls are purely radial, like those of a natural lobule. This pattern scales naturally to larger diameter, adding more sidewalls and more channels while keeping the channel size approximately fixed. This property is visible in the figure: The innermost ring contains 6 sidewalls, and the next ring contains 18; subsequent rings would add sidewalls linearly. Though this architecture more closely approximates that of the original lobule, this particular design does not yet have a smooth, low-bending-energy path from the unfolded to the folded state (unlike the hexagonal-spiral architecture). However, the concept has considerable potential for further development.

4. Self-Actuating Polymer Scaffolds

Choosing a material system for the self-actuated origami scaffold is nontrivial. The materials must be biocompatible to avoid harming the cells of the tissue or of the recipient of the tissue. Ideally the scaffold will biodegrade over time, leaving the cells to carry on the initial structure provided by the scaffold. The byproducts of biodegradation also must be biocompatible. The patterned scaffold must be able to withstand sterilization (increased temperature and pressure); be patternable by molding, printing, or lithography to define the necessary microscale tissue features; and have material stiffness and flexibility that enables folds of up to 180°. Finally, it must be possible to implement self-folding actuators in the material system.

A diverse range of biocompatible, biodegradable polymers has been created for medical applications and tissue engineering [Chen et al. 13]. This research is using members of the poly(polyol sebacate) (PPS) family of biocompatible polymers as the basic scaffold material, with an initial focus on poly(glycerol sebacate) (PGS). PPS polymers have stiffness ranging up to 0.38 Giga-Pascal (GPa, where 1 Pa = 1 N/m^2) and failure strains ranging from 10% to 200% [Chen et al. 13]. The PGS synthesized in our laboratory has a Young's modulus (measure of stiffness of elastic material) of around 6.3 MPa and a failure strain of approximately 12%. The members of the PPS family are generally well studied and can be patterned in the prepolymer stage. They are chemically cross-linked polymers, and the byproducts from the degradation process are absorbable by the human body through metabolic processes. For comparison with the material properties, typical paper has a stiffness of a few GPa [Carson and Worthington 52] and thickness in the range of 50–100 μm; this suggests that PPS polymer sheets in the tens to hundreds of micrometer thickness range also have the potential to be origami folded.

Self-actuating origami scaffolds are implemented for this application by polymer bilayer actuators. One layer of the bilayer actuator is the basic PGS polymer. The second layer is polysuccinimide (PSI). PGS is essentially stable in water-based liquids, whereas PSI undergoes hydrolysis in physiological buffer solution, resulting in the formation of poly(aspartic acid) (PAA). The hydrolysis reaction causes an extreme volume change, with measured isotropic expansions of approximately 500% when cross-linked with 1,4-diaminobutane in 0.5 M imidazole buffer solution, consistent with literature reports of expansion of up to 600% [Zakharchenko et al. 11]. This cross-linked PSI has a measured Young's modulus of approximately 57 MPa and a measured failure strain of 9% in the unswollen state. When PSI is fabricated in a bilayer setup with PGS, the swelling of PSI creates powerful stresses that drive bending of the bilayer, potentially enabling folding of over 180°. The majority of the swelling reaction takes place in the course of 24 hours. It is therefore possible to first microfabricate the scaffold, then use directed assembly to locate the cells in their proper locations on the tissue scaffold (a process that takes 3–5 minutes) [Agarwal and Livermore 11], and finally permit the swelling of the PSI to fold the cell-seeded scaffold over the course of the following hours.

One of the first experiments tested the bilayer actuator behavior of the PSI/PGS combination. The concept is similar to the experiments of [Zakharchenko et al. 11], but the nonexpanding polymer is PGS rather than polycaprolactone. First, a PSI layer (0.7–1 μm) was spin-coated on a silicon substrate, followed by a PGS layer (several μm). A piece of the silicon substrate was then placed in deionized water. The resulting expansion of the PSI enables peeling of the bilayer, and the peeled material immediately forms into rolled tubes with radii of approximately 2 mm. The tubes are resistant to unrolling, indicating that the rolled structures reflect an equilibrium position for the intended bilayer bending.

Although fold patterns as in Figures 2 and 3 are potentially suitable for replicating the structure of liver lobules, the self-actuating folds are first designed and implemented in a simpler Miura fold. Because the Miura system is well-understood, the success of the self-actuated folding will be able to be readily assessed by comparing simulated and experimental results with expected folding outcomes.

5. Simulated Scaffold Self-Folding

In concept, the tissue scaffold should be designed with the geometry that best facilitates self-folding into the appropriate fold architecture. In practice, the scaffold's geometry

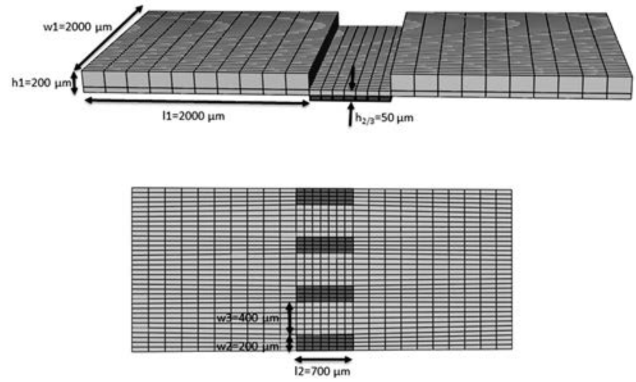

FIGURE 4. Two-rigid-plate system prior to folding, showing structure meshed in Abaqus.

is limited to structures that can readily be fabricated by casting from a mold to replicate the mold's geometry.

Given the microfabrication constraints, the scaffold design comprises thicker, more rigid plates connected by thinner, bilayer hinges. The thinner hinges help to localize the bending in the desired crease regions by reducing their stiffness relative to the more rigid plates. PSI is patterned on one or the other side of each hinge to ensure that it folds in the as-designed direction. The structures are simulated in ANSYS Parametric Design Language (ANSYS APDL) and in Abaqus. Two stages of simulation are carried out. In the first stage, qualitative simulations based on estimated material properties are executed to guide the design concept. A second stage of modeling utilizing experimentally determined material properties is then carried out to finalize the design parameters.

As an initial test of the simulation approach, a simple, two-rigid-plate system with one hinge is studied (Figure 4). The rigid plates and the top layer of the hinge consist of PGS, which is illustrated as a lighter layer. The bottom layer of the hinge is coated with strips of PSI, which is illustrated as a darker layer. When the strips of PSI undergo hydrolysis in physiological buffer solution, the PSI forms PAA, expands, and forces the hinge to bend. The hinge bending is driven by multiple parallel strips of PSI rather than a single uniform layer to minimize bending along the direction of the crease while driving bending perpendicular to the crease. Fixed boundary conditions are placed over 90% of all nodes of the first rigid plate. When the PSI expands, the hinge then bends upward like a cantilever beam, causing the second rigid plate to flip over the first rigid plate.

Each rigid plate has an area of 2000×2000 μm and a height of 200 μm. The hinge is 700 μm long and 2000 μm wide. Each layer of the hinge is 50 μm thick. In the future, hepatic cells will be patterned on the bottom of the rigid plates and endothelial cells will be patterned on the top of the rigid plates (Figure 1), and the hinges will be perforated to allow flow to cross the hinge region. The simulation omits these second-level features, focusing solely on the bilayer scaffold structure.

The models are manually meshed to ensure that the highly deformed hinges have a denser mesh than the nominally rigid plates. The nonuniform mesh decreases the computation time for the models and minimizes the required number of nodes and elements for the simulation. The simulation approach is constrained to use a mapped quadrilateral

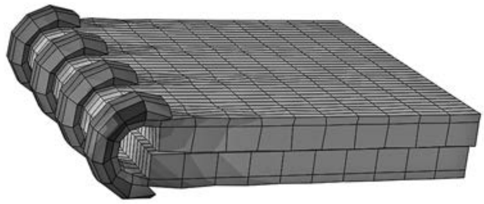

FIGURE 5. Final configuration of the folded two-rigid-plate system simulated in Abaqus.

mesh. In order to avoid triangular transitions and cylindrical inflation, all discretization must spread out like a wave in all directions.

PSI expansion due to hydrolysis is not directly replicated in ANSYS or Abaqus. To create an equivalent mechanical result, the isotropic expansion of PSI in buffer solution is instead modeled as thermal expansion. The thermal coefficient α of PGS is set to zero so that it does not expand when the temperature is increased in the simulation; this mimics the stability of PGS in buffer solution. The thermal coefficient α and the temperature change ΔT together determine the engineering strain ε of the PSI if it were able to expand freely, as described in the following equation:

$$\varepsilon = \alpha \cdot \Delta T.$$

The expansion generates a residual stress σ in the PSI. For the case in which expansion effects may be approximated as uniaxial, residual stress is determined by the Young's modulus E and the engineering strain ε as follows:

$$\sigma = E\varepsilon = E\alpha\Delta T.$$

The residual stress is partially relieved by bending of the bilayer hinge. The simulation gradually increases the PSI's $\alpha \cdot \Delta T$ product, equilibrating the mechanics of the system at each stage until the target PSI expansion has been achieved and the system is in its final configuration.

Because the displacements are large, nonlinear simulations must be used instead of linear simulations. The nonlinear simulations permit displacements of the plates and hinges in the horizontal direction (along the axis of the neutral plane); linear simulations would not allow this key functionality for simulating 180° folding. For the case of Figure 4, a strain of 0.4 causes a folding of around 180°. The folded two-rigid-plate system is illustrated in Figure 5.

The simulation results of Figure 5 predict that folding will be successful when the actuating bilayer is patterned as a set of stripes oriented perpendicular to the fold. Simulations were also carried out with the bilayer patterned along the full length of the crease, so that actuating elements on the hinge are wider than they are long. In this case, the forces developed along the width cause a distortion, including some bending of nominally rigid plates. The thickness of the rigid plates serves to minimize this distortion, but distortion remains. Although actuation with a bilayer patterned along the full length of the hinge may be of interest for the creation of nondevelopable folding surfaces, it is not useful for the present designs.

Figure 6 shows results from a more-complex simulation of a system of nine angled rigid plates. This underlying crease pattern is a 77.5° Miura-ori [Miura 94], in which the creases have been expanded to allow the hinges to bend and holes have been added at the

(a) Side view, unfolded (b) Side view, folded (c) Top view, folded

FIGURE 6. Final configuration of the Miura-fold system with nine angled rigid plates connected by hinges, as simulated in ANSYS.

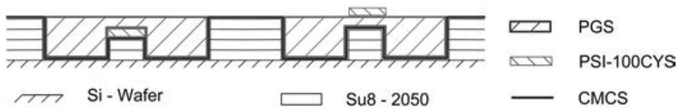

FIGURE 7. Conceptional sketch of the microfabrication process.

vertices where folding takes place in two directions. The holes minimize stretching, stress, and unwanted folding behavior at the vertices.

Figure 6 shows the Miura fold after actuation of the bilayer hinges. The constraints of the multilayer folded structure limit the final fold angle. The structures of Figure 5 achieve nearly 180° folding, whereas the Miura fold does not. The limited folding reflects the finite size of the hinges. For optimal folding, the lengths of the hinges need to be shorter for the inner layers than for the outer layers; this feature is being integrated into subsequent designs. Additionally, the plates of real polymer systems may experience adhesive contact during folding, which may affect the final folded geometry. The effects of interactions such as adhesive contact are best assessed through experimental demonstrations.

6. Experimental Scaffold Self-Folding

A polymer replication process is used to create the scaffold from a master mold. To create the master mold, a silicon wafer is first spin-coated with four layers of SU-8 epoxy (MicroChem Corp.). The SU-8 is patterned using photolithography to create a pattern of raised and lowered regions on the wafer surface; the heights of these regions will define the thicknesses of the hinges and plates, respectively. Details on microfabrication may be found in [Madou 02]. A thin release layer of carboxymethylcellulose sodium (CMCS) is coated over the surface. The CMCS is biocompatible, biodegradable, and water soluble. The polymers (first PSI in liquid, then liquid PGS prepolymer, then PSI in liquid) are applied to the master pattern and cured to form a solid. The PGS's upper surface is planar with the highest SU-8 feature, thereby creating 200 μm thick plates and 50 μm thick hinges (see Figure 7). The CMCS is then dissolved in water to release the scaffold.

When immersed in buffer solution, the hinges bend away from the PSI to accommodate the PSI's expansion. By patterning a first layer of PSI into the mold before the PGS is applied, and by patterning a second layer of PSI on top of the PGS, hinges that fold in either direction may be created. The PGS is cured prior to the addition of the final layer of PSI. Prior to its application onto the hinges, the PSI must be chemically cross-linked so that it will swell when it is exposed to buffer solution. Various chemicals may be used to chemically cross-link PSI, including cystamine dichloride (CYS) and diaminobutane (DAB). Additionally, the use of different physiological buffer solutions (e.g., phosphate

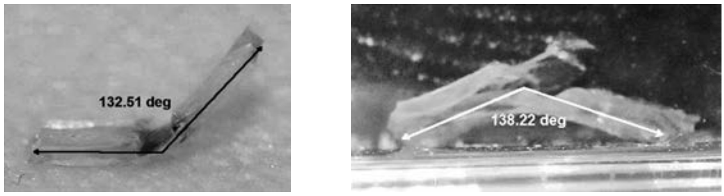

FIGURE 8. Manufactured two-rigid-plate system (a) before actuation of folding and (b) after actuation of folding.

buffer or imidazole buffer) will produce different expansion rates and times. The expansion can therefore be tailored to specific needs by adjusting the chemistry of the polymer bilayer actuator.

To demonstrate that folding is possible with a biocompatible, biodegradable tissue scaffold, a simple system comprising two rigid plates connected by one hinge was created, similar to the concept design in Figure 4. For simplicity in this first design, a single layer of PSI was applied to the full length of each hinge rather than in stripes along each hinge as shown in Figure 4. Applying the PSI expansion layer to the entire hinge area as in this example rather than to localized stripes can in principle result in distortion. The effects of the distortion are minimized in this case by the simplicity of the two-plate design and by the thickness of the plates.

For the present experiments, the synthesized PSI was cross-linked with diaminobutane, which produces a swelling of approximately 500% over 24 hours. In this first demonstration, the scaffold was first released from the mold, and PSI was applied to the hinge with a syringe. As the PSI solidifies from a liquid into a gel, it undergoes a volume shrinkage, causing the hinge to bend opposite from the desired actuation direction. The initial bending angle is therefore $-47°$. After the bilayer hinge structure is immersed in imidazole buffer for 12 hours, the bending direction reverses to a final angle of 42° as shown in Figure 8. The bending angle of the polymer bilayer actuator is therefore measured at 89°. In the present case, the fold angle is limited by adhesion between the PGS and PSI layers; after 89°, the PSI begins to delaminate from the PGS, limiting its ability to drive further folding. The 89° folding shown here is not a universal property of the system. For example, improved adhesion between the PGS and PSI layers, thinner hinges, and greater degrees of PSI expansion may all increase the fold angle, whereas thicker hinges or lesser PSI expansion may decrease the fold angle.

7. Conclusions

A new approach to engineering complex human tissues through a combination of directed cell assembly and origami folding of a two-dimensional scaffold is described. Two new fold patterns are presented as candidates to replicate the geometry of the target tissue (liver) in a 1DOF design that permits folding of the tissue scaffold with minimal contact and minimal potential for contamination. Modeling of the basic polymer system is presented, including results that validate a design in which actuation is driven by stripes of a bilayer actuator that runs perpendicular to the crease direction. Finally, an experimental demonstration of bilayer actuation in the proposed biodegradable, biocompatible system is presented, demonstrating that the present approach can be suitable for passive self-folding of an origami scaffold.

Acknowledgments

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Wearable Metal Origami

Tine De Ruysser

1. Introduction

The art of paper folding has possible applications in design and engineering, but paper itself is often too weak as a material for real-life applications. Durable materials that can be folded with the intricacy of origami patterns are needed but not easily available. This chapter describes one way of making a textile-metal laminate, developed especially for the creation of tessellating origami structures. The material draws upon the knowledge of various design fields and is suitable for the creation of different types of objects. It is particularly relevant to jewelry for its visual character, its flexibility (almost organic movement that easily adjusts to the human body), and the possibility to use precious metals.

2. Context

Folding and pleating are well-known techniques applied within fashion and textiles. They have been used through the centuries to make fabrics drape elegantly on the body. *Folding* in this context is used to describe how folds are pressed into the fabric to make them more permanent. This process is more commonly referred to as *pleating*. The pleats are kept in shape by heat-setting or locally stitching the pleats together in a technique called *smock*. Sometimes the result is a textile version of origami. Several artists have used this to create textile origami pieces. Chris Palmer has described how to fold fabric into tessellating origami patterns [Rutzky and Palmer 11]. Matthew Gardiner makes moving origami "robots," which use pleated polyester textiles and ingenious mechanisms to provide movement [Gardiner 15]. However, the material described in this work has stiff, metalized areas that create a different sort of movement and unique appearance. The way the material moves on the body is more like chain mail or deployable structures. Illan Garibi makes metal origami in both small and large panels by etching metal sheets [Garibi 15]. These stunning pieces do not remain flexible like wearable metal origami (see Section 7).

3. History

The development of this material started 16 years ago and came about for practical reasons: as a jewelry designer, I had discovered a tessellating origami pattern (Figure 1), and I wanted to make it in a material suitable for the creation of jewelry.

I developed two solutions:

The first one, stitching a layer of plastic or paper in between two layers of fabric, allowed me to construct clothing with one layer and to permanently attach an accessory with the other layer. The stitching was done with a computer-aided embroidery machine,

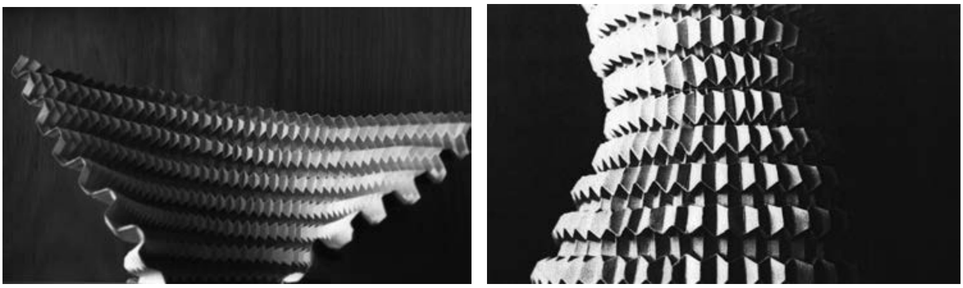
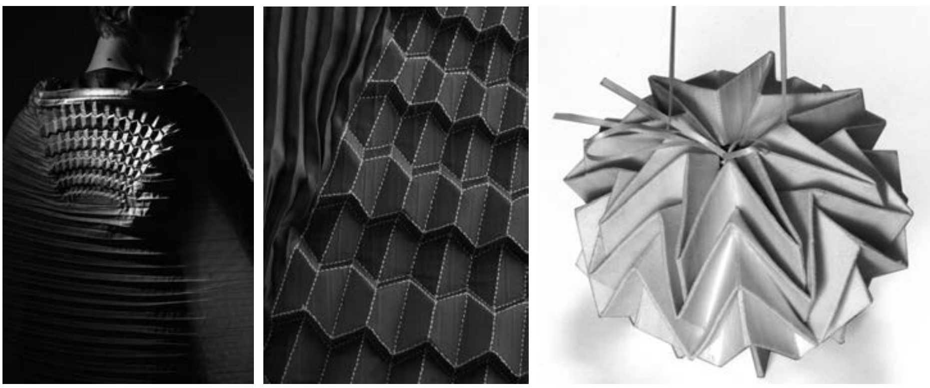


FIGURE 1. Paper structure at the basis of Wearable Metal Origami (1998).



(a) (b) (c)

FIGURE 2. Origami pattern applied to clothing and accessories through stitching paper in between two layers of textile. (a) Dress with scarf (2001), and (b) detail of stitching (2001). (c) White Bag (2002) made on sewing machine.

with the aid of textile technicians at the Royal College of Art in London and the Textile Museum in the Netherlands (Figure 2(a,b)). This combination of stitching and folding was continued in a range of bags and objects, made by hand on a regular sewing machine (Figure 2(c)).

The second solution was more appropriate to the purpose of making jewelry, and the method that was the basis for further research. It consists of a layer of copper platelets applied to a piece of fabric, creating a material that looks like copper, yet can fold on the bare textile folding lines (Figure 3). This is done through the process of electroforming.

4. Electroforming Fabric for the Creation of Metalized Folding Textiles

Electroforming is an electrochemical process in which a layer of metal is deposited on an object. To make this possible, the object is made electrically conductive and is suspended in a solution containing metal particles (Figure 4). An electrical current is run through the solution and the object, so that the metal particles in the solution move toward the object and adhere to the surface. A metal layer forms, and the process continues

(a)

(b)

FIGURE 3. Early work in electroformed textiles (2001). (a) Sample and (b) bag, copper on black fabric.

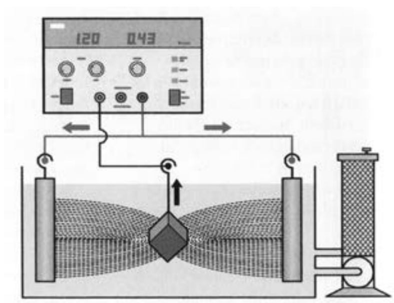


FIGURE 4. The electroforming process [Curtis 04].

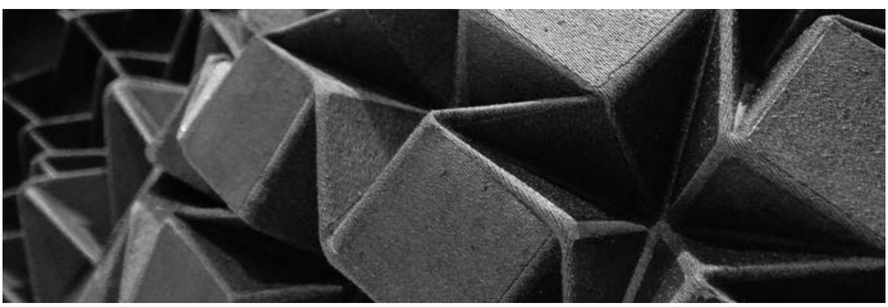
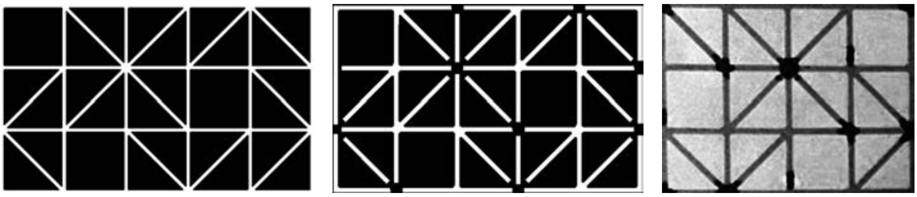


FIGURE 5. Electroformed platelets on textile, with bare fabric hinges.

until the desired thickness is achieved. This process is mostly used on a mold, which is completely covered and later removed so that a metal piece remains.

In contrast to the traditional method, I only applied metal to certain areas of a piece of fabric, and I left the fabric "mold" in place. This allowed me to recreate tessellating origami patterns, with bare fabric hinges for the folding lines and stiff metalized platelets in between (Figure 5). This laminated fabric is called *Metalized Folding Textile* (MFT).

To allow the build-up of metal platelets, the fabric has to be made locally conductive, according to the chosen folding pattern: Platelets have to be conductive on the surface of



(a) (b) (c)

FIGURE 6. (a) Folding pattern is drawn; folding lines are given a certain width. Black areas will be printed in conductive ink, so metal can adhere there. (b) Connections are drawn, so that an electrical current can run through each platelet. (c) Connections are covered with a lacquer to prevent metal from building up in these places.

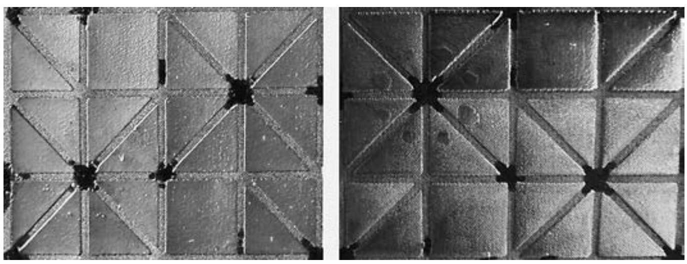


FIGURE 7. The fabric with metal platelets after electroforming, front (left) and back (right).

the fabric; folding lines should not be conductive. The process described here is one of many processes tested, and even though it was the first, it still gives the best results. The chosen images are of a square, "boxy" pattern, but the same principle can be applied to any folding pattern. Fabric is stretched over a frame, which will keep it flat when it is submerged in the solution. Conductive ink is applied where the platelets will be through screen-printing or spray-painting with the aid of a stencil. In both cases, the same basic pattern is drawn (Figure 6(a)). To enable the current to run through all platelets, they have to be electrically connected, so connections are added to the drawing (Figure 6(b)). The pattern is then transferred onto a silk-screen and printed with conductive ink; or, a stencil is cut from self-adhesive vinyl, and the ink is applied with an airbrush through the stencil. The connections between the platelets should not have any metal build up, or the hinges will not be foldable. So, they are covered by hand with a layer of lacquer, which forms a protective layer that cannot be penetrated by the solution (Figure 6(c)). This lacquer is applied to both sides of the fabric.

The fabric is then wired up to electric cables and submerged in the electroforming solution, and a current is sent through it until a metal layer of chosen thickness is achieved (Figure 7).

The fabric is removed from the frame, and the cables and lacquer are removed. Now the material can be folded into shape (Figure 5).

Most of my work is made in copper for practical reasons, but it is possible to use silver or even gold instead.

(a) (b)

FIGURE 8. Shoulder cape (2009), boxy pattern, (a) when on a flat surface and (b) taking the shape of the shoulders of the wearer.

5. Working with Metalized Folding Textile as a Material

5.1. Weight and support. Folded paper is very light, and most types of paper keep their folded shape well. In contrast, MFT is quite heavy because of the metal parts, and the textile does not have a good capacity for keeping its shape. Some folding patterns in MFT will remain folded more easily than others. The first pattern I designed (Figures 1 and 3) keeps it shape well under normal gravitational forces and only unfolds if extra forces are applied through pushing or pulling on the fabric. Boxy patterns will not remain folded unless extra support is given. All patterns need extra support if they are used for the creation of wearable pieces, or pieces that will be handled by non-origami experts. Mostly, it is sufficient to add a few stitches to critical locations to keep the patterns folded. Sometimes the weight and chosen pattern work together for a wearable piece to shape itself to the body of the wearer (Figure 8)

5.2. Metal thickness. The platelets have a certain thickness, greater than that of the average paper. It varies depending on the size of the platelets (larger platelets need to be thicker to remain stiff; smaller platelets need less thickness) and on the location of the platelets in the whole pattern (platelets closest to the electric cables in the electroforming tank build up a thicker layer than those further removed). Even though the thickness is generally never more than 0.8 mm, it still means that even flat-foldable patterns can create considerable thickness in a folded piece. To ensure the pattern folds well, the hinges are given a width of at least twice the thickness of the platelets (Figure 9).

5.3. Metal stiffness. Paper can bend slightly, whereas metal platelets have no such flexibility. They behave like rigid origami: rigid plates connected by hinges [Tachi 09]. Certain tessellating folding patterns rely on the flexibility of paper to go from unfolded to folded state. For these patterns, extra folding lines have to be added in the pattern of MFT to allow for it to be folded like rigid origami (Figure 10).

5.4. Edges. Because MFT has a textile core, extra care needs to be taken to the edge-finish (Figure 11). If all surrounding fabric is removed, this has to be done neatly and in such a way that the risk of tearing is kept to a minimum. For copper electroforming the most suitable choice of textile is polyester because the electroforming solution does not corrode it. The extra advantage is that it can be cut with a hot tool, so that the fibers at the

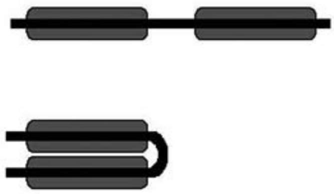


FIGURE 9. The width of the textile hinge is twice the platelet thickness to allow for folding.

FIGURE 10. The hexagons do not need creases to be folded in paper, but they need hinges in the location of the black lines to be foldable in MFT.

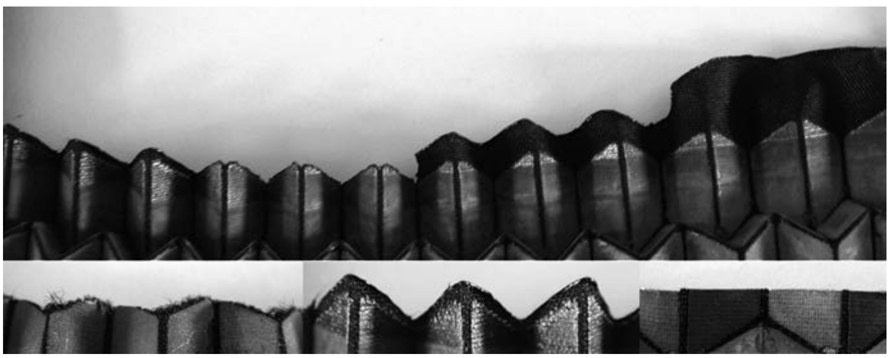


FIGURE 11. Different ways of finishing the edge (top) with close-ups (bottom). Copper on polyester fabric.

edge are melted together and do not fray. The distance to keep from the metal edge is an aesthetic choice, and for a really sharp edge it is even possible to cut through the metal.

5.5. Colors. Apart from the obvious color choices that can be made by selecting colored fabrics and the color of the chosen metal (Figure 12), there is also the option of coloring the metal surface. Both silver and copper can be chemically treated to change their surface color, although copper has a wider range of possibilities than silver. The entire surface can be treated to become one uniform color (often black) or to show a color pattern. By using stencils, selective coloring of certain platelets is also possible (Figure 13)

6. Designing with Metalized Folding Textile

The whole process of making MFT is time consuming, making the creation of pieces in MFT a costly process. For this reason, the design of the finished piece has to be well considered before it is executed in MFT. Critical for the design process is an understanding of how MFT behaves. As mentioned in the previous section, this depends on the specific characteristics of this material, but of course the folding pattern also takes a central role.

FIGURE 12. Three bracelets. Inside-out: copper, gold-plated silver, and silver.

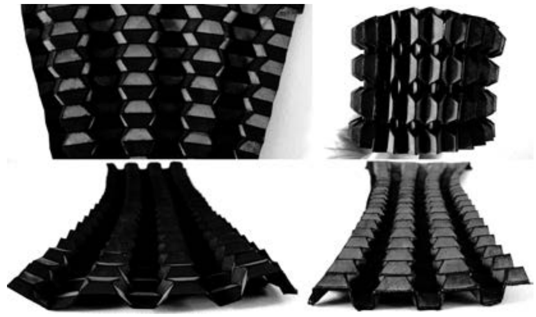


FIGURE 13. By coloring half the platelets, the material seems to change color when seen from different angles.

To understand the different aspects that influence the design process, they were each investigated separately.

6.1. Folding patterns. MFT is developed to transform tessellating origami patterns into wearable pieces that are more durable than paper. Both the shape-change from flat material to folded object and the shape of the folded object are important. An overview of how different patterns behave during the folding process was needed, so that a selection could be more easily made when I had a final design in mind.

When I started this process, useful tools such as the Rigid Origami software [Tachi 09] were not available, so most expertise was built by experimenting with paper and through reverse-engineering the patterns of images I found on the internet [Flickr 14].

All folding patterns were classified based on their crease pattern into groups and mapped out on a family tree (Figure 14). The classification is made on the appearance of the folded model and on how the material moves from the folding pattern to the folded model. Yet, the descriptions on the tree are based on the folding pattern because this is the clearest way of defining them: it is hard to distinguish between two folded models with minor differences, but their folding patterns show differences in angles and size of platelets more easily.

6.1.1. *Accordion models.* These behave like an accordion: the simplest would be a row of parallel folding lines, equal distance apart, alternating valley and mountain folds. All accordion folds have a set of long straight lines running through them, often from one edge of the paper to another, dividing it into strips. They are most useful for objects that need extreme size change or great flexibility. This group can be subdivided in different subcategories. I will describe the different steps as grades (°), following the example of Ray Schamp [Schamp 14]. The first subcategory is whether the straight lines of the first grade (1°) that create a simple accordion when folded are parallel or not and, if they are not parallel, whether they all fan out from a single point or from several points (Figure 15).

This will determine whether in a given pattern the platelets will be the same size throughout the whole piece or whether they will gradually increase and decrease in size.

The second grade (2°) is formed by zig-zag creases going across the first grade creases. This determines whether the pattern will fold into a flat or curved surface—or a combination of both (Figure 16).

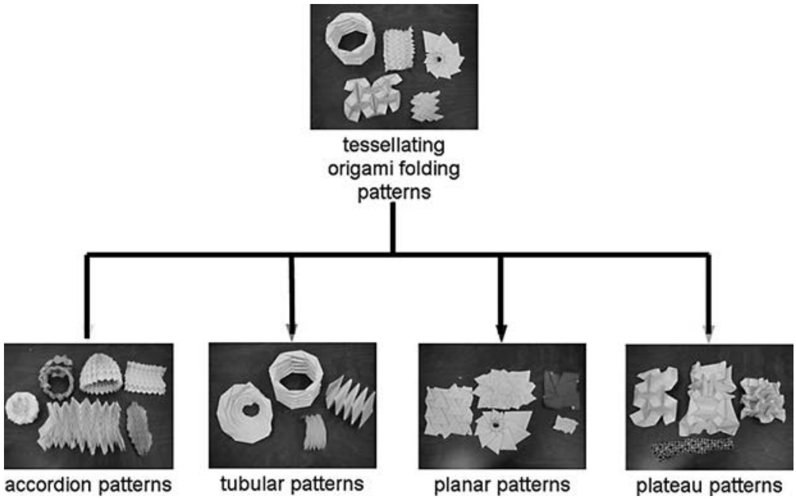


FIGURE 14. Division of tessellating origami patterns in main groups. Each group is further divided.

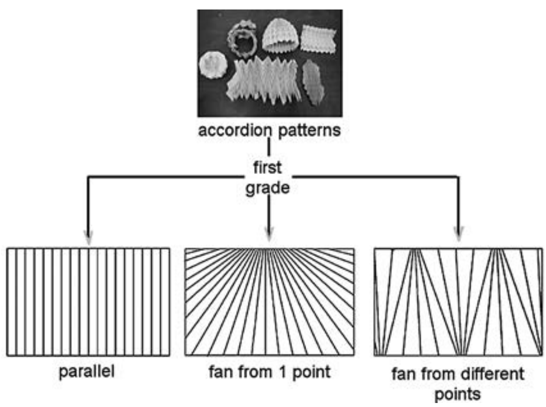


FIGURE 15. First grade division of accordion patterns.

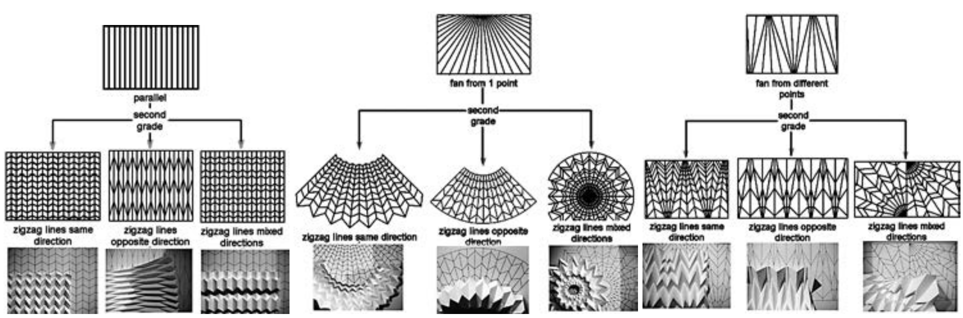


FIGURE 16. Second grade division of accordion patterns.

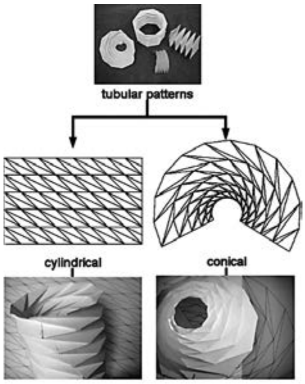


FIGURE 17. Tubular models.

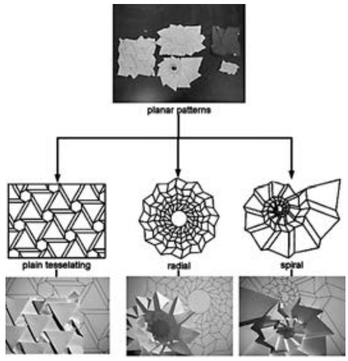


FIGURE 18. Planar models.

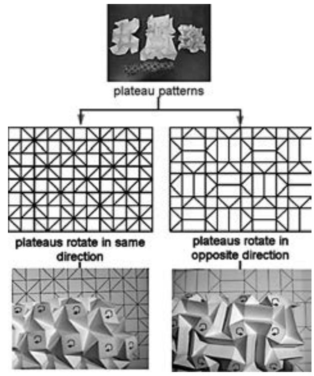


FIGURE 19. Plateau models.

6.1.2. *Tubular models.* This group of patterns (Figure 17) distinguishes itself from the others in that the two sides of the folded material are fixed together to form a tube in both unfolded and folded form. The tube can be cylindrical or conical in shape. These patterns are most useful for making a tubular object collapse into a shape with roughly the same circumference but diminished height, or for creating a design that converts from a flat sheet to a tubular object and back again. Cylindrical patterns are also a subgroup of the accordion models.

6.1.3. *Planar models.* This group (Figure 18) consists of tessellations of clearly recognizable geometric forms, fitting together like Arabic decorations. They are true flat-foldable patterns: The models fold flat into a plane. This group is subdivided depending on whether the tessellated units are all of the same size or if they increase in size as they rotate around a center to form concentric circles or a spiral pattern. Planar models are useful for decreasing the plane of visible area when the object is folded, without creating too much thickness. Unlike the other groups of patterns, they do not curve flexibly in the folded state.

6.1.4. *Plateau models.* This group (Figure 19) resembles the planar models because they are also constructed of tessellating units of geometric forms. They are not flat-foldable but have platelets (plateaus) that rise up to a higher plane, or sink to a lower plane, while the platelets in between form walls perpendicular to the plateaus. This way, a sort of box is created by each of the units, explaining why these patterns are often called *boxy patterns*. Plateau folds create visual depth, and the empty spaces inside the boxes can be used to set stones without hindering the folding. When partly folded, they form spherical shapes, returning to a flat surface when fully folded.

6.1.5. *The use of the family tree.* The family tree makes it possible to quickly develop a pattern for a specific application based on the shape it should be and how it should move. This is done by finding a pattern in the tree that behaves more or less like the one needed and then adjusting it to make it behave exactly as wanted. This reduces the time spent on the trial-and-error process of developing a new pattern.

As more folding patterns are created both by others and me, I keep on discovering new aspects and relationships. The family tree described here is not a final version; it will be adapted as my understanding of the behavior of folding patterns deepens.

FIGURE 20. One of the first samples for a model-making material: laser-cut veneer glued on textile.

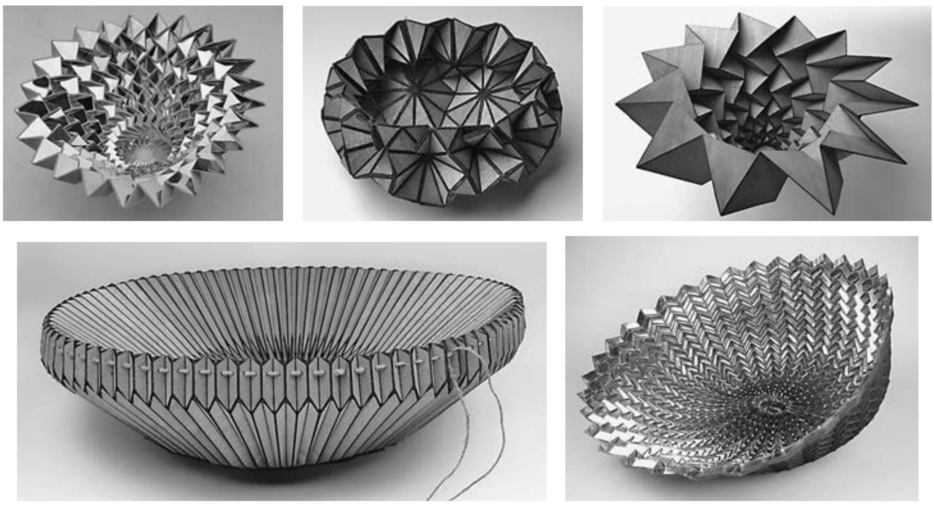


FIGURE 21. Various decorative objects made in textile-plywood, textile-mirror foil, or textile-flock foil laminates.

6.2. Sample materials. Folding paper samples is effective for determining the crease pattern needed. But, as described above, MFT behaves differently from paper because of its weight and the flexibility of the hinges. New model-making materials were developed to more accurately mimic the behavior of MFT. These new materials also consist of a textile base layer and have platelets of different materials applied. The platelets can be laser-cut or cut with a vinyl cutter, and then they are glued onto the fabric (Figure 20).

These new materials are very useful for the design process for MFT. On top of that, they are beautiful in their own right and can be used to create autonomous decorative objects (Figure 21).

7. Wearable Metal Origami

Wearable pieces can be made in Metalized Folding Textiles. A few examples of the most successful pieces made in MFT so far are shown in Figures 22–25.

8. Conclusion

The MFT material is suitable for the creation of a range of applications, especially for jewelry, wearable pieces, and decorative "tableware" objects. It could only be developed

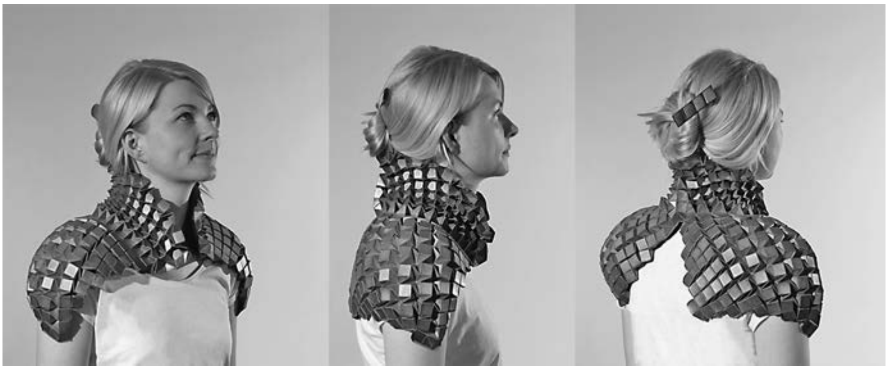


FIGURE 22. Shoulder cape.

FIGURE 23. Silver bracelet.

FIGURE 24. Design for a dress.

FIGURE 25. Bracelet that can be converted into a carrier bag.

through a multidisciplinary approach, revolving around tessellating origami and incorporating printing, electroforming, design methodology, and CAD drawing, as well as the study of material properties and existing folding and flexible structures. All this knowledge is currently brought together in one person, and collaborations with experts in these specific fields would carry it a lot further.

MFT is still difficult to produce, and its use will remain limited to unique art pieces unless the production process can be improved and scaled up. For this, experts in printing and the electroforming process are needed. For the creation of wearable pieces, further knowledge of fashion and textiles should be explored. And last but not least, to expand the range of shapes and applications, further development in knowledge of folding patterns is needed.

This can partly be gained through the use of available software [Lang 14, Tachi 14], but it would improve even more through collaborations with origami experts.

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The Kindergarten Origametria Program

Miri Golan and John Oberman

1. Introduction

The Kindergarten Origametria (KO) program (KOP) is a program to train kindergarten teachers to work with the geometry curriculum of the Israeli Ministry of Education, using origami as a learning tool. The program uses the imagination of kindergarten-age children (aged 4–6 years) as the focus of the activity, involving them in a series of creative folding activities that acknowledge their limited motor skills. The KOP is a tool for the kindergarten teacher to make an activity in a creative environment that builds a strong mathematical base for the children.

The emphasis on imaginative play and experimentation as a means to learn, though common in many kindergarten activities, is historically uncommon as an approach to using origami as a learning tool, where teaching named models is the norm. In this way, the KOP may be considered an unorthodox approach to origami.

This chapter describes the progress of the KOP since the brief account of the pilot KOP eight years ago given in *Origami*[4] [Golan and Jackson 09].

2. Structure of the KOP Courses for Kindergarten Teachers

The first KO pilot course began in 2005. In 2010, the program was rewritten with supervisors from the Israeli Ministry of Education and with input from specialist teachers and professors of mathematics and mathematics education. To date (summer 2014), the KOP has been studied by teachers in 120 state kindergartens, mainly in Tel Aviv. The program is ongoing and will continue to expand in the foreseeable future, supervised and funded jointly by the Ministry of Education and by local departments of education in different cities.

Each course runs for a total of 30 hours, over eight sessions, spread over a period of several months. Each course accepts 20 kindergarten teachers (KTs). Each KT is required as part of her Terms of Service to undertake a minimum number of courses each year, and attending the KO course contributes to meeting this requirement. Some KTs choose to take the course, while others are recommended to participate by their supervisors.

The KO course divides into three parts:

(1) *Learning Topics of Geometry According to the Kindergarten Curriculum (10 hours):* The KTs are taught basic geometric knowledge, which many did not know, had forgotten, or had misremembered. They are taught the terminology and definitions they will need when teaching the KOP, and later, they are taught

additional terminology and definitions in advance of what they will need in order to feel they are teaching within their knowledge.

This knowledge is learned by folding, led by the teacher. The learning is thus folding-based and not lecture-based. During the process of folding, the geometry of the paper is described and analyzed by the KTs.

(2) *The Method of Using the KOP Activity in Kindergarten (12 hours):* The KTs are introduced to the method of how to conduct KOP activities (three sample activities are described below in Section 5). Between each course session, every KT introduces what she has recently learned as an activity in her kindergarten and reports back to the class on her experiences. They are encouraged to take photographs and to make short movies, to assist with the description of their experiences. Feedback is given by the teacher and other KTs.

(3) *Additional Geometric Information (10 hours):* The KTs are taught basic three-dimensional geometry (cubes, cuboids, and pyramids) and the relationships between members of the triangle and quadrilateral families (for the quadrilateral family, for example, the similarities and differences between a square, rectangle, rhombus, parallelogram, trapezium, and more).

The KTs are also introduced to the theories of Piaget [Piaget et al. 99], van Hiele [van Hiele 99, Crowley 87], and Vygotsky [van der Veer and Valsiner 91], regarding how children learn and how this is applied to the KOP.

After the course has concluded, visits are made by the course teacher to each KT's kindergarten to observe a KO activity and to help the teacher fine-tune her implementation of the program. It is important that with these visits the program is tailored to fit the individual circumstances of each kindergarten, not vice versa.

The KOP method is based on encouragement, curiosity, and learning through experimentation, allowing the children to play with their paper as an imaginative and fun activity. The geometric research undertaken by the children during the KOP activity develops strong mathematical thinking skills.

In the past year, the program has received input from Dr. John Oberman, PhD, MSc, DipEd, Director of Pre-service Mathematics Training, Shaanan Academic College, Haifa, Israel, who has helped relate the open-ended folding experiments undertaken by the children during the KOP activities to the kindergarten geometry curriculum.

3. Distinctive Contributions of the KOP to Geometric Education in Kindergarten

The KOP repositions origami as an activity that uses the imagination of young children aged 4–6 as the basis of the teaching method. This focusing of an activity around a child's imagination and on discovery through experimentation is not new in kindergarten education—indeed, it is the basis of well-established methodologies such as the Montessori and Steiner systems—but is an unorthodox use of origami, where teaching named models is the norm.

The KOP, along with many other constructing activities such as working with Plasticine and wooden bricks, helps with developing a child's imagination, fine motor control, spatial awareness, group work, and communication skills. However, there are two aspects to the KOP that may be considered distinctive contributions to geometry education in kindergarten.

(1) The KOP helps young learners differentiate between different polygons by asking them during the process of folding to count the number of corners and sides, to name different polygons, to intuitively recognize right angles in squares and

rectangles, and to create and identify simple mirror symmetry. These concepts are developed by asking the children questions such as, "What is the same and what is different with the shapes you have made?" or "Which shapes would you like to put together?" After discussions between the KT and the children, the formal language of geometry will develop as a need for communication. The children are not given knowledge or asked to learn definitions "by rote"; they are given methods to observe and explore, from which definitions can be deduced. This method, once learned and practiced, can be used at any time.

Many KTs report that after running the activity, the children from the group will teach other children in the kindergarten what they had learned, using correct geometric terminology.

(2) During the process of folding, the paper will change its shape many times: from a square to a rectangle, then perhaps to a triangle or hexagon, and back to a square. This continual process of creation, change, and re-creation allows the child to identify a polygon in different circumstances, at different rotations, and at different sizes. Further, at times the teacher will hold her paper deliberately askew and ask, for example, if her square is still a square. In this way, the children learn to recognize polygons in diverse and unfamiliar situations and thus gain a stronger understanding of the individual characteristics of the shapes.

4. Four Ways to Develop Creative Thinking

These four ways guide the structure of the KOP courses for kindergarten teachers and the approach of the teachers to their KO activities. They are based on the research of Guilford, Christensen, and Torrance [Guilford 67, Guilford and Christensen 73], [Torrance 80].

(1) *Fluency:* The ability of the child to make a few samples, cases, or situations within the limits of the task.
(2) *Flexibility:* The ability of the child to move from one way of thinking to another and to produce samples and solutions that relate to a different category.
(3) *Elaboration:* The ability of the child to expand their knowledge, to add detail, and to develop it in combination with other ideas.
(4) *Originality:* The ability of the child to relate to certain problems in a new way, in a different way, so he can produce unexpected situations.

5. Three Examples of KOP Activities

During their KO course, the KTs are taught twelve KOP activities that relate to different topics within the geometry curriculum. Here are three sample activities, described step by step. The full twelve topics can be found in the appendix (Section 8).

Activity 5.1 (Researching Squares and Rectangles).

(1) The KT gives a sheet of square origami paper to each child.
(2) The children count how many sides and vertices they can find and check the lengths and angles with a straight edge. (Usually a square of paper is folded in half, long edge to long edge, three times.)
(3) The KT asks the group to assemble the squares to make one big square (composition and decomposition). See Figure 1.

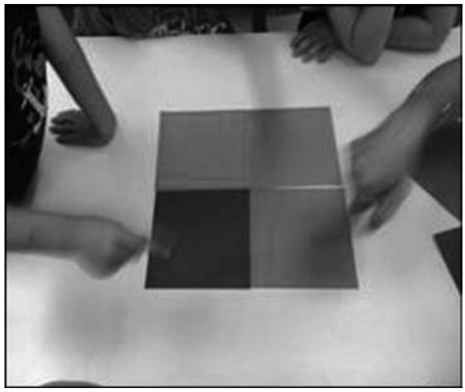

FIGURE 1. Children discovering the characteristics of a large square.

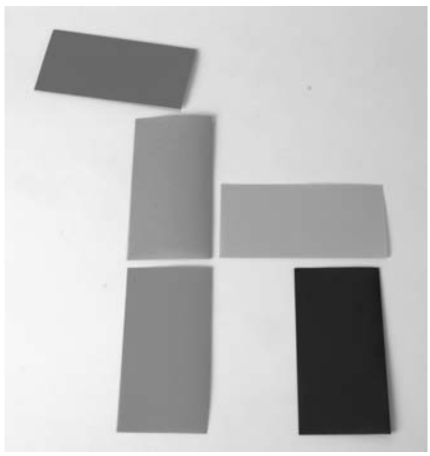

FIGURE 2. An example of an arrangement of rectangles made by a group.

(KT questions: Do all the squares always make a big square? What are the characteristics of the big square? These questions provoke much discussion and research about what is a square.)

(4) The KT shows the children how to fold the square in half to make a rectangle.
(5) She asks the children to count the number of sides and vertices and to measure the lengths of the edges.
(6) The children are asked to assemble the rectangles without overlapping to create an imaginative shape. See Figure 2.
(7) The KT asks each child what he or she can see in the arrangement, asking for a detailed description. (For example, if the answer is "a robot," the child is asked to show the arms, head, legs, etc.) Usually each child sees a different subject (robot, butterfly, spider, etc.).
(8) The KT asks the children what is the difference between a square and a rectangle and how many of these rectangles will make a square. (Note: It is recommended that before this KO activity, the KTs run activities that teach concepts such as *long* and *short*.)

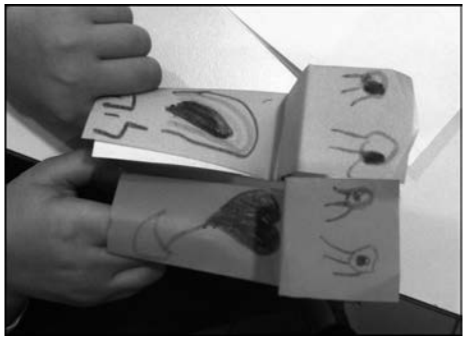

FIGURE 3. Children playing with their finished work.

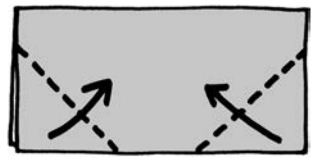

FIGURE 4. Activity 5.2, Step 2.

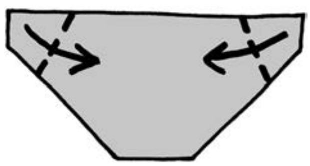

FIGURE 5. Activity 5.2, Step 5.

(9) The KT asks the children to fold a long side to the opposite side. The children again check the polygon.
(10) The KT asks the children to fold one short side to the opposite and parallel short side and to check the polygons that creates.
(11) The KT inserts her finger into the short side of the rectangle and asks each child what it is. The children draw on their own paper. See Figure 3.

ACTIVITY 5.2 (Defining and Finding Polygons).

(1) The KT begins the activity by repeating Steps 1–8 of Activity 5.1.
(2) The KT asks the children to fold back the open corners as shown in Figure 4. The position of the folds is not important.
(3) Turn over.
(4) The children count the number of edges and vertices and discover the shape of the paper is a hexagon.
(5) The children fold in the corners of the long edge as shown in Figure 5. Again, the position of the folds is unimportant.
(6) Turn over.
(7) The children fold back the corners to reveal white paper. See Figure 6.

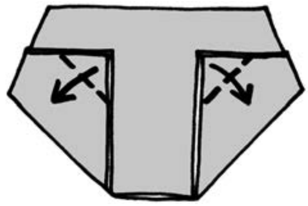

FIGURE 6. Activity 5.2, Step 7.

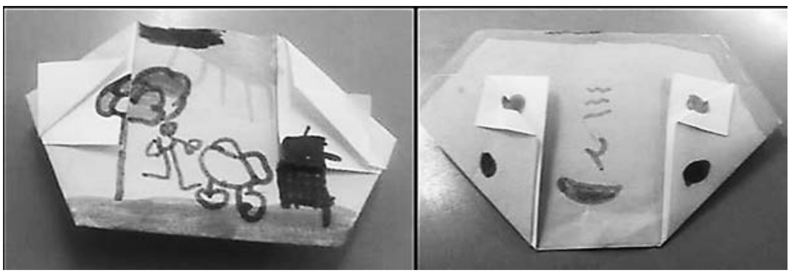

FIGURE 7. An example of how differently two children saw their finished work.

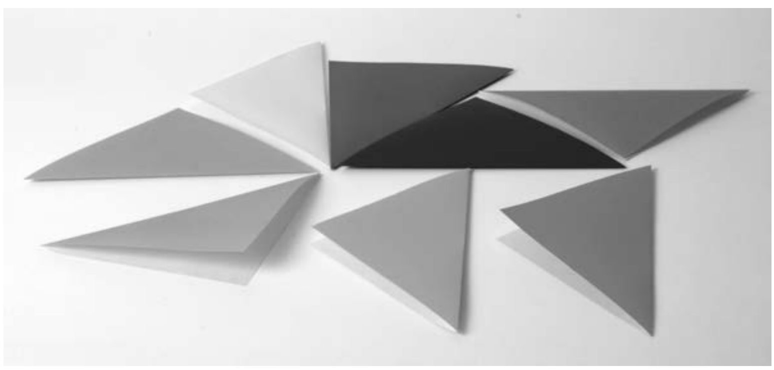

FIGURE 8. An example of an arrangement of triangles made by a group.

(8) The KT inserts her finger into the pocket and asks each child what it is. The children draw on their own paper. See Figure 7.

ACTIVITY 5.3 (Defining and Researching Triangles).

(1) The KT gives a sheet of square origami paper to each child.
(2) Each child folds the square in half, corner to corner, to make a triangle.
(3) The children are asked to assemble the triangles without overlapping, to create an imaginative shape.
(4) The KT asks each child what he or she can see in the arrangement, asking for a detailed description. See Figure 8.
(5) Each child takes back their triangle and checks with the KT how many sides and vertices it has.

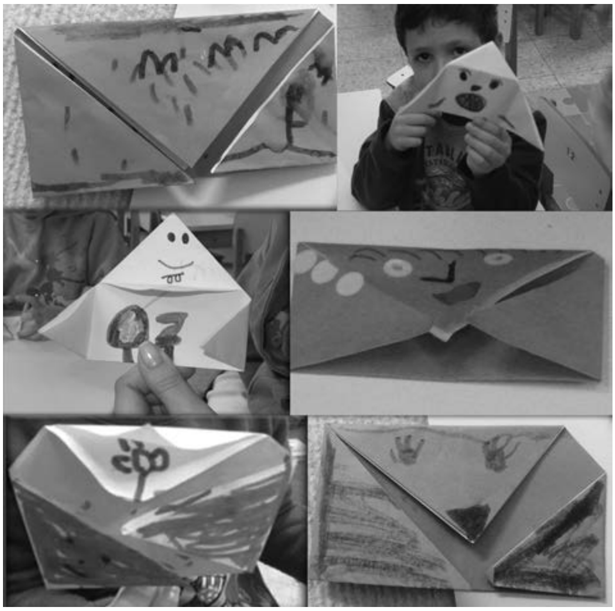

FIGURE 9. Collage of six examples of the same folded shape, perceived as different subjects by different children.

(6) The KT asks the children to try to make a big triangle from four individual triangles (composition and decomposition).

(*KT questions: Do the four triangles always make a big triangle? What are the characteristics of the big triangle?* These questions provoke much discussion and research about what is a triangle.)

(7) Each child takes back his or her triangle. The KT asks the children to fold vertex to vertex to make a smaller triangle and then to open the fold.

(8) The KT asks the children how many triangles they can see. (The answer is three: one large and two small triangles.)

(9) The KT asks the children to fold the apex to the base, to create a trapezium.

(10) Turn over.

(11) The KT asks the children to count the sides and corners to check if the polygon is still a triangle.

(12) Turn over again. The KT asks the children to fold the bottom corners to the middle of the base.

(13) The KT asks the children to name what they have made and to draw on it. See Figure 9.

6. The KOP and Friedrich Froebel

The KOP is often compared to the well-documented use of origami (*papierfalten*) by the German educator Friedrich Froebel (1782–1852), including his concept of Folds of Life [Brosterman 97]. While there are similarities between the two, there are also many differences. Table 1 makes a comparison between the programs.

Froebel	KOP
Origami was taught as the 18th of 20 Gifts, when the children were 7 years old.	The KOP is taught to children aged 4–6.
Froebel's 20 Gifts were all geometric in concept. So, by the 18th Gift, the children were well used to working with geometrical shapes and forms.	For many children, the KOP is their first experience of working with geometric shapes and forms.
An emphasis of Folds of Life is on making recognizable models of objects familiar to the children (furniture, utensils, boxes, etc.).	An emphasis is on imaginative play, with the children naming what they have made.
An emphasis is on the achieving of a final model.	An emphasis is on geometrical analysis and group discussion during the folding.

TABLE 1. A comparison between Froebelian paper folding and the KO program.

7. Conclusion

Although unorthodox in its use of origami, the KOP has quickly established itself as a program for the teaching of the Israeli Ministry of Education's geometry curriculum for kindergarten, proving itself popular with ministry officials, the teachers, and also the children. Formal assessments of the KO courses for KTs written by participating teachers consistently rate the courses very highly for didactic relevance and for consistent success within the demanding real-world circumstances of different kindergartens with different population groups.

The key elements of the program are the emphasis on imaginative play with folded paper and group analysis of a geometric topic or open-ended problem. At no point in the activity can a child consider himself to have failed, thus encouraging participation and a willingness to experiment without limits. This approach, although puzzling to many people familiar with origami and the teaching of origami to older children and to adults, relates to the educational level of kindergarten-age children and their predisposition to learn through imaginative play [Clements and Sarama 09, Cramond et al. 05, Ginsburg 06, Pandisco and Orton 98, Torrence 67].

Further, the structure of the 30-hour courses undertaken by KTs to learn the KOP and the follow-up visits to each teacher's kindergarten to see the program in action, ensure that the philosophy of the program is translated into a successful activity.

Since the relationship between the Ministry of Education (MoE) and the KOP is new and its place within the national curriculum has yet to be fully determined, there is as yet no formal quantitative assessment regarding the comparative effectiveness of the program. However, it is a requirement of the MoE that KTs study and document the progress of each child in each area of the curriculum, including mathematics. From this documentation, it is evident that the KOP makes an effective contribution to the learning of the geometry curriculum and is a popular activity. It is this positive assessment of the KOP that has led directly to rapid growth in the support given to it by the MoE. Many future KOP courses are planned.

Finally, the KOP is best assessed by the teachers who have been trained to use it. Here is a testimonial from one KT who took the KOP course:

At the beginning I thought Origametria was just folding paper models, but then I saw it was really about geometry and I was afraid to introduce it as an activity in my kindergarten because I don't know much about geometry. Although we learned the basics of geometry in the course, I was still afraid and began the activity with a lot of fear, but I saw the children enjoyed it. They loved it! They were excited and waited for their activity.

I didn't have enough time to work with all the children, so I worked only with the oldest group. Afterward, they introduced the activity to the younger children without my involvement and using correct geometric language. It was very beautiful to see!

I feel I'm only at the beginning and I need more time to work with it, but I feel the program is important and makes a valuable contribution to geometry in the kindergarten.

8. Appendix

These are the twelve topics studied on the KOP course for KTs.

Shape:

(1) Identify and research each polygon according to the number of sides and vertices.
(2) Identify and research the difference between long and short sides.
(3) Identify and research quadrilaterals according to the number of sides and vertices.
(4) Create a paper ruler and learn to measure long and short sides and vertices and to identify right angles.
(5) Identify and research squares according to the number of sides, vertices, and right angles.
(6) Identify and research squares and rectangles according to the number of sides, vertices, and right angles.
(7) Identify and research different quadrilaterals such as a square, rhombus, and rectangle according to the lengths of the sides and the number of vertices.

Mirror Symmetry:

(1) Identify and research mirror symmetry in triangles.
(2) Identify and research mirror symmetry in quadrilaterals.

Solids:

(1) Identify and research cubes by building cubes and learning about the structure.
(2) Identify and research three-sided pyramids.

Composition and Decomposition:

(1) Build different polygons from a large number of triangles and research topics studied previously.

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