Design of a Biomimetic Pectoral Fin Joint in an Artificial Fish

by

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ABSTRACT

A biomimetic design of the muscle joint in a pectoral fish fin was produced based on comparisons with four design models. All four design models consisted of a mechanical joint connection and incorporated the functional operation of the pectoral fish fin rays when affected by specific actuators, such as induced contractions of conducting polymer strands.

Design constraints of the joint were determined by the fundamental kinematic elements of motion determined in the Bioinstrumentation Laboratory. A mechanical pin-joint provided correct simulation of movements specialized for this phase of the development of an artificial fish fin. A compression spring with a spring coefficient of K=0.45 was used as a mechanical means to imitate the biological energy conservations produced by each stroke of the pectoral fin. The joint was designed to adhere to displacements by conducting polymer actuators that induced a 2.0% maximal strain on the fish fin ray.

Thesis Supervisor: Ian Hunter
Title: Professor of Mechanical Engineering

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1.0 INTRODUCTION

Frequently, specialized animals are chosen as model organisms to be studied in order to extrapolate certain properties of interest to other systems. In the case under study at the Bioinstrumentation Laboratory, fish were chosen as the model organism to characterize. The main property of interest for the Bioinstrumentation Laboratory focuses on maneuverability and propulsion.

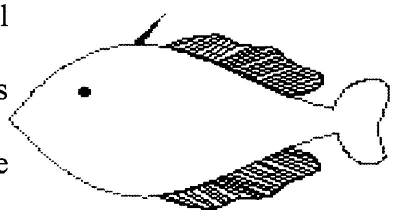

Figure 1. Example of the most common shape of fish, functioning to heighten and maximize the ability of and precision in maneuverability (taken from http://www.csuchico.edu/~pmasli)n/ichthy/fishevtrends

Fish are known as maneuverability specialists. Since in sea-life, small-item resources are overall much more abundant than larger prey, small fish that move fast have evolved as necessary to specialize in delicate, focused movements to avoid capture. Accordingly, many species of fish are specialists for maneuverability rather than speed. A short, rounded body with sculling or undulating fins nearly all the way around it maximizes maneuverability (Figure 1). Compressing the body laterally provides a wide surface to exert force on the water for quick escape movements. The pumpkin-seed or disk shape is one of the most common in the fish world. Additionally, the pectoral fins are handy for braking or steering, but can also be employed in a powerful "breast stroke" as an aid in jump starts. The pectoral fins are the crucial element for quick turns and acceleration[1].

The pectoral fins of fish have shown to exhibit complex movements and intricate maneuverability. A few characteristics of interest in our world today are fish's agility, energy efficiency, and silent maneuverability. The performance characteristics and the remarkable locomotor properties that fish display are highly sought to be simulated in engineering designs for undersea vehicles; however, all large-scale simulation attempts have failed[2].

[1] www.csuchico.edu/~pmaslin/ichthy/loco2.html

The understanding of fish maneuvering and its application to underwater rigid bodies has been an increasing topic of study throughout the past twenty years. The main goals of these studies have been to observe and quantify form and function and to gain insight into stealth. Fish morphology suggests that control fins for maneuverability have unique scalar relationships irrespective of their speed type. In theory, once these aspects of fish morphology are fully understood, control studies can be carried out to demonstrate the feasibility of maneuverability of biologically inspired bodies under surface waves (Bandyopadhyay, 2002)

An impact on design and applications of extrapolating analysis of fish to under water vehicles would be in achieving precision in maneuverability during many challenging or unstable conditions. For example, such understanding of fish kinematics would help achieve stability in turbulent waters and reduce general risks as well as enhance technology so that further explorations in less favorable conditions can be carried out. The application of fish hydrodynamics to the silencing of propulsors is another impact further studies can reveal. In addition to these characteristics, an undersea vehicle demonstrating properties such as agility and energy efficiency has not been attained as of yet by classically engineered systems.

As mentioned before, the focus in the Bioinstrumentation Laboratory is to build and characterize a fully functioning biomimetic sunfish-like low-aspect ratio pectoral fin. The use of actuator technology was the approach used in order to achieve proper simulation of the muscle and its functions. Recent advances in the area of conducting polymers have used this organic material as building blocks to produce a large range of functionalities including artificial muscle, force sensors, and structural elements[1].

In order to study the effects on proposed structural designs of the pectoral fins, an efficient method was necessary to observe, quantify, and simulate similar anatomy and muscular

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[1] Hunter et al., Development of an Integrated Artificial Muscle: *MURI Proposal*, 2000

parameters of the Sunfish. A basic design was constructed that integrated both the structural fin and the biomechanical stimulations of the conducting polymer. This design enhances ease in testing the effect of inducing varied forces from polymers or other mechanisms on the movement of the designed pectoral fin rays. As well, the integrated biological model is adaptable and will aid in attaining response observations and data on other aspects of fin maneuverability such as fluid dynamics of fin strokes[1].

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[1] Hunter et al., Development of an Integrated Artificial Muscle: *MURI Proposal*, 2000

2.0 BACKGROUND

In order to design a biorobotic pectoral fin based on conducting polymer artificial muscles, it is useful to characterize in detail a biological model system on which to base the biorobotic design. Our goal was to mimic the essential parameters for maneuverability and proper kinematic function of the biological fin and not to design a model to simulate every aspect of the fish fin.

2.1 The Pectoral Fin

Basic research has been performed on the pectoral fins of fishes over the past twenty years, including studies concerning the three-dimensional analysis of pectoral fin motion by Gibb, Jayne and Lauder (1994) and examinations characterizing maneuverability by Wilga and Lauder (1999).

2.1.1 Basic Anatomy of the Pectoral Fin

We will first explore the detailed anatomy of the pectoral fin of a fish since a clear understanding of the fin structure is an obvious prerequisite for any biological design. Since anatomical analysis on pectoral fins have only been acquired for two fish, the pectoral fin in a boxfish was used as a reference to characterize gross morphology of the fins. (Gibb, Jayne and Lauder, 1994; Walker and Westneat, 2000) Procedures such as microscopic dissection, scanning electron microscopy, and histological staining of pectoral fin bones, connective tissue, fin rays, and musculature have revealed properties of the basic dimensions of the fins rays and their bony supports and the three-dimensional architecture of the pectoral musculo-skeletal system.

Basic aspects of the fish fin as characterized by Geerlink, 1979, 1989; Gibb et al., 1994; Westneat, 1996; and Drucker and Jensen, 1997 are shown in Figure 2. The fin rays are distally

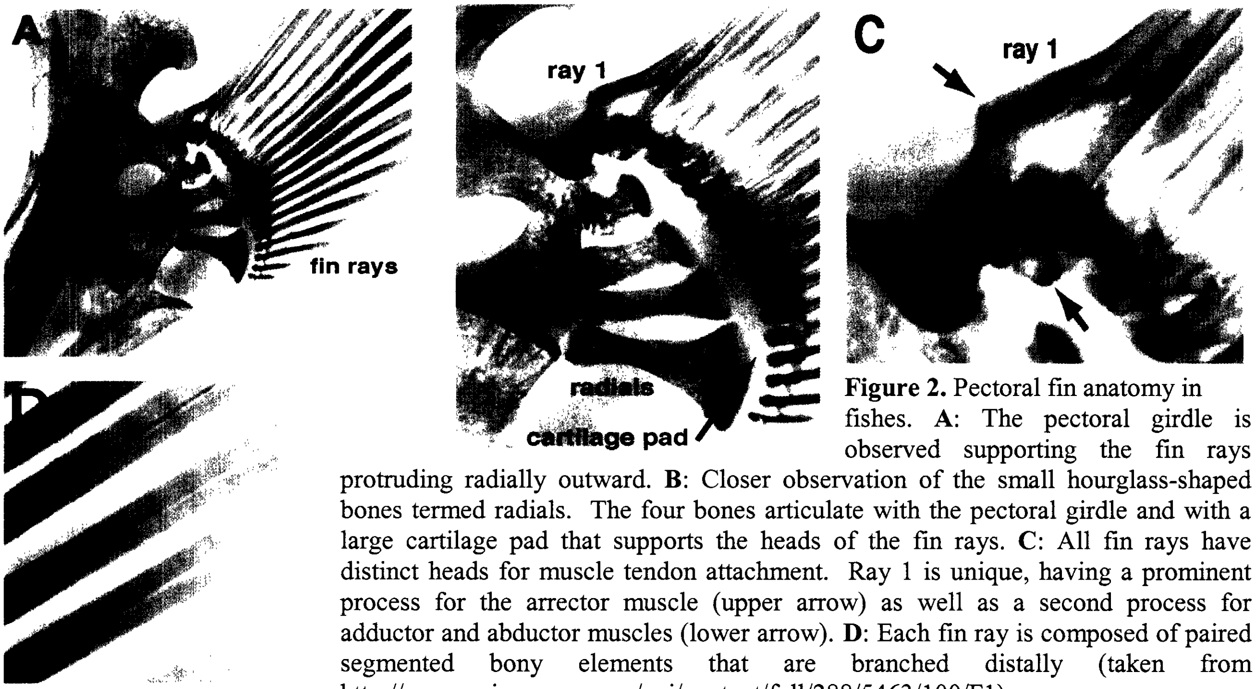

Figure 2. Pectoral fin anatomy in fishes. **A**: The pectoral girdle is observed supporting the fin rays protruding radially outward. **B**: Closer observation of the small hourglass-shaped bones termed radials. The four bones articulate with the pectoral girdle and with a large cartilage pad that supports the heads of the fin rays. **C**: All fin rays have distinct heads for muscle tendon attachment. Ray 1 is unique, having a prominent process for the arrector muscle (upper arrow) as well as a second process for adductor and abductor muscles (lower arrow). **D**: Each fin ray is composed of paired segmented bony elements that are branched distally (taken from http://www.sciencemag.org/cgi/content/full/288/5463/100/F1).

branched and segmented, stemming out from a cartilaginous pad which rests on four expanded radial bones. Interestingly, the first fin ray was observed to play an integral role in controlling fin motion (Gibb et al., 1994). It has a specialized expandable head that is embedded directly into the scapula bone, contrasting to the locations and enclosures for the other fin rays, as seen Figure 2-C. The expandable heads of the all fin rays serve as the attachment sites for separate muscle bundles (Hunter et al., 2000).

When stress-strain experiments were performed on the fin rays, the biomechanical data demonstrated that at a 2.5% strain, corresponding to a 320 MPa stress, would permanently deform the ray. Therefore, this strain defines one specification to take into consideration in the biological design.

The orientation of the muscles relative to the body and fin rays supports a high level of control with regards to fin motion, since each of the main rays receives four separate tendons as seen in Figure 3. The four major muscle groups are: adductor, abductor, and two distinct

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[1] http://www.sciencemag.org/cgi/content/full/288/5463/100/F1

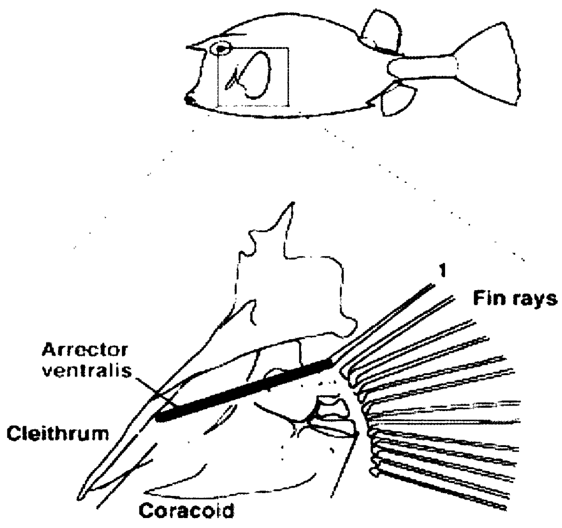

Figure 3. Schematic illustration of major pectoral fin muscle groups. The arrector dorsalis muscle is not shown (teken from Hunter et al., Development of an Integrated Artificial Muscle: *MURI Proposal*, 2000

arrector muscles located at the ventral and dorsal sides of the fish which attach to the first fin. Based on the complexity in condensation and attachments of the fiber bundles, it is easy to comprehend how the boxfish is able to attain such control in maneuverability and rapid reactions to obstacles in its fluid path.

2.1.2 Three-Dimensional Kinematics

Three-dimensional kinematics of the pectoral fish fin of the boxfish have been generally described by Gordon et al, 1996; however, detailed kinematic data does not exist on fin movements and the effects of fin ray functions during maneuvering. With this said, there is still a lack of certain kinematic information that is critical for understanding the mechanisms of fin-based propulsion. An example of a factor to take into consideration is the displacements and velocities along the trailing edge of the fin and to what extent the fin may function as a rigid paddle, which has yet to be determined. The difficulty arising from visualizing the edges of the pectoral fin has contributed to the lack of viable observations and analysis (Gibb, Jayne and Lauder, 1994).

To better understand the locomotor functions of the pectoral fin, it is crucial to perform studies on the maneuvering locomotion, such as has been achieved by introducing visual stimuli in a flow tank to induce a vast array of maneuvers. An important factor to consider when attempting to reproduce the biological functions of the fish fin is to analyze its response to

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[1] Hunter et al., Development of an Integrated Artificial Muscle: *MURI Proposal*, 2000

unsteady conditions (Full et al., 2002). In this way, stability control can be quantified by measuring displacements and surface orientations of the pectoral fin elements. Experiments that have been performed in the Bioinstrumentation Laboratory have used synchronized high-speed video cameras that obtain digital video sequences of pectoral fin movement ad all quantification of defined points in the x, y, and z dimensions.

2.1.3 Locomotion: Propulsion and Maneuverability Activity

The general principles that have been taken into consideration with integrative studies of locomotion in the pectoral fish fin include energy storage and exchange mechanisms. With respect to locomotor control systems, rapid mechanical reflexes are combined with sensory feedback and feedforward commands that are controlled by muscle functions (Dickinson et al., 2000). The muscle attachments to the pectoral fish fin have a variety of functions in locomotion, such as serving as brakes, springs, and struts.

A crucial element in analysis of the propulsion and maneuverability mechanisms in the pectoral fish fin is incorporating analysis of the hydrodynamical performance of the fins. In this way, a connection can be made between the structure and corresponding functions of certain mechanisms within the pectoral fin. Examining the role that fin-flexibility plays in thrust generation will help serve as a tool for the structural and hydrodynamic design of the artificial muscle pectoral fin. Analysis of the surface pressure and shear stress distribution on a structure as delicate as the flapping pectoral fin can provide a good insight into the flow dynamics. However, some difficulties that must be taken into consideration arise from using bioinstrumentation and sensors to measure such precise parameters without causing any disturbances in natural function and behavior.

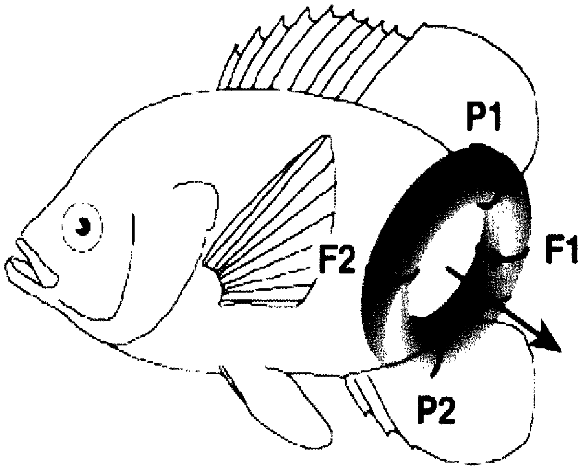

Figure 4. Schematic 3D representation of the vortex ring formed in the wake of the pectoral fin of a sunfish (taken from Drucker and Lauder, 2002)

An interesting and crucial component of the flow dynamics that has been observed has dealt with the reconstruction of vortex wakes behind the swimming fish. The motion of fish causes distortions in the fluid or water with swirl together to form a complex wake. As the tail sweeps back and forth, a series of alternating vortices are created. A single donut-shaped vortex, as shown in Figure 3, is produced from each stroke of the fin. Each subsequent stroke produces other vortex rings that are patterned in such a way that each vortex is linked to the vortices of previous strokes. As the fish continues its movements through the fluid, it creates vorticity, or a circular flow of motion. Each vortex ring represents the momentum subjected onto the water by the fish's body and tail. Analysis of the water velocity induced by each vortex ring reveals a time-averaged hydrodynamic force that the fish is subjected to (C.P. Ellington, 1984).

The reconstruction of the spatial and temporal dynamics of force generation is important for understanding the locomotor functions and forces directly generated by the fish. However, a point to take into consideration is that the geometry of the wakes produced is highly complex and varies from one species to the other, and as well is dependent on the speed of the fins in operation (Dickinson et al., 2000).

2.2 Basic Design Parameters: Stress Specifications

A key parameter to comply with in the pectoral fish fin, as discussed in the section on basic anatomy of the fin and fin rays, is the biomechanical data produced from the stress-strain experiments on the fish fins. Figure 5 demonstrates results attained through analysis in the Bioinstrumentation Laboratory, concluding that at approximately a 2.5% strain corresponding to 320 MPa stress, the fin ray is permanently deformed. The biological model and experimentations performed on potential designs of the fish fin must then comply with this specification and not exceed this strain/stress however simultaneously produce similar movements as observed through previous kinematic studies.

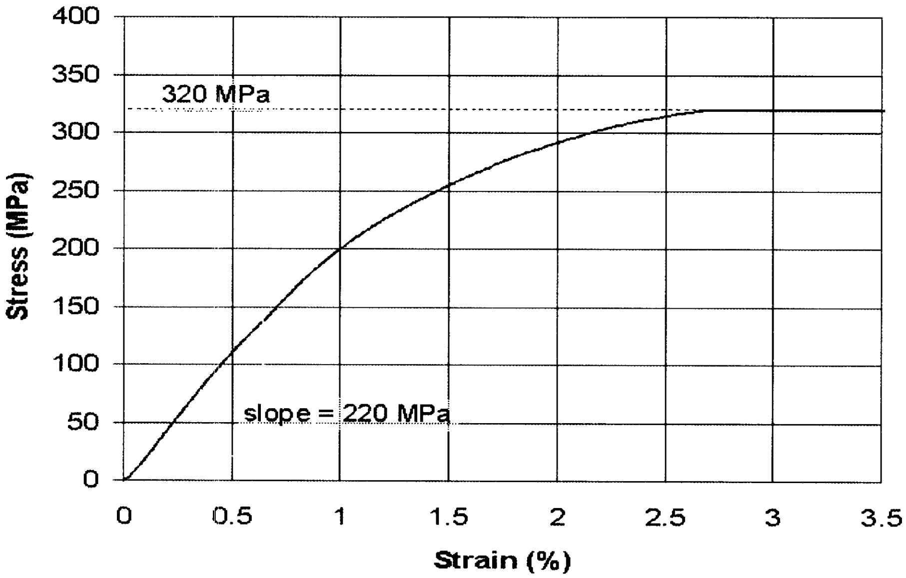

Figure 5. Plot of stress vs. strain measurements obtained from Boxfish fin rays subjected to a 3 point bending test in the Bioinstrumentation Laboratory Lab. Note the very large strains sustainable by the fin ray which only deforms permanently above a 2.5% strain (at 320 MPa stress) (taken from Hunter et al., Development of an Integrated Artificial Muscle: MURI Proposal, 2000)

3.0 EXPERIMENTAL PROCEDURE

In developing a biomimetic design that would incorporate the initial designs of the particular fin rays of the pectoral fish fin into a biomechanical activated mechanism, three main attributes became crucial. One aspect of the model was the compliance of correct displacements of the fins as produced by the actuators to generate rigid maneuverability of the entire fin ray as well as a flapping of the tail-end of the fin ray. Another aspect incorporated the correct anatomical structure of the entire fin ray-fin-muscle attachments as observed through methods discussed in the Pectoral Fish Fin section of the Background. The last aspect dealt with attaining the constrained movements of specific joints within the fin ray to muscle attachment as well as the fin ray to actuator attachment sites.

As well, the integration of a total of three fish fin rays seemed like an ideal number of fins to use to attain and experiment with the proper three-dimensional kinematics of the fins. Incorporating three fin rays would help conduct varied control trials in order to observe aspects of movements previously described.

Unigraphics NX (www.unigraphics.de/produkte/nx/nx.shtml) software was used to design all parts: fin rays, joints, extensions, excluding the mechanical devices. The VIPER (http://www.3dsystems.com/products/sla/viper) Sterile Lens Array stereo lithography three-dimensional printing machine which enabled high-resolution design was used to produce the respective parts.

3.1 Initial Fish Fin Ray Design and Actuator Attachment Analysis

One of the main components of the biological model was the fish fin ray designed by Laura Proctor, Doctoral candidate in Mechanical Engineering, in the Bioinstrumentation Laboratory. Figure 6 shows the most recent design that incorporated optimal strength of the slim junction between the ray extension and the site of attachment to actuators. Through experimentation and testing, the optimal dimensions of the fin ray were found to be converging at the tip at a length of 5 μm and a total extension length of 120 mm. In order to achieve the dual movement along the two different sides of the fin when the fin ray ends of the actuators were attached, the fin ray was designed as a hollow structure in order to limit constraints attain a movement at the tip of the fin ray. The attachment began from the tip of the fin ray and proceeded 40 mm in length towards the bottom. Proctor's initial design also incorporated a break between the anterior and posterior sides of the fin ray in order for the tail end of the fin ray to mimic the biological flapping movements of the fin ends. In this manner, the observed maneuverability and movements with respect to hydrodynamical performance and energy conserving mechanisms as a cause of vortex wakes could be properly imitated.

Observing and testing this model for the pectoral fin rays was valuable in aiding the ability to understand the problems encountered with designing the pectoral fin rays and what kinds of modifications could be made in order improve the basic end attachment site to the actuators.

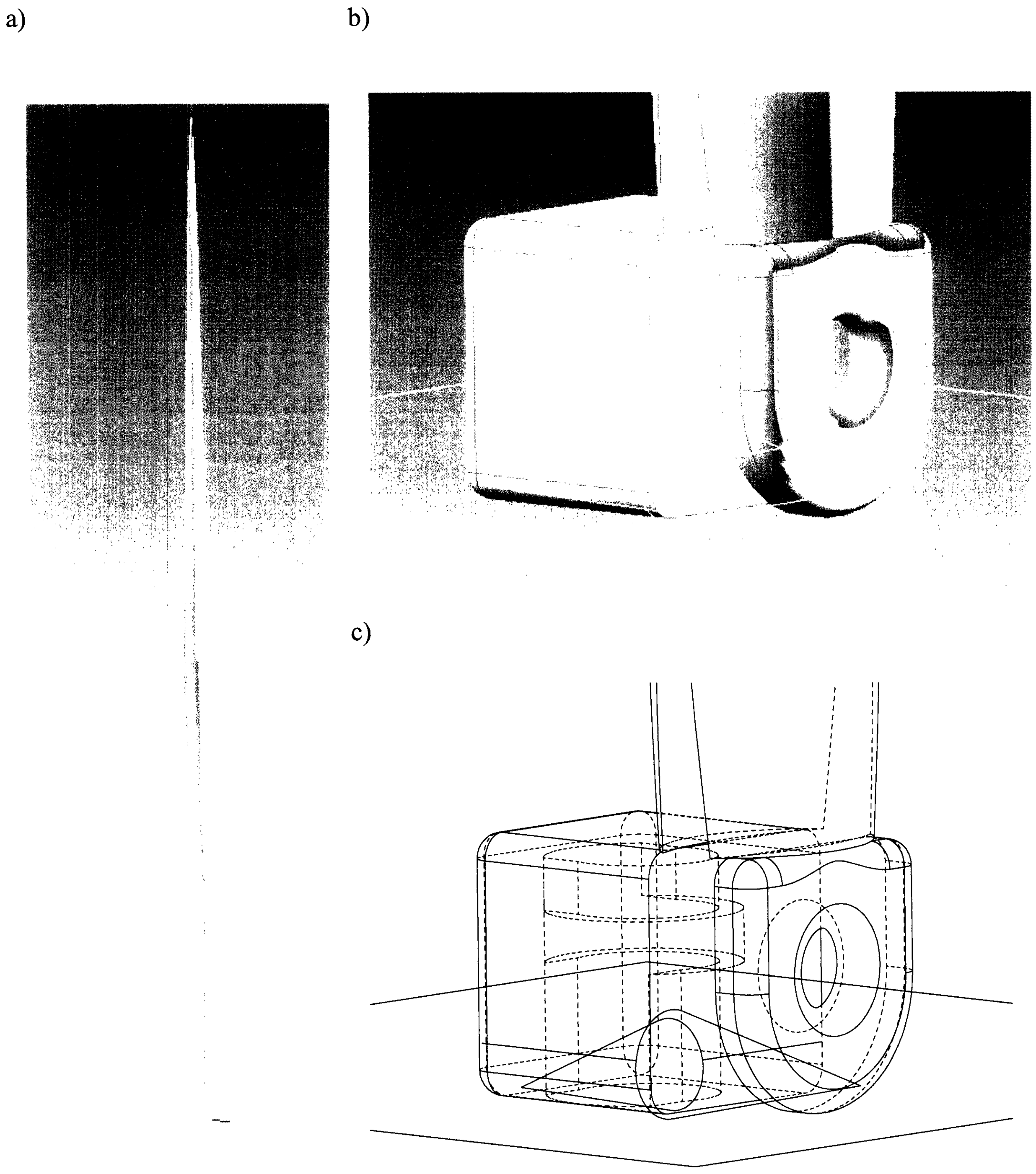

Figure 6. Design of the pectoral fin ray proposed by Laura Proctor. a) The entire fin design as modeled using Unigraphics NX software. The height of the fin ray is 120 mm and is hollow with two separate sides until reaching a height of 80 mm. b) The 3-D visual solid model of the bottom junction or attachment site for a device that will induce force or strain and thus a lateral movement. c) The 3-D sketch model of the bottom junction (taken from Laura Proctor).

3.2 Joint Design and Mechanics

A main aspect as stated before was the reproduction of the dimensional maneuverability of the pectoral fish fin. One limitation to take into account an overall joint was analyzing the necessary constraints. An important constraint was the movement perpendicular in the vertical plane to the strains and displacements induced by the actuators at the ends of the fin rays. As the actuators would pull on the fin ray, to effectively attain a proper flapping of the tail end, the attachment ends of the fin rays had to move linearly to the displacement from the actuators.

3.2.1 Constraint of Compression Spring

In order to simulate some energy conservation that affects the muscles and the propulsion of the fish fins, a compression spring was proposed as a means to capture kinetic and elastic strain energy. The spring would be placed on the end attachment site where the fin ray attaches to the actuators not only to limit moments about the joint, but as well to attain as much of a linear movement as possible for optimal curvature of the tail ends of the fin rays.

Testing of compression springs with varied spring coefficients were analyzed in order to attain a spring that would comply with the forces that were needed for a displacement cuased by a 2.5% strain of the actuators. The dimensions of the compression spring as well were of importance since the design of the joint would contain this spring.

Simple spring mechanics were taken into consideration. The spring rate, *K*, is the load (pounds) it takes to deflect or compress the spring one theoretical inch. Springs with varied spring constants were tested for deflection. As well, since the specific load spring rate was an unknown parameter, the installed working length (W.L.) was used to select the spring[1]. A spring 20% longer than the W.L. was chosen.

3.2.2 Potential Models

After taking all the factors mentioned above into consideration, four potential models were designed that met the specifications for fin ray maneuverability.

3.2.2.1 Rigid and Pin-Joints

As was described briefly in movement analysis, it was observed that mainly the muscle joint of the fish fin acted in a similar manner to the joint of the human wrist, where there was free movement of the overall fin within the x-z and x-y coordinate planes. Research into mechanical joints revealed some potential options to incorporate as the main joint feature. The universal joint was considered as a possible mechanical joint as designed in Unigraphics NX and shown in Figure 7. However, this design allowed for free rotation of the fin ray about any axis. The fin ray has a main constraint in that it the joint can only rotate within two dimensions instead of the three as proposed for the universal joint. This did not seem as the optimal option and would require further modifications of the original mechanical design. A couple other design options taken into consideration included the U-joint and the pin-joint.

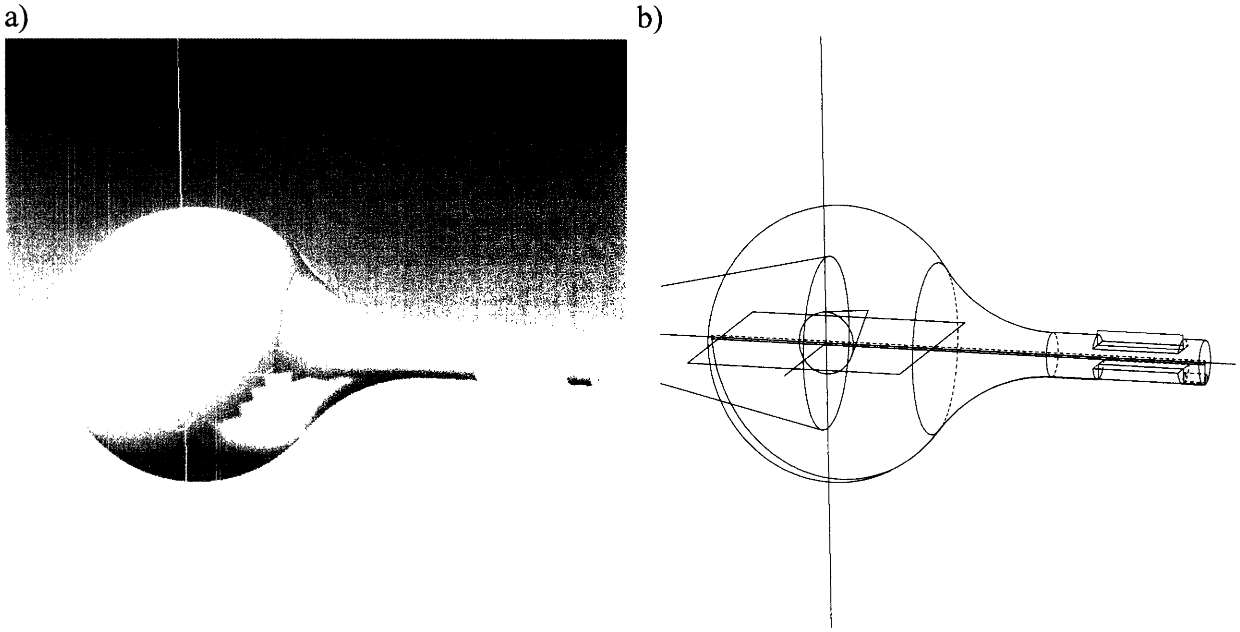

Figure 7. a) Solid model of the universal joint design for the joint attaching the fin ray to actuators and to an envisioned pectoral girdle to constrain overall movement. b) Sketch model of the same universal joint design using Unigraphics NX.

A further analyzed initial design of a more optimal joint incorporated a rigid joint that would extend to attach to the actuator attaching site of the fin ray. This joint model is shown in Figure 8. In this case, the main idea was that movement about the x-axis was simply accomplished through the movement of the actuators integrated with the compression springs.

The compression spring was incorporated into the extension of the cylindrical base as shown in the initial rigid joint design in Figure 8. However, an ideal design incorporated the constraint on the compression spring so that its own motion would not interfere with the natural responses of the fin rays. A second design is shown in Figure 9, where the cylindrical outsettings are placed on both sides as in the initial design. In this way, the spring is constrained tightly against the extension. As well, ease of placing the spring into the extension was aided in this design since the spring could be dropped in without any interference with other aspects of the design and constrained by placing a small rectangular rod across the diameter of each cylindrical outsetting. This feature would constrain the motion in the x-direction so when a force was applied, a reactionary force from the spring would not allow motion or detachment of the spring to the joint.

Another potential design incorporated the pin-joint as the attachment site for the extension that would then attach to the actuator attaching site of the fin ray. The cylindrical base for the joint design is shown in Figure 10. As can be seen, the pin-joint would provide further flexibility in movement in the y-direction. This design would allow not only the movement caused as a result of the actuators on the fin ray tip, but as well the overall movement of the entire fin ray, which is an important attribute of the pectoral fish fin. Biomechanical kinematics has concluded that the maneuverability of fish pectoral fins is quite versatile. Indeed, examined fish were capable of quasi-statically positioning and orienting themselves in three dimensions via a three-axis translation as well as a two-axis rotation. The sunfish in particular are remarkable in their ability to rotate their body about the vertical axis without translation. A rotation about two degrees of freedom was an aspect in maneuverability control that was sought.

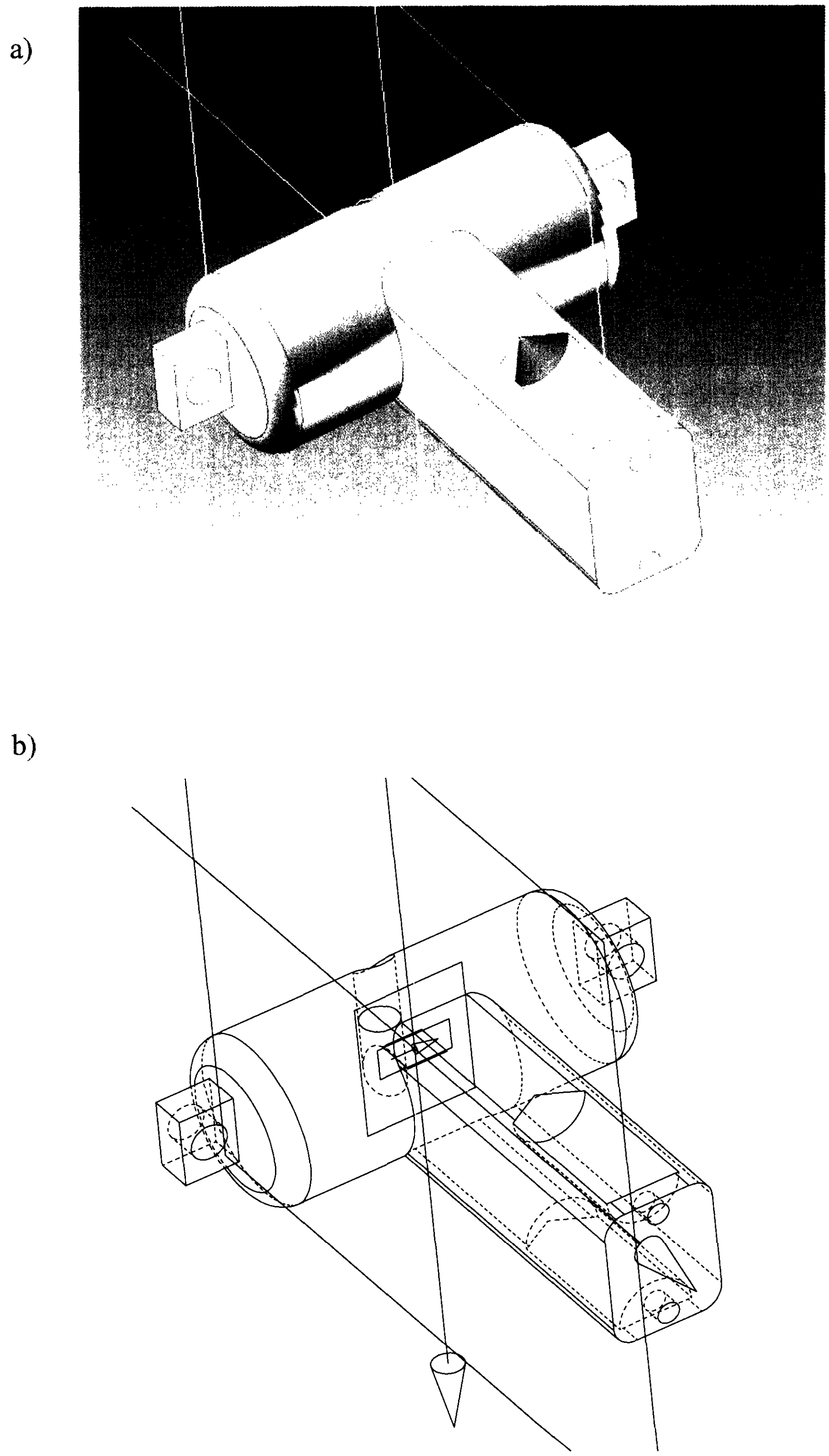

Figure 8. Initial rigid joint as modeled on Unigraphics NX. a) Solid model of the rigid joints designed with two separate alcoves where the spring would be placed and attached to the fin ray. The model incorporated a cylindrical shape as its base attachment. b) Sketch model of the initial rigid joint

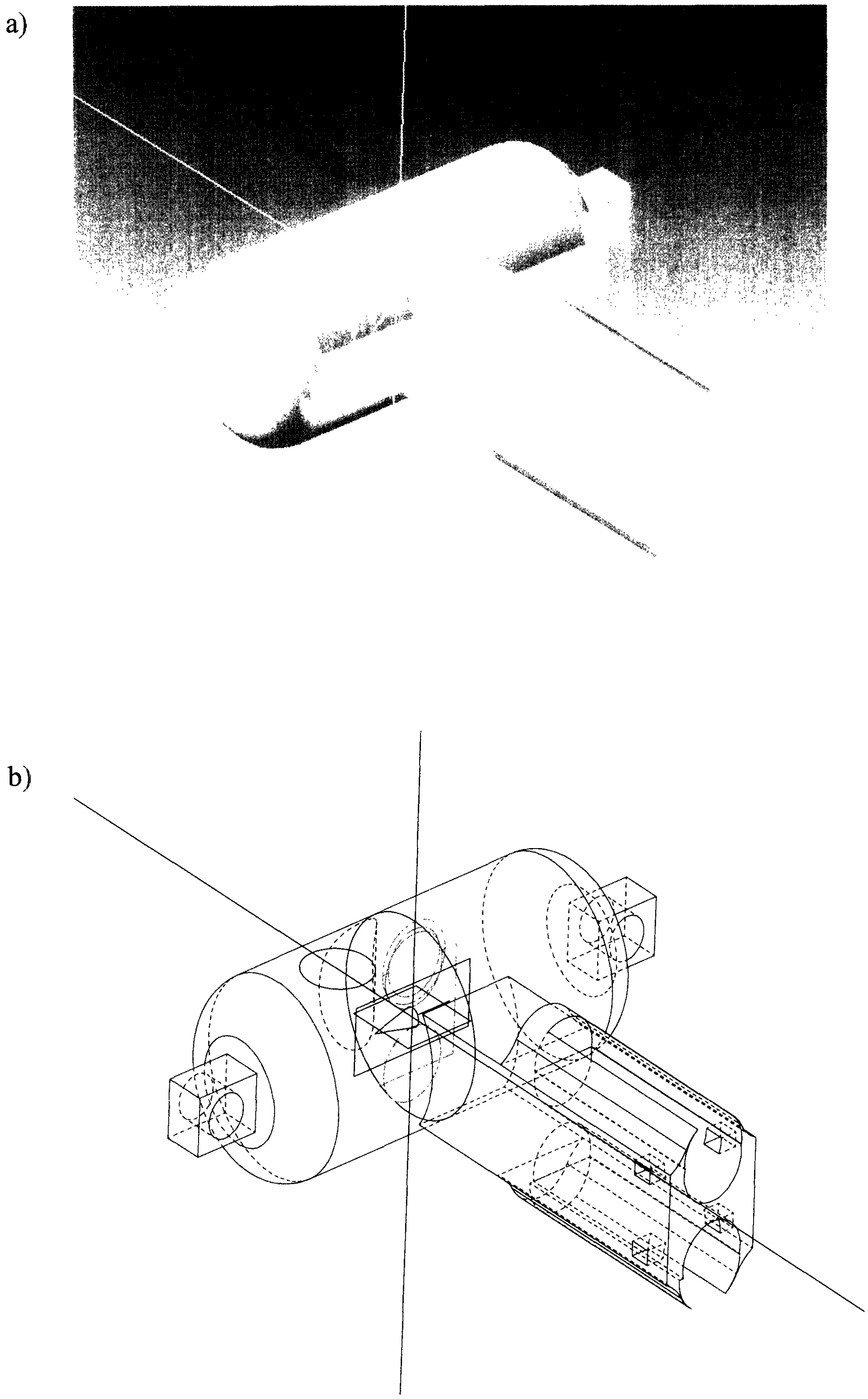

Figure 9. Final rigid joint as modeled on Unigraphics NX. a) Solid model of the rigid joints designed with two separate alcoves where the spring would be placed and attached to the fin ray as in the initial design. This model incorporated a constraint on the compression spring so that it could be easily dropped into the cylindrical outsetting without falling back out while maintaining the ability to attach to the fish fin. b) Sketch model of the second rigid joint.

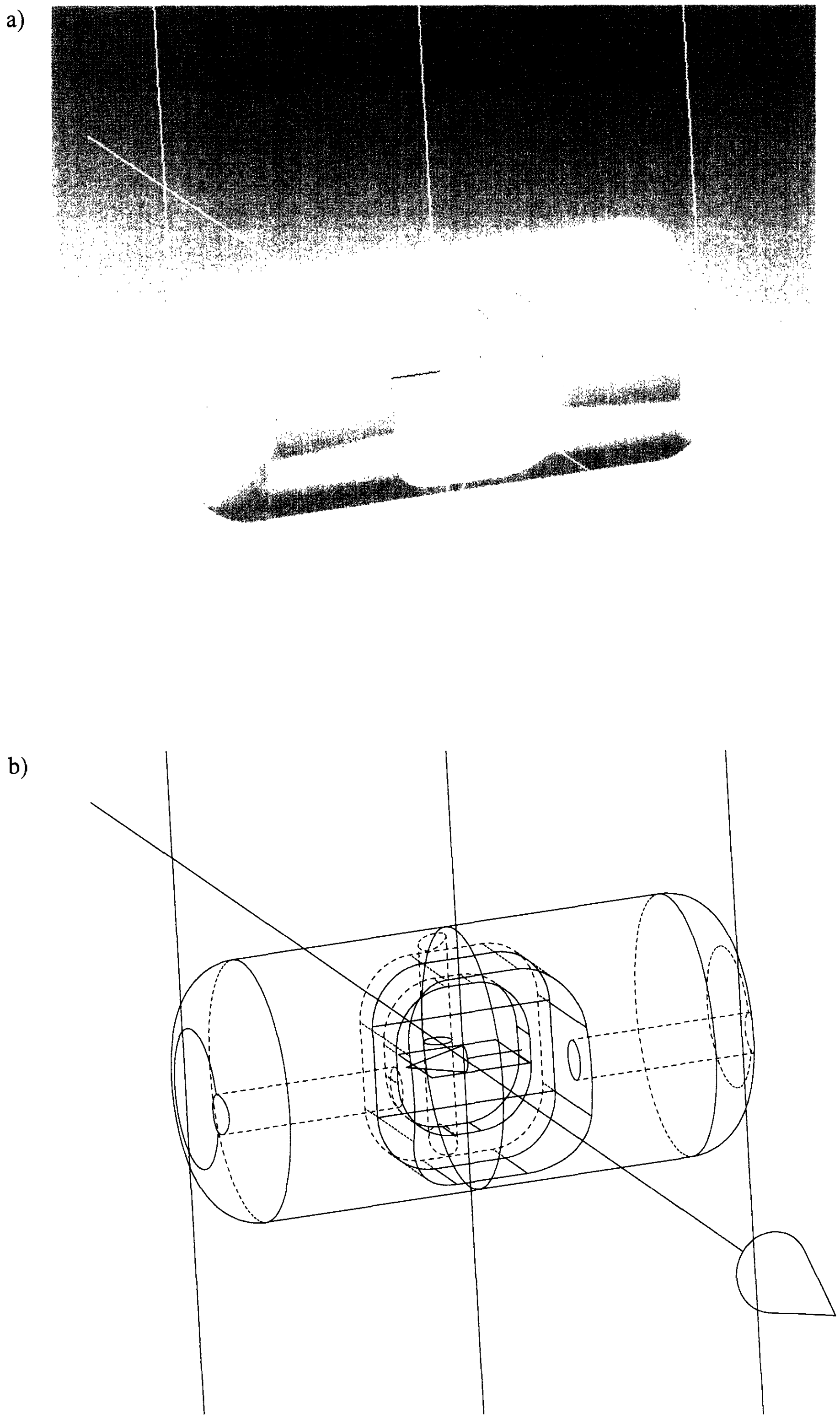

Figure 10. Pin joint as modeled on Unigraphics NX. a) Solid model of the pin joints designed so that the constraint in the vertical y-direction would be minimized. In this way, the overall fin ray would be able to respond to any movements as well as the tip of the fin ray. b) Sketch model of the pin joint.

3.2.2.2 One and Two Side Fin Kinetics

In addition to incorporating the effect of the overall pectoral fin ray movements, the design of incorporating a two side attachment at both the actuator attachment sites versus having the connection limited to just one side was tested. Figure 11 shows the model of the two-sided kinematic constrained extension in the form corresponding to a pin joint attachment.

The one-sided constrained kinematic design of the fin ray joint for the rigid model is shown in Figure 12 and for the pin-joint model is shown in Figure 13. The main attribute to having one side of the movement constrained was analyze whether this modification helped achieve a higher degree of deflection at the tail end of the fin ray. The complexity of the design could be simplified, however comparison testing between the two different designs would conclude whether the one-sided model proved to be a more efficient or an optimal design in achieving greater tip inflection.

As well, the effects on the linear displacement, with respect to the movement as caused by the attached actuators, of one side being completely constrained or pinned will be evaluated as compared with the two sides being free to move and constrained solely through the compression spring.

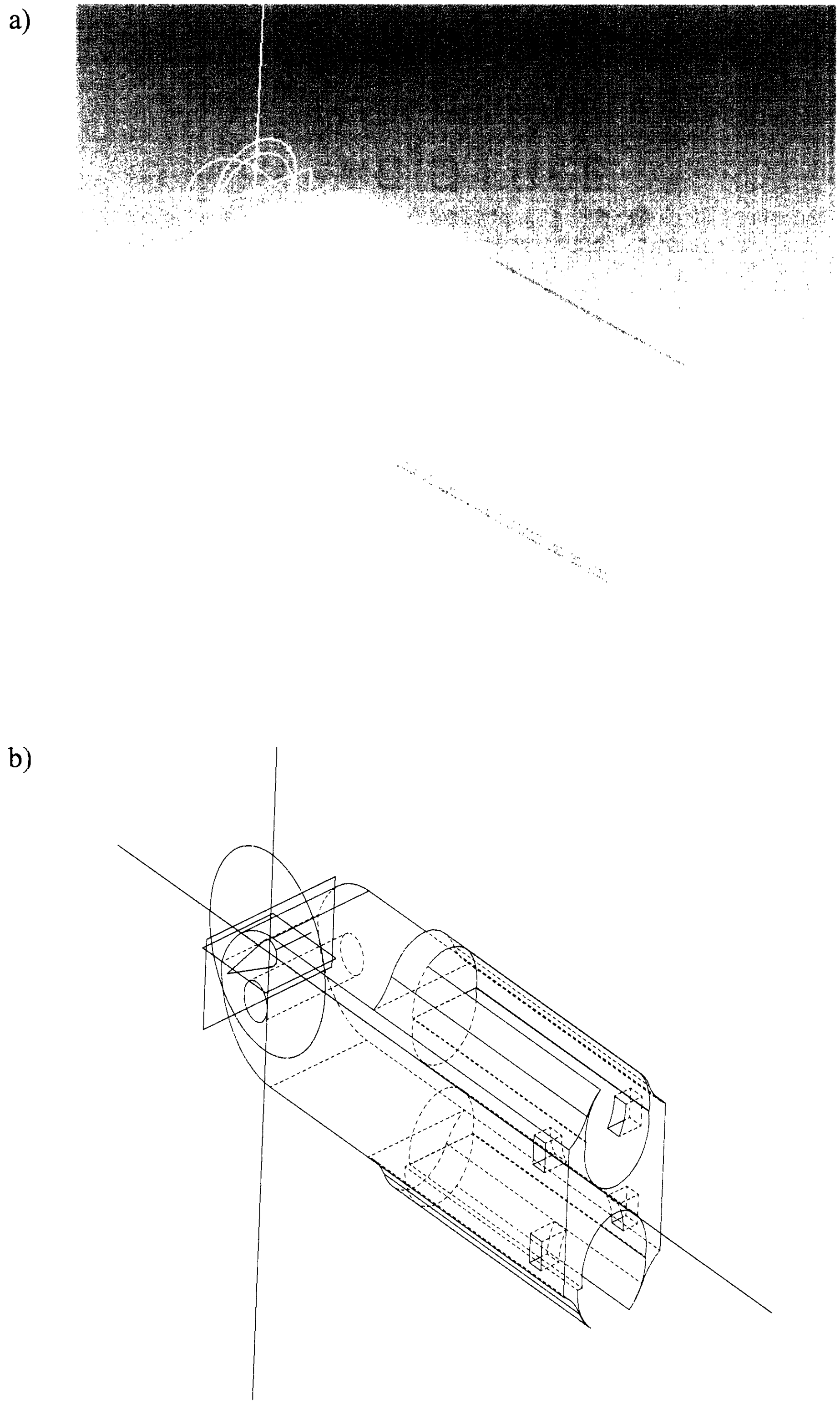

Figure 11. Two sided constrained kinematic design for pin joint as modeled on Unigraphics NX. a) Solid model of the pin joint was designed so that y-directional movement could be enhanced with respect to the overall structure of the fin ray. b) Sketch model of the two-sided pin joint.

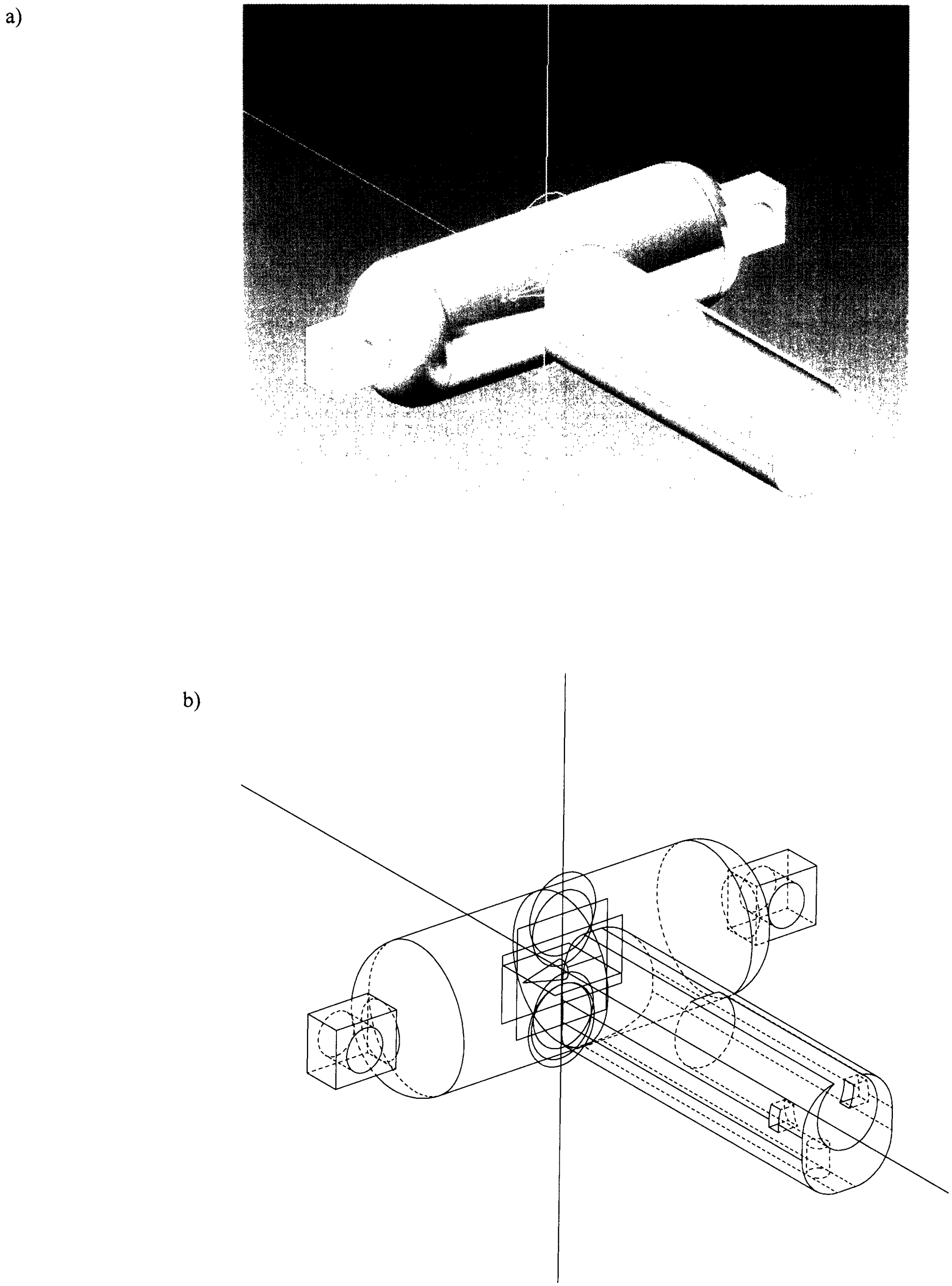

Figure 12. One sided constrained kinematic design for rigid joint as modeled on Unigraphics NX. a) Solid model of the rigid joint designed so that the one side of the fin would be fixed to the extension. b) Sketch model of the one-sided rigid joint.

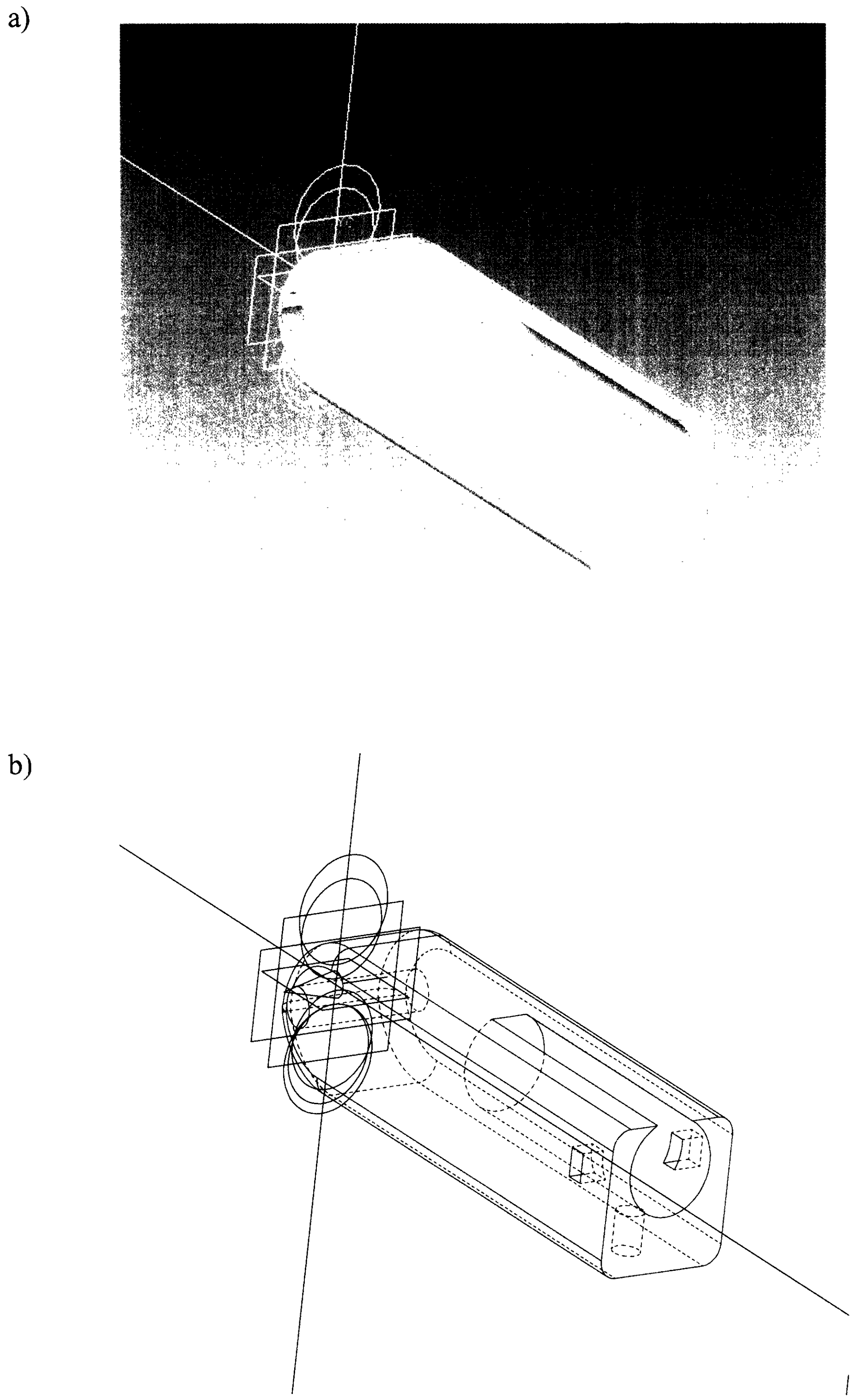

Figure 13. One sided constrained kinematic design for pin joint as modeled on Unigraphics NX. a) Solid model of the pin joint designed so that the one side of the fin would be fixed to the extension. b) Sketch model of the one-sided pin joint.

4.0 RESULTS & DISCUSSION

4.1 Final Biomimetic Model

After producing the respected parts described in the Experimental Procedure using the VIPER SLA machine, the respective rigid joints and pin-joints were assembled. Two main connections areas were tested: the connection to of the joint extension to the fish fin ray, and the connection of the extension arm to the mechanical controller. The movements produced by both the rigid joints versus the pin joints were compared, as well as the movements from using a one-sided kinematic design versus a two-sided kinematic design.

Using benchmarking methods, the pin joints seemed to conform to the ideal movement of the overall pectoral fish fin. By using the pin joints, the extension arm was able to be varied and not completely constrained as seen with the rigid joints. This produced an overall range of movement from zero to 45 degrees within the horizontal direction when the fin rays were placed in a vertical orientation to imitate the continual stroke of the pectoral fin. This was useful in simulating the correct biological parameters that complied with the versatility of the pectoral fin's movements. The use of the pin joint could provide the movement of the overall fin ray without responses to the tip end of the fin rays, contributing another factor as observed in the complexity of the pectoral fin.

When comparing the one-sided kinematic design to the two-sided kinematic design, it was observed that the one-sided design would produce a great inflection of the fin ray end when subjected to a lateral force and therefore achieving an improved simulation of the ideal movements in the true biological system. Another advantage in this design focused on attaining a simpler mechanical form and structure to accomplish similar functions while maintaining the energy conservation of the muscles when reacted to varied forces.

4.2 Compression Spring Specifications

The cylindrical outsettings and insetting of the two-sided and one-sided extension arms of the joints were made to enclose a spring of Working Length (W.L.) of 10 mm. The diameter was made to enclose a 4 mm spring. After testing different combinations of compression springs with varied spring constants, a spring with a constant of K=0.45 was found that showed minimal strength in terms of its constant that it would not interfere with the natural responses of the small contractions, for instance, when the fin ray was attached to a conducting polymer.

The polymer would produce a range of lateral force from 0.098-0.49 N, producing a maximum movement on the connection end of the fin ray of ~20 mm. With such small parameters, a short spring with a small K was the most viable solution to maintain a certain amount of mechanical action and energy conservation displayed in the function of the muscles in the biological model of a sunfish.

4.3 Joint Attributes

4.3.1 Fish Fin End Movement- Connection to Fish Fin Ray

The final assembly of the two-sided kinematic pin-joint design is shown in Figure 14. Control was achieved through mechanical use of the mechanical compression springs placed in the cylindrical outsettings on either side of the extension arm. Through the use of the pin joint, as mentioned previous, an increase in the range of motion of the overall fin ray occurred.

4.3.2 Overall Fish Fin Movement- Connection to Mechanical Controller

The mechanical pin joint was chosen as having the specified properties of movement based on the parameters determined by the Bioinstrumentation Laboratory at this phase of development of an artificial fish fin. A design proposed by Laura Proctor previous to the one shown in Figure 6 is shown in Figure 16. The advantage of using this second design was to achieve a dual response from both sides when actuators are attached to the bottom ends of the fin ray. The same dimensions as the fin ray model in Figure 6 applied to this model: 120 mm in height and a tip of 5 μm. The fin rays were separate revealing a hollow core until reaching a height of 80 mm.

In order to attach the fin rays to the mechanical control, a hook attachment was designed as shown in Figure 17. The shape of the hook was suitable in order to grasp the coils of the spring in a secure fashion. Figure 18 shows how the hook spring attachment is assembled with the fin ray. The small dimensions helped support a tight junction between the spring and the fin ray.

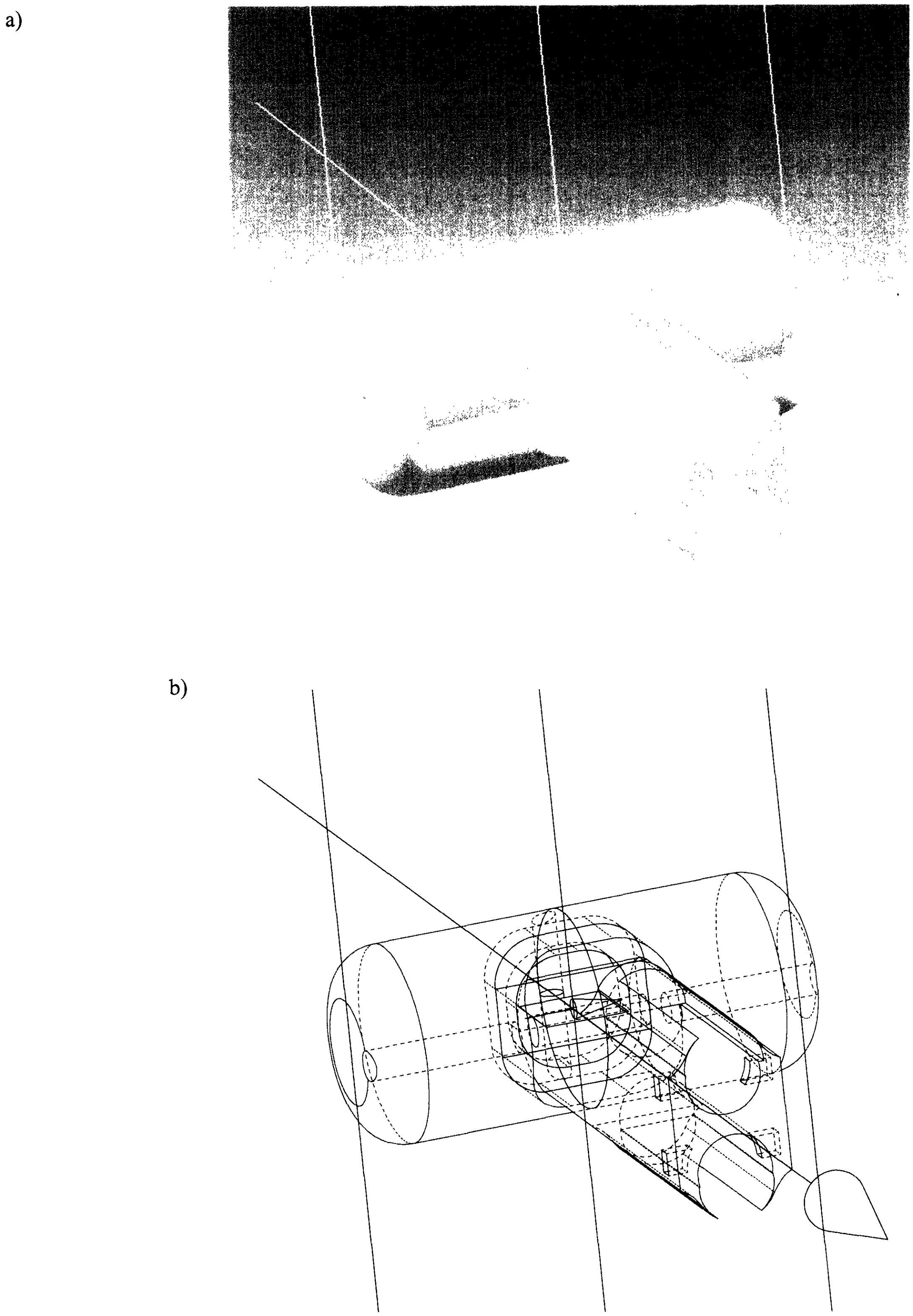

Figure 14. Assembly of final design: two- sided kinematic design for pin joint as modeled on Unigraphics NX. a) Solid model of the with clear maneuverability of the extension arm in the y-direction along the pin joint. b) Sketch model of the two-sided pin joint assembly.

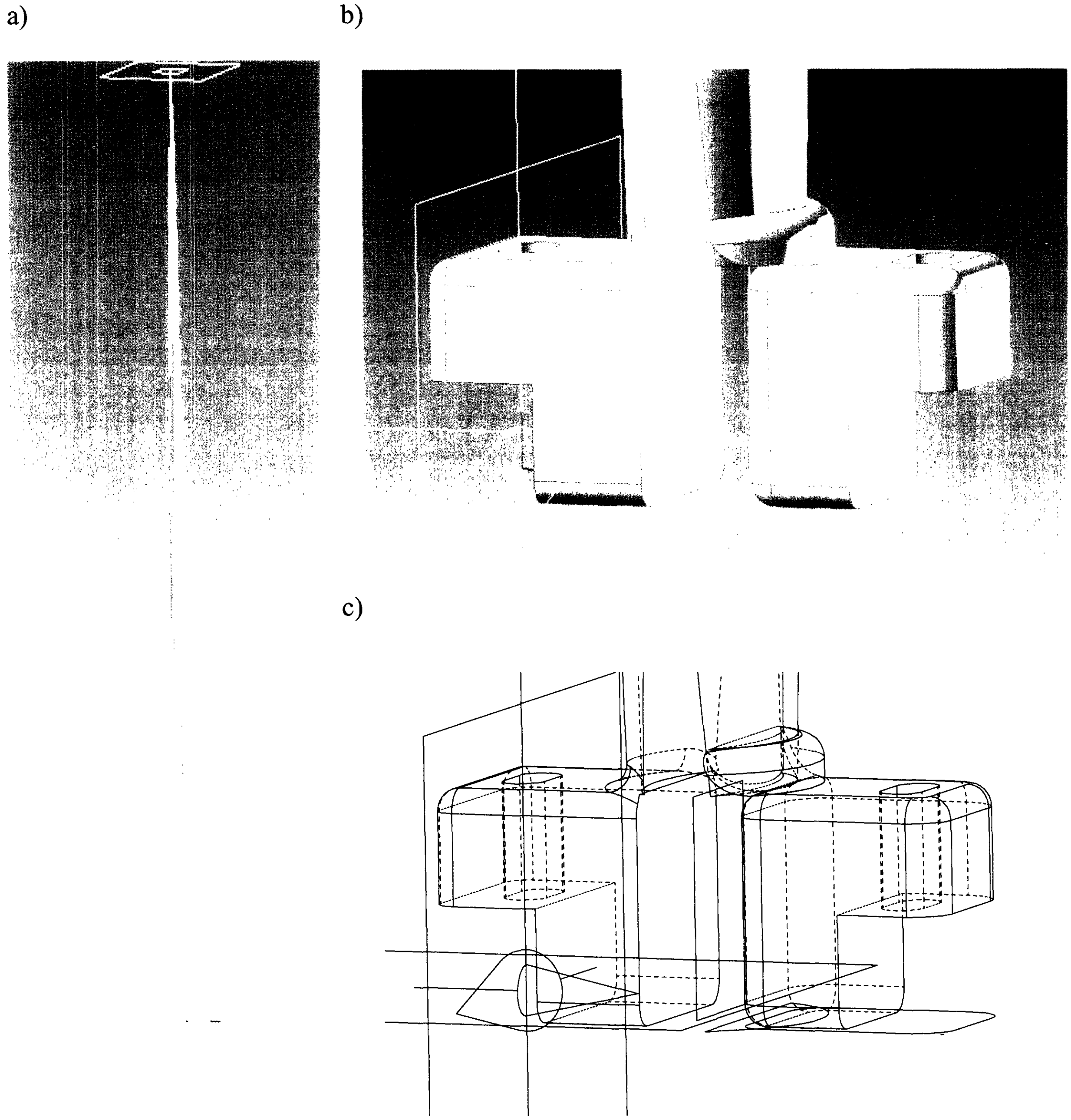

Figure 15. Design of the pectoral fin ray proposed by Laura Proctor. a) The entire fin design as modeled using Unigraphics NX software. The height of the fin ray is 120 mm and is hollow with two separate sides until reaching a height of 380 mm. b) The 3-D visual solid model of the bottom junction having two attachment sites for the device that will induce force or strain and thus a lateral movement. c) The 3-D sketch model of the bottom junction (taken from Laura Proctor).

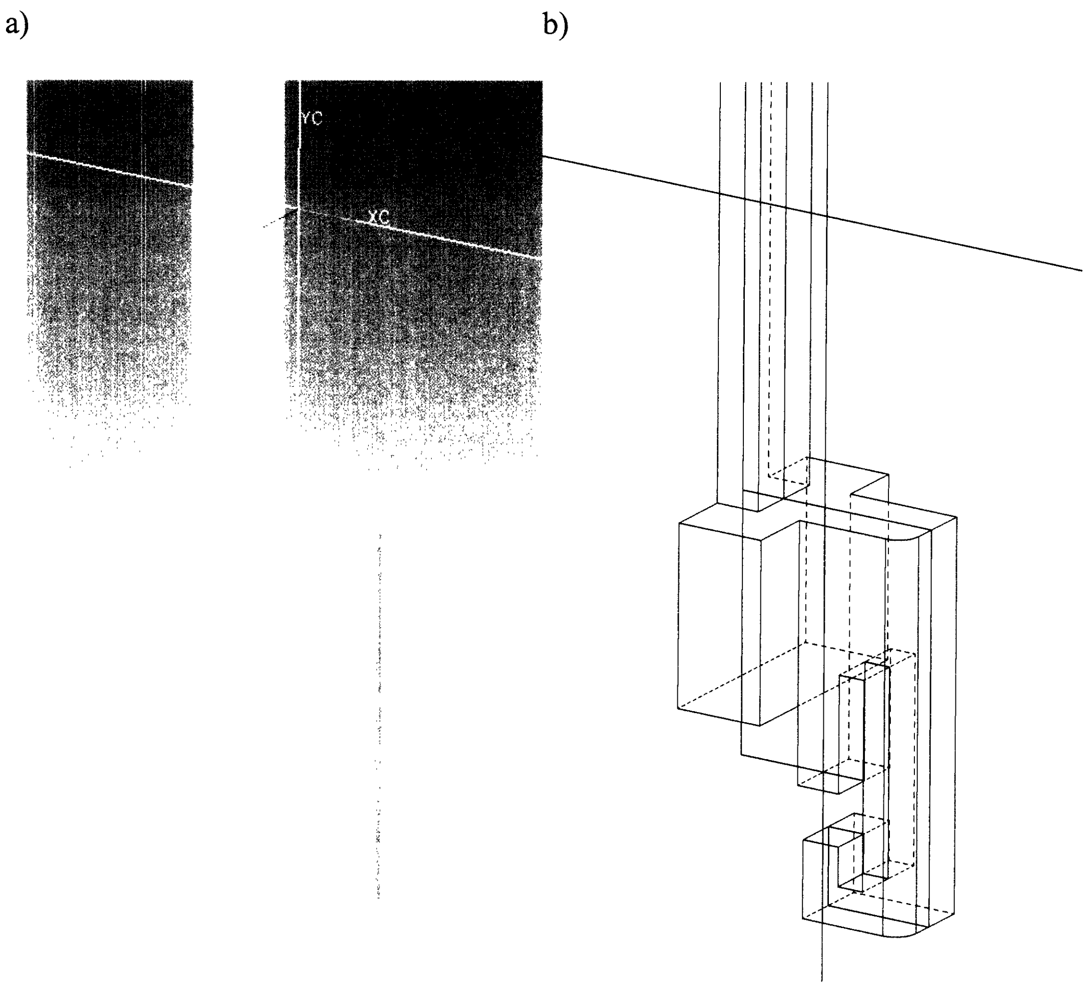

Figure 16. Hook spring attachment of the fin ray ends as modeled on Unigraphics NX. a) Solid model of the hook spring attachment. b) Sketch model of the hook spring attachment.

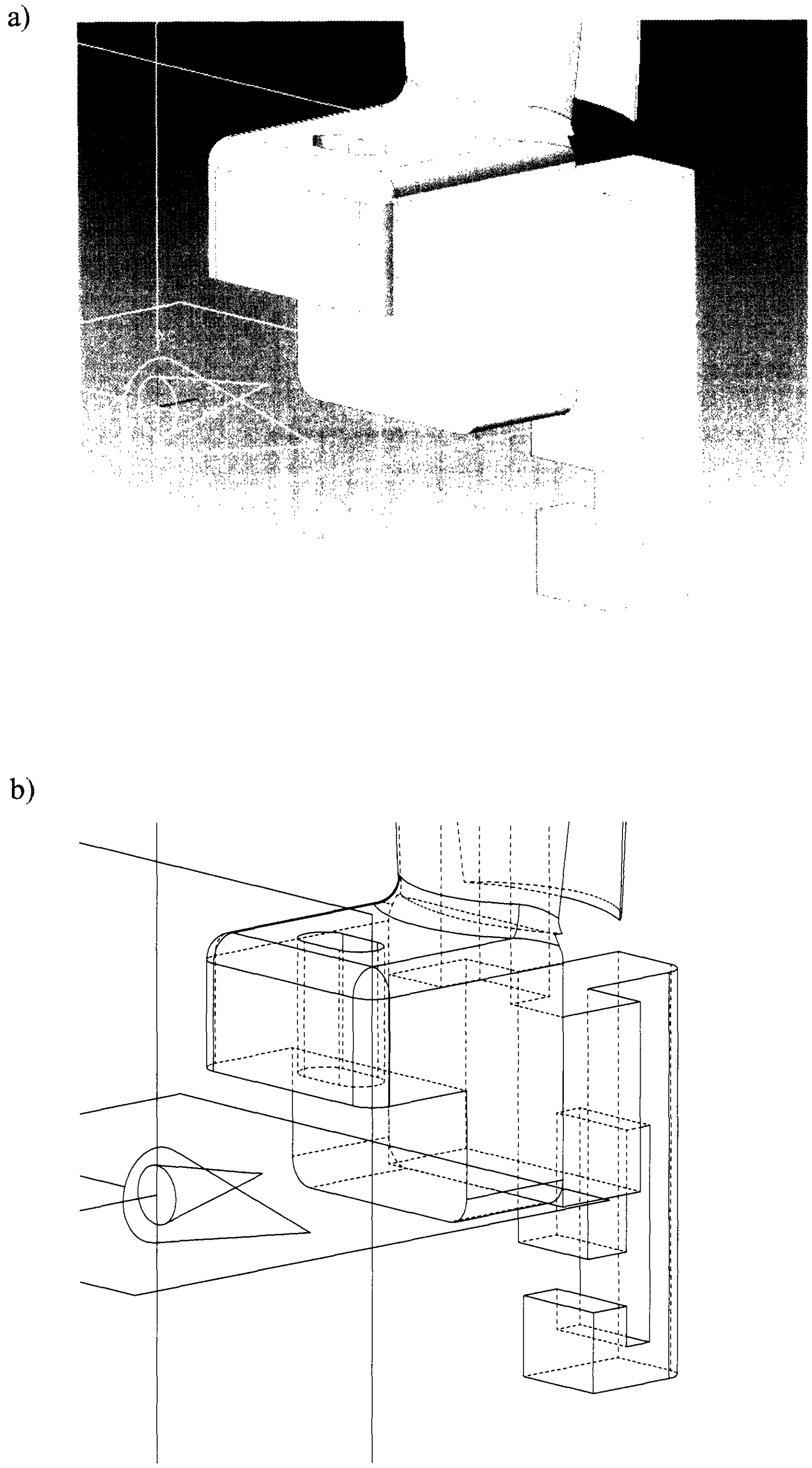

Figure 17. Assembly of fin ray design incorporating Laura Proctor's fin ray design and the attachment to spring as modeled on Unigraphics NX. a) Solid model of one end of the fin ray with attachment. b) Sketch model of the assembly.

4.4 Miscellaneous Specifications

4.4.1 Urethane Mold for Curvature Dynamics

In order to conform to the anatomical structure of the pectoral fish fin, through histological staining described in the Background section, it had been observed that the fin rays were held together by the pectoral girdle. The pectoral girdle itself had been observed to vary in curvature which produced motions of the fin rays that increased the radial distances between each fin ray. This again is another aspect of the observed kinematic motion in the vertical y-axis of the pectoral fin which was essential for complex control of movement within the fluid and was necessary to simulate.

To achieve a potentially varying curvature, the attachment joints, whether rigid or pin-joints, were attached in order to fit tightly into thermo-plastic transparent tubing that was 12.7 mm inner diameter (ID) × 14.29 mm outer diameter (OD). In order to initially attain a slight curvature, urethane molds were installed in specific sections of the tubing and sealed off the tubing ends with Vaseline, a petrochemical grease, which had inorganic properties that limited binding of the urethane to it. Urethane material is a polyether-elastomer that reacts similarly to an incompressible fluid. When a bar mold of urethane was subjected to a force on either ends, the volume of material from the compression of one side move in the form of a bulging side or added length which plays a beneficial role since as the curvature increases, there is a needed increase in length of the side being extended.

The desired curvature was constructed and held in place with clamps, and the pieces of plastic tubing with urethane were left to dry overnight. When dry, the Vaseline segments were removed and the pieces maintained their constructed curvatures. The joint segments could then be tightly fit onto the free ends of the plastic tubing. To avoid slip or reduced friction in this junction, the Vaseline was completely washed and removed with alcohol until the texture was not greasy. This step was highly important for attaining the correct orientation of the pectoral fin rays as compared with one another and in order to eventually attain kinematics data upon experimentation that most closely relates to actual biological functions.

3.4 Dimensional Versatility in Platform

Mainly, the purpose of the versatility in the platform was to have two options in orienting the fish fins- vertically or horizontally. All specifications of joints and coordinate axes refer to the vertical orientation of the pectoral girdle and the consequential horizontal movement of the pectoral fish fin. However, for experimentation purposes and to maximize the diversity and potential for future modifications of the model, versatility in the platform would be a beneficial feature.

5.0 RECOMMENDATIONS

A main constraint in designing and modeling the parts was the use of the Unigraphics NX software in an efficient manner. I had used previous to this project similar software, such as SolidWorks; however, learning the features in Unigraphics NX took much time. As well, because of the limited knowledge of features goes hand in hand with a limited design. Gaining an increased skill in modeling in Unigraphics NX would be a beneficial tool in improving the joint design. As well, feature such as simulations can be performed on Unigraphics NX. Instead of allocating time spending making the parts on the 3-D SLA printing machine, the parts and their connections or responses could be simulated on Unigraphics NX. This would make comparing separate designs more efficient.

Improvements on the actual joints would also be beneficial as the development of the artificial fish fin progresses. The biomimetic joint is a purely mechanical joint and is actually quite complex in nature since there are many connections to either the mechanical controls or the actuators. Future designs should incorporate a simplified model, for example in making the fin ray tip movement and overall fin ray movement respond from one actuator.

An addition to the simplification of the mechanical model, testing of different materials that are similar in properties to the pectoral fin rays and muscles could be further studied. The production of artificial muscles in the biomimetic model would help to further simplify the design by incorporating the determined biological responses from the specific properties of the materials, rather than using a design with purely mechanical features.

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