Modular S-Pen Grip Sleeve – Iterative Mechanical Design & Prototyping

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1 Introduction and Problem Definition

Modern tablet styli are often designed to prioritize compactness and precision, frequently resulting in significantly slimmer form factors than traditional writing instruments. In the case of the Samsung S-Pen, the reduced diameter enables accurate input and convenient storage but diverges noticeably from the ergonomics of standard pens and pencils commonly used for extended writing tasks.

During regular note-taking use, particularly for repetitive writing rather than drawing, the narrow stylus profile was observed to feel unfamiliar and contribute to grip fatigue over longer sessions. While the slim form factor supported precision, it did so at the expense of comfort and stability relative to conventional writing tools. This suggested a tradeoff between accuracy and sustained usability rather than a purely subjective preference.

Existing third-party grip accessories, such as silicone sleeves, were evaluated and found to introduce their own limitations, including long-term deformation and inconsistent retention. These observations motivated further investigation into an add-on solution that could modify the effective grip geometry while preserving the original stylus functionality. This project examines the iterative design of a modular grip sleeve intended to improve handling during extended writing tasks, with emphasis on constraint-driven mechanical design and systematic evaluation of design limitations identified through use.

2 Design Objectives, Constraints, and Requirements

2.1 Design Objectives

The primary objective of this project was to design a modular grip sleeve for the Samsung S-Pen that improves ergonomic comfort and handling during extended writing tasks while preserving the functional precision of the original stylus. The design was not intended to replace the S-Pen, but rather to act as a reversible, non-destructive accessory that augments usability without permanent modification.

Specific objectives included:

- **Increase effective grip diameter** to more closely resemble traditional pens and pencils, reducing hand fatigue during repetitive writing
- **Maintain writing precision**, ensuring that added mass or geometry does not negatively impact fine motor control
- **Enable modularity**, allowing grip geometry or surface texture to be revised independently of the full sleeve design

- **Support rapid iteration**, enabling multiple design revisions to be tested using consumer-grade FDM 3D printing
- **Withstand repeated daily use**, including insertion/removal cycles, sustained handling during note-taking, and repeated transport within a backpack.

Secondary objectives included exploring surface textures (e.g., faceting or knurling) for tactile feedback and evaluating how small geometric changes influence perceived comfort and control.

2.2 Design Constraints

The design space for the grip sleeve was bounded by several practical and functional constraints derived from the S-Pen hardware, manufacturing method, and real-world use conditions.

2.2.1 Stylus Compatibility Constraints

- The sleeve must **fit securely around the S-Pen** without adhesives or permanent modification
- Internal geometry must accommodate **tight tolerances** due to the S-Pen's slim diameter
- The design must not interfere with the **writing tip or sensing functionality** of the stylus

While magnetic attachment and tablet storage were considered early in the design process, full compatibility in these areas was not achievable within the current geometry. This limitation is explicitly acknowledged as a scope constraint rather than a design oversight.

2.2.2 Manufacturing Constraints

- All components must be **manufacturable using consumer-grade FDM 3D printing**
- Designs must be printable without exotic materials or post-processing beyond basic cleanup
- Geometry must avoid extreme overhangs, ultra-thin walls, or features smaller than practical nozzle resolution

These constraints directly influenced wall thickness, fillet usage, and internal retention features, and they encouraged designs that could be iterated quickly without requiring professional manufacturing resources.

2.2.3 Material Constraints

- Common filaments (e.g., PLA-based materials) were used due to availability and print reliability
- Material behavior under **cyclic stress and repeated handling** became a limiting factor during later testing
- Elastic deformation and creep were evaluated informally through use rather than through formal mechanical testing

Durability constraints became increasingly important during the fall 2025 testing period, shifting the project emphasis from purely ergonomic form toward structural longevity.

2.3 Design Requirements

Based on the objectives and constraints above, the following functional requirements were established:

2.3.1 Functional Requirements

- The grip sleeve shall **remain securely attached** during normal writing use
- The sleeve shall **not rotate unintentionally** relative to the stylus axis
- The sleeve shall allow **normal writing posture** without forcing grip repositioning
- The sleeve shall be removable without damage to the stylus

2.3.2 Ergonomic Requirements

- The effective grip diameter shall be **larger than the bare S-Pen**, approximating traditional writing instruments
- Surface geometry shall provide **tactile feedback** without sharp edges or pressure points
- The design shall support **extended writing sessions** without inducing abnormal grip force

No medical or clinical claims are made regarding injury prevention; ergonomic evaluation is based on user experience and qualitative feedback.

2.3.3 Durability Requirements

- The design shall tolerate **repeated insertion and removal cycles**
- Stress concentrations shall be minimized through geometry where feasible
- Failure modes (e.g., cracking, splitting) shall be observable and inform subsequent iterations

Durability is treated as an evolving requirement informed by iterative testing rather than a fixed pass/fail criterion.

2.4 Summary

Section 2 establishes the grip sleeve as a **constraint-driven mechanical design problem**, balancing ergonomics, manufacturability, and durability within the limitations of consumer-grade fabrication and a tightly constrained host device. These objectives and requirements directly informed the design decisions discussed in subsequent sections, particularly geometry selection, modular segmentation, and material usage.

The objectives and constraints described above were formalized into a set of design requirements, summarized in the following table:

Design Requirements Summary				
ID	**Requirement Type**	**Requirement Statement**	**Rationale**	**Verification Method**
FR-01	Functional	The grip sleeve shall remain securely attached during normal writing use.	Prevents unintended movement during note-taking	Manual use testing
FR-02	Functional	The sleeve shall not interfere with the writing tip or sensing functionality.	Preserves stylus precision	Writing accuracy observation
ER-01	Ergonomic	The effective grip diameter shall exceed that of the bare S-Pen.	Reduces ergonomic mismatch	Dimensional measurement
ER-02	Ergonomic	The surface geometry shall avoid sharp edges or pressure points.	Improves comfort during extended use	User feedback
DR-01	Durability	The sleeve shall tolerate repeated insertion and removal cycles.	Reflects daily use conditions	Iterative handling tests
DR-02	Durability	The grip sleeve shall tolerate routine daily handling, including transport in a backpack and incidental drops, without catastrophic failure.	Reflects real-world use conditions beyond installation cycles	Extended daily use observation
MR-01	Manufacturing	The design shall be manufacturable using consumer-grade FDM 3D printing.	Enables rapid iteration	Successful print validation

3 Concept Generation and Early Design Iterations

3.1 Initial Concept Development

Early concept development prioritized **attachment reliability and retention mechanics** rather than full-length ergonomic coverage. Instead of beginning with a monolithic sleeve, the project initially adopted a **two-piece partial-coverage design** consisting of a short grip section and a nozzle/cap-style attachment element. This configuration covered approximately half of the stylus length and was intentionally limited in scope to isolate and evaluate potential attachment mechanisms.

This approach allowed early focus on **FR-01 (secure attachment during writing use)** and **MR-01 (manufacturability using consumer-grade FDM printing)** before introducing additional variables related to grip geometry or full-length coverage. By reducing the number of interacting features, early failures could be attributed more directly to attachment design rather than overall form.

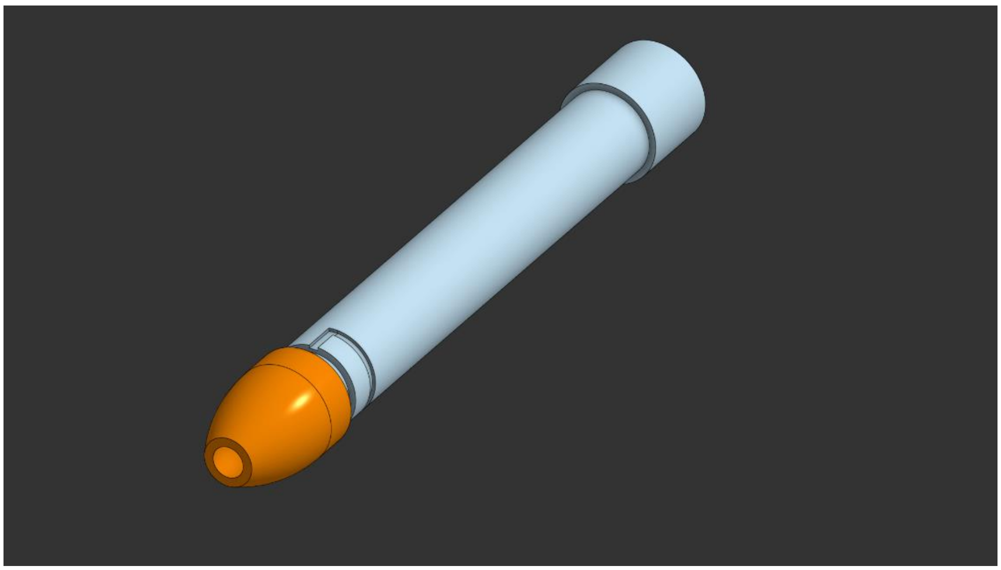

Figure 1. Early two-piece grip sleeve concept consisting of a partial-length grip section and nozzle-style attachment element, used to isolate and evaluate initial attachment mechanisms prior to full-length ergonomic development.

3.2 Early Attachment Mechanism Exploration

The initial attachment strategy explored a **slide-locking interface**, where axial insertion followed by a short rotational or linear engagement was intended to mechanically retain the grip section. This concept was attractive due to its simplicity and minimal added bulk; however, at the scale of the S-Pen, several limitations became evident.

Early prototypes demonstrated that:

- Feature sizes required for a reliable slide-lock exceeded practical FDM resolution
- Small engagement features were susceptible to wear and deformation
- Retention consistency varied significantly between prints

As a result, the slide-lock approach failed to reliably satisfy **FR-01**, and repeatable manufacturing proved inconsistent with **MR-01**. These findings led to the conclusion that the attachment mechanism required a more robust and tolerant interface geometry.

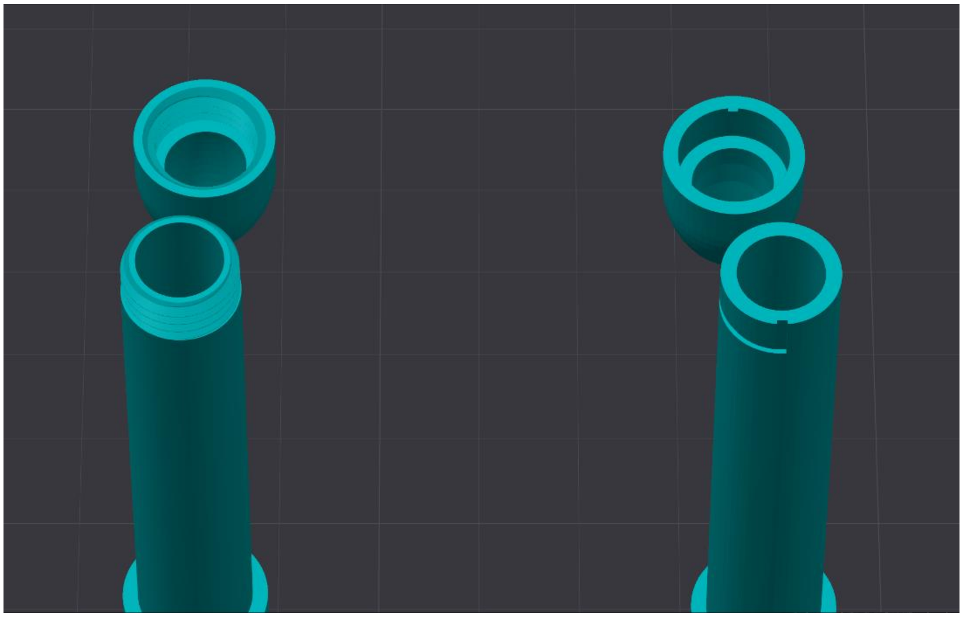

Figure 2. Comparison of early slide-lock attachment geometry and later threaded attachment concepts, illustrating the transition toward threaded interfaces due to improved retention reliability and manufacturability at small scales.

3.3 Additive Manufacturing Resolution Considerations

Early attachment mechanism development revealed that feature resolution imposed a limiting factor on viable designs. In response, a **0.2 mm nozzle** was adopted for the Bambu Lab A1 Mini printer to enable finer feature reproduction compared to the standard 0.4 mm configuration.

The reduced nozzle diameter improved:

- Thread profile definition at small diameters
- Dimensional consistency of fine engagement features
- Evaluation of retention mechanics related to **FR-01**

While the smaller nozzle increased print time and sensitivity to print settings, it enabled design iterations that would not have been practical at coarser resolutions. This decision directly supported **MR-01** by aligning manufacturing capability with design scale rather than forcing the design to conform to default printer limitations.

3.4 Transition to Threaded Interfaces

Following the limitations observed with slide-lock designs, the project transitioned toward **threaded attachment mechanisms**. Threads provided a mechanically familiar and scalable solution that could tolerate minor print variation while offering predictable retention force.

This design shift supported:

- **FR-01**, by providing repeatable and adjustable attachment security

- **MR-01**, as thread geometry printed reliably with consumer-grade nozzles
- **DR-01**, by distributing stress more evenly compared to localized locking features

Early threaded prototypes confirmed that even coarse thread profiles offered superior retention consistency compared to previous slide-lock attempts. This marked a key inflection point in the project, as it enabled further development of modular components without repeated attachment failure dominating iteration outcomes.

3.5 Modular Architecture Refinement

With a viable attachment method established, the design evolved into a more clearly defined **modular architecture**, separating the **core retention interface** from the **external grip geometry**. This separation allowed grip features to be revised independently while maintaining a stable interface with the stylus.

This modular structure directly supported:

- **ER-01**, by enabling experimentation with different grip diameters and profiles
- **DR-01**, by allowing stress-prone features to be redesigned without affecting the full assembly
- **MR-01**, by keeping individual components simple and fast to print

The modular approach also reduced iteration cost and time, encouraging frequent real-world testing during daily use.

3.6 Early Prototypes and Observed Limitations

Early two-piece prototypes successfully demonstrated improved attachment reliability using threaded interfaces, partially satisfying **FR-01**. However, several limitations remained:

- Thread engagement length influenced perceived stability and ease of installation
- Thin-wall regions near threaded sections exhibited early cracking, impacting **DR-01**
- Partial coverage limited ergonomic evaluation relative to **ER-01**

These limitations informed the decision to expand coverage length and refine wall thickness in later iterations, shifting the project focus from attachment feasibility toward durability and ergonomic optimization.

3.7 Iteration Strategy

Rather than pursuing a finalized geometry prematurely, the project adopted an **incremental iteration strategy**. Each design revision adjusted a limited set of parameters—such as thread profile, wall thickness, or engagement depth—allowing observed performance changes to be attributed to specific design decisions.

This strategy enabled:

- Direct evaluation of **FR-01**, **DR-01**, and **MR-01** at each iteration stage
- Early elimination of attachment geometries that failed under normal use
- Progressive expansion of design scope once attachment reliability was established

Once attachment reliability was established, the modular system was expanded to include full-length sleeve coverage, multiple grip geometries, and interchangeable tip elements; these components are discussed in subsequent sections.

3.8 CAD Environment and Thread Modeling Approach

All components were modeled using **Onshape**, selected for its cloud-based workflow, parametric modeling capabilities, and ease of iteration across multiple design variants. Given the small scale of the threaded interfaces required for this project, native thread modeling options were evaluated early in the design process.

Threaded features were implemented using an existing **plastic thread modeling tool** available within the Onshape ecosystem. This tool was not authored by the designer but was selected after evaluation due to its ability to generate printable thread profiles suitable for thermoplastic materials and consumer-grade FDM printing.

Adopting this tool enabled rapid iteration of thread geometry and parameters while maintaining consistent modeling practices across components. Thread design decisions were subsequently refined through physical testing and durability-driven revision, as discussed in later sections.

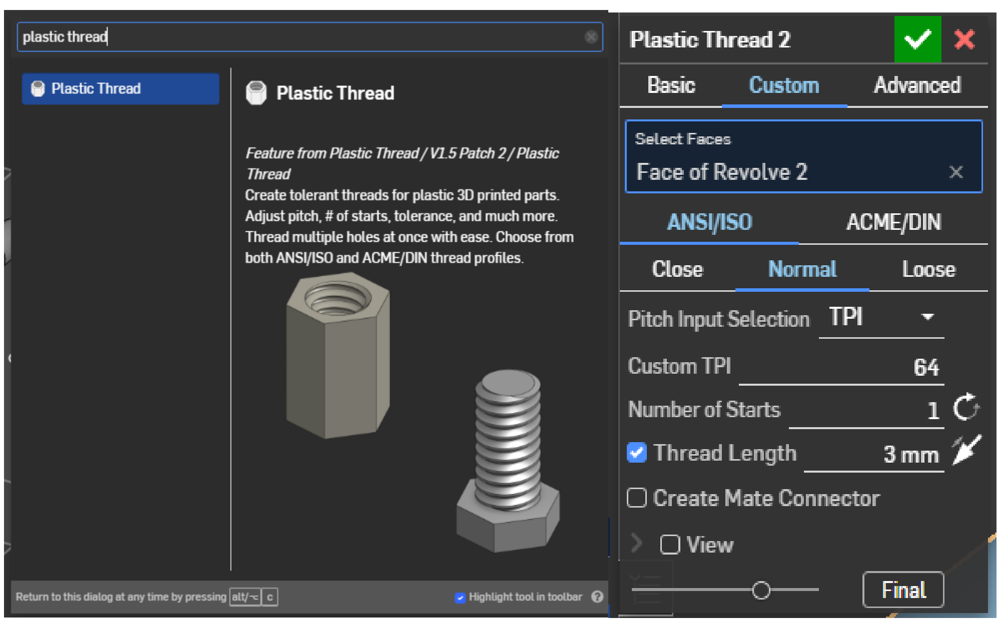

Figure 3 & 4. Onshape plastic thread modeling tool and representative parameter settings used to generate printable thermoplastic thread profiles. Adjustable pitch, tolerance, and engagement length enabled iterative tuning of small-scale threaded interfaces for consumer-grade FDM printing.

4 Geometry Refinement and Ergonomic Features

4.1 Expansion to Full-Length Sleeve Coverage

Following the establishment of a reliable threaded attachment interface, the design scope expanded from partial coverage to a **full-length grip sleeve**. This expansion enabled more realistic ergonomic evaluation during extended writing tasks and directly supported **ER-01** by increasing the effective contact area between the user's hand and the stylus.

The second half of the sleeve was designed to maintain axial alignment with the primary grip section while avoiding interference with the writing tip, buttons, or sensing functionality of the stylus, preserving compliance with **FR-02**. Extending coverage also introduced new considerations related to wall thickness continuity and load transfer across modular joints, which later informed durability-focused revisions.

Figure 5. Progression of grip sleeve prototypes showing the evolution from partial-coverage designs to a full-length modular sleeve with refined geometry and attachment interfaces.

4.2 Grip Diameter Evolution

Grip diameter was incrementally adjusted across multiple iterations to balance comfort, control, and perceived bulk. Early increases in diameter yielded noticeable reductions in hand fatigue during repetitive writing, confirming compliance with **ER-01**. However, excessively large diameters reduced fine motor control and increased leverage on the attachment interface, creating secondary impacts on **FR-01**.

Rather than pursuing a single target diameter, the design space was intentionally explored through multiple variants. This approach allowed qualitative comparison under real writing conditions and helped identify practical bounds within which ergonomic improvements could be achieved without compromising stability or precision.

4.3 Surface Geometry and Tactile Features

Multiple surface geometries were evaluated to improve grip stability without relying on high-friction materials. These included smooth cylindrical surfaces, faceted profiles, and knurled patterns.

Faceted geometries provided clear tactile indexing and improved rotational stability during writing. However, early designs with sharp transitions introduced localized stress concentrations, which later affected **DR-01** performance. Subsequent iterations incorporated fillets and chamfers to reduce stress while preserving tactile feedback.

Knurled surface geometries were also designed, printed, and evaluated as part of the modular grip system. At the scale of the S-Pen, knurling required careful consideration of feature size and print resolution; however, the use of a 0.2 mm nozzle enabled several knurled grip variants to be manufactured successfully. These designs demonstrated acceptable tactile performance and confirmed compatibility with **MR-01**.

Rather than converging on a single knurled pattern or surface profile, the project intentionally preserved modularity to accommodate **subjective ergonomic preferences**. This decision reflects a human-centered design philosophy under **ER-01**, recognizing that no single grip geometry optimally serves all users or writing styles.

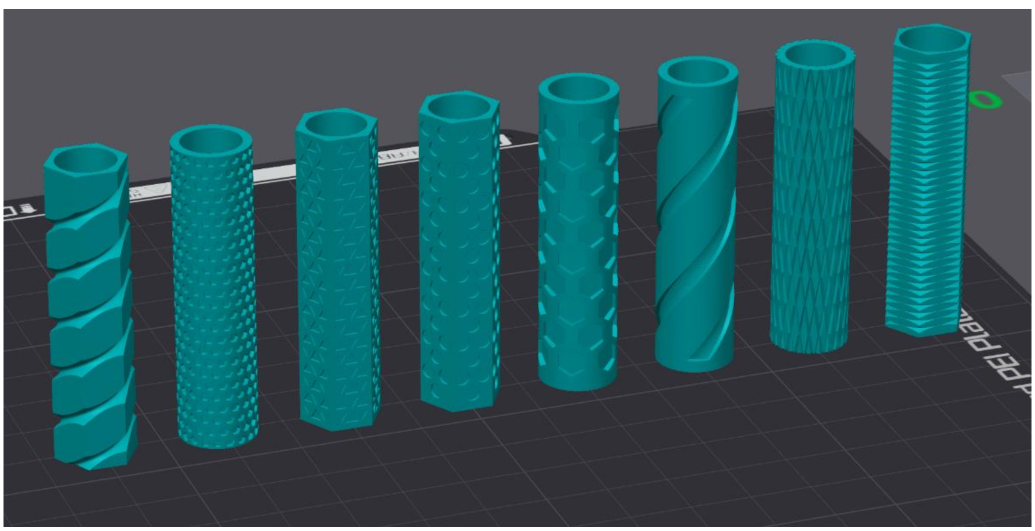

Figure 6. CAD models of modular grip sleeve variants illustrating differences in surface geometry, diameter, and axial length used to explore ergonomic tradeoffs.

Figure 7. 3D-printed grip sleeve variants produced using consumer-grade FDM printing, demonstrating the physical realization of different surface textures and feature resolutions.

4.4 Modular Grip Variants

The modular architecture enabled the creation of multiple interchangeable grip variants without redesigning the full sleeve assembly. Variants differed in surface geometry, diameter, and axial length, allowing focused exploration of ergonomic tradeoffs during daily use.

This approach supported rapid iteration aligned with **ER-01**, while also isolating geometry-related durability concerns under **DR-01**. By treating grip geometry as a configurable parameter rather than a fixed design outcome, the system remained adaptable without forcing premature convergence on a single solution.

The absence of a single finalized grip geometry is therefore a deliberate design outcome rather than an unresolved design decision.

4.5 Tip and Transition Geometry Considerations

The geometry near the writing tip required careful refinement to ensure that the added sleeve material did not obstruct visibility or alter natural writing posture. Transition regions between the grip sleeve and the exposed stylus tip were tapered gradually to maintain ergonomic continuity while preserving sufficient wall thickness for structural integrity.

These refinements ensured continued compliance with **FR-02** and minimized abrupt geometric changes that could introduce stress risers affecting **DR-01**.

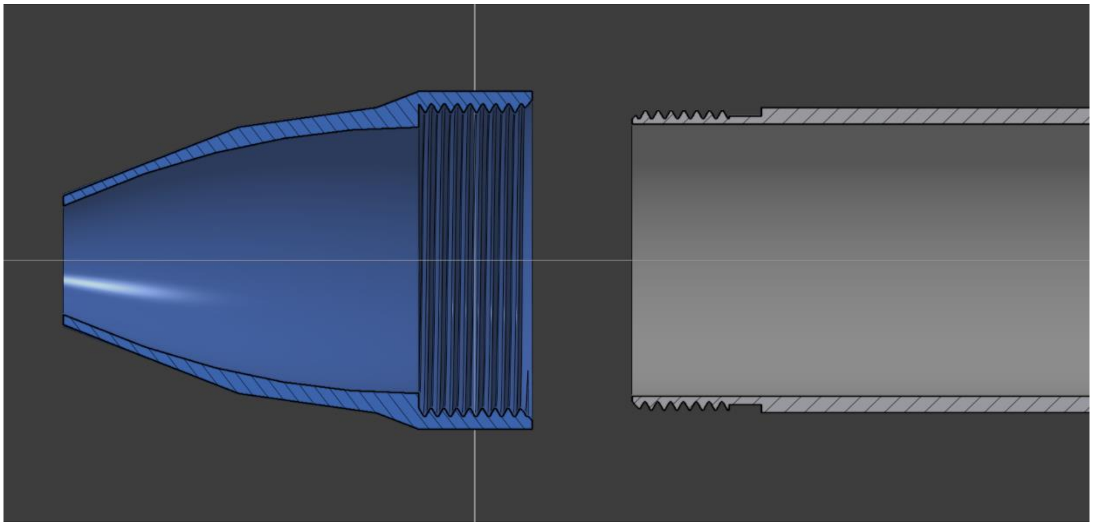

Figure 8. Cross-sectional view of the tip nozzle and threaded interface, highlighting thread relief features and wall thickness transitions implemented to reduce stress concentration.

4.6 Ergonomic Evaluation Approach

Ergonomic performance was evaluated qualitatively through extended note-taking sessions rather than controlled laboratory testing. Observations focused on perceived comfort, grip force consistency, and fatigue during repetitive writing tasks.

While subjective, this evaluation approach aligned with the project's scope and provided meaningful insight into compliance with **ER-01** without making medical or clinical claims.

4.7 Section Summary

Section 4 documents the refinement of sleeve geometry to improve ergonomic performance while preserving functional reliability and manufacturability. Through iterative adjustment of grip diameter, surface features, and transition geometry, the design progressed toward satisfying **ER-01** without compromising **FR-01**, **FR-02**, **DR-01**, or **MR-01**. The modular philosophy adopted here enabled ergonomic flexibility while preparing the system for deeper evaluation of manufacturing and durability tradeoffs in subsequent sections.

5 Manufacturing Considerations and Print Optimization

5.1 Manufacturing Method Selection

All components of the grip sleeve system were manufactured using **consumer-grade fused deposition modeling (FDM) 3D printing**. This method was selected to support rapid iteration, low material cost, and direct integration with parametric CAD workflows, consistent with **MR-01**.

Rather than treating manufacturing as a downstream step, printability constraints were incorporated early in the design process, influencing geometry, feature size, and modular segmentation.

5.2 Nozzle Size Selection and Feature Resolution

Early attachment mechanism development revealed that feature resolution imposed a practical limit on viable designs. To address this, a **0.2 mm nozzle** was adopted for the Bambu Lab A1 Mini printer in place of the standard 0.4 mm nozzle.

The reduced nozzle diameter improved:

- Thread profile fidelity at small diameters
- Dimensional consistency of fine engagement features
- Repeatability of attachment performance related to **FR-01**

These improvements enabled design iterations that would not have been practical at coarser resolutions. However, the smaller nozzle increased print time and sensitivity to slicing parameters, reinforcing the need to balance resolution with throughput under **MR-01**.

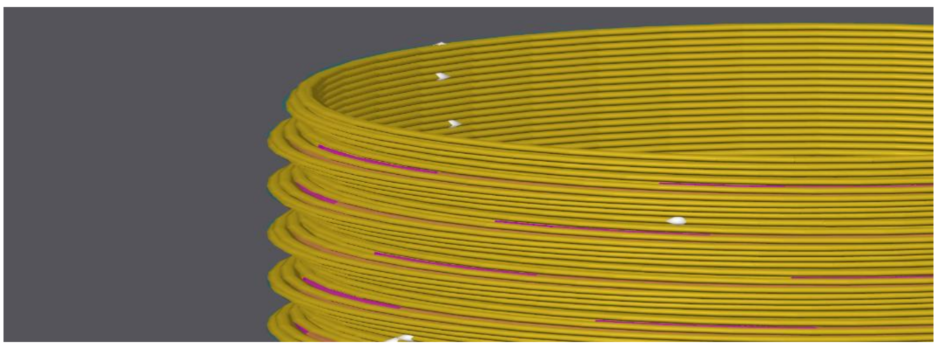

Figure 9. Close-up view of printed thread geometry illustrating line width, layer resolution, and thread fidelity achieved using a 0.2 mm nozzle.

5.3 Wall Thickness and Structural Considerations

Wall thickness was a critical design parameter due to the small overall diameter of the sleeve and the use of brittle thermoplastic materials. Early designs with minimal wall thickness improved slimness but exhibited cracking during repeated insertion and removal, indicating partial failure of **DR-01**.

Subsequent iterations increased wall thickness selectively in high-stress regions such as threaded interfaces and transition zones. These changes improved durability while preserving ergonomic performance under **ER-01** and manufacturability under **MR-01**.

5.4 Print Orientation and Anisotropy

Print orientation significantly influenced part strength and failure behavior due to the anisotropic nature of FDM prints. Components were oriented to align layer lines with expected load paths where feasible, particularly around threaded regions.

Orientation tradeoffs included:

- Improved thread strength when printed with axial alignment
- Increased print time and support requirements for certain orientations
- Surface finish variation affecting tactile features

These tradeoffs required balancing **DR-01** and **MR-01**, as orientations that maximized strength were not always the most efficient or reliable to print.

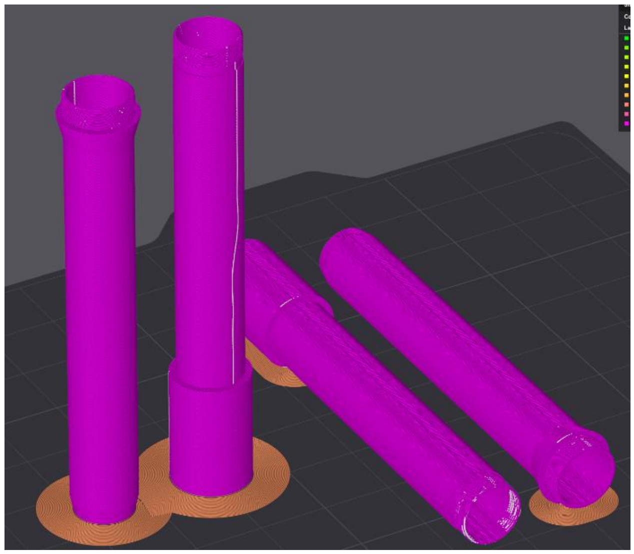

Figure 10. Comparison of vertical and horizontal print orientations evaluated during prototyping, illustrating tradeoffs between thread accuracy, structural anisotropy, and print reliability.

5.5 Tolerance and Fit Management

Due to the tight dimensional requirements imposed by the S-Pen's slim diameter, minor dimensional variations had a noticeable impact on fit and retention. Rather than relying on a single nominal dimension, fit was tuned through small incremental adjustments to internal diameters and thread profiles.

This approach allowed compensation for printer-specific variation while maintaining compliance with **FR-01**. Fit tuning was treated as an iterative calibration process rather than a one-time specification.

5.6 Print Failures and Iterative Refinement

Print failures—including layer separation, thread deformation, and incomplete features—were treated as informative feedback rather than isolated errors. Observed failures directly informed geometry changes, slicing adjustments, and orientation choices.

This feedback loop reinforced the iterative design philosophy and ensured that manufacturing limitations were explicitly addressed rather than abstracted away, maintaining alignment with **MR-01** throughout the project.

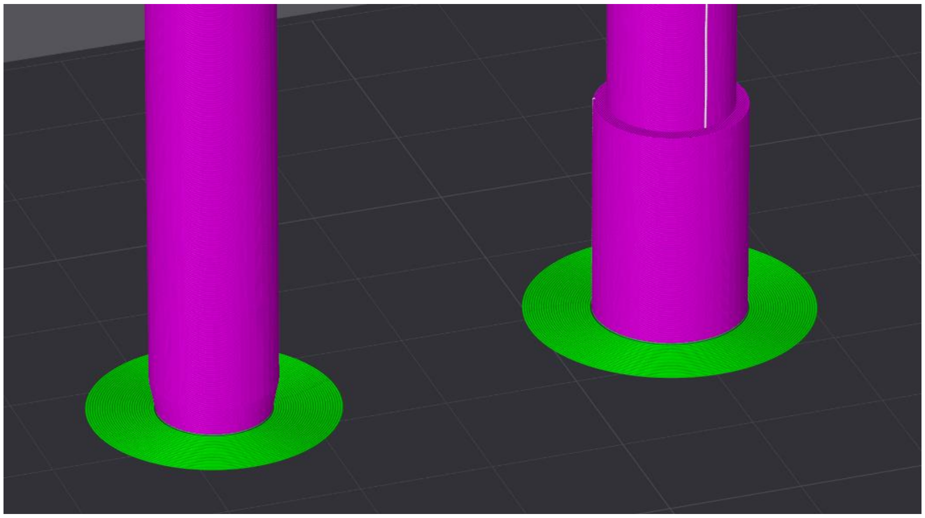

Figure 4. Use of a print skirt to improve bed adhesion and stability for vertically oriented prints with tall, slender geometries.

5.7 Slicing Parameter Optimization

Printing was performed using **Bambu Studio**, which provided granular control over slicing parameters critical to thread fidelity and part durability. Beyond nozzle selection, multiple slicing parameters were iteratively adjusted to improve printed thread resolution and structural performance.

Key adjustments included:

- Reduced layer heights to improve thread definition
- Increased wall loops to reinforce threaded regions
- Modified extrusion and cooling behavior to reduce layer separation

These changes increased overall print time but significantly improved dimensional accuracy and durability, supporting **MR-01** and contributing to improved outcomes under **DR-01** and **DR-02**.

For vertically oriented prints, **skirts** were added to improve bed adhesion and stability. Although horizontal orientation could have improved layer-aligned strength, it was avoided due to unacceptable degradation of thread accuracy and fit consistency. Vertical orientation was therefore selected as an intentional tradeoff between structural anisotropy and functional thread performance.

5.8 Section Summary

Section 5 documents how manufacturing considerations influenced geometry, attachment reliability, and durability. Through deliberate nozzle selection, wall thickness refinement, orientation optimization, and tolerance management, the design maintained compliance with **MR-01** while supporting **FR-01** and **DR-01**. These manufacturing-driven decisions set the stage for focused durability testing and failure analysis discussed in the following section.

6 Durability Testing and Failure Analysis

6.1 Durability as an Evolving Design Requirement

Durability was not a primary objective at the outset of the project but emerged as a critical design consideration through extended real-world use. Early iterations primarily evaluated attachment reliability and ergonomics; however, as the grip sleeve transitioned into daily use during the fall 2025 academic semester, additional failure modes became apparent.

As a result, durability considerations expanded beyond repeated installation cycles (**DR-01**) to include **routine daily handling and transport conditions** (**DR-02**). This distinction allowed installation-induced failures and environmental handling failures to be evaluated independently rather than being conflated under a single requirement.

6.2 Testing Conditions and Use Scenarios

Durability evaluation was conducted under realistic use conditions rather than controlled laboratory testing. Two primary categories of stress were considered:

- **Installation-related loading (DR-01):**
  - Repeated insertion and removal from the stylus
  - Repeated tightening and loosening of threaded interfaces
- **Daily handling and environmental loading (DR-02):**
  - Transport in a backpack alongside other items
  - Incidental drops from desk height
  - Handling during movement between classes and workspaces

This testing approach prioritized ecological validity and reflected the intended use environment of the device.

6.3 Observed Failure Modes

Distinct failure modes were associated with each durability requirement:

- **DR-01-related failures:**
  - Cracking near threaded interfaces
  - Radial splitting due to hoop stress during installation
  - Progressive thread deformation under repeated tightening
- **DR-02-related failures:**
  - Cracking initiated by impact during drops

- Fracture at thin-wall regions subjected to bending
- Damage concentrated at geometric transitions and modular joints

In most cases, failures were progressive rather than catastrophic, allowing continued use for a limited period before complete part failure.

Figure 5. Observed cracking and thread damage in early mid-to-end body section designs following repeated installation cycles, indicating insufficient wall thickness and stress concentration.

6.4 Stress Concentration and Geometry-Driven Failures

Early in the semester, durability issues were most prominent at the **threaded connection between the middle body section and the end body section**. Cracking and thread deformation indicated insufficient material cross-section to support repeated installation cycles and incidental bending loads.

To address this, the threaded region between these two body sections was **thickened**, increasing both thread engagement depth and surrounding wall thickness. This change distributed load more evenly across the threaded interface and reduced localized stress concentration.

This revision significantly improved resistance to thread stripping and cracking under **DR-01**, while also improving structural resilience under **DR-02** without noticeably impacting ergonomics or manufacturability.

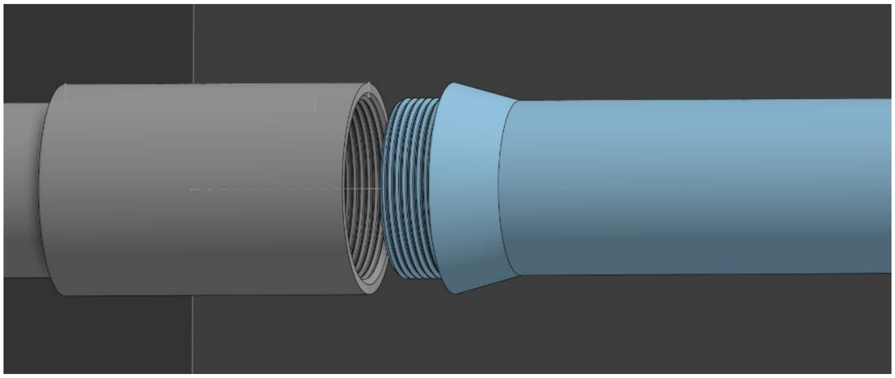

Figure 13. Revised mid-to-end body threaded interface with increased engagement length and surrounding wall thickness to improve durability under cyclic loading.

6.5 Mid-Semester Revisions: Thread Relief at the Tip Nozzle Interface

As testing progressed toward midterms, failures increasingly appeared at the **thread start between the tip nozzle and the middle body section**. Cracks consistently initiated at the first engaged thread, indicating a sharp stress concentration at the thread runout.

To mitigate this failure mode, a **thread relief / neck feature** was added at the base of the tip-to-body threaded interface. This relief reduced abrupt stiffness transitions and allowed stress to distribute more gradually into the surrounding material.

The addition of the thread relief substantially reduced material splitting at the start of the thread, improving compliance with **DR-01** while also reducing crack propagation under impact and handling conditions related to **DR-02**.

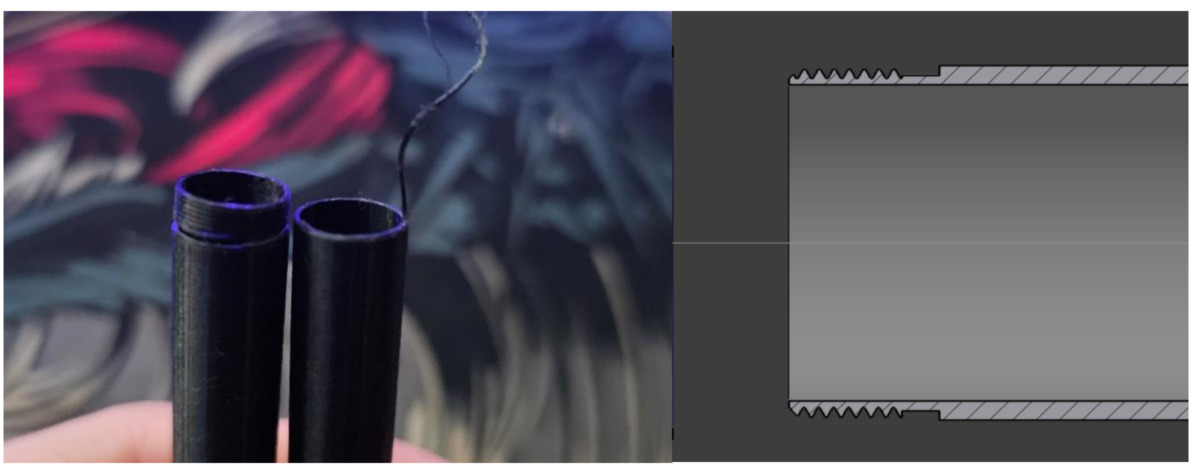

Figure 6 & 15. Comparison of thread failure at the nozzle–mid body interface and the subsequent addition of a thread relief feature to reduce stress concentration at thread runout.

6.6 Mid-Semester Revisions: Tip Nozzle Length Adjustment

Further observation revealed that the **tip nozzle geometry itself contributed to thread loading** during removal. Shorter nozzle designs caused the user's fingers to apply force closer to the threaded interface, increasing tensile and bending loads on the threads when pushing the sleeve off the pen.

In response, the tip nozzle was made **slightly longer**, shifting applied forces away from the threaded interface during removal. This change reduced the tendency for the nozzle to pull directly on the threads, lowering stress during installation and removal cycles.

This modification improved durability under **DR-01** and indirectly benefited **DR-02** by reducing the likelihood of crack initiation that could later propagate during impact events.

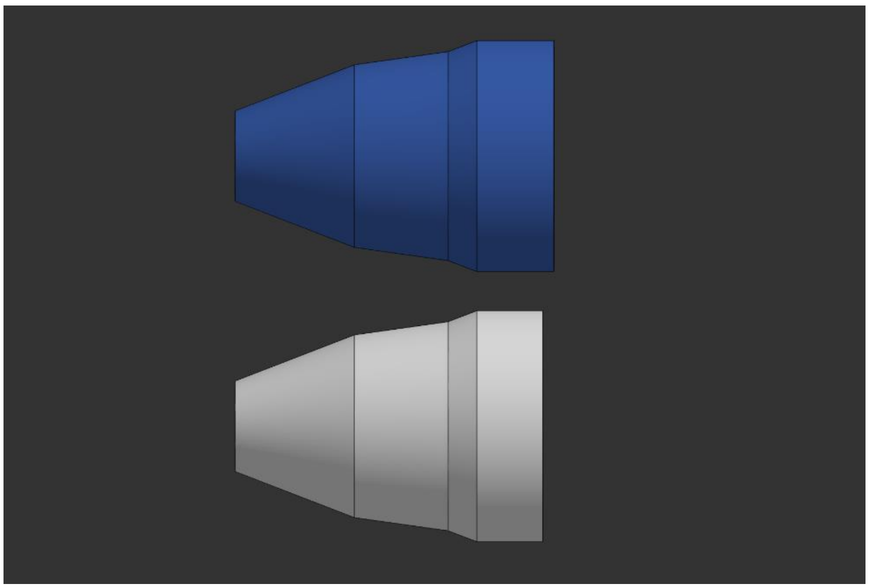

Figure 7. Extended tip nozzle geometry used to shift applied removal forces away from the threaded interface, reducing tensile and bending loads during installation and removal.

6.7 Thread Length and Parameter Tuning

In addition to geometric reinforcement, durability improvements were achieved through **iterative tuning of thread parameters**, including thread length and profile depth, for each interface within the modular system. The threaded connection between the tip nozzle and middle body section used shorter engagement lengths to minimize wall thinning, while the middle-to-end body interface employed longer engagement to distribute load across a larger area.

Thread parameters were adjusted to avoid excessively thin material at thread roots while ensuring sufficient engagement depth to maintain attachment reliability. Threads that were too fine exhibited poor print fidelity and rapid wear, while overly coarse threads reduced engagement consistency and compromised **FR-01**.

This tuning process highlighted the sensitivity of small-scale plastic threads to both geometry and manufacturing parameters and reinforced the need to treat each threaded interface as a distinct design problem rather than applying a single thread specification universally.

6.8 Material Behavior Under Cyclic and Impact Loading

The thermoplastic materials used exhibited limited tolerance for repeated elastic deformation and impact loading at small cross-sectional areas. Under **DR-01**, cyclic hoop stress led to microcracking over time, while **DR-02** introduced localized bending and tensile stresses that accelerated crack growth.

Rather than relying on material substitution, durability improvements were achieved primarily through **geometry-driven stress reduction**, reinforcing the importance of structural design choices within the constraints of consumer-grade FDM printing.

6.9 Iteration Outcomes and Requirement Satisfaction

Later iterations incorporating thicker threaded sections, thread relief features, and adjusted nozzle length demonstrated improved durability across both categories of loading:

- **DR-01** performance improved through reduced thread splitting and increased resistance to cyclic installation stresses
- **DR-02** performance improved through better impact tolerance and reduced crack initiation during transport and handling

Despite these gains, durability outcomes remained sensitive to wall thickness, print orientation, and impact direction. As a result, **DR-01 and DR-02 are considered partially satisfied**, reflecting intentional tradeoffs between slim ergonomic design, manufacturability, and structural robustness rather than unresolved design deficiencies.

6.10 Section Summary

Section 6 documents how durability evolved into a multidimensional engineering challenge requiring separation into installation-driven (**DR-01**) and handling-driven (**DR-02**) requirements. Through chronological observation of failure modes and targeted geometry revisions—including reinforced threaded interfaces, thread relief features, and nozzle length adjustments—the design achieved improved resilience under daily use while maintaining ergonomic and manufacturing constraints. These findings directly inform the tradeoffs and outcomes discussed in the following section.

7 Discussion of Tradeoffs and Design Outcomes

7.1 Ergonomics Versus Durability

A central tradeoff throughout the project was the balance between ergonomic slimness and structural durability. Increasing grip diameter and reducing sharp surface transitions improved comfort and reduced grip force, supporting **ER-01**. However, slimmer geometries and reduced wall thickness increased susceptibility to cracking under both installation-related loading (**DR-01**) and impact-related handling (**DR-02**).

Design revisions sought to balance these competing requirements by selectively reinforcing high-stress regions—such as threaded interfaces—while preserving a relatively slim profile in areas less critical to structural integrity. This compromise reflects an intentional design decision rather than a failure to meet durability objectives.

7.2 Modularity Versus Convergence

The project intentionally avoided convergence on a single finalized grip geometry. While a single optimized design might simplify manufacturing or evaluation, ergonomic comfort is inherently subjective and dependent on individual hand size, grip style, and writing habits.

By preserving modularity, the design supports **ER-01** across a broader range of users while enabling independent iteration of grip geometry, attachment interfaces, and tip components. This modular approach introduced additional interfaces that required durability consideration under **DR-01** and **DR-02**, but it ultimately provided greater flexibility and long-term adaptability.

7.3 Precision Versus Comfort

The S-Pen's original slim form factor offers high precision at the expense of long-term comfort during repetitive writing tasks. Increasing the effective grip diameter improved comfort and reduced fatigue but introduced additional mass and altered hand posture, which could marginally affect fine motor control.

Rather than eliminating this tradeoff, the project aimed to provide configurable solutions that allow users to prioritize precision or comfort depending on the task. This outcome aligns with the project's human-centered design goals and reinforces the value of modular grip variants.

7.4 Manufacturability Versus Structural Robustness

Manufacturing constraints imposed by consumer-grade FDM printing influenced nearly every design decision. Increasing wall thickness and adding fillets improved durability but also increased print time and material usage, intersecting with **MR-01**.

The adoption of a 0.2 mm nozzle enabled finer feature resolution but introduced longer print times and greater sensitivity to print settings. These tradeoffs were accepted to maintain design feasibility at small scales rather than forcing the geometry to conform to default manufacturing limitations.

7.5 Magnetic Storage and Scope Limitations

Magnetic attachment and tablet storage compatibility were considered early in the project but were not fully achieved within the final design. Achieving full magnetic compatibility would have required compromises in grip geometry, wall thickness, or modularity that conflicted with **ER-01**, **DR-01**, and **DR-02**.

Additionally, the grip sleeve obstructs access to the S-Pen's side button. Maintaining full button accessibility would have required reducing grip coverage or introducing complex cutouts that negatively impacted ergonomics and durability. This limitation was therefore accepted as a scope tradeoff in favor of improved writing comfort and structural robustness.

Neither magnetic compatibility nor button accessibility is claimed as an improvement of the final design. Both are explicitly acknowledged limitations resulting from intentional prioritization of ergonomic and durability objectives.

7.6 Requirement Satisfaction Summary

Overall, the project demonstrates partial or full satisfaction of its primary design requirements:

- **ER-01** was satisfied through increased grip diameter and modular ergonomic features
- **FR-01** and **FR-02** were satisfied through reliable attachment and functional preservation
- **MR-01** was satisfied through consistent manufacturability using consumer-grade FDM printing
- **DR-01** and **DR-02** were partially satisfied due to intentional tradeoffs between slimness and durability

This outcome reflects a realistic design process in which competing requirements are balanced rather than optimized independently.

7.7 Section Summary

Section 7 synthesizes the design decisions and outcomes of the project, emphasizing how competing requirements were balanced through modularity, geometry refinement, and manufacturing-aware design. The resulting system demonstrates improved ergonomic performance and practical durability within defined scope limitations, providing a strong foundation for future refinement and extension.

8 Conclusion and Future Work

8.1 Project Summary

This project documented the iterative engineering design of a modular grip sleeve for the Samsung S-Pen, developed to address ergonomic limitations encountered during extended writing tasks. The design process emphasized constraint-driven decision-making, balancing ergonomics, manufacturability, durability, and functional compatibility within the limitations of consumer-grade fabrication and a tightly constrained host device.

Beginning with early attachment mechanism exploration, the project progressed through modular architecture development, ergonomic geometry refinement, manufacturing optimization, and durability-driven redesign. Each phase informed subsequent iterations through real-world testing rather than abstract optimization.

8.2 Design Outcomes

The final design achieved its primary objectives:

- Improved ergonomic comfort relative to the bare stylus, satisfying **ER-01**
- Reliable attachment without interfering with stylus functionality, satisfying **FR-01** and **FR-02**
- Manufacturability using consumer-grade FDM 3D printing, satisfying **MR-01**
- Meaningful durability improvements through geometry-driven revisions, partially satisfying **DR-01** and **DR-02**

Importantly, the project intentionally avoided convergence on a single finalized grip geometry. Instead, modularity was preserved to accommodate subjective ergonomic preferences and differing writing styles, reflecting a human-centered design philosophy rather than a one-size-fits-all solution.

8.3 Lessons Learned

Several key engineering insights emerged from the project:

- **Attachment reliability must be established early** to enable meaningful downstream iteration
- **Small-scale threaded interfaces are highly sensitive to geometry**, particularly at thread runout and transition regions
- **Durability often emerges as a dominant constraint** only after extended real-world use
- **Manufacturing capability should shape design decisions**, not merely validate them afterward

These lessons reinforce the value of iterative prototyping, failure analysis, and requirement evolution in small-scale mechanical design.

8.4 Limitations

The project was intentionally scoped to qualitative evaluation and rapid iteration rather than formal mechanical testing. As a result:

- Durability performance was assessed through observation rather than quantified impact or fatigue testing
- Ergonomic evaluation relied on subjective user experience rather than biomechanical metrics
- Magnetic attachment and tablet storage compatibility were not fully addressed

These limitations are acknowledged as design tradeoffs rather than unresolved oversights.

8.5 Future Work

Several avenues for future development were identified:

- Exploration of alternative materials (e.g., elastomers or composite designs) to improve impact resistance
- Expanded user testing to evaluate ergonomic preferences across a broader population
- Refinement of magnetic compatibility while preserving modularity and durability

Additionally, the modular architecture developed in this project provides a transferable framework for other small-scale human-interface devices.

8.6 Final Remarks

This project demonstrates how a seemingly simple accessory can present a complex mechanical design problem when real-world constraints, user experience, and manufacturability are considered together. By treating the grip sleeve as a constraint-driven engineering system rather than a cosmetic add-on, the project achieved meaningful ergonomic improvement while maintaining transparency about tradeoffs and limitations.

The documentation presented here reflects an iterative, failure-informed design process consistent with professional engineering practice and serves as a foundation for future work and portfolio presentation.