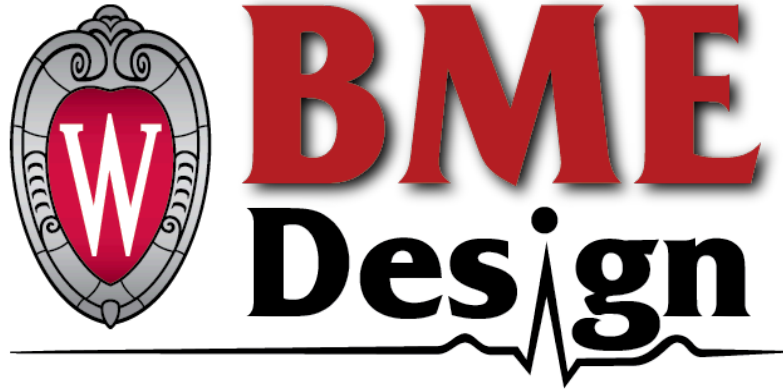




ADAPTIVE OVERHEAD TREADMILL FOR FREELY MOVING SWINE

PRELIMINARY DESIGN REPORT

Fall 2026 BME 300/200 Lab 308

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Abstract

When cardiac arrest occurs, effective blood flow throughout the body stops, quickly depriving the brain of oxygen. Little is currently known about the short-term effects of this brain deoxygenation on patient recovery and rehabilitation, which is why the University of Wisconsin-Madison Department of Neurosurgery is studying the short-term effects of cardiac arrest on the pediatric brain. To do this, a cerebral open flow microperfusion (cOFM) will be used to monitor the effects once a cardiac arrest takes place on a swine model. The Department of Neurosurgery has developed a cranial catheter fixation device that secures neuromonitoring catheters to the swine subject's cranium. The Neurosurgery team requires the development of a complementary system that integrates with the cranial catheter fixation device and continuous monitoring equipment, while also allowing the swine subjects to engage in natural behaviors such as feeding and resting. To address this, a harness-tether system called the *SwineSupport* will be developed. The SwineSupport system protects the integrity of the neuromonitoring catheters while allowing the pig to comfortably engage in natural behaviors. This solution allows the team to forgo costly long-term anesthetization of the pig and obtain relevant recovery data.

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Introduction

The UW–Madison Department of Neurosurgery is developing a chronic large-animal neuromonitoring platform that uses multiple intracranial catheters for continuous brain interstitial fluid sampling. The Neurosurgery Department is studying the short-term effects of cardiac arrest on the brain, specifically in pediatric patients. Pediatric cardiac arrest affects more than 20,000 children annually in the United States [1]. These cases are largely made up of infants under 1 year old, and roughly 6-10% of these children survive to hospital discharge [2]. When cardiac arrest occurs, effective blood flow throughout the body stops, quickly depriving the brain of oxygen. Post-cardiac arrest brain injury caused by this oxygen-deprivation is the main cause of death in patients resuscitated from cardiac arrest, and the main cause of long-term disability in those who survive the acute phase [3].

For this large-animal neuromonitoring platform, Wisconsin Miniature swine [4] will be used due to their physiological similarities to humans [5]. Current neuromonitoring methods require researchers to keep the swine subject anesthetized 72-96 hours post acute respiratory distress to record and measure health parameters. This long-term anesthetization does not accurately reflect standard recovery conditions and is expensive, costing the Department of Neurosurgery \$3,000 per day to maintain [6].

The goal of the project is to develop a system that allows swine subjects to actively recover from acute respiratory distress while under continuous monitoring without the use of long-term anesthetization. A cranial catheter fixation device that organizes and fixes the catheters to the swine's skull has been developed for this project; however, it requires a complementary overhead system to manage the catheters extending from the port and allow the animal to move

naturally within a stationary enclosure. The developed system must dynamically follow the animal, maintain appropriate tubing length, minimize tensile and rotational forces, prevent entanglement or kinking, and allow normal behaviors. Several current large-animal monitoring systems exist, however these systems were developed to monitor cardiovascular health, not brain health, and thus do not accommodate the required neuromonitoring equipment.

Background

The client, Dr. Marco Failla Mulone (MD), is a post-doc research associate at the University of Wisconsin-Madison's Department of Neurosurgery. Dr. Failla Mulone works under Dr. Dominic Siler (MD, PhD), who is a UW Health neurosurgeon and an assistant professor in the Department of Neurological Surgery at the University of Wisconsin School of Medicine and Public Health. Dr. Failla Mulone and Dr. Dominic Siler are developing a chronic large-animal neuromonitoring platform using multiple intracranial catheters for continuous or repeated brain interstitial fluid sampling to study the short-term effects of cardiac arrest on the brain. Heart attacks are one of the most common causes of nontraumatic brain injuries. This is because cardiac arrest disrupts the supply of blood and oxygen to the brain, which is essential to maintain healthy brain function [7]. Current research proposes that the brain ages the equivalent of several years within the few minutes taken to resuscitate a patient from cardiac arrest [8].

Current research on comparative mapping of functional and structural homologies across humans, small animals, and nonhuman primates shows that swine are a promising alternative because of their neuroanatomical and physiological similarities to the human brain [5] [9]. Cross-species comparisons have found substantial similarities in major white matter pathways and their spatial organization and supporting structural correspondence. Therefore, the swine

model is supported as a neurobiologically relevant method for investigating human brain function, structural organization, and related neurological disorders.

The University of Wisconsin-Madison breeds and maintains several lines of swine, including the Wisconsin Miniature Swine (Figure 1). The Wisconsin Miniature Swine (WMS) is specifically bred for biomedical research as the physiology of the breed more closely resembles humans when compared to conventional breeds. At full maturity, the WMS are approximately the size of an average human. Additionally, WMS easily accommodates the use of human clinical medical devices and imaging modalities such as PET/CT and MRI in research [4]. Because of this, the Department of Neurological Surgery plans to utilize the WMS for their study.

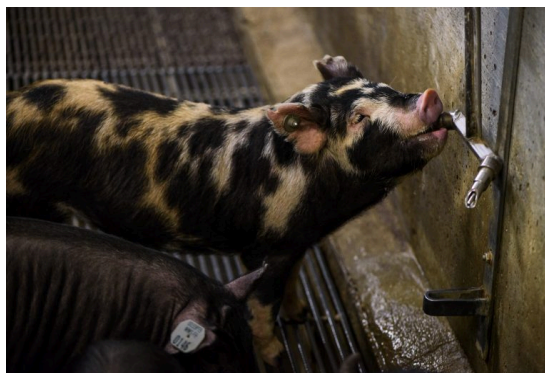


Figure 1. The Wisconsin Miniature Swine (WMS) is bred specifically for biomedical research due to its physiological similarities to humans. WMS will be used by UW-Madison's Department of Neurosurgery for their research into the short-term effects of Cardiac Arrest on brain health [2]. (Photo by Jeff Miller/UW-Madison)

The client will first introduce the WMS to the study at two weeks of age. At this point, baseline health information such as, but not limited to, intracranial pressure, brain tissue oxygen levels, and spinal interstitial fluid composition will be collected over a period of up to a week. After baseline health information is collected, the client will induce cardiac arrest in the porcine model and perform cardiopulmonary resuscitation (CPR) to evaluate the subsequent

neuroprotective and neuropathological effects on the brain. Because of the swine model's immaturity, the developed system will need to account for the growth of the swine subject throughout the study, as during their peak juvenile growth stage, WMS grows roughly 0.2 to 0.4 kg per day [4].

Currently, the client monitors these effects by keeping the swine model under anesthesia for 72-96 hours post-cardiac arrest. This prolonged anesthetization costs the Department of Neurosurgery up to \$3,000 per day to maintain. Additionally, because the swine are kept in a state of unconsciousness after the procedure, the neurochemical results are less applicable to human post-cardiac arrest recovery, as the majority of individuals who experience a cardiac arrest and survive to discharge awaken within 72 hours [10]. Therefore, Dr. Failla Mulone and Dr. Siler require the development of an overhead system that integrates with a pen enclosure and manages tubing and cables extending from the cranial fixation device (Figure 2). The team's focus is on developing the harness and tether portion of the overall system.

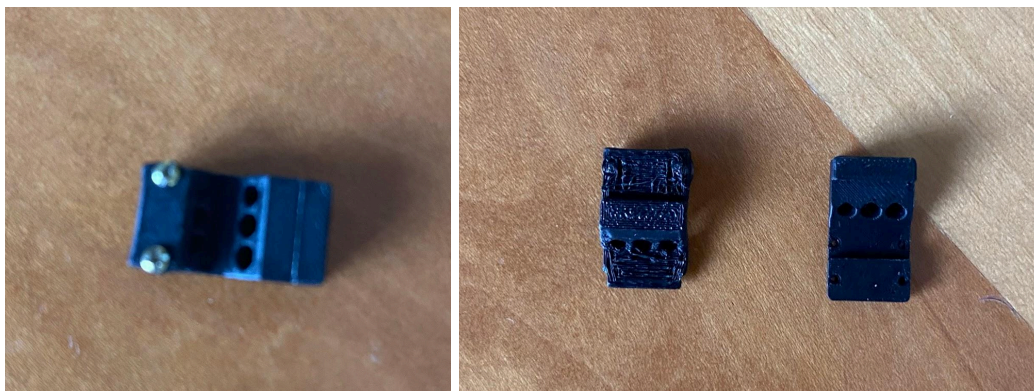


Figure 2. Cranial fixation device developed by Dr. Failla Mulone to permanently secure neural monitoring catheters to swine skulls. The left-most image features the fully assembled device as it would be mounted onto the pig skull. The image on the right features the disassembled fixation device, as it would be before securing the catheters. The three ports allow for three individual catheters to be implanted; however, the cranial fixation device can be fabricated with additional ports as needed. This cranial fixation device would be secured to the pig skull via glue cement.

The overall system developed must prioritize the safety and integrity of the permanent intracranial catheters. This includes minimizing the tensile and rotational forces these catheters are subjected to, reducing tugging or pulling at the intracranial fixation site, and reducing the likelihood of the animal being harmed by becoming entangled or strangled. The overall system must also minimize undue stress on the pig, and stress factors such as noise, visual motion, and range of motion need to be considered. It is important to minimize environmental stress for the swine subjects, as stress will negatively affect the integrity and relevance of the study's results due to the effects of stress-related hormones [11][12]. More thorough design specifications can be found in the Product Design Specifications document in Appendix A.

Previous and Competing Designs

There have been several published systems developed for continuous large-animal monitoring. However, none that fully satisfy the client's needs are commercially sold. Three of such systems include the "Animal Cage with Motor Assisted Swivel" (Figure 3) [13], "A tether system for cardiovascular studies with the behaving micropig" (Figure 4) [14], and the PigTurn® Prototype (Figure 5) [13].

The "Animal Cage with Motor Assisted Swivel" system in Figure 3 allows for the integration of fluid conduits or electrical or optical leads inside a semi-flexible metal cover. A switching mechanism determines the direction of rotation of the tether and activates a motor to rotate the swivel in the direction of rotation. When rotation of the tether stops, further rotation of the swivel triggers the mechanism to deactivate the motor [15]. Despite its ability to integrate catheters, there is minimal room for the monitoring and collection equipment to be stored at the end of the tether. Additionally, the tether restricts the pig's movement to the length of the catheter

and does not protect catheters from animal behavior (i.e., resting and rolling). Although this design features these drawbacks, the team adopted a version of the semi-flexible metal lead cover into preliminary design proposals.

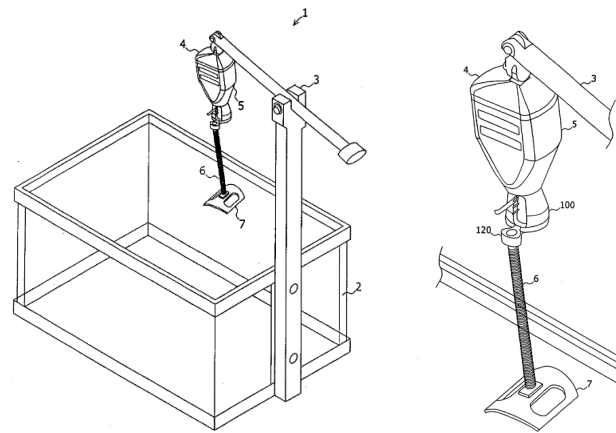


Figure 3. “Animal Cage with Motor Assisted Swivel” US20050076847A. A competing design for a motor-assisted swivel system with an attached harness [13].

The tether system for cardiovascular studies with the behaving micropig [14] featured in Figure 4 was developed for the continuous monitoring of blood pressure in the micropig. The system consists of a metal boom, attached via a universal joint to a wall 6 feet (approximately 1.83 meters) above floor level, that extends horizontally to the center of the enclosure. Additionally, a fluid electronic swivel fixed to the boom is connected to a flexible, hollow, metal tether that descends to a vest worn by the micropig. This system was found to be effective for continuous studies over intervals of a month or more. Unlike the design specifications outlined by Dr. Failla Mulone (Appendix A), this system does not move with the pig subject, as the tether system is anchored to the wall. Despite this, the team adopted the function of a universal joint and a flexible, hollow, metal tether in preliminary design proposals.

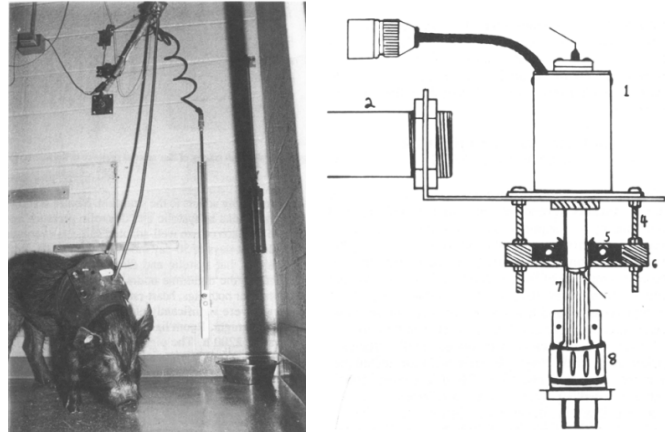


Figure 4. “A tether system for cardiovascular studies with the behaving micropig”. A competing system that is designed for animals over 35 lbs and features a flexible catheter protection cover [14].

The PigTurn® prototype [15] was one of Dr. Siler’s main points of inspiration for this project. The PigTurn® prototype is a ‘scale-up’ of Bioanalytical Systems Inc.’s successful RatUrn®, in which the animal’s pen counter-rotates in response to the animal subject’s movement. This function prevents catheters from twisting and blocking, and allows the animal subject to engage in semi-normal behaviors including rooting, feeding, and resting. While the prototype integrates the necessary monitoring equipment and allows the animal subject to “explore” its enclosure, the clients want a system that accommodates the pig to the environment, not the environment to the pig, unlike the PigTurn®. This is because Dr. Failla Mulone and Dr. Siler do not want the swine subject to feel restricted in their environment, as this is a known stressor for animal subjects.

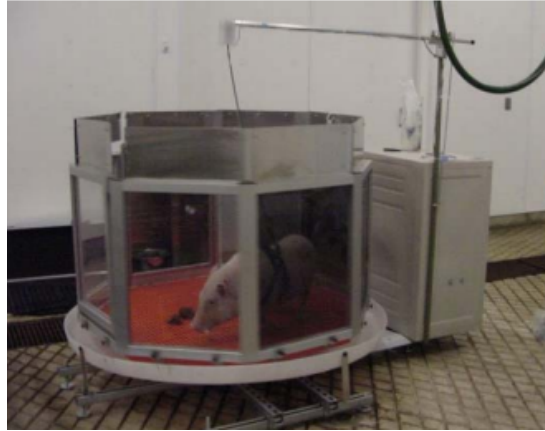


Figure 5. The PigTurn® Prototype is a competing design featuring an above-head fixed-point tether system and counter-rotating pen that moves in reaction to the animal's movement. This counter-rotation prevents catheters from twisting and blocking, while simultaneously allowing the pig to engage in normal behaviors such as eating, drinking, napping, and moving about its environment. This prototype was designed through a collaboration between the Livestock Behavior Research Unit and Bioanalytical Systems Inc. (BASi) of West Lafayette [15].

Preliminary Designs

Preliminary Tether Designs

Design 1: Vacuum Hose Tether Cover

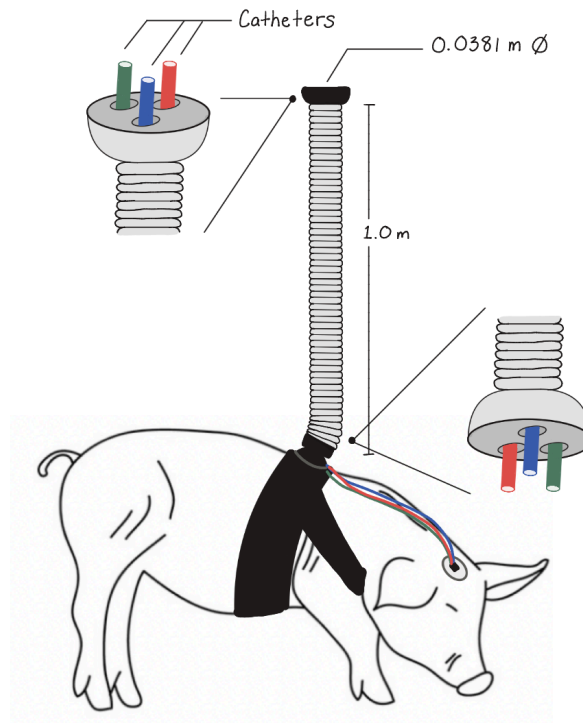


Figure 6. The Vacuum Hose Tether Cover design features a semi-flexible corrugated length and catheter organization system. The tether cover provides structural support to the catheters and protects the catheters from pulling and twisting.

The vacuum hose tether cover design (Figure 6) features a semi-flexible, corrugated shaft that encloses the set of catheters. This tether cover protects the catheters from tensile forces and debris from the environment. The tether cover has a total length of approximately 1.0 meters and a diameter of approximately 38.1 millimeters, allowing the system to accommodate at least 3 catheters. In addition, this design includes a catheter organization system that is composed of two

plate covers, one secured on each end of the tether cover. These plate covers feature boreholes that maintain the alignment and organization of the catheters within the tether.

Design 2: Wireless Tether

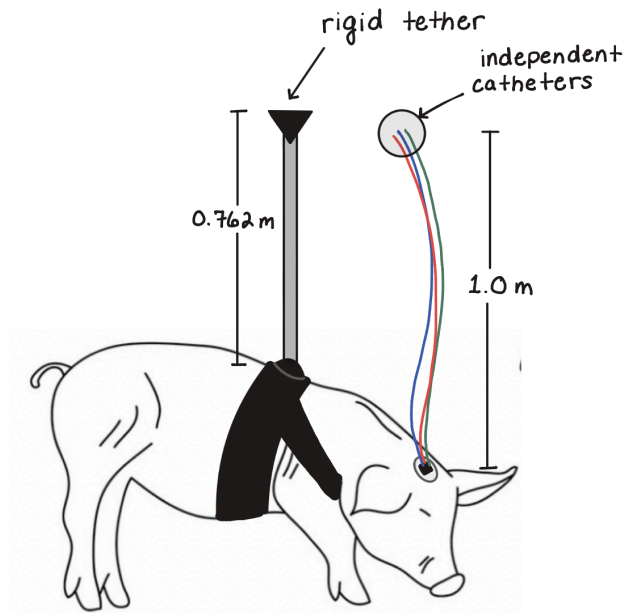


Figure 7. The Wireless Tether design features a restrictive tether that acts independently of the catheters. This restrictive tether is shorter in length than the reach of the catheters, thus preventing the catheters from being pulled from the insertion site.

The Wireless Tether design (Figure 7) features a restrictive tether that acts independently from the catheters. The Wireless Tether was specifically designed to be shorter in length than the independent catheters. This is to ensure that the brunt of the tensile forces the system experiences are borne by the tether, rather than by the catheters themselves. This reduces the likelihood of the catheters being pulled from the insertion site or otherwise causing site irritation or harm to the pig model.

Design 3: Rigid Hollow Rod Cover

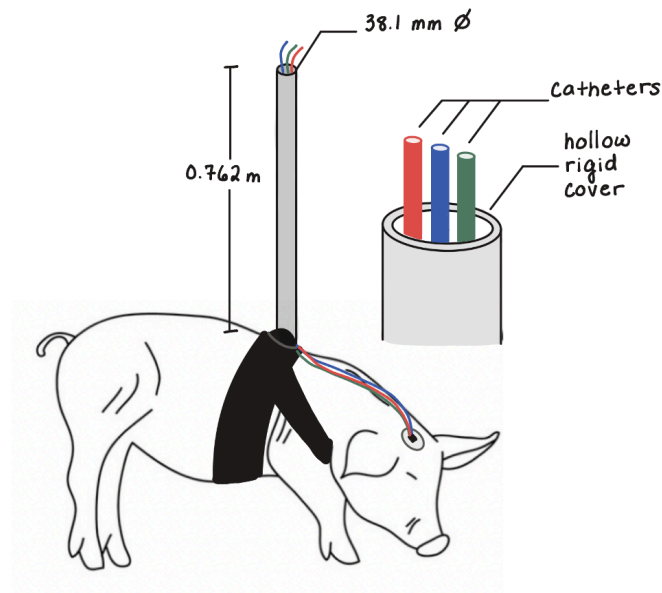


Figure 8. The Rigid Hollow Rod Cover features a rigid catheter cover that protects the catheters from tensile forces and provides direct translation of rotational forces from the swine harness.

The Rigid Hollow Rod Cover (Figure 8) features a rigid catheter cover that protects the catheters from tensile forces, bending, kinking, and environmental debris. Because of its rigidity, this design is able to translate rotational forces to a connected system. This ability to translate rotational forces could be used to develop a complementary equipment organizational system that prevents the entanglement of catheters within the rigid hollow rod cover. This tether design can accommodate at least three catheters and can be easily scaled to fit the changing needs of the client.

Preliminary Harness Designs

Design 1: Traffic Cone Harness

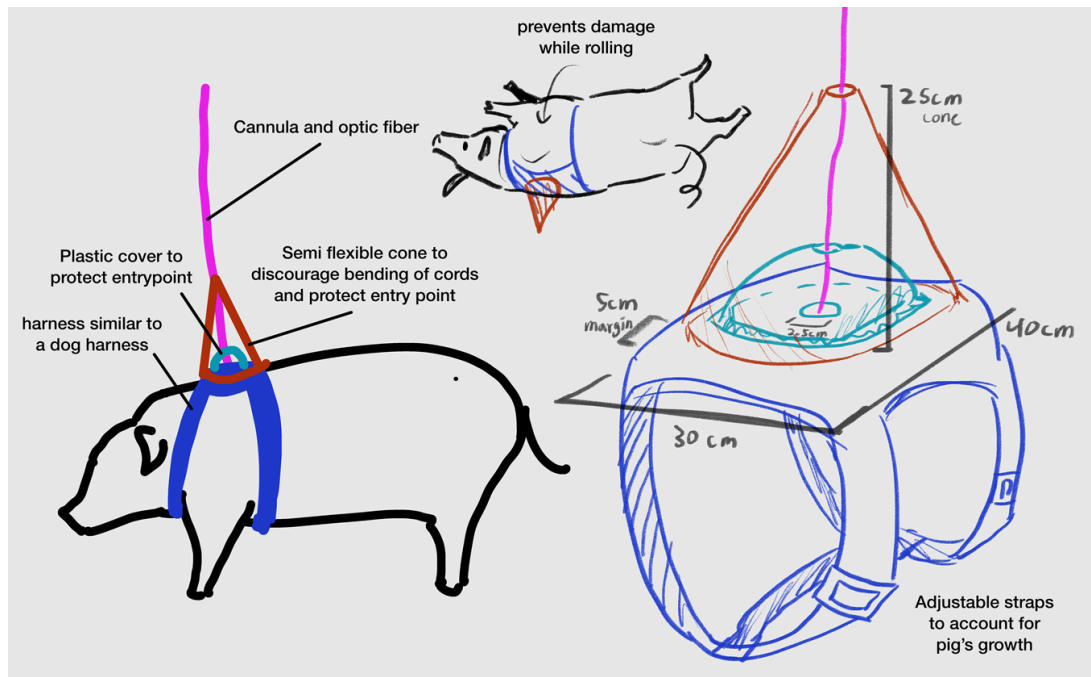


Figure 9. The Traffic Cone Harness design features a cone-shaped cover that sits above the catheter anchor point. This cover prevents damage to the catheter insertion site caused by the pig subject rolling and provides an additional layer of stability and structural support to the catheters.

The Traffic Cone Harness design (Figure 9) integrates a standard medium-sized dog harness design with a semi-flexible cone-shaped cover. This cone-shaped cover sits above the catheter anchor point and prevents damage to the catheter insertion site caused by the pig subject rolling onto its back and side. In addition, the cone cover provides extra stability and structural support to the lower length of the catheters at the point where they are at the greatest risk of experiencing tensile and rotational stresses. The harness features adjustable straps to accommodate the rapid growth rate of the young pig subjects, and provides a window for veterinary staff to apply and monitor wound dressings.

Design 2: Piggyback Harness

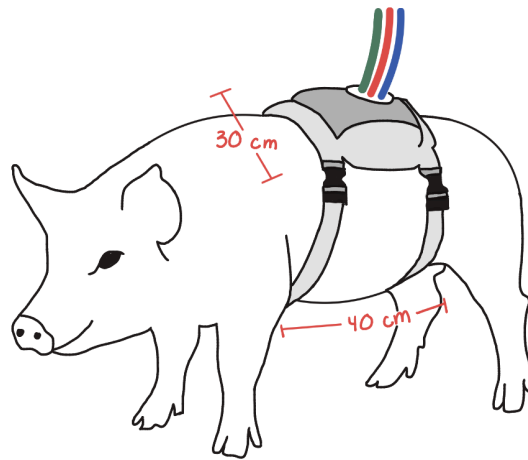


Figure 10. The Piggyback Harness is secured around the swine subject's barrel and features adjustable straps to accommodate the fast-growing pig.

The Piggyback Harness (Figure 10) is modeled after the AI-generated image provided by Dr. Failla Mulone (Figure 11). This harness design is secured around the swine subject's barrel and features adjustable straps to accommodate the fast growth rate of the young pigs. The harness incorporates a port through which the catheters feed through, and provides structured padded protection around the catheter insertion site to reduce site irritation. This design is contingent on the client using a catheter insertion site above the cranial thoracic region.

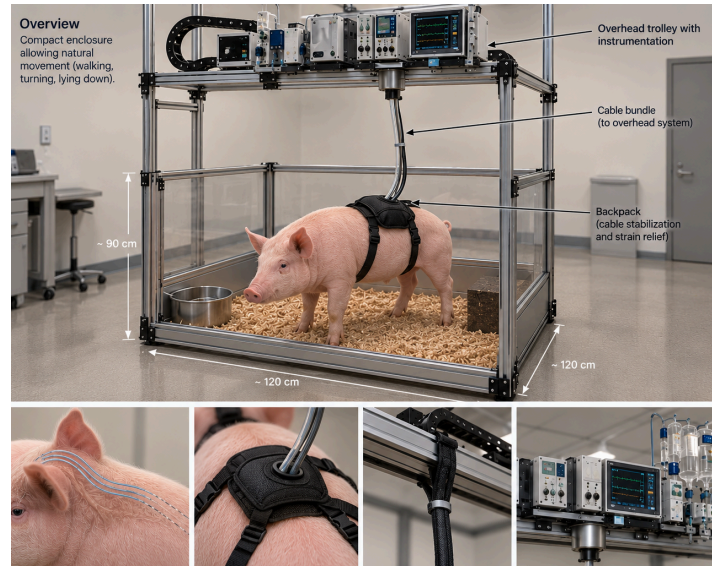


Figure 11. Image provided by Dr. Failla Mulone as a visual guide for the project overview. This design outlines the client's expectations regarding the integration of the tether and harness system with a computer-tracking equipment platform.

Design 3: Basket Harness



Figure 12. The Basket Harness Design is directly derived from a standard nylon dog harness like the PETSAFE Easy Walk Dog Harness [16].

The Basket Harness Design (Figure 12) is directly derived from a standard nylon dog harness, like the PETSAFE Easy Walk Dog Harness [16] (Figure 13). This design features several means of adjustability, as well as three D-hook locations that can be used by veterinary staff to secure the swine subject for veterinary procedures and to connect the harness and tether system together. This is a durable design that can be reused between subjects without issue. In addition, the snap buckles allow for quick application and removal of the harness, and the chest and barrel straps allow for direct translation of movement for future integrated systems.

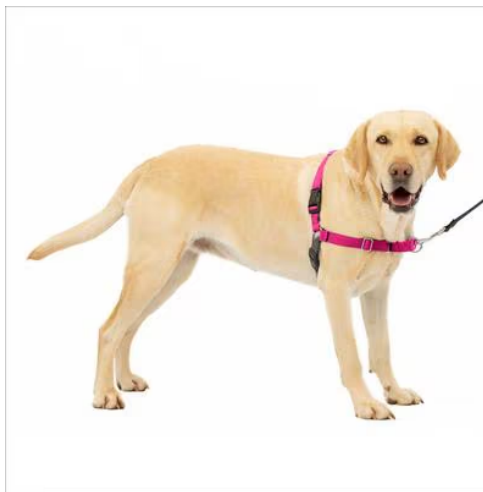
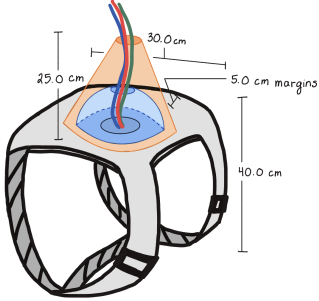
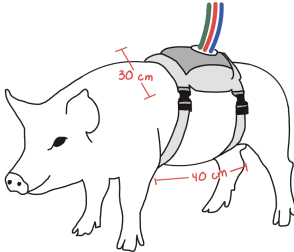


Figure 13. The PETSAFE Easy Walk Dog Harness [16] was used as a model for the Basket Harness Design due to its design simplicity and easy use.

Preliminary Design Evaluation

Tether Design Matrix

Table 1. The design matrix compares the final three design ideas for the harness across five relevant categories, with the weight of each being determined by the project's requirements and the importance of allowing natural movement.

HARNESS DESIGN MATRIX		Design 1: Traffic Cone Harness		Design 2: PiggyBack		Design 3: Basket Harness	
							
Design Criteria		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Catheter Protection	25	4/5	20	3/5	15	2/5	10
Pig Safety	20	4/5	16	3/5	12	4/5	16
Size Scalability	20	5/5	20	4/5	16	4/5	16
Mobility	20	2/5	8	3/5	12	4/5	16
Cost	15	3/5	9	3/5	9	4/5	12
Total	100	73		64		70	

The design evaluation compared three prototypes: the Vacuum Hose Tether Cover, Wireless Tether, and Rigid Hollow Rod Cover. Each design was assessed according to 6 criteria:

Subject Safety and Comfort, Fiber Optic Catheter Protection, Catheter Entanglement Prevention, Ease of Use, Future Scalability, and Cost. The criteria were weighted according to their relative importance to the client's requirements, and each design was assigned a score based on its ability to satisfy the corresponding criterion.

Subject Safety and Comfort (30%):

Subject Safety and Comfort received the highest weighting because the client's primary need for the tether management system is to protect the swine from injury during neuromonitoring while allowing natural movement within the enclosure. This criterion evaluated each design's ability to manage tensile forces to reduce the likelihood of intracranial tubing being pulled from the insertion site. Both the Vacuum Hose Tether Cover and the Rigid Hollow Rod Cover designs received scores of 3 because their protective outer covers can shield the catheters from external forces, preventing them from being pulled from the insertion site. However, neither design can fully transfer tensile loads away from the catheter insertion site. Although the shorter length of the Wireless Tether design allows it to bear tensile loads independently of catheters, it received a score of 2 due to the high amount of tensile loads still able to reach the catheter insertion sites without any protective covering to help absorb these loads.

Fiber Optic Catheter Protection (25%):

Fiber Optic Catheter Protection received the second highest weighting due to the fiber optic cable only being able to withstand bending within 20 times the diameter's radius, making it necessary for the fiber optic catheter to remain within its allowable bending radius to maintain its structural integrity and functionality. This criterion evaluated each design's ability to limit bending of the fiber optic cable during the swine's movement. The Rigid Hollow Rod Cover was

assigned the highest score of 5 because its rigid structure limits and protects the fiber optic catheter against any external bending forces. The Vacuum Hose Tether Cover received a score of 4 because its semi-flexible cover design limits the bending of the fiber optic catheter, but also allows for some bending under certain loading conditions. Because the Wireless Tether design does not enclose the catheters, the design received a score of 1, since it leaves the catheters more exposed to external bending forces.

Catheter Entanglement Prevention (20%):

Catheter Entanglement Prevention was assigned a weighting of 20% because even though catheter entanglement could compromise the experiment's data and results, the experiment would still be able to be performed and completed. This criterion evaluated each design's ability to organize the catheters and accommodate rotational movement without causing them to become tangled. The Vacuum Hose Tether received a score of 5 due to its incorporation of a swivel mechanism that will rotate along with the intracranial tubing's rotation to maintain catheter separation during rotational movement of the swine. The Rigid Hollow Rod received a score of 2 since its rigid structure can limit the amount of rotational force able to be applied to the catheters, but cannot fully limit and prevent entanglement under rotational forces. The Wireless Tether design received a score of 1 as the design does not provide any structure that maintains the catheter alignment and organization to prevent catheter entanglement during the swine's movement.

Ease of Use (10%):

Ease of Use was weighted 10% as an efficient setup and maintenance process helps minimize variability in experimental workflows, but doesn't have a direct impact on results and

data obtained from the experiment. This criterion was evaluated on the accessibility of the catheters and ease of threading them through each design. The Wireless Tether scored a 5 because its independent tether does not enclose the catheters, allowing the catheters to be accessed and positioned directly. The Rigid Hollow Rod cover received a score of 4 since the catheters must be threaded through the rigid cover, but require little difficulty in doing so. The Vacuum Hose Tether received a score of 1 because the catheters must be threaded through the swivel, requiring precision that makes it difficult to use the design with the experiment.

Future Scalability (10%):

Future scalability was also weighted 10% since the client will use the device with additional equipment in future neuromonitoring studies, but accommodating future expansions is secondary to the device's primary goals. This criterion was assessed based on how easily catheters could be incorporated within the tether design. The Wireless tether received a score of 5, as more catheters can be added with little to no difficulty. The Rigid Hollow Cover received a score of 4, as the rigid tubing provides extra space for the insertion of more catheters. The Vacuum Hose Tether received a score of 2, as the extra catheters can only be incorporated in limited amounts due to the need to increase the number of holes in the swivel without hindering its function.

Cost (5%):

Cost received the lowest rating as the client gave us a budget of \$10,000 to adhere to, providing substantial flexibility for prototype development. The criterion evaluated the material and fabrication costs associated with each design. The Wireless Tether design received a score of 5 because it requires few components and primarily relies on a tether that can be purchased or

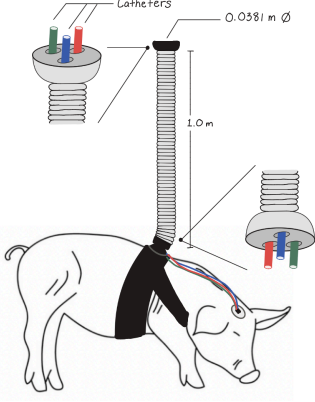
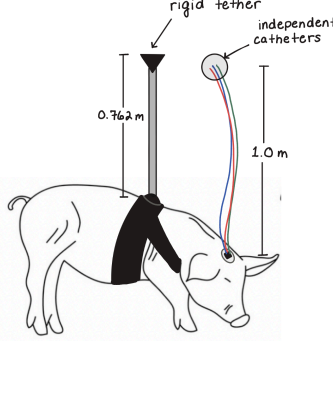
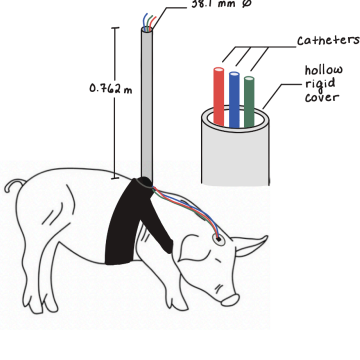
fabricated at a low cost. The Vacuum Hose Tether scored a 4, as the material needed for the swivel and end plates introduced additional cost. The Rigid Hollow Cover received a score of 3, as the rigid cover and organizational components may require more expensive materials and fabrication.

Final Design:

The Vacuum Hose Tether and Rigid Hollow Rod Cover tied with the highest weighted score of 68. Since the Vacuum Hose design was well-suited for Subject Safety and Comfort and Catheter Entanglement Protection, while the Rigid Hollow Rod Cover provided Subject Safety and Comfort and also Fiber Optic Catheter Protection, the tether designs were combined to create a final tether design that allowed for Subject Safety and Comfort, Fiber Optic Catheter Protection, and Catheter Entanglement Protection.

Harness Design Matrix

Table 2. The design matrix compares the final three design ideas for the harness across five relevant categories, with the weight of each being determined by the project's requirements and its compatibility with catheters.

TETHER DESIGN MATRIX		Design 1: Vacuum Hose Tether Cover		Design 2: Wireless Tether		Design 3: Rigid Hollow Rod Cover	
							
Design Criteria		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Subject Safety and Comfort	30	3/5	18	2/5	12	3/5	18
Fiber Optic Catheter Protection	25	4/5	20	1/5	5	5/5	25
Catheter Entanglement Prevention	20	5/5	20	1/5	4	2/5	8
Ease of Use	10	1/5	2	5/5	10	4/5	8
Future Scalability	10	2/5	4	5/5	10	3/5	6
Cost	5	4/5	4	5/5	5	3/5	3
Total	100		68		46		68

The design evaluation compared the three prototypes: Traffic Cone Harness, PiggyBack, and Basket Harness, against the 5 criteria: Catheter Protection, Pig Safety, Size Scalability, Mobility, and Cost. Each criterion was assigned a weighting based on its importance to the client's requirements, and each design was scored according to its ability to meet those requirements.

Catheter Protection (25%):

Catheter Protection was given the highest weighting because protecting the intracranial catheters and their insertion sites from damage during the swine's natural movements is a primary design requirement. The criteria evaluated each harness's ability to protect the catheter insertion site from external contact and reduce the risk of catheter kinking or damage. The Traffic Cone Harness received a score of 4 because the design encompasses a semi-flexible cone-shaped cover above the catheter anchor point that provides a protective barrier on the lower ends of the catheters from kinking and rotational forces. The Piggy Back design received a score of 3 since structured padding surrounding the catheter insertion site reduces the amount of rotational force from the catheters to the insertion site. However, it doesn't provide the same extended protective coverage as the Traffic Cone Harness. The Basket Harness was given a score of 2 because its adjustable straps and attachment points secure the harness to the subject, reducing a slight amount of rotational forces on the catheters. However, it does not have a protective structure around the catheter insertion site.

Pig Safety (20%):

Pig Safety was assigned the next highest weighting because the harness must minimize skin irritation, excessive pressure, and potentially harmful forces to the swine. However, this

criterion was not as important as catheter protection for the harness design. This criterion was evaluated on the harness's ability to reduce the amount of irritation it had on the pigs' skin and its coverage and fit on the swine. Both the Basket Harness and Traffic Cone Harness were given scores of 4. The Basket Harness received this score because its lightweight nylon construction and adjustable straps provide a relatively simple fit without adding excessive weight that would increase friction on the pig's skin, but it does not protect the insertion site of the catheters on the pig. The Traffic Cone Harness was also given a score of 4 because its semi-flexible protective cone protects the pig near the catheter insertion site, but it also introduced more weight onto the pig's back that could increase the likelihood of irritation to the pig's skin. The PiggyBack design was given a score of 3 because its padded structure around the catheter insertion site may introduce additional contact, pressure, or friction onto the swine's back.

Size Scalability (20%):

Size Scalability was also given a weighting of 20% due to the device needing to accommodate the rapid growth of 2-4 week old swine during the experiment. This criterion evaluated the adjustability of each harness and its ability to accommodate changes in subject size without requiring substantial redesign. The Traffic Cone Harness received a score of 5 because the design incorporated adjustable straps that allow for adjustment to changes in body size in the swine during growth. Additionally, the design allowed for the protective cover to be adapted to maintain full coverage around the catheter insertion point. The Piggy Back Harness and Basket Harness both received a score of 4 because these designs incorporated adjustable straps to accommodate growth, but could not adjust the protective padding or catheter protection components to maintain full coverage and protection around the catheter insertion site.

Mobility (20%):

Mobility was given a weighting of 20% as well, because the harness shouldn't limit the natural movement of the swine within its enclosure. This criterion evaluated how the harness's structure, attachment points, and connection to the tether could affect the subject's range of movement. The Basket Harness received a score of 4 because it can be worn independently of the tether system and therefore only has a slight limitation on mobility of the swine. The PiggyBack Harness received a score of 3 because its integrated catheter port and padded protection introduce some additional restrictions depending on the length of the tether and the harness fit. The Traffic Cone Harness received a low score of 2 because its cone-shaped protective power extends above the catheter anchor point and will likely interfere with the swine's natural movements such as rolling.

Cost (15%):

Cost was assigned a weight of 15% because the client established a budget of \$10,000, which provided flexibility in material selection and fabrication. This criterion evaluated the material and fabrication costs of each harness design. The Basket Harness received a score of 4 because it is based on a commercially available nylon dog harness and requires few additional components to fabricate. The Piggy Back Harness and the Traffic Cone Harness both received a score of 3 because their additional protective structures and fabrication requirements may cause a slight increase in the material and assembly costs.

Final Design:

The Traffic Cone Harness received the highest weighted score of 73, due to its advantages in Catheter Protection, Pig Safety, and Size Scalability. While it may reduce some

restrictions on mobility, its protective advantages make it the most promising candidate for the final harness design. Therefore, the Traffic Cone Harness will be incorporated into the final design.

Fabrication

Materials

The materials chosen for the prototype should be lightweight so that the animals have as little weight to drag around as possible. Additionally, any material chosen for the harness must not irritate the pig's skin. Following the product design specifications, this means no coarse fabric materials, materials with chemical treatment and dyes, or synthetic fibers like nylon and polyester. With this considered, the harness will be made out of a fabric mesh used in dog harnesses. The material chosen for the catheter tubing must be able to withstand 30 kg shear force, and the material chosen for the flexible ends of the tube must be able to bend and reform to its original shape. For the traffic cone part of the harness, PLA is chosen because it is cheap and quick to prototype with, so multiple designs can be tested. The protective catheter tubing for the initial prototype will be made out of PVC pipe as it is lightweight, cheap, and upholds the design requirements outlined in the PDS (Appendix A) [17]. If PVC does not pass testing or the team is looking for something stronger, lightweight metals such as aluminum will be considered for the final prototype. The flexible ends will be made out of polyethylene tubing, which is commonly used in vacuum hoses for its light weight and malleability [18].

Methods

To make the harness, the group plans to purchase a small dog harness and cut a hole in the back so that the traffic cone can be attached and the harness will not interfere with the exit point of the catheters. The traffic cone element will be designed in SolidWorks and 3D printed. To cut the PVC to a length of 1 m, the group will use a plastic pipe shear, which can be found at Wendt. For the fabrication of the flexible ends, the polyethylene tubing will be cut to a length of 3 inches, and one end will be glued to the traffic cone. The other end will be screwed into the PVC pipe. To make the discs in the pipe that will keep the catheters organized, the team will 3D print the discs and glue them into the pipe at the ends.

Final Prototype

SwineSupport

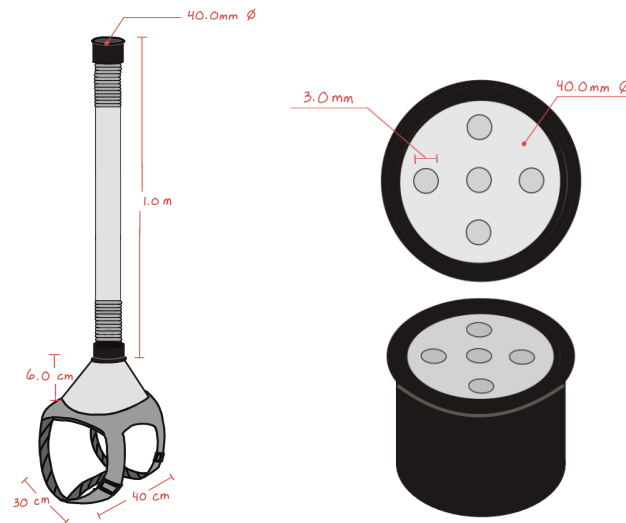


Figure 16. The rightmost image depicts the fully assembled final design of the tether and harness device. The tether will have flexible tubing at the top and bottom with a rigid cover in the center. The left-most image depicts the catheter organization covers at the ends of the tether. The catheters will be threaded through the holes in the discs, preventing entanglement.

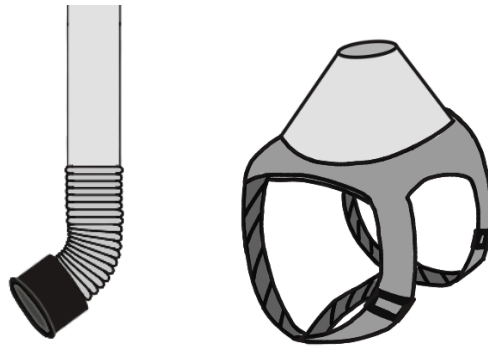


Figure 17. Close-up depictions of the final prototype. The right-most image depicts the flexible tubing at the ends of the tether. The left-most image depicts the harness with the traffic-cone style cover on the back, with no tether attached.

The final prototype's dimension and materials may be modified after fabrication and testing. Other details, such as the flexible tubing of the catheter covers and the attachment points on the harness and traffic cone may be changed should more structural stability in the device be required.

Testing and Results

Mechanical Stress/strain Testing

Three different tests will be performed on *SwineSupport*. The first test will map out a stress and strain graph, locating the ultimate tensile strength of the tether to ensure durability using equations 1 and 2. By performing a strain and stress analysis, this will verify that the tether can withstand at least 30 kg of force, as WMS can produce a force exceeding double their body weight [4]. The tether has to withstand more than 30 kg of force.

$$\text{Equation 1: } \sigma = \frac{F}{A}$$

$$\text{Equation 2: } \varepsilon = \frac{\delta}{L}$$

Fiber Optic Range of Motion

The second test will find the range of motion of the fiber optic catheter while it's in the tether. To verify that the fiber optic catheter will not be damaged by the movement of the pig, the final design incorporates flexible ends of the tether. This test will guide any further adjustments to the final design to determine additional range of flexibility at the ends of our tether or to elongate the length of flexibility, so the tether can provide enough space for the fiber optic catheter to move around and keep it from breaking.

Torsion/ Kink Resistance of Catheters

The last test will simulate movement (twisting and swinging) while 3-4 catheters are inside the tether for 10 minutes of continuous movement. Then, checking at the end, to ensure that the catheters are still organized without any kinking inside the tether, and at the ends of the tether. This test will guarantee the protection of all the catheters while inside the tether. The catheters are expected to maintain their organization while inside the tether.

Discussion

Results from testing the durability of the fiber optic catheters will determine the final design of the harness and tether cover device. Adjustments in material or dimensions of the device may be needed to ensure the safety of the swine. If the catheters are found to become damaged or nonfunctional within the range of flexibility [19] of the tether cover a more protective or rigid material will be used, such as aluminum for the catheter covers [20] or PETG for the traffic-cone cover [21]. The flexible portion of the catheter cover may use a tubing with a larger radius of curvature to prevent excessive bending. A fabric with a higher tensile strength, such as nylon, may be used for the harness for more durability [22].

The three tests performed on the catheters and tether cover do not fully simulate continuous use, where the device will endure moderate repeated strain rather than the acute bending and thrashing during trials. Tests with a longer duration of stress may be needed to ensure reliability of the catheter cover over the week-long operation period. Other assessments for catheter functionality, especially for qualities such as sensor accuracy and fluid movement may be performed for device reliability. In addition, assessments of the durability of attachment points from the tether to the harness should be performed to ensure there is no detachment during operation.

The ultimate goal of SwineSupport is to enable natural movement behaviors of the swine while the fully assembled device is implemented, and at minimum support ethical conditions to the swine while in use [23]. The device should allow for the swine to roll onto its back, feed, rest, and be maintained regularly with minimal disturbance [24]. Further development of a complementary overhead tether system is necessary to properly test the effectiveness of the tether and harness. Changes to the device may be necessary if functionality in terms of security, durability, range of motion, performance of the testing materials, and/or wellbeing of the swine is reduced when the harness, tether cover, and overhead tether system are used in combination.

Conclusion

Neuromonitoring of repeated brain interstitial fluid samples is needed to assess the effects of cardiac arrest. Intracranial catheters will be placed on a Wisconsin Miniature Swine patient to collect the interstitial fluid samples as the swine is awake and moving around naturally in an enclosure. For the collection of brain interstitial fluid, a complementary overhead tether system must be developed to manage the tubing and cables extending from the cranial catheter fixation device that organizes the catheters from within and out the middle of the back to the overhead tether system. The final design, *SwineSupport*, provides catheter organization and protection from damage, with flexible ends that connect to the overhead system and the harness for ease of natural movement for the swine. The tether must withstand the pulling force of the swine and keep the catheters organized as it comes out from the swine and into the overhead tether system. The team will then conduct testing to ensure that the tether is durable and keeps the catheters organized. After testing, the results will be evaluated, and any necessary changes to the final tether design will be implemented. In the future, an overhead system that connects to the tether

will be developed, so the swine can move around naturally in an enclosure while maintaining organization of the catheters into the medical devices.

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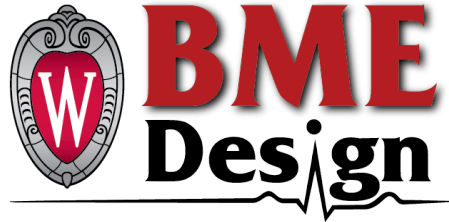
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Appendix

Appendix A: Product Design Specifications



ADAPTIVE OVERHEAD TETHER SYSTEM FOR FREELY MOVING SWINE

PRELIMINARY PRODUCT DESIGN SPECIFICATIONS

Fall 2026 BME 200/300 Lab 308

Team Name:

P.I.G.

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September 18, 2026

Problem Statement:

The UW-Madison Department of Neurosurgery is developing a chronic large-animal neuromonitoring platform using multiple intracranial catheters for continuous or repeated brain interstitial fluid sampling to study the short-term effects of cardiac arrest on the brain. A cranial fixation device that organizes and protects these catheters has already been developed; however, the lab requires the development of a complementary overhead system that manages tubing and cables extending from the cranial device, while simultaneously allowing the animal to move naturally within a stationary enclosure. The developed system needs to be able to dynamically follow the animal, maintain appropriate tubing length, minimize tensile and rotational forces, prevent entanglement or kinking, and allow normal behaviors of the animal.

Client Requirements:

- The device moves to accommodate the animal rather than the animal moving to accommodate the device.
- Create a complementary device used on a pre-existing catheter device.
- The apparatus must allow the animal to participate in natural environmental behaviors.
- The device must prevent the entanglement of catheters and minimize tensile forces.
- The device must minimize the likelihood of agitation in the test animal.

Design Requirements:

1. Physical and Operational Characteristics

a. Performance Requirements

- i. The apparatus must be able to accommodate the natural environmental behaviors of the animal subject, including movement within the environment, feeding, and resting.
- ii. The system should dynamically follow the animal, maintain appropriate tubing length under 1 meter that minimizes tensile and rotational forces, and prevent entanglement or kinking.
 1. Must withstand tensile force of over double the Wisconsin Miniature Swines body weight, approximately 122.58 to 245.17 N of force [1].
 2. The catheters must be organized during movement within the tether.
- iii. The tether management system must interface with the cranial catheter fixation device supplied by the client.
- iv. The system should withstand uninterrupted, constant daily use within the testing timeframe of approximately 2 weeks.
- v. The system must be reusable and adjustable to different catheter placements.

- vi. The apparatus must be able to incorporate all necessary monitoring equipment, including a Hemedex Bowman Perfusion Monitor [2].
- b. *Safety***
 - i. The device must not harm the animal by tangling, strangling, or pulling out any of the catheters. It should not have any components that could pinch or cut the animal.
 - ii. The device should be designed with cleanliness in mind to prevent any infections and make any necessary cleaning of the device as easy as possible for caretaking staff.
 - iii. The device and restraint should cause the least amount of stress possible to the swine. Stress factors to be monitored include noise, visual motion, and physical disturbances.
- c. *Accuracy and Reliability***
 - i. The animal-tracking device should be able to detect the Cartesian coordinate position of the animal within a tolerance of ± 0.2 mm [3].
 - ii. The overhead tether system should be reliable enough to minimize tensile and rotational forces to protect the fiberoptic catheter and the wider plastic catheters from damage during a 2-week timespan.
- d. *Life in Service***
 - i. The entire apparatus must maintain full operation for the entirety of each subject period with no maintenance required, and should require minimal maintenance for the entirety of the studies length, approximately 3 years.
 - ii. Each subject period will last a maximum of 2 weeks, 336 hours.
- e. *Shelf Life***
 - i. The entire apparatus must be able to be stored independently of the cranial fixation device until attachment takes place.
- f. *Operating Environment***
 - i. The apparatus must be able to be utilized at room temperature of approximately 20°C - 22°C.
 - ii. The device will be stored in a WIMR - affiliated large-animal veterinary care facility. At this facility, the device will be exposed to humidity, dirt or dust, animal bedding, animal waste and body fluids, and antibacterial chemical sanitizers.
 - iii. The apparatus will be used by both researchers and by veterinary care staff.
- g. *Ergonomics***
 - i. The device must allow veterinary care staff access to clean the living area of the pig at least every three days to ensure dry resting and feeding areas [4].

- ii. The device must allow veterinary staff frequent access to care for the pig eg. feeding, watering, vital measurements.
- iii. The apparatus must allow staff to walk/guide the pig into the pen without requiring staff to lift them.
- iv. The apparatus must allow staff to attach the cranial catheter fixation device and associated harness to the necessary medical equipment. Once attached, the pig should not need to be disconnected until the end of the 2-week study period. Due to the nature of the study, the disconnection method does not need to be “quick release”, and should rather prioritize security over ease of use.
- v. The harness girth strap must sit far back enough to clear the armpits to allow for unobstructed movement.

h. Size

- i. The tether must be as short as possible, maximum of 1 meter in length before it connects to the collection device and additional medical devices.
- ii. The harness must fit a 2 week old Wisconsin Miniature Swine, allowing expansion as the Wisconsin Miniature Swine grows to 4 weeks.
- iii. The apparatus must fit within the designated laboratory space at the *UW-Madison Department of Neurological Surgery*, while also allowing for enough room for researchers to operate within the space as well.

i. Weight

- i. To ensure safety and structural integrity, the device must be able to withstand a minimum compression load of 58.84 N (6.0 kg) to ensure that the Hemedex Bowman Perfusion Monitor and any other medical devices can rest on top of the overhead tether system connected to the tether [2].
- ii. The harness must be able to support an additional 15 – 25 kg of the Wisconsin Miniature Swine test animal [5].
- iii. The weight of the tethering strap used on the test animal must be no more than 2% of the animal’s body weight [6].

j. Materials

- i. The device must not use coarse fabric materials, materials with chemical treatment and dyes, or synthetic fibers like nylon and polyester to prevent irritation of the animal's skin [7].
- ii. The apparatus should not visually hinder the ability of veterinary staff and researchers to constantly monitor the swine subject [8].

k. Aesthetics, Appearance, and Finish

- i. To prevent injury, the product should have a non-slip, non -porous and seamless finish that withstands chemical sanitization and animal rooting [9].

- ii. The product must also feature visual transparency to allow for veterinary care observation [8].

2. Production Characteristics

a. *Quantity*

- i. The construction of a tether, maintaining organization of the catheters for repeated use is required.
- ii. A harness will provide adjustable straps accommodating the Miniature Swine growth.

b. *Target Product Cost*

- i. A flexible budget has been administered based on design needs. The financial goal of the project is to develop a system that appropriately replaces long-term anesthetization of the animal subjects, which costs the client up to \$3,000 per day to maintain. Therefore, the target product cost should provide a meaningful reduction in the client's overall operating expenses. The total cost should fall well under \$42,000, which is the current cost for keeping the pig anesthetized for two weeks.

3. Miscellaneous

a. *Standards and Specifications*

- i. ISO 62366-1
 - 1. This standard outlines the usability engineering process for medical devices. It provides manufacturers with guidance on how to analyze, design, and test the user-friendliness of their medical devices, and how to identify and reduce risks that may arise during normal device use [10].
- ii. ASCE 7-22
 - 1. This standard provides a comprehensive guide on the minimum requirement caused by environmental loads for structural stability, adequate strength and structural integrity accounting for risk of human life, health, and welfare that can result from structural failure [11].
- iii. ISO 14971:2019
 - 1. This standard overviews Medical devices — Application of risk management to medical devices. Implementing these outlined practices enhances the swine subject's safety and the overall system's performance. These practices also encourage the early identification of potential hazards during design and development, when mitigation strategies are most cost-effective and impactful. [12]
- iv. ISO 9851:1990

1. This standard provides the basic safety requirements for an overhead electrical rail, covering the materials handling, such as tracks, and load-supporting devices [13].
 - v. Code of practice for the tethering of animals
 1. This code of practice provides the guidelines of how animals must be safely tethered. The appropriate tether material that should be used, frequency of inspection, and duration of tethering [14].
 - vi. ISO 13485
 1. This standard gives requirements for a medical device manufacturer's quality management system (QMS). The standard outlines the QMS requirements necessary to demonstrate that the product can be produced safely and be an effective medical device that meets clients' needs [15].
 2. The QMS will ensure safety, effectiveness, and regulatory compliance are maintained during the design, fabrication, and operation of the device.
- b. Customer**
- i. The device is intended for housing 2-4 week old Wisconsin Miniature Swine [5]. In order to be suitable for this purpose, the device will need to adhere to the requirements of UW-Madison Institutional Animal Care and Use Committee for laboratory use of large-animals [16].
 - ii. The device is intended to assist laboratory researchers within the UW-Madison Department of Neurological Surgery, and therefore must be capable of aiding research by minimizing catheter lengths, reducing the likelihood of test animal agitation, and being detachable for use on multiple test animals.
- c. Patient-related concerns**
- i. The apparatus must decrease the likelihood of causing excessive stress on the test animal. To promote animal well-being: operational noises must not exceed 85 dB, the test animal's movement should not be restricted by the tethering equipment, and devices implanted within the pig should be sterilized before use to avoid infection [17].
 - ii. In accordance with institutional policy UW-4091, medical records must be maintained for the test animals used in research [18]
- d. Competition**
- i. *SAI Tethered Infusion System for Pigs* is a tether and jacket system that reduces the risk of pump damage by keeping the pump outside of the enclosure for easy accessibility and maintenance [19].

- ii. *Ludomed Tether System for large animals* allows for uninterrupted delivery of test specimens while allowing the animal to comfortably move as a catheter integratable jacket minimizes stress on the animal [20].
- iii. *LOMiR Medical Inc. Large Animal Tether* provides ease of movement, made up from an interlocking stainless steel, eliminating interference and damage to the catheter [21].
- iv. *INSTECH Five-Channel Swivel* is an immediate response swivel that has up to 5, 22ga catheter channels, with a stainless steel body, self-adjusting seals, and a motorized rotation that adapts to the animals' movement, minimizing the stress on the animal [22].
- v. *Protech International Inc. Large Animal Swivel* is a 3 channel, 16-22 standard gauge for repeated use. [23].
- vi. *Harness interface conduit, tether line, and swivel for use in animals* is a continuous tethered infusion system, modeled on a rat, that uses a harness for easy fluid communication access. [24].

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