TILLER EXTENSION

PRODUCT DESIGN SPECIFICATION

MAE 5630
Advanced Product Design

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1. Product Description Executive Summary

1.1 Team Name and Summary of Participants

Team Name: **ANCORE**

Summary of Participants: **Mae Sliwinski, Garrett Smith, Alex Jenkins, Jeffrey Kagle**

1.2 Product Name

Product Name: **U Tiller Extension Joint**

1.3 Problem you are solving

- The majority of collegiate sailors (83%) experience mid-race tiller extension failures, with 61% of those failures originating at the joint
- Joint failures during competition present direct safety hazards for racers
- Frequent equipment failures increase total cost of ownership through repeated replacement purchases
- Current designs do not provide the reliability collegiate racers require to compete with confidence

1.4. Basic Functions of Product to Solve Problem

- **Improved Joint Geometry** – By changing the geometry of the joint we can improve the force distribution along the rubber joint
- **Joint Mesh Layer** – Added a biaxial braid of nylon to the tiller joint to improve force distribution during extreme tiller adjustments
- **Joint Rope Core**– Integrated rope core in the joint improves joint force distribution and allows device to function at a limited capacity even after joint failure

1.5. Special Features of Product Beyond the Core Problem Solution

- **Aluminum Tiller Extension** – User data showed an aluminum tiller extension was preferable to users. Customized specifically to best fit our joint design.
- **Contoured Grip** – Allows more comfortable holding of the tiller extension

1.6. Picture of Highest Level Product Refinement



Figure 1 & 2: CAD Rendering of Tiller Extension Product

2. Physical Description

2.1. House of Quality Level 1

The customer requirements are derived from analyzing needs of sailing students, the Cornell Varsity Sailing team, and other sailing hobbyists surveyed through the r/sailing subreddit.

These carefully distilled requirements formed the foundation of our House of Quality analysis and guided our engineering targets and subsystem selection throughout development, enabling us to create a solution that addresses durability and lifetime of a tiller extension joint.

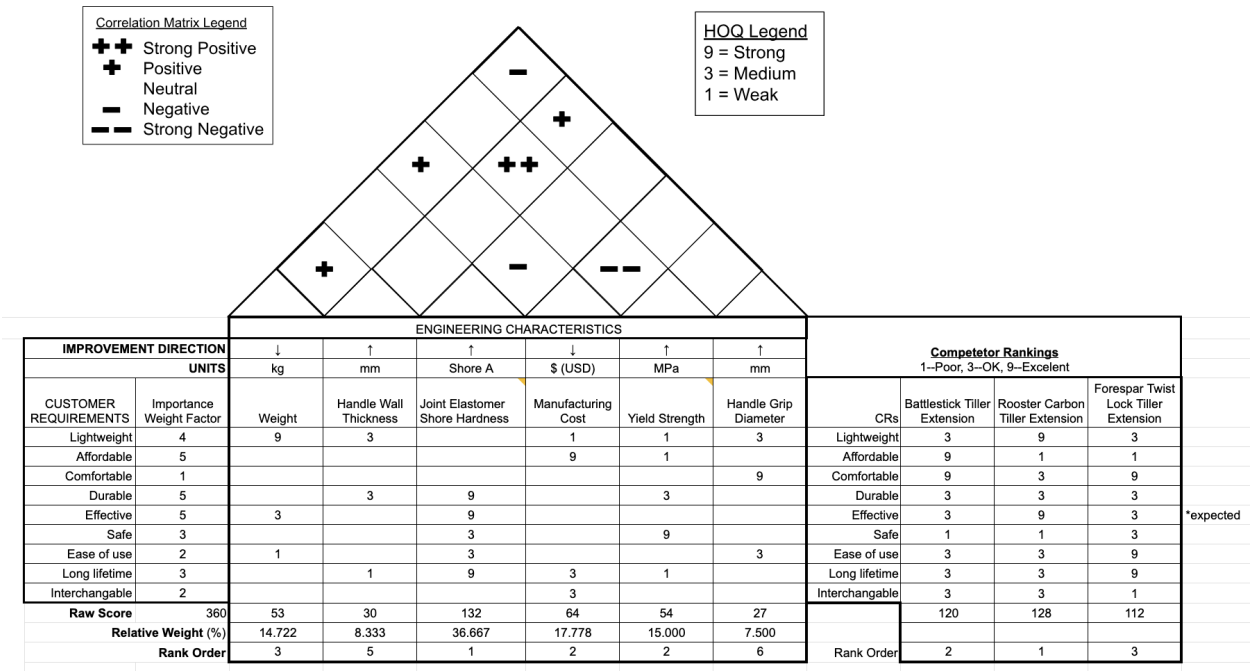


Figure 24: House of Quality

2.2. Describe List of Requirements from Customer

Table 1: Customer Requirement to Customer Insight Mapping

Customer Requirement	Importance (1-5)	Customer Insight
Lightweight	4	The lighter the total boat mass is, the faster you can go on the water
Affordable	5	Conjoint analysis had lower prices as a highly desirable trait
Durable	5	“More resilience" - Jonny

Effective	5	Must actually function as a tiller extension or will not be used
Safe	3	Should not harm customer if used properly “I don’t want to lose control of my boat and injure myself, just because the joint on my tiller extension snapped” - Felicia
Ease of use	2	“Easy connection and detachment from tiller” - Keiran
Long lifetime	3	“...just long-lasting please…” - Dustin, “[the U-joints] tend to fail all in one go” - Keiran
Interchangeable	2	“Easier to replace if joint is broken” - Keiran

2.2.1 Empathy field work

We asked sailors what a day of sailing looks like from practice to competition, and we asked them what is frustrating about their boat or sport to better understand their needs.

2.2.2 Customer interviews (n, quotes)

Part of our conjoint analysis survey had space for comments.
n=50 for demographic data, n=11 for demographic data and conjoint analysis, n=6 in person interviews from Cornell sailors

“Easier to replace if joint is broken” - Keiran
“...just long-lasting please…” - Dustin, “[the U-joints] tend to fail all in one go” - Keiran
“Easy connection and detachment from tiller” - Keiran
Should not harm customer if used properly
“I don’t want to lose control of my boat and injure myself, just because the joint on my tiller extension snapped” - Felicia
“More resilience" - Jonny
“Without a solution it's a Unequivocal nightmare” -Kate

2.3. Conjoint Analysis

2.3.1 Conjoint Test 1

The attributes we set out to assess from the Conjoint Analysis survey include joint type, length adjustment, material, price, and lifetime of the product.

Specifically, tiller extensions typically have multiple joint types including a mechanical universal joint, ball and socket joint, two flexor joints, and a rubber universal joint.



Figure 3: Types of Joints Commonly Used for Tiller Extensions

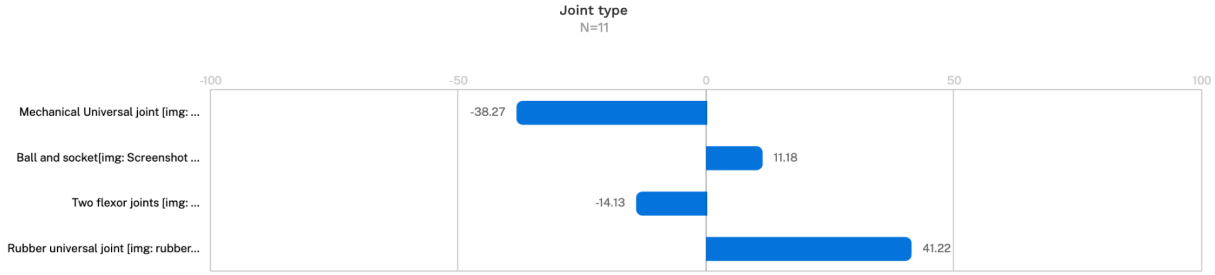


Figure 4: Conjoint Analysis Survey Results for Attribute 'Joint type'

The results demonstrate that the rubber-like universal joint is the preferred joint type by the end users.

The second attribute we brought into consideration is the length adjustment of the tiller extension, namely adjustability, telescoping adjustability, or a fixed length.

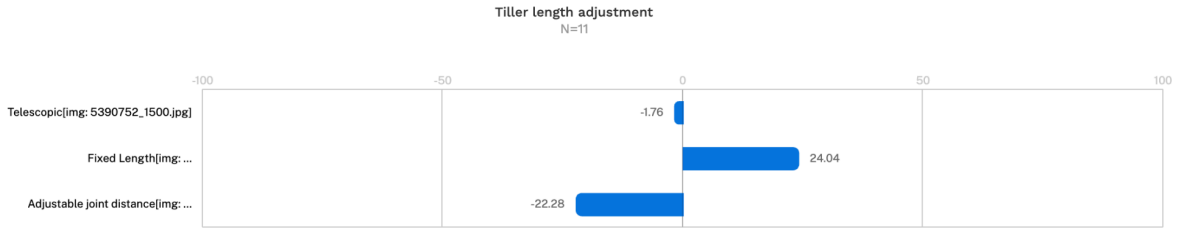


Figure 5: Conjoint Analysis Survey Results for Attribute 'Tiller Length Adjustment'

The results indicate that fixed length of the tiller extension is overwhelmingly preferred by the end users.

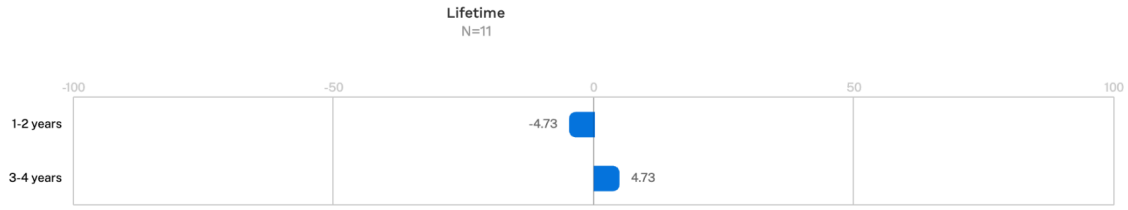


Figure 6: Conjoint Analysis Survey Results for Attribute 'Lifetime of the Product'

The results echo the assumed sentiment that the longer life for the product is the better.

Next up was the material selection attribute, based on the current market landscape and light weight materials that are accessible through common modes of manufacturing we chose carbon fiber properties, aluminum, and epoxy composite.

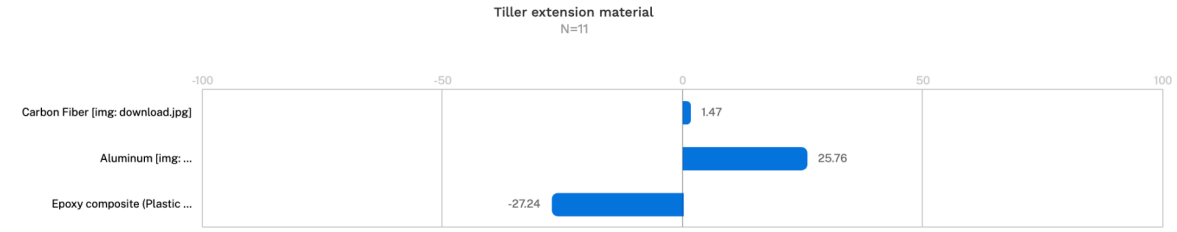


Figure 7: Conjoint Analysis Survey Results for Attribute 'Tiller extension material'

The result was that aluminum is highly preferred for the base material of the tiller extension rod.

Lastly, the price of the product was assessed by the users to see how much they would be willing to pay for a tiller extension that gave them ease of use and a competitive edge

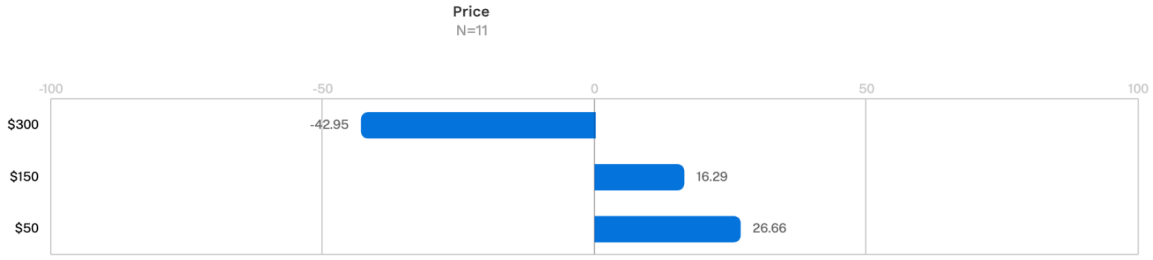


Figure 8: Conjoint Analysis Survey Results for Attribute 'Price'

The results demonstrate that the cheaper the product the better for the consumers, but also our customers would be willing to pay up to $150 for a quality product which gives us room to add features and position ourselves competitively within the market.

2.3.2 Conjoint Test 2

Overall, price and joint type were the most significant attributes to the intended end users of our product.

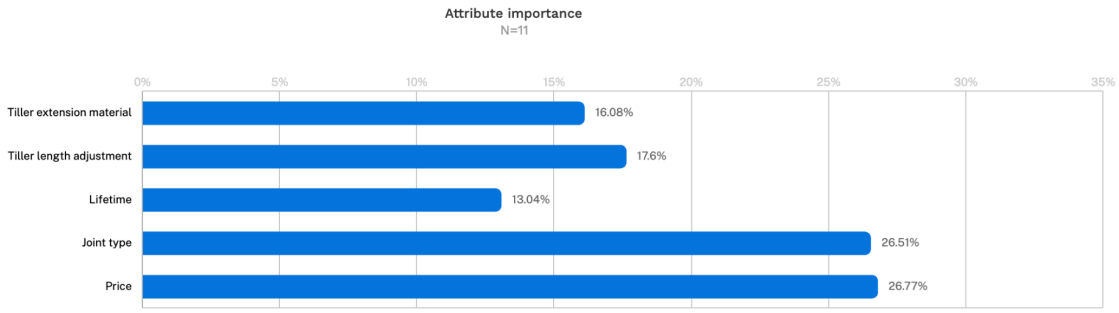


Figure 9: Conjoint Analysis Survey Results for Perceived Attribute Importance

2.3.3 Design/Engineering hypothesis impact

Our survey allowed us to collect crucial demographic data so we could have an accurate estimate of the typical lifetime and failure rate of a tiller extension before our innovation is implemented. Accordingly, we were able to finalize our engineering design hypothesis based on the preferred attributes to the following statement:

> A universal joint for sailing tiller extensions featuring a rope core, polyurethane rubber structure, and a weaved polymer mesh — priced between $10 - $25 — will survive 3-4 full sailing seasons of collegiate racing use with a field failure rate below 10%, compared to current designs where 83% of surveyed sailors reported at least one mid-race tiller extension failure, with 61% of those failures occurring at the joint. By reinforcing the primary failure point identified in user research, this product will reduce safety hazards, lower the total cost of ownership from repeated replacements, and give collegiate racers measurable confidence that their equipment won't fail them during competition.
>
> Null Hypothesis: A universal joint that operates similarly to rubber, with mesh load reducer and rope core, at the $10–$25 price point will not meaningfully reduce the 61% sailor-reported failure rate, safety incidents, or racer confidence compared to existing universal joints currently used in collegiate sailing tiller extensions.

2.4. Describe Engineering Characteristics of Concept

The engineering characteristics we aim to validate include joint durability through cyclic loading and Factor of Safety via FEA. Durability and product lifetime are the main engineering characteristics expressed by our engineering hypothesis, and striking an ergonomic balance of lightweight material that is also durable.

2.4.1. What subsystems output engineering features that address the customer requirements?

The joint subsystem includes the rigid base, a polyurethane elastomer(rubber-like characteristics) universal joint, and a rope core and interacts with the force distribution module of a woven composite sleeve to address the engineering characteristic of joint durability for customer requirement to reduce the failure of the joint so that the product lasts 3-4 sailing seasons. The polymer mesh takes the load off the joint, and absorbs and distributes the stress across a distance instead of concentrating it at a failure point. The weaved polymer mesh increases part count and interface complexity however this is a trade off with durability and lifetime customer requirements. For the requirement of a lightweight material that is ergonomic

and easy to use, the corresponding engineering features are a low density material for the polymer mesh such as polyurethane and rope core used in the joint subsystem. Also, it makes it easy to replace and interchangeable just like other tiller extension products on the market. Additionally, the customers require an effective and safe user experience as the rope ensures the tiller and tiller extension remains connected, the mesh ensures compression and the tension forces are more distributed to prevent the joint from becoming compromised.

2.4.2.1. Units

Table 2: Units for Engineering Characteristics

Weight	Handle Thickness	Joint Elastomer	Manufacturing cost	Yield Strength	Handle Grip Diameter
kg	mm	Shore A	USD	MPa	mm

2.4.2.2. Subsystem interactions

The sailor interacts with the grip module which has the handle and ergonomic rubber mold in this subsystem. Then, the mold is formed over the shaft subsystem which is attached to the joint module but overlapped by the force distribution module and controls the boats steering through tactile feedback back to the sailor.

2.5. Product Architecture

Our product is a weaved polymer mesh on outside of tiller extension rod

Rope core fused to polyurethane in manufacturing process,

2.5.1. Functional decomposition into modules/subsystems

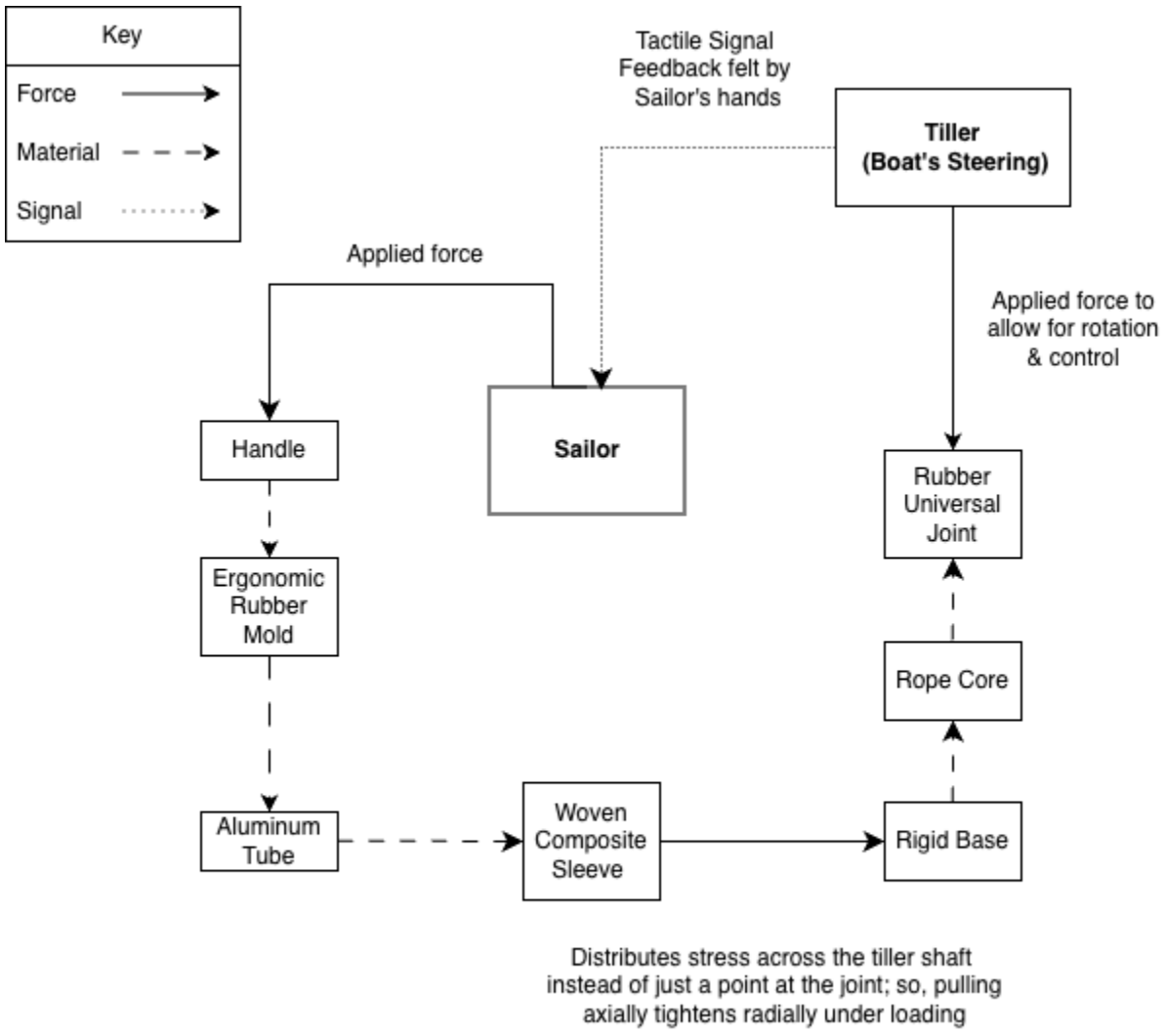


Figure 10: Sailor & Tiller Modules and Subsystem Interaction

2.5.2. Clustered module schematic diagram with item numbers

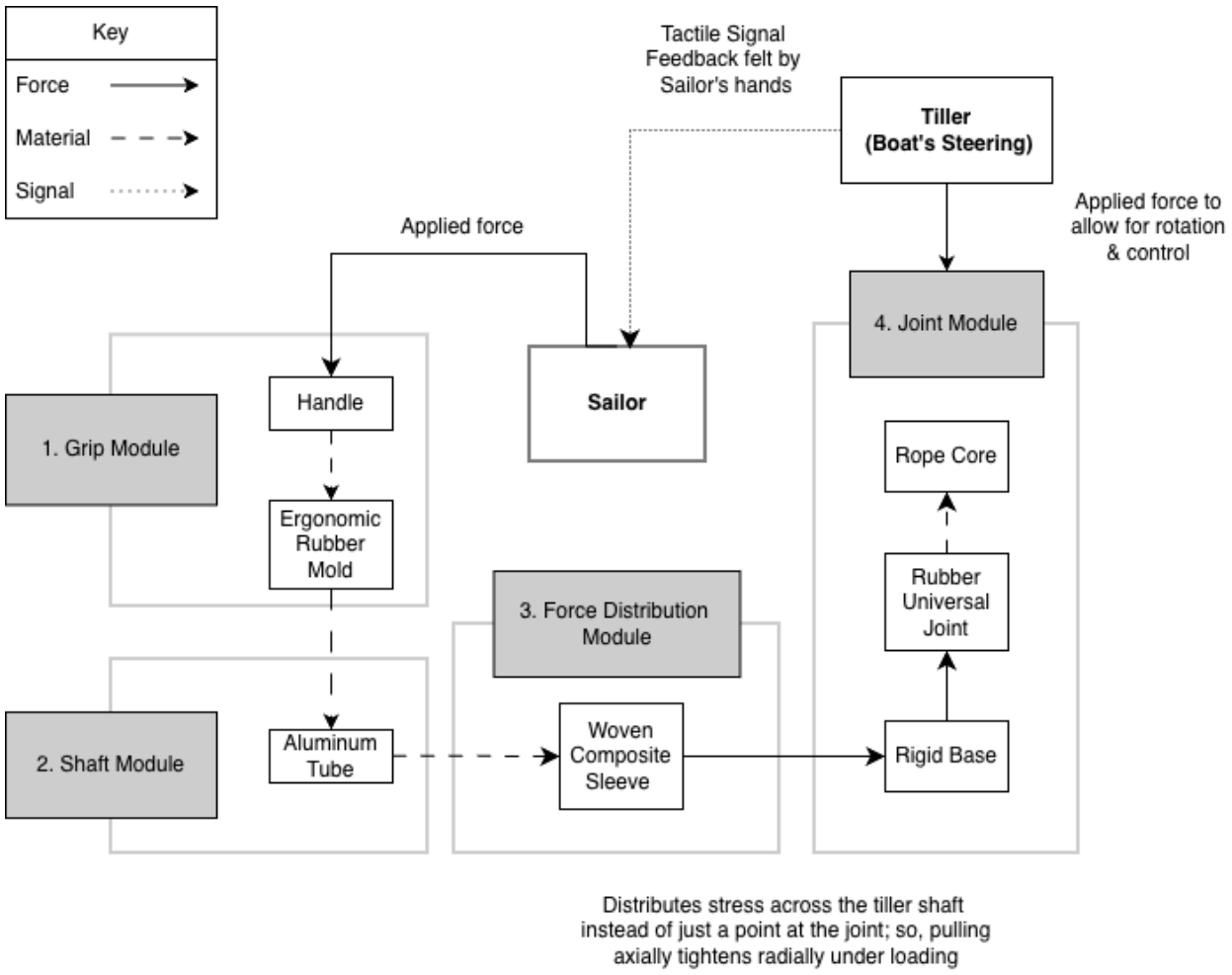
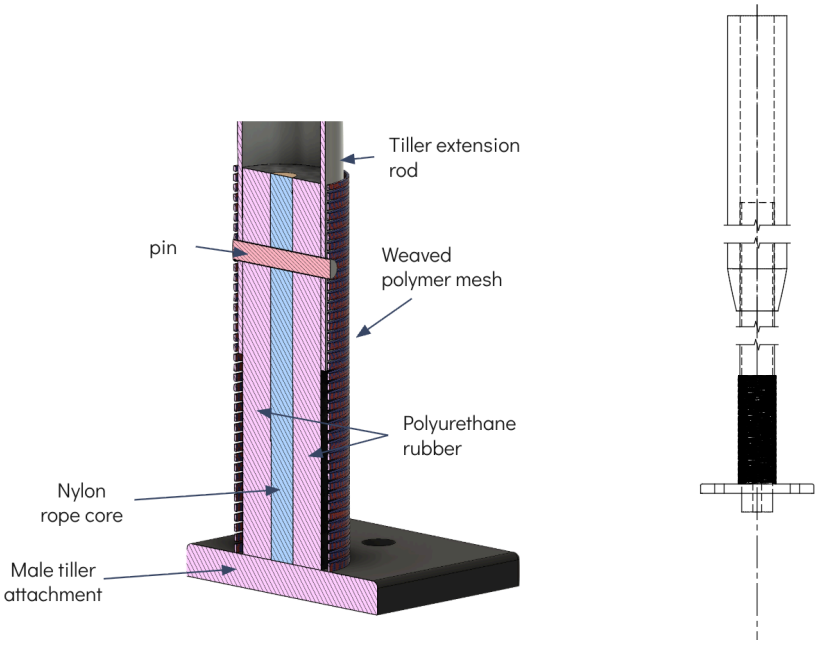


Figure 11: Sailor & Tiller System-Subsystem Interactions with Clustered Modules

2.5.3. Geometric layout of final configuration



2.5.4. Module interface documentation

The ANCORE joint uses a reinforced modular architecture designed to improve durability while maintaining flexibility and compatibility with the existing tiller assembly. The interface design focuses on reducing failure risk, simplifying assembly, and improving long-term performance under repeated cyclic loading.

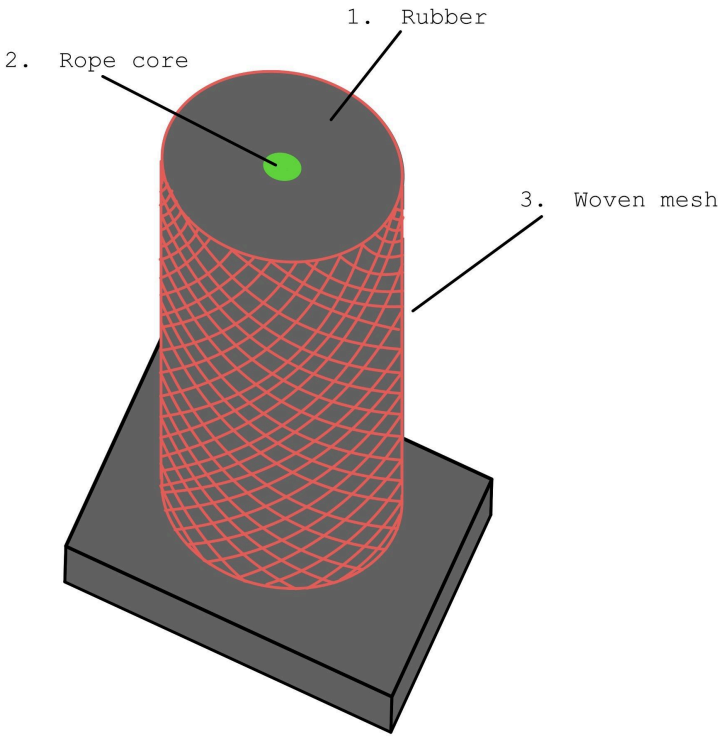


Fig 12: Internal reinforced joint module showing the elastomer body, centered rope core, and external woven mesh reinforcement layer.

Fig 12 shows the internal module structure of the joint. The rope core is positioned concentrically within the elastomer body, while the woven mesh reinforcement surrounds the exterior surface of the joint. The mesh layer was positioned externally to improve stress distribution while simplifying manufacturing and inspection.

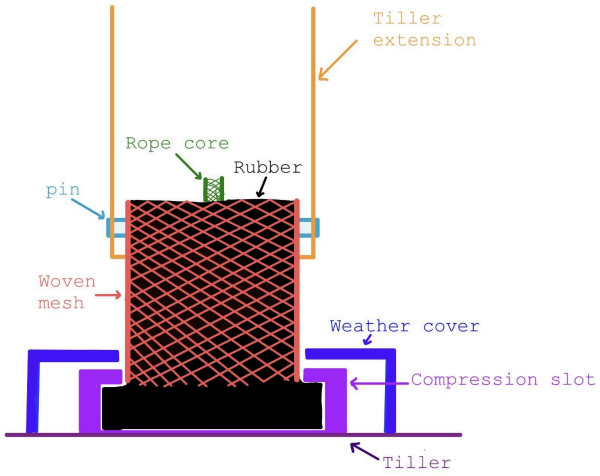


Fig 13. Cross-sectional interface view of the ANCORE joint integrated with the tiller extension and tiller assembly, including the pin connection, compression slot, and weather cover.

Fig 13. shows the interface between the joint module and the surrounding tiller assembly. The upper interface connects to the tiller extension through a pinned rotational connection, allowing angular motion during steering inputs. The lower interface uses a compression-fit slot geometry to secure the joint within the tiller assembly. A weather cover was added around the lower interface region to reduce environmental exposure during use.

The interface design primarily considers spatial interaction, load transfer, and manufacturability between neighboring modules. The final geometry was also designed to minimize unnecessary assembly steps and maintain compatibility with standard manufacturing processes.

2.5.5. Modular vs. integral architecture justification

The final design uses a partially modular architecture. The reinforced universal joint assembly remains replaceable independently from the tiller extension while internally integrating the rope core, woven mesh sleeve, and polyurethane body into a single reinforced structure. This approach improves serviceability while maintaining structural continuity under cyclic loading.

2.6. House of Quality Level 2

2.6.1. Engineering Characteristics from Level 1 HOQ

The most significant engineering characteristic identified in the Level 1 HOQ was joint elastomer shore hardness because it directly affects flexibility, fatigue resistance, and steering feel during operation. Manufacturing cost, yield strength, and assembly weight were also major design drivers.

The final joint body material was selected as a UV-stabilized 90 Shore A polyurethane rubber due to its balance between flexibility, toughness, and environmental resistance. Material stiffness assumptions used during preliminary FEA analysis were estimated using the Shore hardness-to-modulus relationship described by Gent [22]. The selected elastomer model was also consistent with nonlinear large-deformation behavior described by Mooney [23].

Fatigue behavior under repeated cyclic loading was a major consideration during material selection because conventional sailing joints commonly fail through crack initiation and propagation

within the elastomer body. Fatigue analysis approaches for rubber materials discussed by Mars and Fatemi [26] were used to guide reinforcement strategy and cyclic loading assumptions.

The rope core uses marine-grade braided polyester cordage due to its flexibility, low moisture absorption, and high tensile strength-to-weight ratio. The woven reinforcement layer was modeled using representative Nylon 6/6 material properties obtained from MatWeb [24].

Engineering Characteristic	Importance Weight	Primary Influence
Joint Elastomer Shore Hardness	36.70%	Flexibility and fatigue resistance
Manufacturing Cost	17.80%	Product affordability
Yield Strength	15.00%	Structural durability
Weight	14.70%	Handling performance
Handle Wall Thickness	8.30%	Stiffness and ergonomics
Grip Diameter	7.50%	User comfort

Table X:

2.6.2. Part Characteristics

Material selection focused on fatigue resistance, environmental durability, manufacturability, and low weight.

Component	Material	Key Properties	Design Function
Joint Body	UV-Stabilized TPU (90A)	Flexible, fatigue resistant, abrasion resistant	Primary flexible structure
Rope Core	Marine Polyester Rope	High tensile strength, low moisture absorption	Secondary load path
Mesh Reinforcement	Woven Polymer Mesh	Lightweight, stress redistribution	Fatigue reinforcement
Attachment Pin	Aluminum 6061-T6	Corrosion resistant, lightweight	Rotational interface
Weather Cover	Flexible TPU	UV and moisture resistance	Environmental protection

Material	Property	Approximate Value	Source
90A Polyurethane	Young’s Modulus	~7–12 MPa	[22]

90A Polyurethane	Shore Hardness	90A	Manufacturer specification
Nylon 6/6 Mesh	Elastic Modulus	~2.7 GPa	[24]
Nylon 6/6 Mesh	Tensile Strength	~83 MPa	[24]
Polyester Rope Core	Tensile Strength	~4–6 kN typical	Manufacturer estimates
Aluminum 6061-T6 Pin	Yield Strength	~276 MPa	Standard handbook value

The reinforced elastomer structure was designed to reduce localized tensile stress concentration during cyclic bending while maintaining steering flexibility. Representative Nylon 6/6 material properties from MatWeb [24] were used during preliminary reinforcement analysis. Nonlinear deformation behavior and large-strain assumptions were guided using methodologies described by Belytschko et al. [25].

Aluminum 6061-T6 was selected for the pin interface because of its corrosion resistance, machinability, and low mass.

2.6.3. How strongly each module contributes to each EC

The TPU/polyurethane body primarily contributes to flexibility and articulation, while the woven Nylon 6/6 reinforcement layer improves durability by reducing localized stress concentrations during bending. The rope core functions primarily as a safety and failure-mitigation feature by maintaining steering continuity after elastomer failure.

Repeated cyclic deformation and elastomer softening behavior discussed by Mullins [28] were considered during subsystem interaction analysis and reinforcement placement.

2.6.4. performance targets derived from Level 1

Performance targets were established directly from the customer requirements and engineering characteristics identified during the Level 1 HOQ analysis. The primary objective was increasing operational lifespan while maintaining steering flexibility, low weight, and low manufacturing cost.

Performance Metric	Target Value
Operational Lifespan	3–4 sailing seasons
Factor of Safety	>2.0
Cyclic Loading Resistance	>500 loading cycles
Steering Continuity After Failure	Maintained
Saltwater Resistance	No major degradation

Total Assembly Weight	<350 g

The reinforced architecture was designed to improve fatigue life compared to conventional elastomer-only joints while maintaining compatibility with existing tiller hardware and steering geometry.

Based on sailing force estimates discussed by Practical Sailor [21], competitive tiller steering loads were approximated at approximately 10 lbf applied near the tiller extension handle during aggressive steering conditions. Using a representative extension length of approximately 0.6 m, the resulting peak steering moment was estimated at approximately 27 N·m. Performance targets and cyclic loading conditions were therefore based on this estimated operational steering load. The prototype was designed to withstand at least 150% of this rated loading condition while maintaining a factor of safety greater than 2.0.

2.6.5. Module-to-module interactions

The final assembly relies on coordinated interaction between the polyurethane joint body, woven Nylon reinforcement layer, rope-core subsystem, and attachment interfaces. During steering deformation, the polyurethane body carries most of the bending strain while the woven reinforcement redistributes tensile stresses around the outer surface of the joint.

If localized fatigue cracking develops within the elastomer body, the internal rope core becomes the primary load-bearing member and maintains steering continuity between the tiller and tiller extension. Fatigue and cyclic deformation behavior discussed by Mars and Fatemi [26] and Mullins [28] were considered during reinforcement placement and subsystem interaction analysis.

Potential failure regions identified during development included elastomer tearing near the pin interface, mesh delamination, and rope-core slippage during repeated cyclic loading.

During steering input, bending loads are initially carried by the polyurethane body as the tiller extension rotates relative to the tiller. As deformation increases, tensile stresses develop along the outer surface of the joint, where the woven Nylon reinforcement begins redistributing strain around the circumference of the elastomer body. This reduces localized crack initiation within high-strain regions near the pin interface. If fatigue tearing propagates through the polyurethane body, the internal rope core becomes the primary tensile load path and maintains mechanical connection between the tiller and extension, preventing complete steering separation during operation.

2.7. Requirements Traceability Matrix

2.7.1. Map every CR through ECs to PCs

Customer requirements including durability, affordability, reliability, lightweight construction, and safety were translated into engineering characteristics during the Level 1 HOQ process and then mapped to measurable part characteristics during Level 2 development.

Customer Requirement	Engineering Characteristic	Part Characteristic
Durability	Fatigue Resistance	TPU hardness and mesh reinforcement
Affordability	Manufacturing Cost	Compression molding and material selection
Reliability	Tensile Strength	Rope-core tensile capacity
Lightweight Design	Low Assembly Weight	Polymer reinforcement and aluminum pin
Safety	Failure Mitigation	Internal rope-core system

2.7.2. Design gaps

Several early concepts improved durability but introduced excessive stiffness, additional weight, or unnecessary manufacturing complexity. Fully metallic joints reduced steering flexibility and introduced corrosion concerns, while internal reinforcement sleeves complicated manufacturing and assembly.

The final reinforced elastomer architecture provided the best balance between flexibility, durability, manufacturability, and cost.

2.7.3. Scope creep

Scope creep was controlled by limiting the project focus to the universal joint assembly rather than redesigning the entire tiller extension system. Concepts involving adjustable handles, grip redesigns, and interchangeable hardware were excluded because they did not directly address the primary failure mode identified during customer analysis.

2.7.4. Item numbering system:

A consistent item numbering system was used throughout the CAD renderings and assembly drawings to identify major components within the final ANCORE joint architecture. This numbering structure was maintained across section views, exploded renderings, and subsystem diagrams to improve drawing readability and component traceability.

The final assembly numbering system is defined as follows:

1. Polyurethane elastomeric body
2. Nylon rope core
3. Woven polymer mesh sleeve
4. Plastic weather cover
5. Rigid base plate and compression fitting

6. Tiller bar
7. Tiller extension
8. Transverse pin

The subsystem numbering used within the substance-field analysis was maintained separately for conceptual interaction modeling and was not used within the final assembly drawings.

2.8. Use of TRIZ throughout iteration

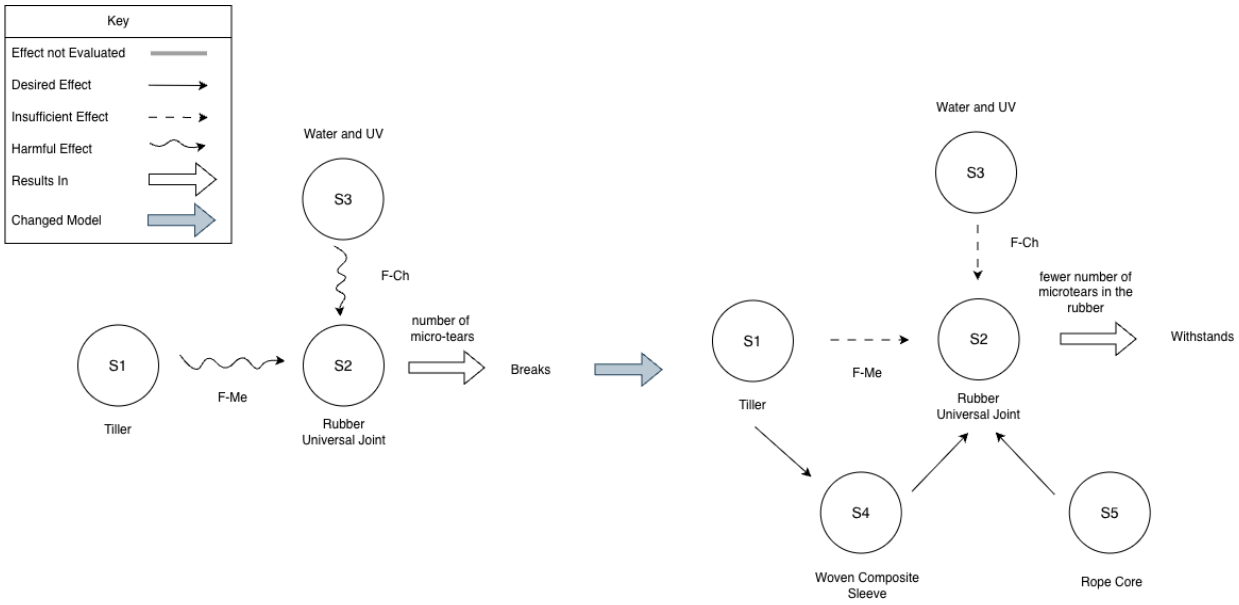


Figure 12: Substance Field Analysis

In the substance-field analysis, F-Me represents cyclic mechanical steering loads and F-Ch represents environmental chemical degradation from water and UV exposure. The left side of Figure 12 represents the original system state, where cyclic mechanical loading and environmental exposure lead to progressive elastomer damage and joint failure. The right side represents the modified system state after implementation of the woven reinforcement sleeve and rope-core subsystem.

TRIZ methodology was used during concept development to address the primary contradiction between flexibility and durability within conventional rubber universal joints.

Existing joints rely entirely on the elastomer body to absorb cyclic steering loads, which commonly leads to fatigue cracking and eventual separation under repeated use.

The substance-field analysis shown in Figure 12 identified the harmful interaction between cyclic mechanical loading and environmental exposure on the rubber joint body. Water, UV exposure, and repeated bending increase the formation of micro-tears within the elastomer, eventually causing structural failure.

To resolve this contradiction without significantly increasing stiffness or weight, the final design introduced two additional reinforcing subsystems: a woven composite sleeve and an internal rope-core failsafe. The woven reinforcement redistributes tensile stresses around the outer surface of the joint, while the rope core maintains steering continuity if partial elastomer failure occurs. This modified interaction model reduces crack propagation and improves operational lifespan while preserving the flexibility required for sailing performance.

The subsystem numbering shown in the substance-field analysis was used specifically for conceptual interaction modeling and differs from the assembly numbering system used in the CAD renderings and final drawings.

2.9. What is the embodiment of your solution?

The final ANCORE embodiment consists of a reinforced polyurethane universal joint assembly designed to improve fatigue life while maintaining the flexibility and steering response required for competitive sailing applications. The design integrates three primary subsystems: a polyurethane elastomer body, a woven Nylon reinforcement sleeve, and an internal rope-core failsafe structure. Together, these subsystems distribute cyclic steering loads while reducing localized crack propagation within the elastomer body.

The embodiment shown in the following renderings was developed from the Level 2 HOQ process and refined through CAD-based subsystem analysis, section visualization, and preliminary structural evaluation.

2.9.1. HOQ Level 2 – PCs

The Level 2 HOQ process translated customer requirements and engineering characteristics into measurable part characteristics and subsystem-level design decisions. Material selection, reinforcement geometry, and interface layout were all selected to improve durability without significantly increasing stiffness, weight, or manufacturing complexity.

Part Characteristic	Design Implementation

Fatigue Resistance	Woven Nylon reinforcement sleeve
Steering Continuity	Internal rope-core failsafe
Environmental Resistance	UV-stabilized polyurethane body
Lightweight Construction	Polymer-based reinforcement architecture
Manufacturability	Compression-molded elastomer geometry

2.9.1.1. Static Renderings

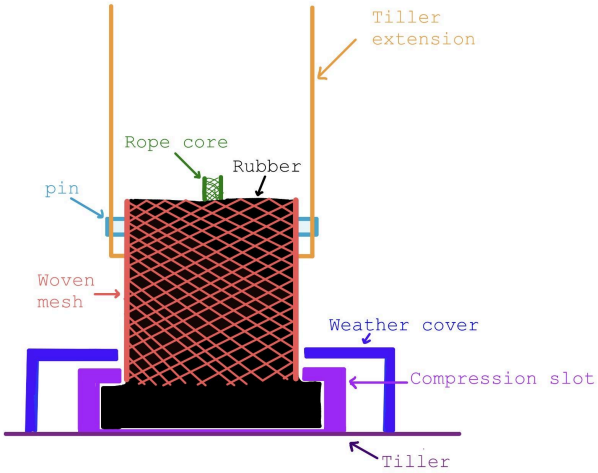


Figure 13. Cross-sectional rendering of final ANCORE universal joint assembly.

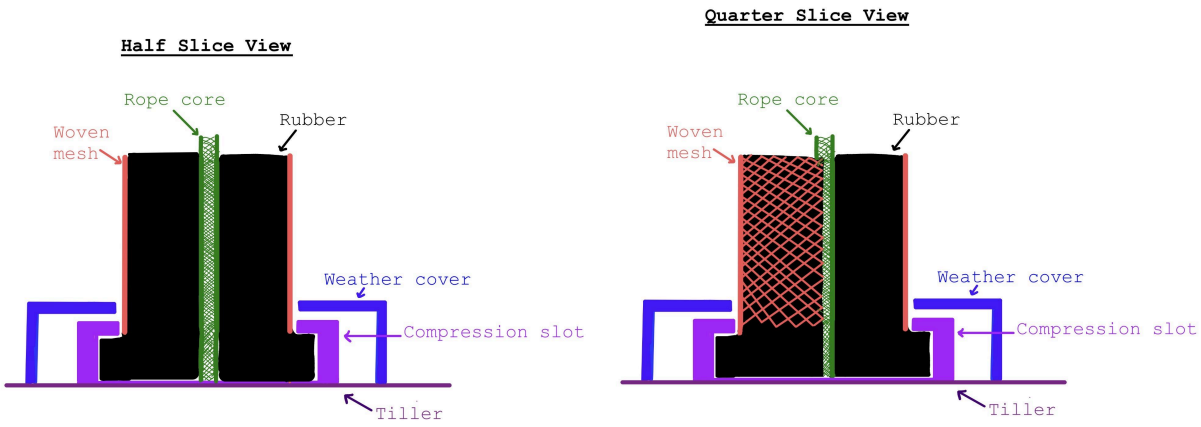


Figure 14. Half-section view & Figure 15. Quarter-section view showing reinforcement sleeve placement within the elastomer body.

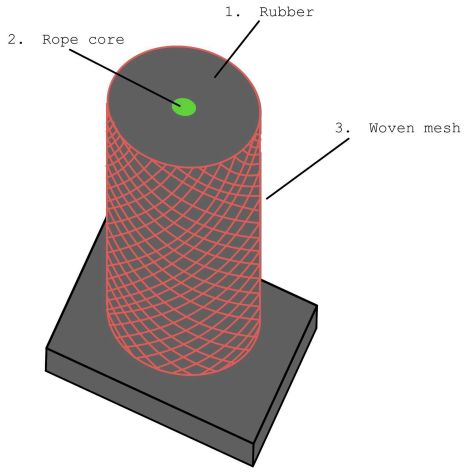


Figure 16. Internal reinforcement layout showing rope-core and woven mesh subsystem integration.

Figures 13–16 illustrate the final reinforced joint embodiment and internal subsystem architecture. Section views were used to visualize how the polyurethane body, reinforcement sleeve, and rope-core subsystem interact during steering deformation and cyclic loading conditions.

The section views demonstrate how steering loads are transferred through the elastomer body during articulation while the woven reinforcement redistributes tensile stresses around the outer surface of the joint. The rope core remains mechanically connected between the tiller and tiller extension and functions as a secondary load path if elastomer fatigue failure occurs.

2.9.1.3 Final Works Like Prototype



Prototype shows that pulling axially on the mesh distributes the load across the joint and onto the shaft instead of concentrating it at one point.

2.10. Traceability Matrix

Customer Requirement (CR)	Engineering Characteristic (EC)	Part Characteristic (PC)	Final Design Response
Increased durability	Fatigue resistance	TPU shore hardness, woven mesh reinforcement	Reinforced TPU body with external mesh sleeve
Reduced failure during racing	Tensile strength	Rope-core tensile capacity	Internal marine polyester rope core
Maintain steering flexibility	Joint flexibility	TPU modulus and geometry	90A UV-stabilized TPU body
Lightweight construction	Low assembly weight	Polymer reinforcement and aluminum pin	Aluminum 6061-T6 pin and polymer subsystems
Low replacement cost	Manufacturing cost	Compression molding compatibility	Simple molded geometry and low-cost materials
Corrosion resistance	Environmental resistance	UV- and saltwater-resistant materials	UV-stabilized TPU and marine-grade materials
Safety after joint damage	Failure mitigation	Secondary load path	Rope-core failsafe system
Compatibility with existing hardware	Interface geometry	Compression-fit base and pin spacing	Standard tiller/tiller-extension interfaces
Long operational lifespan	Cyclic loading resistance	Reinforcement architecture	Mesh reinforcement and distributed load transfer
Ease of manufacturing	Manufacturability	Simplified subsystem geometry	Single molded joint body with integrated reinforcement

2.11. Mechanical Analysis

2.11.1. Analytical

Two configurations were assessed: the joint in isolation and the joint fitted with a 1.5 mm thick woven nylon mesh sleeve. The objective was to determine whether the mesh sleeve reduces peak strain and strain energy density in the rubber under representative collegiate racing loads and angular deflection, in support of the product hypothesis that the reinforced joint will survive 3 to 4 full sailing seasons with a field failure rate below 10 percent.

Because no manufacturer material datasheet was available, the initial Young's modulus was estimated using the Gent (1958) relationship between Shore A hardness and elastic modulus [22]:

$$E \approx 0.0981 \times (56 + 7.66S)$$

where S is the Shore A hardness value. Substituting S = 90 gives an estimated Young's modulus of approximately 73 MPa. Note that the Gent equation is most accurate in the range of 40 to 60 Shore A and becomes less reliable approaching 90 Shore A [22]; therefore, the derived constants are therefore treated as estimates. For a nearly incompressible elastomer, the relationship E = 3G holds, yielding an initial shear modulus of:

$$G = \frac{E}{3} \approx 24.3 \text{ MPa}$$

This value was used to derive the Mooney-Rivlin hyperelastic constants C10 and C01 required for finite element input. The initial shear modulus of a two-parameter Mooney-Rivlin material is related to the constants by [23]:

$$G = 2(C_{10} + C_{01})$$

The research paper referenced found the coefficients to be C10 = 16 MPa and C01 = 8 MPa [23]. The incompressibility parameter D1 was calculated from the elastic modulus K, derived assuming a Poisson's ratio of 0.4995:

$$K = \frac{2G(1+\nu)}{3(1-2\nu)}$$

$$D_1 = \frac{2}{K} \approx 8 \times 10^{-5} \text{ MPa}^{-1}$$

The resulting material properties used in the FEA are summarised in Table 3:

Table 3: Material Properties for 90 Shore A Rubber

Parameter	Value	Notes
Young's Modulus E	73 MPa	Estimated from Gent (1958) at S = 90
Initial Shear Modulus G	24.3 MPa	Derived: G = E/3 for near-incompressible elastomer
Mooney-Rivlin C10	16 MPa	2:1 split: C10 = 2G/3
Mooney-Rivlin C01	8 MPa	2:1 split: C01 = G/3

Incompressibility D1	8 x 10^-5 MPa^-1	Derived from K = 2G(1+v)/3(1-2v), D1 = 2/K
Poisson's Ratio v	0.4995	Near-incompressible; 0.5 avoided to prevent singularity

The boundary loading was estimated from rudder hydrodynamic theory. For a C420 sailing in approximately 20 knots of wind at a boat speed of 4 m/s, the dynamic pressure in water is:

$$q = \frac{1}{2}\rho_{water} v^2 = \frac{1}{2}(1025)(4)^2 \approx 8200 \text{ Pa}$$

Using a rudder planform area of 0.12 m², a lift coefficient of 0.5, a tiller arm of 0.35 m, and an extension length of 0.70 m, the design lateral force at the pin was derived as:

$$F_{grip} = \frac{F_{rudder} \times L_{tiller}}{L_{ext}} \approx 500 \text{ N}$$

An amplification factor of 1.5 was implicitly captured by rounding to 500 N to account for crash tacks and gusts. An axial force of 250 N was applied to represent the helmsman pulling the extension while hiking.

2.11.2. FEA

The joint assembly was modelled in ANSYS using a nonlinear static structural analysis with large deflection enabled. The rubber was assigned a two-parameter Mooney-Rivlin hyperelastic material model with the constants defined in Table 4. The nylon base was modelled as an orthotropic linear elastic solid with Young's modulus of 3000 MPa and Poisson's ratio of 0.35 [24].

Two different FEA set ups were created: just the joint and the joint with a 1.5 mm thick nylon mesh sleeve. The sleeve was approximated as an orthotropic linear elastic solid with effective properties (as seen in Table 4) scaled to 50 percent of nylon stiffness to account for the open weave geometry. The shear moduli were computed directly from the elastic moduli and Poisson's ratios.

Table 4: Material properties of Nylon Mesh

Property	50% Fill (Typical)
E_hoop (X)	1500 MPa

E_axial (Y)	800 MPa
E_radial (Z)	200 MPa
G_XY	555.6 MPa
G_YZ	333.3 MPa
G_XZ	83.3 MPa
v_XY	0.35

The boundary condition was that a fixed support was applied to the bottom face of the rectangular base. A remote displacement of 45 degrees rotation about the X-axis was imposed at the top of the cylindrical post to represent the helmsman holding the extension at full lateral articulation. A transverse bearing load of 500 N was applied inside the pin hole, and an axial force of 250 N was applied to the top face of the post to represent the force while steering.



Figure 17: Rubber Joint Articulation

Table 5: FEA Conditions Applied to both Joint Configurations

Load Case	Location	Direction	Magnitude
Fixed Support	Base bottom face	All DOF constrained	N/A
Lateral Bearing Load	Pin hole bore surface	Transverse to post axis	500 N

Axial Force	Top face of post	Along post axis	250 N
Remote Displacement	Top face of post	Rotation about X-axis	45 degrees

The equivalent elastic strain results showed a maximum strain of 0.29853 mm/mm in the joint without the sleeve, with the peak located at the compression face of the joint neck at the point of maximum curvature because of the combined angular displacement and lateral load. With the mesh sleeve, the maximum equivalent elastic strain reduced to 0.25703 mm/mm, a reduction of 13.9%. The strain distribution in the sleeved configuration was more uniform, thus redistributing load.

The strain energy results showed a more substantial difference. Without the sleeve the maximum strain energy was 33.254 mJ, with values up to 22.17 mJ concentrated around the base of the joint where it transitions into the nylon post. With the sleeve fitted the maximum strain energy is reduced to 14.062 mJ, with the majority of the body falling in the range of 8.177 x 10^-7 mJ to 9.375 mJ. This represents a peak strain energy reduction of 57.7 percent, indicating that the sleeve significantly reduces the energy available to drive crack initiation and propagation at the most vulnerable region of the joint. The total deformation of the joint with sleeve under the 45 degree articulation and combined loading reached a maximum of 17.595 mm at the tip of the post, consistent with the geometry and confirming that the large deflection solution is behaving correctly.

2.11.2.1. Static

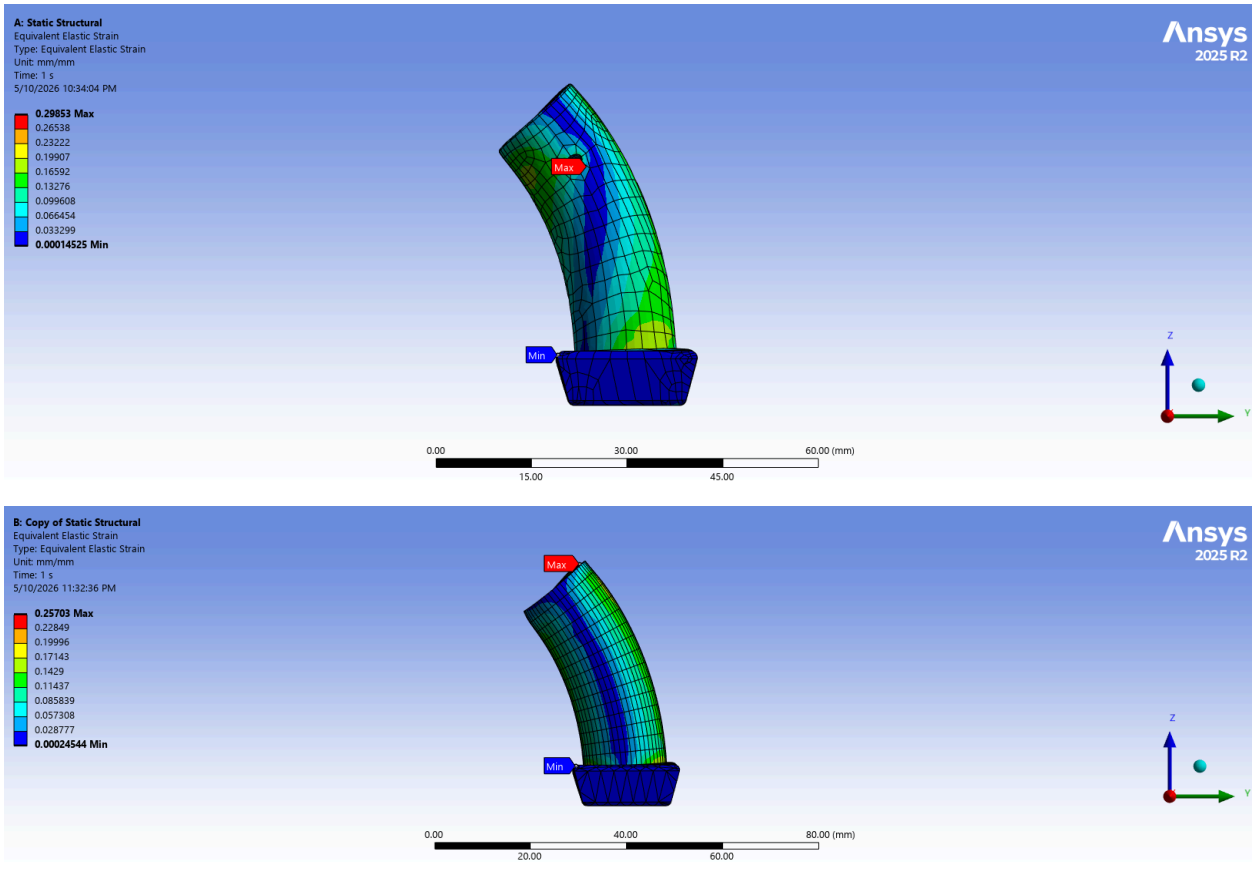


Figure 18 & 19: Equivalent Elastic Strain FEA Result

Table 6: FEA Static Structural Results

Result	Without Sleeve	With Sleeve
Max Equivalent Elastic Strain	0.29853 mm/mm	0.25703 mm/mm
Max Strain Energy	33.254 mJ	14.062 mJ
Strain Energy at Joint Base	~22.17 mJ	~9.375 mJ
Max Total Deformation	18.469 mm at tip	17.595 mm at tip
Strain Reduction	N/A	**13.9%**
Strain Energy Reduction	—	57.7%

2.11.2.2. Cyclic Loading

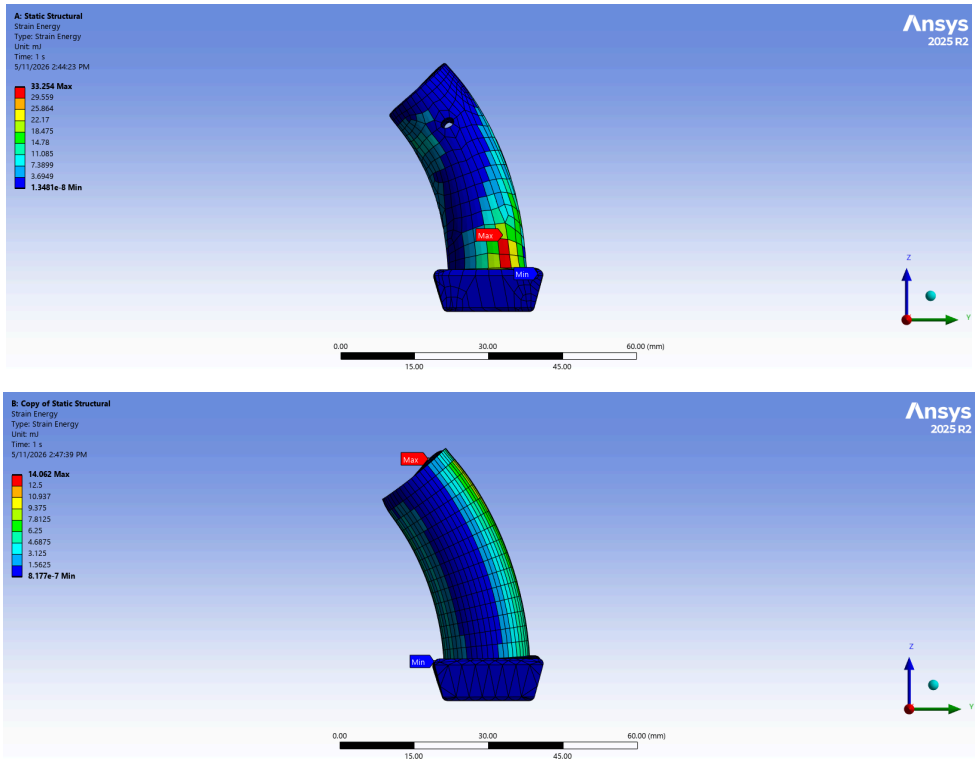


Figure 20 & 21: FEA Strain Energy FEA Result

Von Mises stress is not used as the failure criterion in this analysis. This is because Rubber does not have a well-defined yield stress, and failure in cyclic service is driven by crack initiation and growth, which correlates to strain energy density rather than stress amplitude. This is consistent with ASTM D412 and the rubber fatigue, which universally adopt strain energy or strain amplitude as the governing fatigue parameter [26].

Rubber at 90 Shore A has an elongation at break of approximately 400 percent [24]. The static factor of safety is:

$$FOS_{static} = \frac{\varepsilon_{break}}{\varepsilon_{max}} = \frac{4.00}{0.29853} = 13.4$$

This confirms that the joint will not fail under a single load application at the design load. The failure mode is fatigue accumulation, consistent with the conjoint analysis survey data showing failures accumulating over a racing season rather than in single events.

A cyclic fatigue simulation for hyperelastic rubber materials cannot be performed using ANSYS, and the built-in fatigue module relies on S-N curve data defined in stress terms and assumes linear elastic material behaviour. Neither of these failure modes are suitable/applicable to a rubber elastomer, and no standardized S-N data exists for 90 Shore Rubber. An analytical estimation of fatigue life was then performed instead using the strain energy density approach:

Following the 2002 research published by Mars-Fatemi, the fatigue crack initiation life of a rubber component under cyclic loading is estimated from the peak strain energy density W using the power law relation [26]:

$$N_f = A \cdot W_{max}^{-b}$$

where A and b are material constants. For polyurethane elastomers, representative values are A = 2 x 10^4 and b = 2.0 [26]. The strain energy density was computed analytically from the peak equivalent elastic strains extracted from the FEA using the Mooney-Rivlin strain energy function. Assuming the peak strain state at the neck is approximately uniaxial, the stretch ratio is lambda = 1 + epsilon_max, and the invariants are:

$$I_1 = \lambda^2 + \frac{2}{\lambda}, \quad I_2 = 2\lambda + \frac{1}{\lambda^2}$$

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3)$$

For the joint without the sleeve (epsilon_max = 0.29853, lambda = 1.29853), the computed strain energy density is W = 5.14 MJ/m^3, giving a predicted fatigue life of:

$$N_{f,no\ sleeve} = 20000 \times (5.14)^{-2} \approx 757 \text{ cycles}$$

For the joint with the sleeve (epsilon_max = 0.25703, lambda = 1.25703), the computed strain energy density is W = 3.91 MJ/m^3, giving a predicted fatigue life of:

$$N_{f,sleeve} = 20000 \times (3.91)^{-2} \approx 1308 \text{ cycles}$$

$$\frac{N_{f,sleeve}}{N_{f,no\ sleeve}} = \left(\frac{W_{no\ sleeve}}{W_{sleeve}}\right)^b = \left(\frac{5.14}{3.91}\right)^2 = 1.73$$

The sleeve therefore may extend predicted fatigue life by 73 percent regardless of the value of A. This figure, combined with the 57.7 percent reduction in peak strain energy from the FEA, creates a result that supports the hypothesis that the mesh sleeve reinforces the primary failure point by distributing the load more uniformly.

A representative race day loading was constructed to contextualise the fatigue life estimates using Miner's cumulative damage rule [27]:

$$D = \sum_{i} \frac{n_i}{N_{f,i}}$$

where n_i is the number of applied cycles at load level i and N_f,i is the predicted life at that load level. Failure is predicted when D approaches 1.0. The loading used is given in Table 7:

Table 7: Representative collegiate race day loading spectrum for Miner's rule application

Loading Event	Cycles (n_i)	Load Fraction	Severity
Normal steering cycles	5,000	30% of F_max	Low
Tacking and gybing*	200	80% of F_max	High
Loading Due to Wind	500	60% of F_max	Medium
Crash tacks	10	100% of F_max	Peak
Capsize/wipeout	2	100% + impact	Extreme

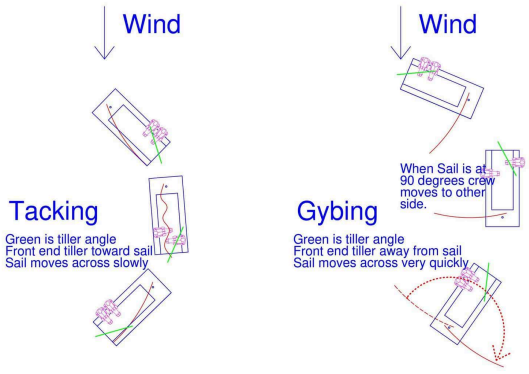


**Figure 22: Image of Sailing Maneuvers that cause Loading on Joint*

A 3 to 4 season target corresponds to approximately 54,000 to 72,000 steering cycles based on an estimate of 15 regattas per season, 6 races per regatta, and 200 significant tacking manoeuvres per race. Both configurations fall significantly short of this target; however, a shortcoming of this analysis is that Nf values require physical test data for calibration to fully assess the validity of the fatigue life from this method.

Also note that the static FEA results represent the unused loading state of the rubber, which is the stiffest condition. Under repeated cycling, 90 Shore A Rubber exhibits the Mullins effect, in which the stress response softens during the first three to five cycles before stabilising at a lower repeatable hysteresis loop [28]. The peak stresses and strains predicted by the static FEA are therefore conservative upper bounds for the cyclic loading condition, and the actual fatigue driving force would be somewhat lower than the FEA results suggest.

2.12. Project Deadlines

2.12.1. GANTT Chart

Gantt Chart is on ClickUp, and is fully up to date

Table 8: Project Task Ownership

Section	Responsible
1-2.2	Jeffrey Kagle
2.2.1-2.5.2	Mae Sliwinski
2.5.3-2.5.4	Alex Jenkins Garrett Smith
2.5.5	Mae Sliwinski
2.6-2.10	Alex Jenkins
2.11-2.11.2.2	Mae Sliwinski
2.12-2.12.2	Mae Sliwinski
3-3.4	Alex Jenkins
4-4.4.2	Garrett Smith
5-5.9	Jeffrey Kagle
Patent	Jeffrey Kagle Alex Jenkins

2.12.2. Significant Dates

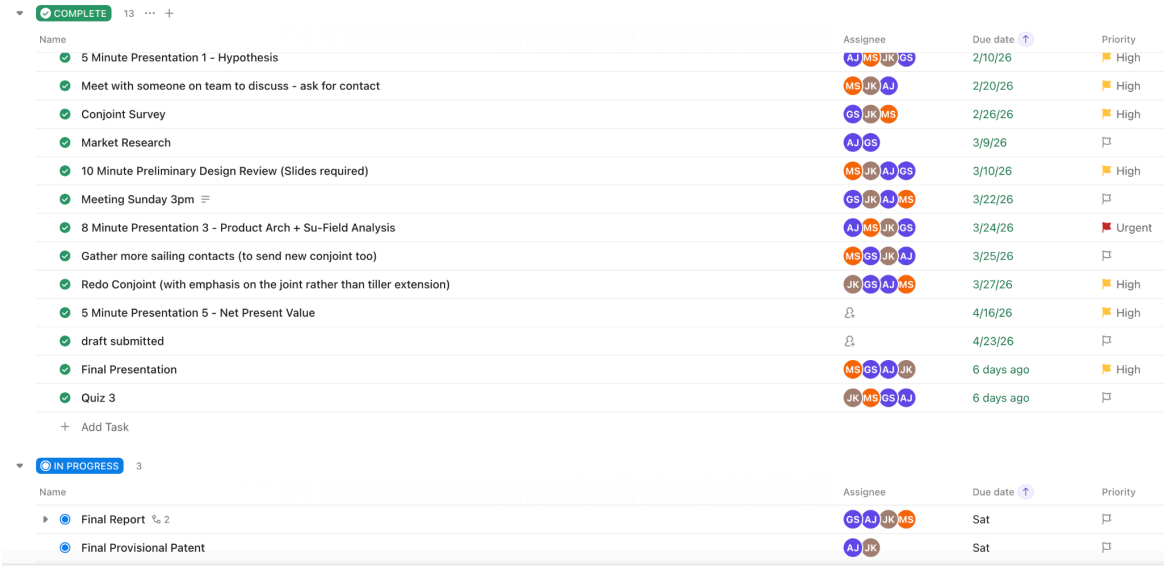


Figure 23: Gantt Chart along with Significant Dates

3. Market Identification

3.1. Target Market

Our target market consists primarily of competitive and collegiate sailors who operate small, high-performance dinghies such as the Laser, FJ, and C420. These sailors rely heavily on tiller extensions for steering and routinely sail in high-load racing conditions where equipment reliability is critical. In addition to this core group, the market also includes recreational sailors, sailing coaches, youth sailing organizations, and team programs that use similar equipment in training and competition settings.

This product is particularly valuable to these users because it addresses a well-documented failure point in existing systems: the universal joint. Current solutions often fail under cyclic loading, leading to frequent replacement and increased risk during use. The ANCORE design provides a lower-cost, longer-lasting alternative by improving fatigue resistance and reducing lifecycle cost.

3.1.1. Market Size – IBISworld/other market reports

The product is positioned within the broader recreational boating and sailing equipment market. Mordor Intelligence estimates the global recreational boating market at approximately $30.8 billion in 2026, with projected growth to $37.6 billion by 2031 at a compound annual growth rate (CAGR) of approximately 5.1% [29]. Additional market research from Persistence Market Research estimates the global sailboat market at approximately $3.9 billion in 2026, with projected growth to $5.5 billion by 2033. [30]

Within this larger market, the small-boat sailing segment represents a recurring replacement market driven by collegiate fleets, youth sailing programs, sailing clubs, and recreational racers. According to U.S. Sailing participation data, the United States contains over 350 high school sailing programs, approximately 190 collegiate sailing teams, and more than 1,300 yacht clubs and community sailing organizations [20]. These groups routinely purchase replacement tiller extension components due to fatigue and environmental degradation.

Unlike many marine hardware products, tiller extension universal joints behave more like consumable components than long-term equipment. Existing elastomer joints commonly require replacement after one to two seasons of use under competitive sailing conditions. The reinforced ANCORE design targets an operational life of approximately three to four seasons, reducing lifecycle replacement frequency while maintaining a competitive price point relative to existing market offerings.

3.2. Consumer Behaviour

Consumer decisions in this market are primarily driven by durability, affordability, and performance reliability, which aligns directly with the highest-weighted customer requirements identified in the House of Quality. Based on our HOQ, where importance is ranked on a scale from 1 (least important) to 5 (most important), affordability, durability, and effectiveness all received the highest rating of 5, followed by lightweight at 4 and safety at 3. This distribution indicates that users prioritize long-term value and consistent performance over premium materials or brand differentiation.

Although the industry has largely transitioned to polymer-based joints to improve corrosion resistance and flexibility, these designs remain susceptible to fatigue failure due to repeated cyclic loading and environmental exposure. As a result, consumers have adapted predictable behaviors, including frequent replacement of joints, a preference for cost-effective solutions, and growing interest in designs that improve durability or incorporate failsafe features. Conjoint analysis further reinforces these trends, showing that price, durability, and product

lifetime are the dominant factors influencing purchasing decisions, while comfort and interchangeability play a secondary role. Our design aligns directly with these preferences by reinforcing the joint structure to improve durability while maintaining a low cost, ultimately reducing the total cost of ownership over time.

3.3. House of Quality

The House of Quality analysis identified joint durability, manufacturing cost, and structural reliability as the dominant engineering considerations for the ANCORE design. These priorities align directly with the primary shortcomings observed in existing commercial tiller extension joints.

Current competitor products largely rely on molded elastomer universal joints with limited structural reinforcement. While these systems maintain low manufacturing cost and acceptable steering flexibility, they remain susceptible to fatigue cracking caused by repeated steering articulation, UV exposure, and environmental aging. Competitor analysis showed that no evaluated product scored highly across durability, affordability, and lifecycle performance simultaneously.

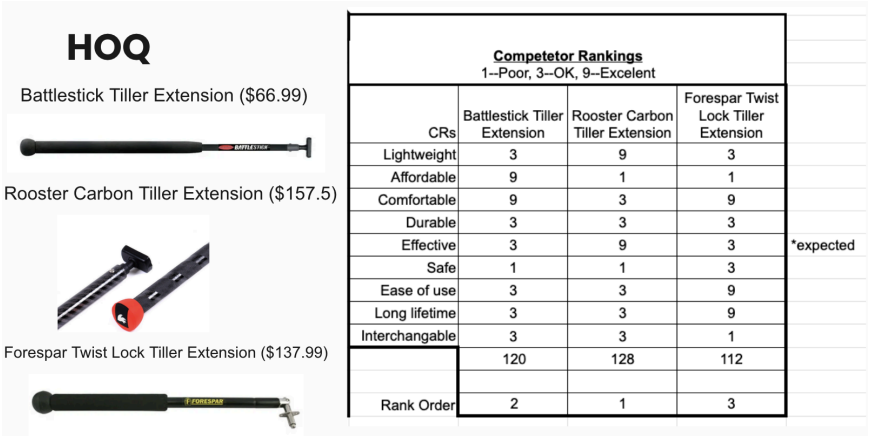
The ANCORE design was positioned as a reinforced mid-market solution that addresses this gap through the integration of a woven Nylon reinforcement sleeve and internal rope-core failsafe system. The reinforcement architecture redistributes tensile stresses around the outer elastomer body while the rope core provides secondary steering continuity if partial elastomer failure occurs. This allows the joint to maintain flexibility while improving fatigue resistance relative to conventional elastomer-only designs.

Engineering characteristics identified within the HOQ process also influenced material selection and subsystem layout. A UV-stabilized polyurethane elastomer was selected as the primary joint material due to its combination of flexibility, environmental resistance, and manufacturability. Nylon reinforcement components were selected for their tensile strength, fatigue resistance, and compatibility with cyclic marine loading environments [24].

3.3.1. Competitor Analysis

Current market competitors include Allen, Ronstan, Optiparts, RS Sailing, and JCD Composite products. Lower-cost products such as Allen and Ronstan provide affordable replacement joints but generally rely on conventional elastomer-only designs with limited fatigue reinforcement. Higher-end products improve stiffness and structural performance but introduce

significantly higher price points that are less practical for large collegiate fleets and recreational sailors.



Competetor Rankings
1--Poor, 3--OK, 9--Excelent

CRs	Battlestick Tiller Extension	Rooster Carbon Tiller Extension	Forespar Twist Lock Tiller Extension	
Lightweight	3	9	3	
Affordable	9	1	1	
Comfortable	9	3	9	
Durable	3	3	3	
Effective	3	9	3	*expected
Safe	1	1	3	
Ease of use	3	3	9	
Long lifetime	3	3	9	
Interchangable	3	3	1	
	120	128	112	
Rank Order	2	1	3	

Figure 25: Competitor Analysis Chart from the HOQ

Table 9: Competitor Analysis, Joint Specific

Manufacturer	**Material Composition**	**Retail Price (USD)**	**Targeted Market Segment**
Allen	Standard Flexible Rubber	$10.40	Entry-level / High-frequency replacement
Ronstan	UV-Stabilized PU Tendon	$17.31	Standard Club/OEM replacement
Optiparts	Rope Core (Standard Blue)	$18.25	Specialized youth/Opti fleets
OUR JOINT	Mesh-Reinforced Rope Core	$19.99	Collegiate Performance / High Reliability
RWO	Omniflex with Rope Core	$22.00	Upgraded performance
RS Sailing	Custom Universal Joint	$41.88	Brand-specific proprietary replacement

JCD Custom	Machined Socket w/ Rope Core	$75.00	Elite-level custom racing

From our Competitor Analysis we see that the high-end products (Rooster) perform well in weight and effectiveness, but score poorly in affordability. Whereas the lower-cost products (Ronstan, Forespar) perform well in cost, but still score low in durability (all ~3) And competitor scores highly in durability, confirming a market-wide failure point

Competitors:

- Forespar Twist Lock Tiller Extension Score: 112 Rank 3
- Rooster Carbon Tiller Extension Score: 128 Rank 1
- Battlestick Tiller Extension Score: 120 Rank 2

The ANCORE design is positioned between low-cost replacement products and premium specialty systems. The objective is to improve operational lifespan and structural reliability without significantly increasing manufacturing complexity or market price.

3.3.1.1. BOM

Table 10: House of Quality Level 2

Materials	UV-Stabilized TPU (Grade 90A)	$1.45	~$4.50/kg, ~320g part
Materials	Marine Polyester Rope Core	$0.35	Bulk reel ($0.17/ft)
Materials	Polymer Mesh Reinforcement	$0.40	Custom die-cut weave

A more detailed cost of goods sold is detailed in 4.1.4.2.

3.4.Bass Model Forecast

Using the Bass diffusion model, the following parameters were selected to estimate adoption within the competitive dinghy sailing market:

- Market Potential (M) = 6,260 users
- Coefficient of Innovation (p) = 0.015
- Coefficient of Imitation (q) = 0.45

- Forecast horizon = 10 years
- Year 1 cumulative adopters begins at 0 ($N_0 = 0$)

(M was found by the total number of collegiate sailing teams with around 15 boats per team and 3% of the US sailing membership for the 18-25 year group.)

- Number of 18-25 age group numbers(3% of the total US sailing membership demographics): (42,000 total members)*(3% of the age bracket doing more intense sailing) = 1,260 people [20]
- With 190 Collegiate teams with around ~15 boats per team and also 350 High school teams with about ~6 boats each and a little more for safety

The estimated market potential was derived from the combined population of collegiate sailors, youth racing programs, sailing instructors, and high-frequency recreational racers operating small dinghy fleets within the United States. The estimate also considers recurring replacement demand associated with tiller extension universal joints in competitive sailing environments.

A relatively low innovation coefficient was selected because marine hardware adoption typically occurs gradually through testing and community validation. A higher imitation coefficient was used to reflect the strong word-of-mouth influence within collegiate and competitive sailing communities, where equipment recommendations and observed race performance significantly affect purchasing behavior.

The Bass Model demand for year *t* is:

$$S(t) = \left(\frac{M(p+q)^2}{p}\right)\left(\frac{e^{-(p+q)t}}{\left(1+\frac{q}{p}e^{-(p+q)t}\right)^2}\right)$$

Table 11: Bass Model Forecast

Year	New Adopters	Cumulative Adopters	Percent Adoption (%)
0	94	94	1.50
1	144	238	3.80
2	216	454	7.25
3	314	768	12.27

4	437	1205	19.25
5	570	1775	28.35
6	686	2461	39.31
7	748	3209	51.26
8	733	3942	62.97
9	647	4589	73.31
10	521	5110	81.63

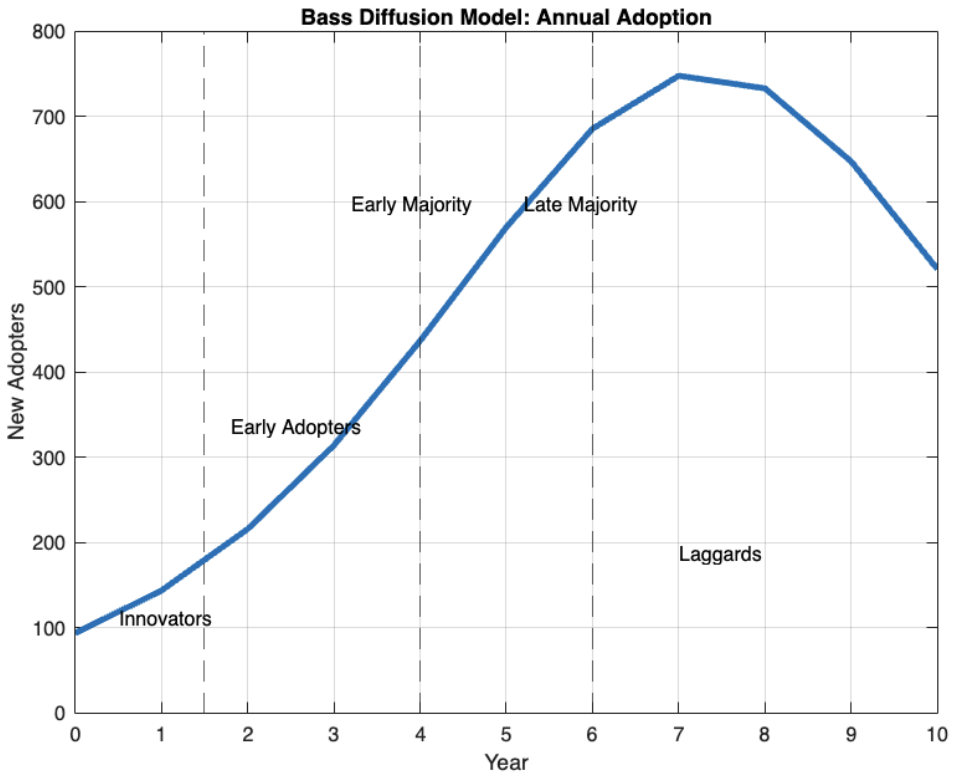


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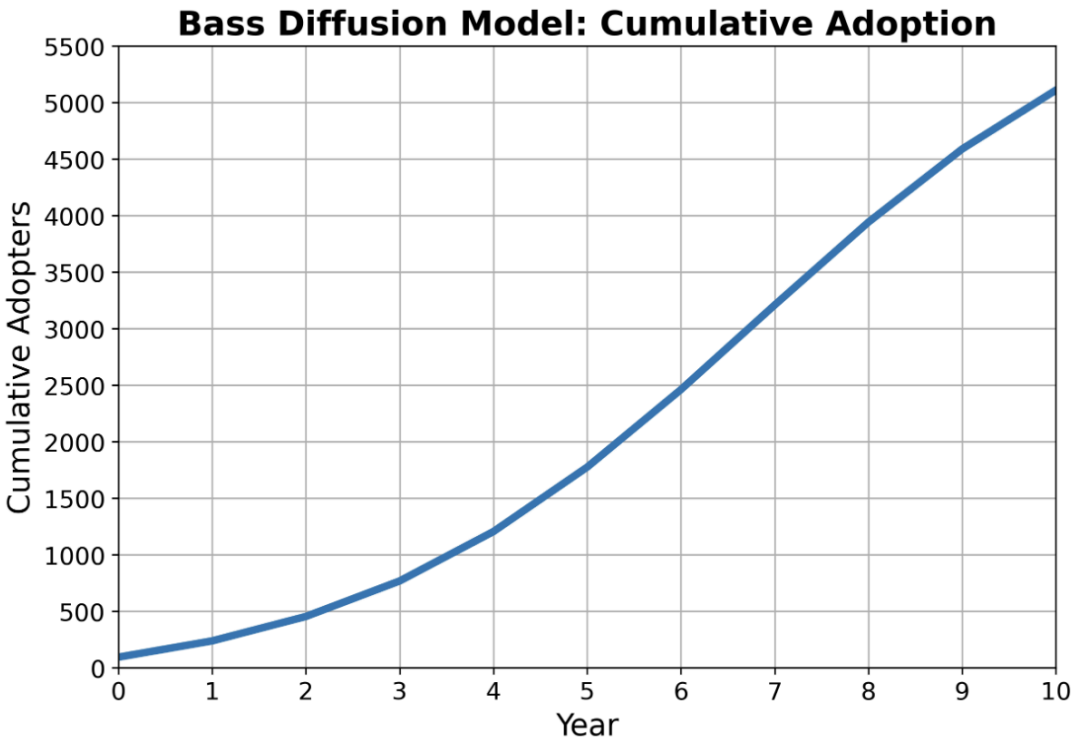


Fig x:

Using the Bass diffusion model, the market potential was estimated at approximately 6,260 users, representing the active population of collegiate sailors, youth racing programs, sailing instructors, and high-frequency recreational sailors who regularly use tiller extensions within the United States. A coefficient of innovation (p) of 0.015 was selected to reflect the relatively slow initial adoption typical of niche marine hardware markets, while a coefficient of imitation (q) of 0.45 captures the strong influence of word-of-mouth recommendations, observed race performance, and team-based purchasing behavior within competitive sailing communities.

The model predicts gradual early adoption followed by accelerated growth as the product demonstrates improved durability and reliability under repeated cyclic loading and marine exposure. Annual adoption increases most rapidly between Years 5–8, where yearly adopters rise from approximately 570 to 748 new users. Cumulative adoption is projected to reach approximately 51% of the target market by Year 7, 63% by Year 8, and over 81% by Year 10, corresponding to roughly 5,110 cumulative adopters. The forecast reflects the highly networked nature of the sailing community, where equipment validation through peer recommendation, regatta visibility, and long-term reliability strongly influences purchasing decisions.

4. Financial Requirements

4.1. Financial Executive Summary

4.1.1. Price

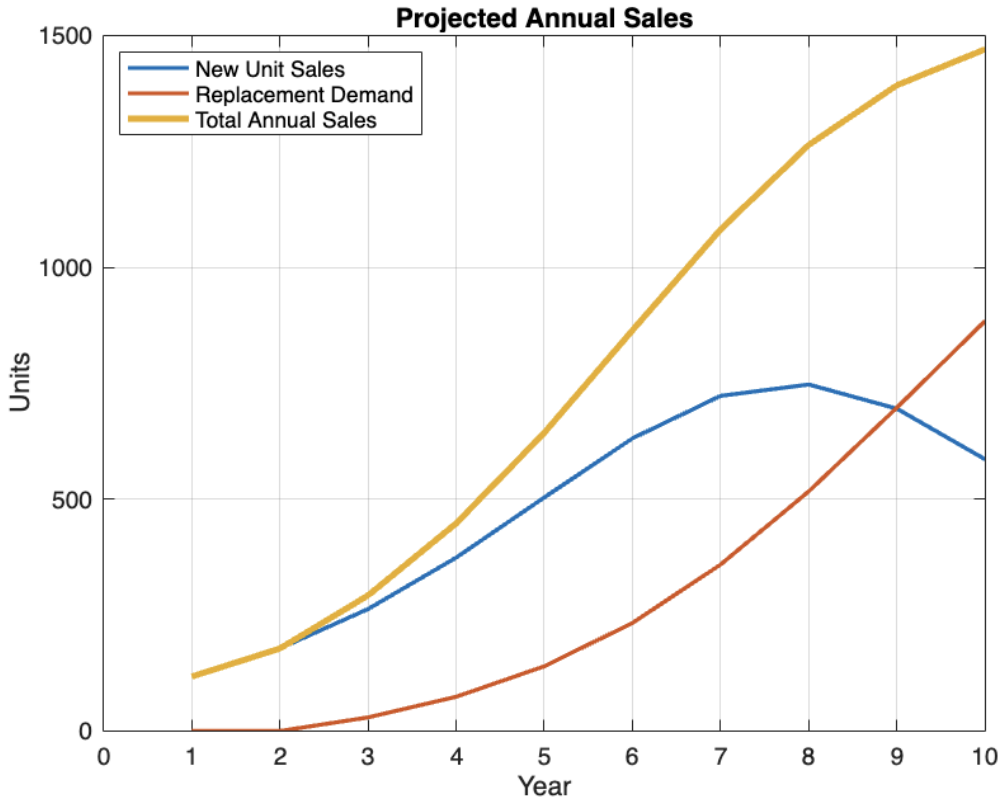
The planned product is the full tiller extension, with the specialized reinforced joint included, priced at $80.

4.1.2. Expected Sales

The expected sales are directly predicted using the Bass Model Forecast shown in section 3.4.

Table 13: Adoption Prediction

Year	Adoption Fraction (%)	New Unit Sales	Replacement Demand	Total Annual Sales
1	3.80	144	0	144
2	7.25	216	0	216
3	12.27	314	29	343
4	19.25	437	74	511
5	28.35	570	140	710
6	39.31	686	233	919
7	51.26	748	359	1107
8	62.97	733	517	1250
9	73.31	647	697	1344
10	81.63	521	884	1405



The sales trajectory shows exponential growth of the new unit sales until year 5. The acceleration is driven by the 3-4 season lifespan, as early adopters in Year 1 reach the end of their second season without a single failure, the “imitator” segment will transition from legacy tiller extensions to the ANCORE tiller extension. The decline in new unit sales after Year 7 reflects the saturation of the primary market, however as the replacement cycles repeat, the replacement demand continues to spike.

4.1.3. Cost

The cost structure is categorized into variable production costs and the reduction of development and manufacturing overhead costs. The Bill of Materials below reflects the 2025/2026 commodity pricing for marine-grade materials.

4.1.4. Net Present Value over 5 years of sale

The New Present Value analysis evaluates the financial viability of the ANCORE replacement joint over a 10-year commercialization horizon. The analysis utilizes the cumulative

adoption rates combined with the predicted hardware replacement cycles to generate accurate cash flow projections.

4.1.4.1. Fixed cost to produce

The primary upfront capital expenditure involves the design, CNC machining, and polishing of the injection mold tooling required to produce the polyurethane elastomer body and seamlessly over-mold the internal ropecore [31]. Given the projected 10-year cumulative volume of about 5,110 units, purchasing a high volume, multi-cavity hardened steel mold is certainly economically inefficient.

Rather, a low-to-mid volume bridge tooling strategy would be a much better allocation of startup capital [32]. Based on CustomPartNew and industry standard estimates for a component of this volumetric complexity, incorporating side actions for the compression slot and side tolerances for insert-molding the mesh sleeve, produced in batch sizes of 300 to 400 units, the initial fixed tooling and engineering cost sits around $8,500 [33].

4.1.4.2. COGS

As detailed in the fundamental Bill of Materials (Table 12), the variable Cost of Goods Sold is highly optimized at exactly $6.30 per unit. This metric is a comprehensive sum of all the direct materials, direct labor, and other variable manufacturing overhead costs. It includes the raw UV-stabilized TPU 90A resin ($1.45), the marine-grade polyester rope core ($0.35), the custom die-cut polymer mesh reinforcement ($0.40), automated machine setup and cycle labor ($1.80), energy consumption and machine maintenance per cycle ($0.60), and rigorous 100$ tensile quality control inspection ($0.50), and inbound freight with sustainable packing ($1.20).

Table 12: COGS

Category	**Component**	**Cost per Unit (USD)**	**Source/Note**
Materials	UV-Stabilized TPU (Grade 90A)	$1.45	~$4.50/kg, ~320g part
Materials	Marine Polyester Rope Core	$0.35	Bulk reel ($0.17/ft)

Materials	Polymer Mesh Reinforcement	$0.40	Custom die-cut weave
Labor	Machine Set-up & Cycle Labor	$1.80	Automated injection
Machine	Energy & Maintenance	$0.60	$0.50-$2.00 range
Overhead	QC & Inspection	$0.50	100% tensile testing
Logistics	Inbound Freight & Packaging	$1.20	Sustainable materials
Total		$6.30	

4.1.4.3. Annual net: (price-cost)*quantity

The financial model focuses exclusively on the core consumable product: $19.99 replacement joint. Assuming a uniform wholesale/retail unit price of $19.99 against the COGS of $6.30, the gross margin per unit is $13.69, a solid 68.48% margin.

The annual net cash flows are calculated by multiplying this unit margin by the total annual sales trajectory established by the Bass Diffusion Model. This trajectory combines new and adopting users with the recurring maintenance and replacement demand from previously saturated early-adopters who have exceeded their 3 to 4 season lifecycle limit.

Table 14: *Annual Net Cash Flow over 5-years*

Formula: $Annual\ Net\ Cash\ Flow_t = (Price - COGS) * Total\ Quantity_t$

Year (t)	Total Annual Sales (Units)	Gross Margin per Unit	Annual Net Cash Flow
1	144	$13.69	$1,971.36
2	216	$13.69	$2,957.04
3	343	$13.69	$4,695.67
4	511	$13.69	$6,995.59
5	710	$13.69	$9,719.90

4.1.4.4. Estimated Weighted Average Cost of Capital

In order to appropriately discount future cash flows for a hardware startup operating within the specialized sailing equipment market, the Weighted Average Cost of Capital needs to both reflect established industry baselines and the inherent risks of early-stage hardware commercialization. While specific data for the sailing market is not publicly available, the WACC for the closely aligned "Recreation" sector sits around 8.5% based on Damodaran's comprehensive January 2026 corporate finance datasets.

4.1.4.5. Compounded annually

The Net Present Value is computed by discounting the projected Annual Net Cash Flows over the 10-year period at the 8.5% WACC, and subtracting the initial Year 0 fixed capital expenditure.

Formula:

$$NPV = \sum_{t=1}^{10} \frac{CF_t}{(1+WACC)^t} - C_0$$

Figure 15: Net Present Value Over 5 Years

Year (t)	Annual Net Cash Flow	Weighted Average Cost of Capital	Present Value
1	$1,971.36	8.50%	$1,816.92
2	$2,957.04	8.50%	$2,511.87
3	$4,695.67	8.50%	$3,676.28
4	$6,995.59	8.50%	$5,047.84
5	$9,719.90	8.50%	$6,464.18
		Sum of Present Values (Years 1-5)	$19,517.09
		Minus Fixed Tooling Cost (C0)	-$8,500.00
		Net Present Value over 5 years	$11,017.09

The NPV of $11,000 over a highly conservative 5 year commercialization window shows that the project is fundamentally financially viable. The product will generate shareholder value exceeding the cost of capital.

4.2. Pricing Policy

The determination of a strategic price point for the tiller extension requires a deep understanding of the existing market within the niche sailing tiller extension industry. Section 3.3.1 outlines three competitors at two pricepoints. The Ronstan Battlestick is at the lower end of the spectrum, along with other commodity manufacturers such as Allen who offer basic aluminum tiller extensions priced between $50 and $80 [36]. At the high end of the market, manufacturers like JCD Custom Race Parts and Rooster produce tiller extensions priced between $130 to even $250. Based on the conjoint analysis in section 2.3, users would prefer a tiller extension on the lower end of the market.

Before determining a pricing policy for the tiller extension set, a pricing policy for the Ancore tiller extension joint must be considered first. The joints used in the cheaper tiller extensions are basic polyurethane based joints priced between $10.40 and $17.31 (MSRP for replacement joints, source). These components are known to fail early, especially under the high-frequency use typical of collegiate racing environments where boats are rotated between divisions throughout 12 to 18 races per weekend. At the high end of the market, manufacturers like JCD Custom Race Parts produce swiveling rope-core joints that are priced as high as $75.00 [36]. While reliable, these products are priced beyond the ideal price point for collegiate teams with constrained budgets. The proposed pricing for the triple reinforced replacement joint is established at a primary retail MSRP of $19.99. This price targets the “performance value” segment, offering significantly increased safety and longevity at a cost profile comparable to the standard mid-range options. It’s far less expensive than the RS Sailing universal joint ($41.88) or the JCD joint ($75.00), while addressing the core failure mechanisms like tearing and delamination that make the Allen and Ronstan models prone to early failure.

Now, the pricing policy of the Ancore tiller extension is as follows: (average of lower end tiller extensions) - (avg low end replacement joint cost) + (proposed $19.99 cost of Ancore replacement joint). This policy sets the price of the full tiller extension, joint included, at roughly $80.00.

4.3. Production Cost

4.3.1. What manufacturing process will you use based on

4.3.1.1. Economic Batch Size

The Economic Batch Size is calculated using the following formula: $EBS = \sqrt{\frac{2DS}{H}}$, where D is the annual demand (estimated at ~2,000 units), S is the setup cost per batch (machine cleaning, mold mounting, etc.), and H is the annual holding cost per unit. Based on standard injection molding trends for small parts, the optimal batch size is likely around 300 to 400 units per run, allowing for 5 to 6 production cycles per year to meet average annual sales trajectory.

4.3.1.2. Surface Roughness

A surface roughness of Ra 3.2 μm is specified for the exterior of the joint (industry standard for commercial molded finishes). For the internal mating surfaces that interface with the tiller extension tubing, a higher precision finish of Ra 1.6 μm is necessary to ensure a secure, friction-stable fit in order to prevent premature wear in high-cycles.

4.3.1.3. Part Architecture

Utilizing 90 Shore-A TPU for the rubber provides the required flexibility for steering, while the internal 16mm rope core and polymer mesh serve as high-tensile skeleton. The joint will feature a fixed base with standard 32mm mounting holes in order to ensure compatibility with all C420s in collegiate fleets.

4.3.2. Tooling parameters and costs for the selected process

Given the projected economic batch size of 300 to 400 units per run, the tooling parameters must be optimized for low-volume bridge tooling rather than high-volume hardened steel production [32]. The planned tooling will require a 2-cavity mold. Because the elastomer body will contain the internal rope core and must also integrate the woven mesh reinforcement, the tooling will require over-molding and insert-molding capabilities. The operational cycle time is estimated at around 40 seconds. This duration is mostly driven by the cooling phase which accounts for roughly 50 to 70% of standard injection cycles. This is required to thermally stabilize the thick sections of the 90A TPU without inducing any internal shrinkage voids or warpage upon ejection [34].

4.3.2.1. Custompartnet.com

Due to our specialized injection molding process, with 90 Shore A polyurethane elastomer, custompartnet.com is not able to accurately give us a quote for our selected process outlined above.

4.3.2.2. Quotes from manufacturer

Based on typical percentage of material, machining, assembly, mold design, and tax costs, the below table shows a realistic manufacturing quote.

Tooling Phase	Cost Estimation (USD)	Technical Description
Design and Engineering	$1,200	Gate sizing is critical to prevent premature freezing before the thermodynamic cooling channel layout. Critical mold flow analysis by certified engineers is necessary for this.
Mold Fabrication	$5,800	CNC roughing and Electrical Discharge machining for the joint geometry and pin interfaces.
Insert-Molding Fixtures	$800	Custom alignment sliders and lifters will be needed in order to ensure the rope core and polymer mesh are securely held centrally during the TPU injection phase.
Testing and Validation	$700	Parameter dialing and tolerance validation.
Total Quoted Investment	**$8,500**	Full ownership of the mold will be transferred to ANCORE upon

		completion.

4.4. Capital Investment Required

4.4.1. How will you raise money for manufacturing equipment or afford to outsource

To fund the $8,500 needed for the injection mold tooling and potentially afford initial outsourcing minimum order quantities in order to not prematurely dilute founder equity, ANCORE plans to aggressively target localized startup accelerators.

ANCORE plans to initially apply to Rev: Ithaca Startup Works Protofacturing Accelerator and its subsequent manufacturing track [35]. Backed by Cornell University and additionally also expanding via a $2 million “Build to Scale” grant from the US Economic Development Administration, Rev seems to be a good option for ANCORE to continue to build up proof of concept and manufacturing path. The program provides hardware startups with access to physical marketplaces and direct stipends to cover prototyping and initial tooling costs (20).

4.4.2. How will you raise money to pay employees to scale up production?

In order to fund the raw material inventory and secure payroll for production scale up, ANCORE will need to look into broader capital injection strategies beyond relying on startup accelerators. Once the engineering prototype is physically validated and the initial low volume runs are secured, ANCORE will rely on B2B Presales and Fleet Contracts.

Given that the target market heavily relies on institutional consumers (collegiate varsity and club sailing fleets), ANCORE will secure pre-orders and pilot-program letters of intent from university athletic departments. By structuring initial wholesale transitions with a 30% upfront deposit on fleet outfitting, ANCORE will have access to immediate, non-dilutive working capital. This capital will be used to fund the COGS for the production run and cover contract labor.

5. Legal Requirements

5.1. Safety & Environmental Regulations for your product's manufacturing

The primary materials used in manufacturing this tiller extension joint — polyurethane rubber, nylon rope, and woven polymer mesh — are subject to OSHA's General Industry Standards (29 CFR 1910), which govern worker safety during casting and molding processes that may release volatile organic compounds. The 6061 aluminum tiller extension shaft, produced via lathe or extrusion, must comply with EPA Clean Air Act regulations for metalworking facilities. The injection-molded PETG or ASA tiller attachment components fall under EPA 40 CFR Part 63 emission standards for plastic parts manufacturing. As a consumer product with direct safety implications, the assembly should also be documented in accordance with the Consumer Product Safety Improvement Act (CPSIA), which requires safety testing and recordkeeping for products that pose potential physical injury risks.

5.2. Safety & Environmental Regulations for your product's use

As a handheld sailing control component used in competitive racing, the tiller extension and joint must not create a safety hazard to the sailor or other competitors during use. U.S. Sailing's Equipment Rules of Sailing (ERS) govern what materials and configurations are permissible on racing dinghies, and any tiller extension used in collegiate competition must conform to class rules for the specific boat being raced. The nylon and polyurethane components are subject to UV and saltwater degradation over time, and as microplastic shedding in marine environments faces increasing regulatory scrutiny under the EPA's Trash-Free Waters program, the long-term environmental impact of material breakdown during use should be considered in design iteration. Sailors should be advised against continued use of a visibly degraded joint, as a mid-race failure presents a direct loss-of-control hazard consistent with the safety concerns identified in user research.

5.3. How will the products reduce environmental impact on production?

The material choices for this tiller extension inherently limit manufacturing complexity and associated environmental impact. Polyurethane casting and nylon rope are low-energy production processes compared to alternatives like carbon fiber layup, and the woven polymer mesh requires no chemical treatment during fabrication. The injection-molded PETG tiller attachments are thermoplastics, meaning rejected or defective parts can be reground and reprocessed rather than scrapped, reducing material waste. Sourcing 6061 aluminum for the

shaft, which has a well-established domestic recycling infrastructure, further limits the product's overall production footprint.

5.4. How Products Reduce Environmental Impact Upon End of life

The tiller extension's modular architecture, in which the joint is designed to be interchangeable and replaceable independent of the shaft, directly reduces waste by allowing sailors to replace only the failed component rather than discarding the entire assembly. The 6061 aluminum shaft is fully recyclable through existing municipal and industrial metal recycling streams. The PETG tiller attachment components are recyclable thermoplastics, though sailors should check local recycling program acceptance. The polyurethane joint and nylon mesh are more difficult to recycle and will likely enter the waste stream at end of life; however, the extended 3–4 season product lifetime significantly reduces the frequency of disposal compared to current designs that fail within a single season.

5.5. Potential Liability Issues for Use

As a safety-critical component in competitive sailing, the tiller extension and joint present product liability exposure if a failure results in loss of vessel control, collision, or sailor injury during racing. Given that user research identified an 83% mid-race failure rate among current designs, the product's core value proposition is improved reliability — meaning any failure of the new joint that results in injury could be subject to negligence claims if the design does not demonstrably meet its stated engineering hypothesis of a factor of safety above 2.0 and a field failure rate below 10%. Adequate physical load testing, FEA documentation, and clear labeling of the product's intended use and load limits will be essential in limiting liability exposure.

5.5.1. Prediction of Misuse Cases

The most foreseeable misuse cases include sailors using the tiller extension beyond its intended range of motion, placing excessive lateral force on the joint during aggressive maneuvers beyond what the design was tested for. Additionally, sailors may continue using a visibly degraded or partially failed joint rather than replacing it, particularly during competition when equipment swaps are not possible. Using the joint on boat classes or tiller configurations outside of the intended fit is another likely misuse scenario, as is improper installation of the compression clamp and bolt attachments, which could accelerate joint fatigue or cause sudden detachment at the tiller interface.

5.6. Failure Mode and Effect Analysis

A Failure Mode and Effect Analysis (FMEA) was conducted to systematically identify potential failure points in the tiller extension joint, assess their impact on sailor safety and product performance, and prioritize mitigation strategies based on risk priority numbers (RPN).

5.6.1. Identify potential failure modes, effects, and severity

Failure Mode	Component	Effect	Severity (1-10)
Rubber joint fracture	Polyurethane Joint	Loss of Steering Control	9
Mesh delamination	Woven polymer mesh	Reduced load distribution, faster joint failure	6
Rope core breakage	Nylon rope core	Tiller extension fully detaches from tiller	10
Compression clamp loosening	Base attachment	Joint detaches from tiller mid-race	9
UV/saltwater degradation	Polyurethane, nylon	Reduced material strength over time	5
Fitting fracture	PETG/ASA attachment	Loss of tiller connection	8

5.6.2. Prediction of misuse cases

Misuse Case	Likelihood (1-10)	Potential Effect
Exceeding intended range of motion during aggressive maneuvers	8	Accelerated rubber fatigue, premature fracture
Continued use of visibly degraded joint	7	Sudden mid-race failure, loss of steering
Improper installation of compression clamp	6	Joint detachment from tiller under load

Use on incompatible tiller configurations	5	Misaligned load path, stress concentration at base
Failure to replace joint after partial failure	7	Full fracture during subsequent maneuvers

5.6.3. Risk priority numbers (RPN) and mitigation strategies

Failure Mode	**Severity (S)**	**Occurrence (O)**	**Detechability (D)**	**RPN**	**Mitigation Strategy**
Rope core breakage	10	2	4	80	Use high-tenacity nylon, conduct cyclic load testing to 500 cycles at 150% rated load
Compression clamp loosening	9	4	5	180	Specify torque requirement on installation, add locking feature to clamp design
Rubber joint Fracture	9	5	6	270	Polymer mesh stress distribution, FEA validation to FOS > 2.0
Fitting Failure	8	4	5	160	Transition to injection-molded production parts, material testing of PETG/ASA
Mesh delamination	6	4	6	144	Adhesive bonding validation, inclusion in cyclic load test protocol
UV/saltwater	5	7	4	140	Accelerated weathering testing, recommended replacement interval documentation

5.6.4. Risk mitigation to lower RPN

Failure Mode	Pre-Mitigation RPN	Mitigation Applied	Post-Mitigation Occurrence (O)	Post-Mitigation Detectability (D)	Post-Mitigation RPN
Rope core breakage	80	High-tenacity nylon, cyclic testing	1	3	30
Compression clamp loosening	180	Torque spec, locking feature	2	3	54
Rubber Joint Fracture	270	Polymer mesh, FEA validation	3	4	108
Fitting fracture	160	Injection molding, material testing	2	3	48
Mesh delamination	144	Adhesive validation, load testing	2	4	48
UV/saltwater degradation	140	Weathering testing, replacement guidelines	4	3	60

5.7. Industry Standards and Certifications

5.7.1. Relevant Industry Standards

Standard	Issuing Body	Relevance to Product
ISO 12215	ISO	Defines minimum material strength requirements for the aluminum shaft and rigid base under combined tiller loading
ASTM D412	ASTM	Defines tensile and elongation testing for the polyurethane

	International	joint to validate FOS > 2.0 under maximum tiller load
ASTM D638	ASTM International	Defines tensile strength validation for the PETG/ASA male and female tiller attachment components
ASTM D4329	ASTM International	Governs accelerated UV weathering testing for the polyurethane joint and nylon mesh across 3–4 simulated seasons
ISO 1817	ISO	Defines saltwater immersion testing for the polyurethane joint to validate integrity over the intended product lifetime
World Sailing ERS	World Sailing	Defines permissible tiller extension materials and joint configurations for sanctioned collegiate racing
U.S. Sailing RRS	U.S. Sailing	Governs tiller extension equipment legality in U.S. collegiate conference racing and applicable dinghy class rules

5.7.2. Certifications Required

Certification	**Issuing Body**	**Requirement**	**Applicability**
CPSC Compliance	U.S. CPSC	Safety testing and recordkeeping for consumer products posing physical injury risk	Required for domestic retail sale
ISO 9001	ISO	Quality control across polyurethane casting, mesh weaving, and injection molding to ensure consistent part tolerances	Recommended at production scale
World Sailing Approved Equipment	World Sailing	Joint must conform to dinghy class rules and ERS material requirements	Required for sanctioned collegiate racing
REACH Compliance	ECHA	Disclosure of hazardous substances in polyurethane, nylon, and PETG/ASA components	Required for European market sales
RoHS Compliance	European Commission	Restriction of hazardous substances in plastic and elastomer joint components	Required for European market sales

5.8. Intellectual Property Considerations

5.8.1. Utility & Design patents

A utility patent will be filed covering the three-layer structural composition of the tiller extension joint, specifically the combination of a nylon rope core, polyurethane rubber body, and woven polymer mesh sleeve as an integrated system for reinforcing universal joints in competitive sailing applications. The patent claims will focus on this combination as a novel approach to joint failure prevention, as no current product on the market addresses the primary failure point identified in user research through this method. Additional claims will cover the compression clamp attachment mechanism connecting the joint assembly to the tiller, preventing competitors from developing compatible attachment interfaces that interface with our joint without licensing rights. A design patent will also be pursued covering the distinctive hourglass geometry of the joint as visible in the CAD and cross-sectional drawings, protecting the external appearance of the product in addition to its functional architecture.

5.8.2. Trade secrets

Trade secret protection will be applied to two key aspects of the joint's manufacturing process: the specific chemical formulation of the polyurethane elastomer body and the weave pattern geometry of the nylon mesh sleeve. The rubber formulation, while not novel enough to meet the non-obviousness threshold required for patent protection given the breadth of existing elastomer chemistry, represents a tuned combination of shore hardness, elongation, and UV resistance optimized for the marine sailing environment that would be difficult for competitors to replicate without direct access to the formula. Similarly, the specific weave pattern and fiber orientation of the nylon mesh, while not independently patentable, provides a measurable performance advantage in stress distribution across the joint that constitutes protectable proprietary information. Both trade secrets will be enforced through non-disclosure agreements (NDAs) with all manufacturing partners and employees involved in the casting and weaving processes, as well as non-compete agreements restricting the ability of those parties to produce functionally identical components for competing products.

5.8.3. Trademark

5.8.3.1. Team name and logo

The company name ANCORE will be pursued for trademark registration with the U.S. Patent and Trademark Office under International Class 28, which covers sporting goods and equipment. A preliminary trademark search confirms that ANCORE is not currently in use within the competitive sailing or marine equipment product category, satisfying the distinctiveness requirement for registration. Both the ANCORE wordmark and associated logo will be filed for trademark protection, preventing competitors from adopting confusingly similar branding within the same product category.



5.8.3.2. Other trademark opportunities

The product name, the *ANCORE U Tiller Extension Joint*, will also be filed for trademark protection under International Class 28, preventing competitors from adopting functionally similar product names that could cause customer confusion in the sailing equipment market. As ANCORE builds brand recognition within the collegiate sailing segment, a distinctive and protected product name reinforces customer trust and ensures that sailors seeking the specific performance benefits of the joint are directed to the authentic product rather than imitations. Together, the company and product trademarks form a layered brand protection strategy.

5.9. What are your next steps?

The immediate next step for ANCORE is to file a provisional utility patent application covering the three-layer joint architecture with the USPTO, which will establish a priority date and provide 12 months of patent-pending protection during which the design can be openly shared with potential customers and investors. During this window, the team will present the ANCORE U Tiller Extension Joint and physical prototypes to stakeholders under NDAs to gather final design feedback before committing to the non-provisional patent submission. Concurrently, trademark registration for both the ANCORE company name and the ANCORE U Tiller Extension Joint product name will be filed to secure brand protection ahead of any public product launch or investor presentations. This parallel filing strategy ensures that intellectual property protections are established before the product enters broader market exposure.

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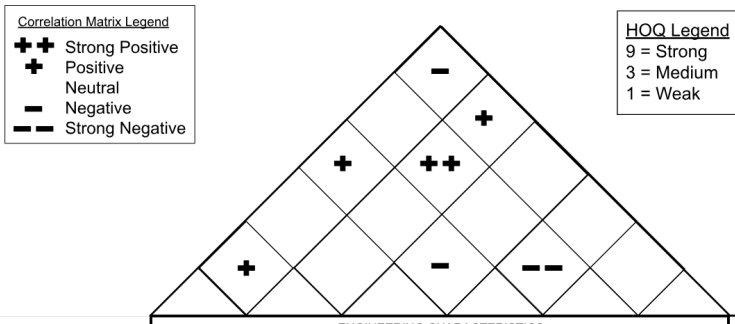
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6.2. Appendices

A. HOQ



		ENGINEERING CHARACTERISTICS									
IMPROVEMENT DIRECTION		↓	↑	↑	↓	↑	↑	**Competetor Rankings** 1--Poor, 3--OK, 9--Excelent			
UNITS		kg	mm	Shore A	$ (USD)	MPa	mm				
CUSTOMER REQUIREMENTS	Importance Weight Factor	Weight	Handle Wall Thickness	Joint Elastomer Shore Hardness	Manufacturing Cost	Yield Strength	Handle Grip Diameter	CRs	Battlestick Tiller Extension	Rooster Carbon Tiller Extension	Forespar Twist Lock Tiller Extension	
Lightweight	4	9	3		1	1	3	Lightweight	3	9	3	
Affordable	5				9	1		Affordable	9	1	1	
Comfortable	1						9	Comfortable	9	3	9	
Durable	5		3	9		3		Durable	3	3	3	
Effective	5	3		9				Effective	3	9	3	*expected
Safe	3			3		9		Safe	1	1	3	
Ease of use	2	1		3			3	Ease of use	3	3	9	
Long lifetime	3		1	9	3	1		Long lifetime	3	3	9	
Interchangable	2				3			Interchangable	3	3	1	
Raw Score	360	53	30	132	64	54	27		120	128	112	
Relative Weight (%)		14.722	8.333	36.667	17.778	15.000	7.500					
Rank Order		3	5	1	2	2	6	Rank Order	2	1	3	

B. Circuit Design Or PCB