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Unpowered Assistive Knee Brace for Sit-to-Stand Transition

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Abstract

Individuals experiencing diminished leg strength often encounter difficulty performing the transition from a sitting to a standing position. A healthy adult will complete an average of sixty transitions per day, making it one of the most physically demanding tasks performed in day-to-day life. The septuagenarian population of the United States increased by 7% in fifty years, and as such the number of persons lacking the ability to successfully complete the Sit to Stand Transition (STST) has also been increasing. To address this growing need, this project designed and fabricated a portable, wearable, passive mechanism that can be mounted on an individual's leg to provide an assistive knee extension moment during the STST. The final design is a spring-driven ratchet and cam system that stores the potential energy expended during sitting for usage during standing in order to deliver between 10 and 15 Newtons of lifting force. This mechanism serves as the prototype and proof-of-concept for an eventual market-ready product.

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Capstone Design Intent

This Major Qualifying Project seeks to demonstrate the applicability of engineering design principles and practices to challenges encountered in the modern adult lifestyle. The requirement for capstone design will be completed through the development of an assistive living device for individuals experiencing muscular degradation due to injury or aging. The device aims to make easier the Sit to Stand Transition (STST) process in such individuals by providing additional supportive forces during the transition. To ensure the validity of the proposed design, a series of constraints were determined for the design based on a review of clinical trials and scientific literature. These constraints, outlined below, define the parameters for a completed STST enhancement device, and by extension the parameters for the completion of this MQP.

1. Mechanical assistance to improve a patient's ability to perform a STST
2. Avoidance of interference with other activities the patient may perform
3. Simplicity of materials and manufacturing process in order to minimize construction cost

Assistive Requirements

The primary design directive for this device is to improve the mobility and independence of its user by assisting with the STST. Studies of the STST process before and after simulated muscular damage have shown as much as a 25% increase in the relative effort required from the participant[1]. The simulated muscular damage for this study was designed present with symptoms similar to acute tissue damage caused by sporting injuries; however, the same muscle damage index[2] calculations can be applied to septuagenarians experiencing muscular degradation. Based on the data gathered in these studies, specific mechanical goals for an STST assistive device can be declared: such a device must provide a mass-dependent assistive moment to a subject's knee joint that is equal to at least 25% of the subject's maximal isometric knee moment.

Safety and Lifestyle Integration

A well designed assistive medical device should be able to perform the intended task without significantly impacting the already existing lifestyle, routine, or activities of the patient. For a STST assistive device this directive is even more imperative due to the critical nature of the STST process in day-to-day life; a device designed to improve a regular routine that

[1]The percentage is out of the calculated maximal isometric knee moment for each participant; absolute units are measured in N*m/kg

[2]Muscle damage indices are determined by participant-reported experienced pain on a 10 point scale when joints are stressed to specified parameters.

simultaneously disrupts other routines is poorly designed. This device will target the movement of the joints at and below the hip, which are utilized by numerous other processes such as, but not limited to, walking, running, lifting, and kneeling. To meet this design restraint, a STST assistance device will need to perform its function without significantly impacting the joint-moments needed to perform these other tasks.

Economic Viability

Patients that may benefit from the use of an assistive STST device will have experienced chronic loss of muscle strength from one of two primary circumstances: injury or stroke resulting in physical muscle loss or partial paralysis, and naturally occurring sarcopenia onset with advanced age. For design purposes, this means that the target demographic for such a device is males and females older than twenty-one that experience chronic gluteus, thigh, or calf muscle weakness but maintain some ability to perform the STST process on their own. Due to the diverse and expansive target demographic, it is a design requirement to minimize the complexity of the devices design and manufacturing process in order to reduce its construction cost per unit without sacrificing reliability or function. In doing so the number of reachable patients in the target demographic is greatly increased; low cost will allow more potential patients to afford the device without assistance from insurance companies.

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1 Introduction

The Sit to Stand Transition (STST) is the biomechanical process by which a person moves from a vertically-static sitting position to a laterally balanced standing position. This is a physically strenuous process as it involves shifting the vast majority of a person's mass both horizontally and vertically while also maintaining balance. This procedure, and its inverse, are performed by an average adult upwards of sixty times per day[8], making it one of the most physically demanding tasks performed in day to day life.

The ability to reliably perform the STST is central to an adult's ability to lead an independent life. However, this ability can become severely diminished in elderly individuals; the onset of sarcopenia with old age or related muscular degeneration from injuries or misuse can limit an individual's ability to perform an STST. As the number of elderly in the population increases[13], the number of people with a decreased ability to execute STST will continue to rise as more individuals lose the muscle strength required.

Figure 1: Complete, Final Design

In order to address the growing rate of STST deficiency in the general populace, this project's goal is to propose a design for a device that will compensate for a degenerated STST ability in an individual. This design aims to be an iterative improvement over currently available solutions to the problem: by incorporating design elements of already existing assistive devices this new solution can avoid those same design's disadvantages. In order to create the design parameters for this project, existing research on both healthy and degraded transitions must be analyzed and then compared to the operational parameters of the existing assistive device designs. This analysis is presented in Section 2 on the following page and the design parameters are outlined in Section 3 on page 14.

The final design proposed by this project is a wearable device that targets the flexion moment about an individual's knee joint during the Sit to Stand Transition. Specifically, it decreases the relative load that an individual must exert during the transition by adding an assistive force that compensates for a portion of the individual's weight. A digital representation of the full final design is shown in Figure 1 on page 1. The decision to focus on the knee flexion moment is based on data gathered from scientific papers that demonstrate that the knee joint experiences the greatest strain during the STST process.

In summary, the goal of this paper is to present a complete design for a new assistive device which aims to compensate for an elderly or injured individual's decreased ability to execute a Sit to Stand transition. This design is created based on mechanical principles used in existing STST assistive devices, yet aims to avoid the drawbacks of those devices.

2 Literature Review & Background

The background research section will provide the necessary overview on Sit to Stand Transition research and geriatric medicine in order to establish the academic context for the work contained in this paper. This section will cover two primary areas of foundational knowledge: the first is a review of the medical and biomechanical problems encountered by individuals with depreciated muscle strength; the second will discuss previous work in the study of the Sit to Stand Transition (STST) process.

This section will establish the fundamentals required to understand and analyze the remainder of this document for both critique and further development. By quantifying the transition and discussing existing assistive devices, this section will establish these devices' shortcomings to be corrected by this reports' featured design.

2.1 Existing Research on the STST Process

Due to the ever increasing life expectancy[13], the percentage of the United States population over the age of 65 has risen from 8% in 1960 to 15% in 2015[24]. This renewed scientific interest in independent living requirements as new health care methods are developed to care for the aging populace. The ability to successfully perform the STST was quickly identified as one of the most essential components of an independent lifestyle, as it is one of the most frequently performed actions in day-to-day life[8][2].

Not coincidentally, the transition is a more challenging task for elderly individuals[12] than their younger peers due to the muscle degeneration that comes with advanced age; muscular strength can decrease by up to 50% by age 70[25]. This degradation, known as sarcopenia, has been shown in laboratory tests to impede an individual's ability to perform the STST in a similar manner to that of muscular injury[21]. There is a distinct correlation between low proficiency at this transition and lower independence, in which decreased STST performance has been reported to affect 6% of independently-living elderly people compared to more than 60% of assisted-living individuals[17]. Due to the increasing elderly population, attributed to improved access to health care, research into quantifying and improving biomechanical performance is greatly encouraged.

The STST has been studied extensively in the past three decades. Sit to Stand Transition studies can be sorted into one of two categories: those examining healthy individuals to determine frequency, baseline physical exertion requirements, and biomechanical force distributions; and those examining injured or geriatric patients to determine their reduced capacity to perform a STST. Both types of studies are crucial for designing an STST corrective device; the difference in the ability between the healthy and the disabled individuals to perform the STST is the gap that a corrective device aims to bridge[6].

2.2 STST in Daily Life

The Sit to Stand Transition (STST) is central to daily living [8][22][17][2]. This process is performed very often by active adults, on average 60 times per day[8], more than any other full-body movement[6].

The number of STSTs that an individual performs per day is affected by the demands of the individual's job and their employment status[8] as shown in Figure 2 on the next page. However even the lowest number of STSTs performed in any given day were above 30, with the average person performing approximately sixty STSTs per day[8]. Extrapolation to the general American populace means that the average American adult performs, on average, slightly less than four transitions per hour; assuming sixteen hours of wakefulness per day[7].

Further, Figure 2 on the following page also displays the contrast between the number of transitions executed by middle-aged individuals and the number executed by the elderly. Specifically, this data looked at partially independent individuals over the age of 65 in an assisted living or hospital environment and discovered that such people perform, on average, 36 Sit to Stand Transitions per day[14]. This stands in sharp contrast to the average of 60 transitions per day for adults ranged 25 to 45[8].

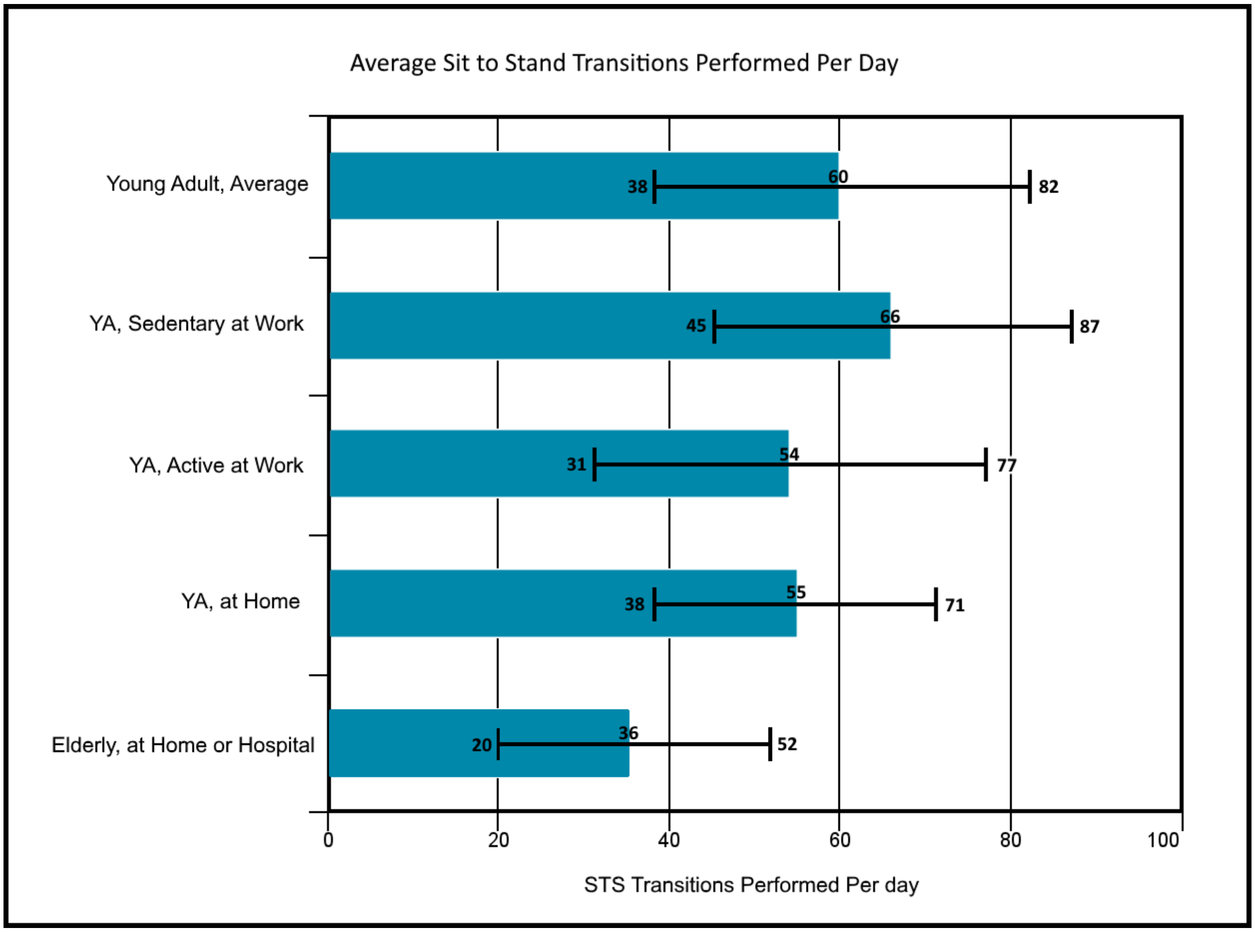


Figure 2: STST Frequency in Active Adults[8][14]

The World Health Organization periodically publishes a guide to classifying body function and activity for the purpose of determining the existence and severity of physical impairments. This document, the International Classification of Functioning, Disability, and Health (ICF), lists mobility, managing domestic life tasks, and engaging in life areas such as employment as some of the most critical categories for consideration when assessing disability and impairment[9]. All of these categories of action either require or incorporate the use of the STST process, and therefore can suffer as a result of an individual's degraded ability to execute it.

2.3 Mechanical Attributes of the STST

The STST has been categorized as one of the most demanding tasks performed by the average adult on a daily basis[28][8]. The centrality of the STST process is further reinforced by its complexity and inherent difficulty: by definition, the procedure moves an individual from a stable static posture to a less stable semi-balanced upright position [28]. Patients of varying physical characteristics perform this task, making the most applicable unit for measuring the STST relative effort. Also known as the load-to-capacity ratio, relative effort takes into account both an individual's physical load bearing ability and and the load that their physical frame presents[28]. This presents two variables that can be manipulated for experimentation: the load, or mass distribution, and the lifting capacity of the patient[28][16].

A study was conducted by the University of Thessaly in Greece on a set of female adults with no musculoskeletal injuries or impairments to determine reference points for the relative effort exercised during a STST. This study is noteworthy because it utilized healthy individuals for the control group, and then artificially induced muscular stresses to simulate injury in the same test subjects for a second set of data. This provides an essential comparison by removing many other variable factors that may arise when comparing healthy individuals to impaired ones[28]. A second study was conducted at the University of Delaware that analyzed the mechanical attributes of individuals completing the STST before and after undergoing reconstructive hip surgery[1]. This study, like the Thessaly University paper, used the same individuals for before and after measurements, while collecting data on hip and knee flexion moments. The data from the Thessaly and Delaware studies are tabulated in Table 1 on the next page and Table 2 on the following page, respectively.

The University of Thessaly study concludes that the knee joint experiences the largest moment of the three assessed joints (pelvis, hip, knee)[28]. The validity of these data sets is reinforced by its experimental replication in a separate study performed at Tohoku University in Japan: the Tohoku study assessed the usage of inertial sensor-based joint moment estimation during the sit to stand process[18]. Due to the nature of the Tohoku study, the data it provides is not directly applicable to building a simulation model for testing this project's design; however it does serve to independently corroborate the data from the Thessaly study.

Table 1: Normal and Simulated Injury STST Comparison Kinematic Data[28]

	Pre-Stressing	**Post-Stressing**
Total Time (s)	2.53	2.91
Plevis Variation		
Minimum, Maximum, Range (°)	-10.12, 26.50, 36.63	-12.84, 22.94, 35.77
Hip Joints		
Minimum, Maximum, Range (°)	2.39, 85.84, 83.45	5.04, 79.59, 74.55
Flexion Velocity (°/s)	108	80
Moment (Nm/kg)	0.21	0.18
Knee Joints		
Minimum, Maximum, Range (°)	-1.32, 86.01, 87.34	1.33, 83.7, 82.37
Flexion Velocity (°/s)	172	123
Moment (Nm/kg)	0.77	0.64
Ankle Joints		
Minimum, Maximum, Range (°)	2.28, 19.82, 17.54	4.01, 19.71, 15.70
Moment (Nm/kg)	0.43	0.44

Table 2: STST Measurements Before and After Total Hip Arthoplasty; with Control Set[1]

Measurement	**Pre-Op**	**Post-Op**	**Control**
Peak hip flexion moment ($Nm/kg*m$)	0.36	0.39	0.48
Peak knee flexion moment ($Nm/kg*m$)	0.40	0.45	0.54
Lateral trunk angle (°)	3.95	2.36	0.15

For the purposes of basic simulation, the vastly complex human body can be simplified to a series of members and joints. This also allows for a simple calculation of an approximate center of mass[16]. It should also be noted that the data above represents only the plane of motion that is utilized in a normal STST; for the purposes of laboratory experimentation, only the Superior-Anterior plane need be considered. From this analysis, the STST can be divided into three primary phases[22][3] that each present independent

[3]The three-phase model was adapted from a study at Massachusetts General Hospital[22]

challenges:

1. **Momentum Initiation** - begins with the pelvis and upper body moving forward to adjust the center of mass. It also transfers the subjects body weight load from the posterior to the feet, meaning that the posterior-to-surface contact is used only for balance.
   - Defined as the period between initiation of movement and the moment before the posterior leaves the supporting surface.
2. **Momentum Transfer** - begins when the subject becomes entirely self supporting; that is, there is no no contact with the supporting surface. This phase transfers the center of mass over the central axis of the subject's feet and increases the forward momentum in the torso.
   - Defined as the period between separation of the buttocks from the supporting surface and the maximum ankle flexion angle was achieved.
3. **Extension** - begins when the ankle joint begins rotating from its maximum deflection angle backwards horizontal. This phase completes the STST and involves recentering the center of mass over the feet, as well as arresting the momentum of the upper body in order to regain balance.
   - Defined as the period between ankle rotation direction reversal and the net momentum returning to zero.

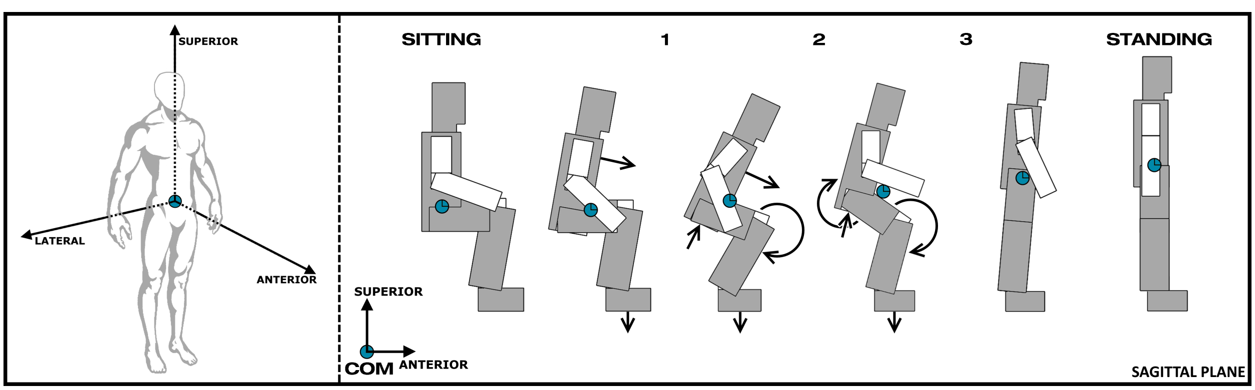


Figure 3: STST Phase Progression With Force and Moment Notations

2.4 Existing Classes of STST Assistive Devices

Within both the healthcare and home-living markets, there are many products to assist muscularly deficient individuals make the transition from sitting to standing[5][10][27]. Sit-to-stand transition (STST) assistance devices can be broken into three overall categories, denoted by the component of the transition that they are designed to target for improvement[26]. Each of them function differently, but all possess key shortcomings that make them less than ideal as an unobtrusive addition to an individual's life.

- Push-support devices supply an upward force normal-to the seat surface in order to reduce the force that needs to be supplied by the individual.
- Lift-support devices provide an additional support framework for the individual, thereby momentarily reducing their functional weight, and therefore the force needed to lift themselves.
- Upper-body assistance devices allow an individual to use their upper body muscles, including arms and chest, to assist with the STST.

To design a new, superior, STST assistance device it is essential to understand both how the existing devices work and how they fail to meet individual's needs. This section will explore the three classes of STST assistive devices in order to establish a sufficient understanding of the existing technologies.

2.4.1 Push-Support Devices

An assistive force can be administered to a individual attempting to execute the STST by pushing up from beneath the individual's posterior[22]. This class of devices, termed push-support, includes spring chairs, gas-propelled launching seats, and hydraulic posture adjustment tools[4]. These devices function by using a form of active launching mechanism, such as a compressed gas cylinder, hydraulic system, or compressed spring. Most devices in this class operate by having the individual sit on the device and trigger the mechanical assistance at the beginning of the transition.

These devices provide a pushing force, propelling the individual upwards which moves the them through the most energy intensive part of the Sit to Stand Transition process[28]. By providing an extra upward force during the initial phase of the STST the individual need only provide the force needed for the latter two thirds of the transition[26]. This increases the individual's functional lifting capacity and therefore enables them to move their own body mass through the STST without further issue.

A commercially common implementation of this device class is the Lift Chair, first patented in 1999[19]. One of the many variants of this design is shown in Figure 4. The key drawback to these devices is their size and immobility: the most common push-support devices are the size of an armchair or bench and can cost upwards of $500 USD[4][27].

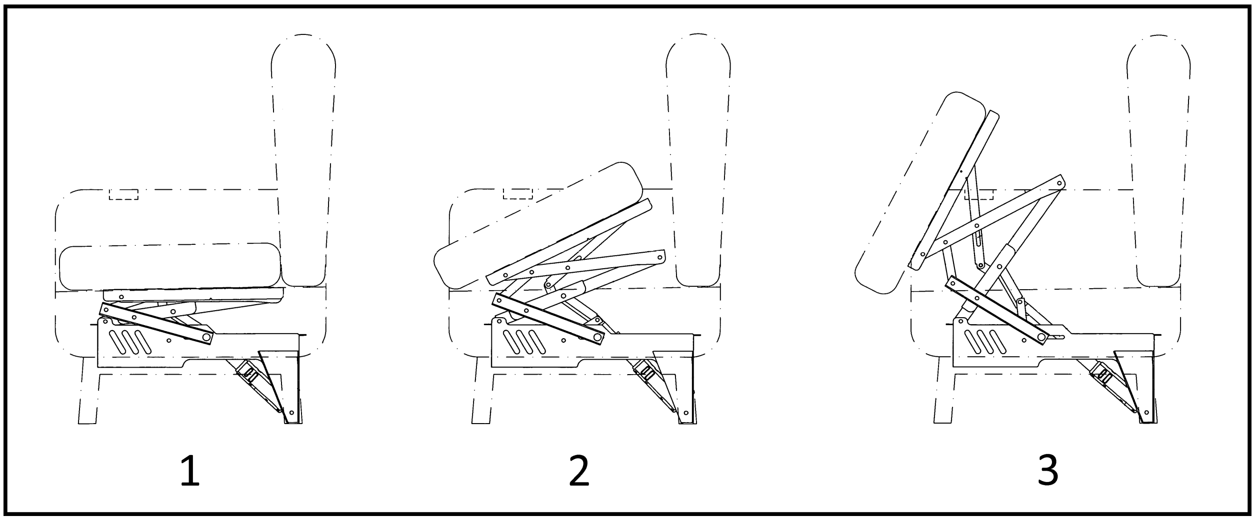


Figure 4: Diagram of a Lift Chair push-support STST assistive device; adapted from US Patent #8398171B2[19]

This class of devices is best suited for a home or assisted living setting: due to the customizability and personal control over the environment in both of these settings, installing and using a push-support device is relatively simple. However, in a public place or temporary living space an individual may not have the luxury of control over their environment. When this drawback is considered with the limited portability of these devices their usefulness is severely diminished, in spite of the significant STST performance improvements they provide[22].

2.4.2 Lift-Support Devices

The STST capability of an individual can be improved by applying an offsetting lifting force, thereby functionally decreasing the load that they are lifting[17]. Devices that operate in this manner are most commonly used in hospitals and assisted living facilities[10] for individuals with limited mobility.

This class of device aims to reduce the load that the individual must lift when performing the STST[22]. This load can be reduced by providing a force that counters some or all of the individual's weight[26]. Refer to an example of this device class in Figure 5. By providing a counter weight of equal or lesser mass to that of the individual, a force is applied that counters a portion of the individual's weight. From the perspective of the individual, the load being lifted during the STST is reduced and therefore the transition requires less exertion to complete.

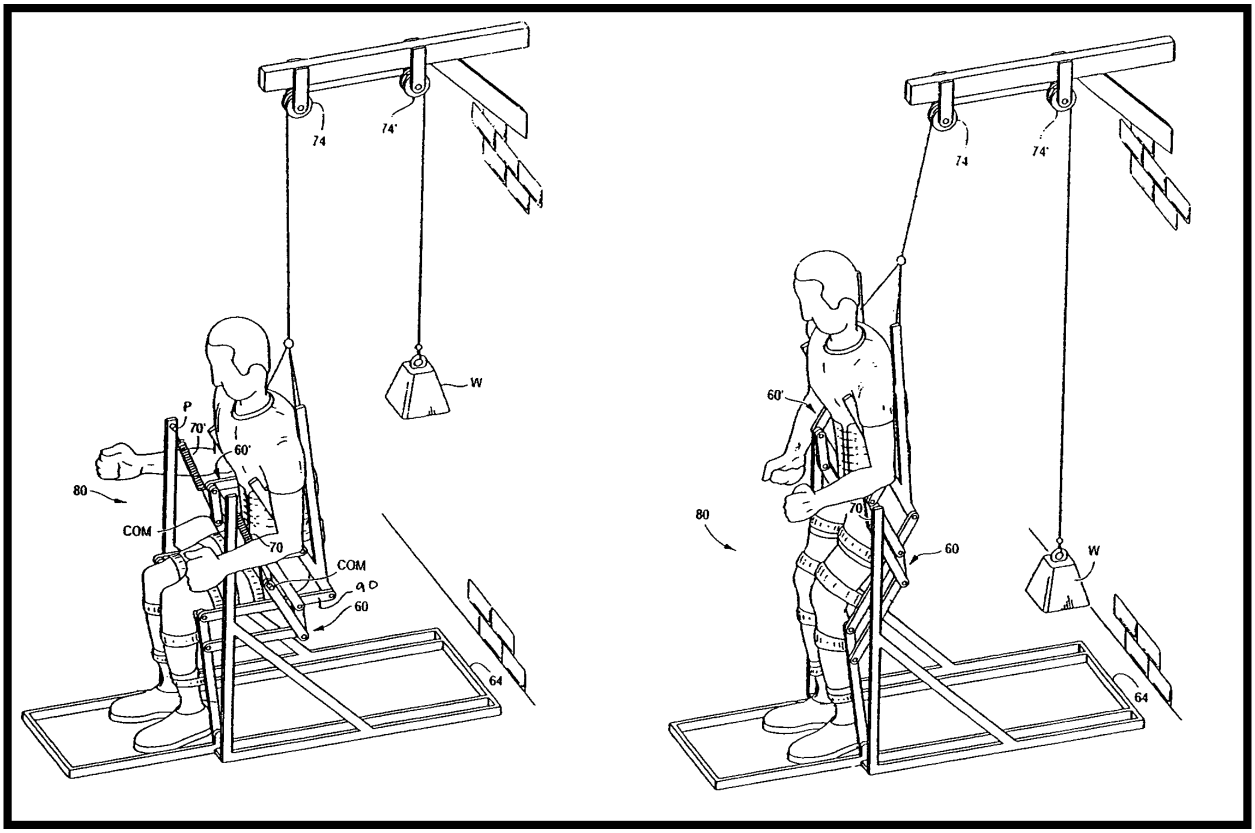


Figure 5: Diagram of a Gravity Balanced lift-support STST assistive device; adapted from US Patent #20060260621A1[3]

This class of device suffers from the same drawbacks as push-support devices: namely immobility and cost. Devices of this type can cost more than $1,000 USD and weigh in excess of 400 pounds[10]. However a crucial advantage lift-support devices hold over push-support devices is their ability to be fully mechanized, resulting in a safer and more controlled STST. The trade off is the increased cost and weight that these more complex mechanics produce[10][4].

2.4.3 Upper-body Assistance Devices

Devices that allow individuals to use their upper body strength to assist with lower body movements are some of the oldest geriatric tools still used in the modern world. The simplest example of this device class is the classic walking cane or crutch[5]. These tools allow an individual to use their upper torso and arm muscles to assist with the transition from sitting to standing.

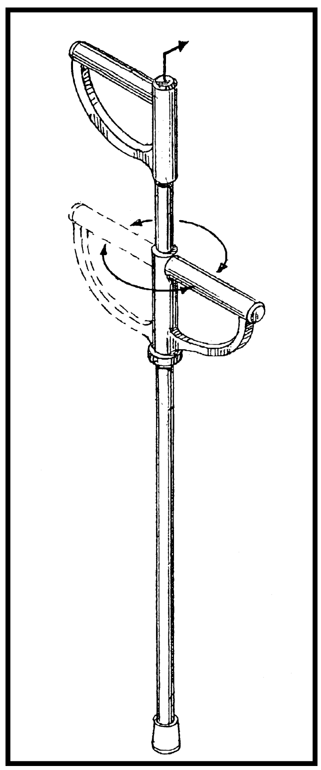


Figure 6: Diagram of an Upper-body STST assistive device; adapted from US Patent #6834660B1[30]

Similar to the push-support class of devices, this class also targets the force needed to lift the individual by allowing muscle groups not usually involved in the STST to assist. Most commonly this means that the device provides a lever or handle so that the individual can utilize their upper body muscles to provide extra lifting force. However, unlike the push-support devices this class relies largely on passive components to facilitate the transition. This can be done by providing a lever or brace so as to give the individual's upper body a mechanical advantage when lifting themselves from sitting to standing[30]. The most common devices that fall into this category are walkers, arm rests, and canes; an example of the lattermost is shown in Figure 6 on page 12.

This type of device has several advantages over push-support and lift-support devices, in that they are commonly portable and designed for use in many different scenarios. However, the lower weight and cost associated with these devices mandates stripping them of any active components or complex mechanics. In addition, they require the user to hold onto the device and keep it with them during any period in which they may want to use it.

3 Methodology

This section outlines the approach to this design project. It establishes parameters for design success, a standard design procedure, and a schedule for the execution of the procedure.

3.1 Derivation of Design Requirements

In order to assess the validity of the design put forward in this paper, it is necessary to define the objectives of the device outright. In this section, the required specifications and constraints of the final device's design will be outlined in detail so that multiple designs can be vetted. This will be achieved by establishing specific numerical requirements so that design variants can be compared to one another using clear and direct methods of measurement.

The design requirements have been divided into three categories that will be detailed below: mechanical STST improvement, ergonomics and safety, and manufacturing cost.

3.1.1 Mechanical Improvement

The most effective measurement developed for benchmarking Sit-to-Stand Transition performance comes from a study performed at the University of Thessaly in 2012. This measurement, named simply Relative Effort, is a patient-specific ratio of that patient's load over their muscular capacity. Mathematically, this is expressed as the patient's maximum torque exerted at the knee joint in newton-meters divided by the patient's total mass in kilograms. The data in this study allows for a direct comparison of measurements for both healthy and disabled subject, and that completeness makes it ideal for use as a framework for device design. The full data from this study can be found in Table 1 on page 7.

The key finding of the University of Thessaly study was the dramatic increase in the percentage-relative effort required by a patient with simulated muscular deficiencies. Participants in the study utilized 40% of their maximum relative effort to perform the STST under normal circumstances, but 65% of their maximum relative effort after simulated muscle damage. The precise numbers for this deficit are listed in Table 3 on the next page.

Table 3: Relative Effort in STST Before and After Simulated Injury[28]

	Max Knee Moment (Nm/Kg)	Knee Moment During STST (Nm/Kg)
Before Stressing	1.88	0.77
After Stressing	1.06	0.64

In order to achieve an appreciable improvement in STST performance, the relative effort must be equalized, or the disparity narrowed, between injured and uninjured patients. To this end, this project's design will aim to provide an additional 0.2 newton-meters per kilogram (N*m/Kg) during STST. This will reduce the maximum knee joint moment to relative effort ratio to 40%, which is identical to the corresponding ratio in an unstressed individual.

3.1.2 Ergonomics and Safety

In order to justify the usefulness of any corrective device, it must be able to perform its function without significantly negatively impacting any other attribute of the user's lifestyle. An example of a design idea that might fail this requirement would be an overly heavy device that would limit a patient's mobility outside of the Sit-to-Stand Transition.

For this reason, a requirement of this design is its ability to seamlessly integrate with a user's existing lifestyle without having a detrimental impact. This design must not inhibit a user's ability to perform other common tasks including, but not limited to, walking, running, sitting, standing, or operating a vehicle. This means that the device, when worn, must not mandate an adjustment period of more than two to five seconds when performing any of the previously mentioned tasks.

In addition, a device that is designed for near-continuous use for extended periods must be reliable and contain safety systems that prevent harm to the user in the event of mechanical failure. Based on the average of sixty Sit-to-Stand Transitions per day[8], the device should reliably be able to operate without failure or repair for eleven-thousand cycles (one cycle is equal to one Sit-to-Stand Transition and one Stand-to-Sit Transition), or approximately six months of continuous usage.

In the event that the final design utilizes active components, including but not limited to pistons, actuators, or hydraulics, they should be sufficiently distanced from direct user contact so as to pose no threat in the event of failure. This same principle applies to passive components with the ability to store energy, such as springs.

3.1.3 Manufacturing Cost

One of the key determinants of existing STST corrective solutions that this design aims to correct is the exorbitant cost. This increased cost limits both a potential user's ability to purchase the device and discourages retailers from stocking it. This new design will aim to reduce the cost to the end user by utilizing standard manufacturing techniques and components wherever possible and making maximal use of low cost materials.

By calculating the necessary material properties for each design and selecting low cost materials that meet those requirements, the lowest price point can be selected without sacrificing functionality. The price can be reduced further by using standardized components wherever possible, rather than creating a design that relies on custom fabricated parts.

With these techniques, it should be possible to limit the cost of this device to less than $300 for the end consumer[6]. This grossly undercuts the $1,000 competitive price point[10] of static lift devices, and and the $700 starting price[4] for common lift chair models.

3.2 Design Process

The process of determining design candidates will be structured to achieve two goals: the first will be to create a series of designs that can be tested and analyzed in direct contrast with one another. This will allow for direct vetting between the proposed design candidates in order to determine which best fulfills the design requirements listed in Section 3.1 on page 14. The second goal of structuring the design process is to ensure the most efficient usage of the time allotted for this design project.

The distinguishing features of each individual design candidate will be the mechanical principle or mechanism that the design is based on, and though not explicitly noted in the descriptions below, it is assumed that at any point in the design process any design candidate may be modified or corrected as necessary. This allows for new ideas to be considered at any point in the design process, within reason.

Early Concept Creation

The initial stages of the design process will consist of paper sketches and conceptual vector drawings. The principle of each design candidate will be denoted in simple Free Body Diagram form with lines and arrows denoting force and moment vectors. This level of simple, rapid concept creation generates a large quantity of ideas and allows for a quick assessment of their validity without a large time commitment to any one concept.

Once an initial series of design concepts have been selected, more detailed paper sketches and schematics will be created. This simple analysis will aim to translate the rough vectors and moment delimiters into physical components that may be used in the final design. The construction of very basic physical models will eliminate design candidates that would be impossible to implement effectively, while still remaining in a medium that allows easy implementation. Once these more detailed schematics have been created, or are under development, a consultation with the WPI Department of Mechanical Engineering will be organized in order to review the validity of the various designs.

Iterative Design Prototypes

Review from the Mechanical Engineering Department and further vetting based on the design requirements will aim to reduce the number of potential candidates further. At this stage, no more than three to five potential designs should remain for consideration. Once these semi-final designs have been selected, three dimensional computer models will be created using the SolidWorks© 2016 Student Edition software package.

The models created in this software will facilitate both digital simulation and physical prototyping in later design stages. However, the immediate benefit is further investigation of potential failings and inefficiencies in the assembled designs that may disqualify them from consideration.

This stage of the design process will see the creation of rapidly created prototypes through the use of a Three Dimensional Rapid Prototyping Machine (3D Printer). These rapid prototypes will be utilized for practicality and ergonomic testing; it will also allow for testing mounting considerations and other design attributes not easily accounted for in a software model. As this process continues the remaining design candidates will be scrutinized in detail for disqualifying characteristics.

In addition to the physical 3D printed prototypes, the SolidDWorks© 2016 Student Edition Simulation software package will be used to perform tests of the designs. The simulated forces, moments, and loading values will be taken from Table 1 on page 7 and Table 2 on page 7. The results of these simulations will help to determine the material requirements of the device and the material selection process will begin. This will make use of the CES EDUPack 2016 software in order to ensure that as many materials are considered as possible.

Final Design Selection and Testing

The final design stage utilizes data from the simulations and rapid prototypes to select a final design candidate. It is possible that the data at this point will be insufficient to select only one, in which case a second may remain for consideration, though for the sake of time this is not ideal.

Once the final design candidate(s) is/are chosen, work will begin on constructing full-functionality prototypes of the computer models. Given a limited operating budget and time frame for the prototyping process, it is critical that the design still under consideration at this stage have already met the design requirements, as outlined in Section 3.1 on page 14, in all the previous tests. After testing of the final prototype(s) and determining their success in addressing the design goals of this project, the final design will be definitively selected and documented for submission.

3.3 Verification of Design

The Design Process calls for a verification stage wherein the final prototype is tested against the original design parameters in order to determine the success, or failure, of the final prototype in addressing the goals of the project. This process will involve several phases of testing in order to validate the design requirements as described in Section 3.1 on page 14.

Informal experimentation will be conducted by volunteers wearing the prototype device. They will report on subjective attributes of the Ergonomics requirement such as comfort, ease of use, and perceived impact on other activities such as walking and sitting. These same participants will also be examined using simple motion analysis to determine whether the device has the desired impact on the subject's ability to perform the STST.

The manufacturing cost requirement of the design will be examined in depth using data from the CES Edupack 2016 material library and database software, as well as the estimation capabilities of the SolidWorks© 2016 Student Edition Costing Tool. The first of these will allow for an estimation of the material costs of the design prototype. The second will provide a comprehensive analysis of the hypothetical manufacturing methods for the material and the financial impact on the end cost. The data and analysis tools provided by this software tool will allow for a complete estimation of not just the material costs, but also shipping, manufacturing, and storage costs for the final product.

Further experimentation will be conducted in a laboratory environment to determine whether the final prototype meets the remaining design requirements of administering adequate mechanical advantage and longevity. Laboratory testing can be conducted to measure the force applied to a human leg wearing the final prototype in order to verify that the end result meets the 0.2 newton-meters per kilogram goal of the design. Similarly, usage of a cyclic loading testing device can verify the prototype's ability to maintain functionality for the required number of cycles. These same mechanical tests will also be repeated via the SolidWorks© 2016 Student Edition Simulation software as a secondary source of data in order to verify the validity of the design.

3.4 Schedule for Execution

The schedule laid out in this section will remain a work in progress until the completion of the project. The approximate distribution of work will be as follows: A Term (August 31 - October 13)l entails background research, design requirements, project planning, and the writing of the Introduction, Background, and Methodology sections. B Term (October 25 - December 15) represents the bulk of the digital simulation and design candidate selection work; early rapid prototypes will also be created in B Term. C Term (January 12 - March 3) encompases the finalization of the computer models and the creation of the final prototypes. D Term (March 13 - May 2) ends the project with the bulk of the design documentation, writing of the results section, and review of the full paper.

The exact breakdown of task and their progression periods are detailed in Figure 7 on the next page:

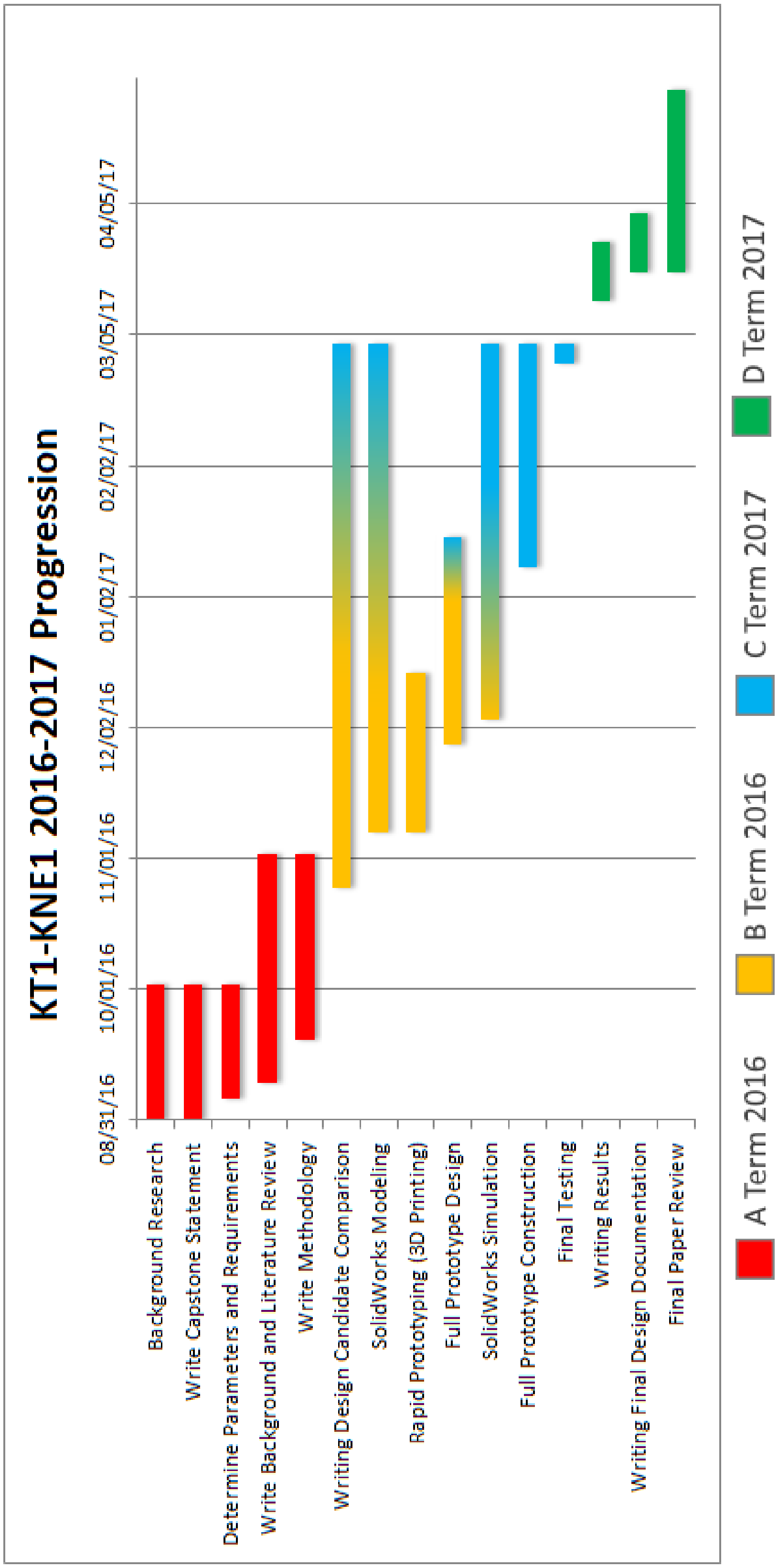


Figure 7: Task-Specific Project Execution Schedule

3.5 Project Scope and Focus Adjustment

At the conclusion of B Term 2016, the scope of this project was reassessed based on the work that had been completed up to that point, and the work involved in carrying the project to fruition. Based on this analysis, the project scope was redefined in order to maximize the usefulness of the resultant device. The original scope of the project called for the design of an end-product that satisfied the project specifications. However, the reassessment indicated that the best course of action moving forward would be to focus the design efforts solely on the mechanism component that delivers the assistive force.

Functionally, this means that the project omits consideration of potential marketability of the device, as well as user-experience refinements such as ergonomics and safety considerations. Further, the truss assembly that attaches the mechanism to the wearer's leg, as shown in the final design diagrams, will not be evaluated for force loading distribution; it is simply a placeholder meant to provide the necessary context for the mechanism itself. What has been evaluated is the final design mechanism, as detailed in Section 5 on page 44.

4 Design Process

The design process for any mechanically complex device must be thoroughly documented so that any future designers have a complete justification for the existing design decisions, and therefore can work most efficiently. Further, the initial designer can benefit from thorough process documentation so that previously unidentified flaws can be recognized and removed before a prototype is constructed. In the interest of providing design process documentation, this section will give details on the execution of the design steps put forward in Section 3.2 on page 16.

The documentation provided in this section includes the justification for the proposed final design as well as the various analytical steps that led from one design stage to the next; however it does not include the final design documentation, such as operation, assembly, and necessary components. For this information, please see Section 5 on page 44.

In its most simplistic form, this project seeks to develop a rotary actuator in order to apply a moment about an individual's knee on command. Using this most basic guiding principle, three unrefined designs were conceptualized for the initial design stage, each of which employs a different central mechanical principle: spring compression and lever arms, spring expansion and cabling, and active cable spooling. These three initial designs, and their refinement, will be covered in detail below.

4.1 Problem Analysis

In the early phases of design, the most restrictive design goal was the aim to create a wearable, ergonomic device, as laid out in Section 3.1.2 on page 15. Due to this aim, it became apparent that the device would need to be mounted to the individual's leg, and therefore both size and weight would need to be minimized in the final design. This led to the derivation of the basic truss and hinge layout, shown in Figure 8 on the following page. In the figure the wearer's knee-joint axis in each phase is shown with a blue marking.

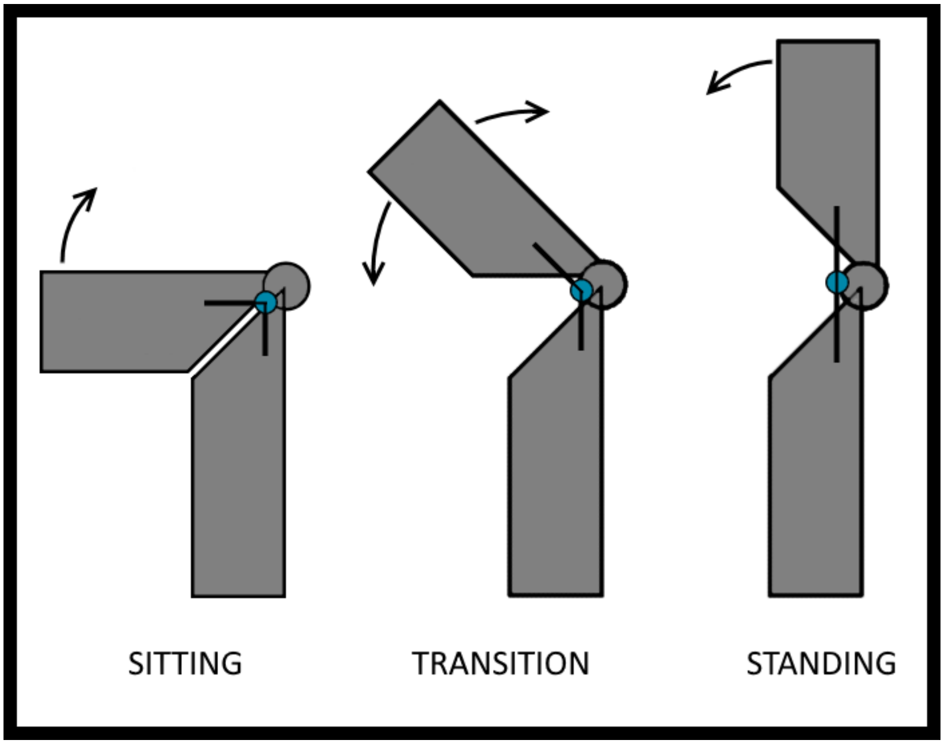


Figure 8: Simplified Truss-transition Diagram for Mechanism Analysis[4]

This truss and hinge structure is based on the layout of the leg itself, comprised of an upper and lower segment with a single joint located at the knee. By including this truss in the design, it allows the device to apply its forces and moments to the truss, rather than the leg directly. This adds a level of separation between the mechanical system and the individual, which both increases the variability of the design and reduces risk for the user by adding a buffer space for padding, dampening, or shock absorption.

The truss is securely mounted to the user's leg while being composed of a much stronger material, and therefore able to take much higher stress. The addition of this abstraction, separating the support framework from the user's body, means that the mechanism that applies the moment about the knee does not need to be adjusted to prevent injury to the user; instead the forces can be applied in the most efficient manner while the truss redistributes the lifting-effect across the user's leg.

4.2 Initial Design Candidates

Before progressing to the details of the design candidates, it is important to note the differences between passive and active actuators: passive actuators, as used in the spring compression and spring expansion designs, use stored mechanical-potential energy directly to perform work. However ative actuators, such as in the cable spooling design, use an alternative source of energy to accomplish work, such as an electric battery or chemical reaction. There are distinct advantages and disadvantages to both devices, which are explored at length in the respective subsections below.

4.2.1 Compression-Force Spring Piston

The compressed spring piston-arm design was one of the initial designs that used a compression-force spring. The inspiration for the design came from a conventional automobile's suspension system[29], and was adapted to provide a dynamic force about a joint. The mechanism has each end of a piston assembly affixed to a point below and above the joint to be extended, while a compression-force spring stores the mechanical energy generated by the wearer when sitting so that it can be expanded during standing. A diagram of the mechanism is shown in Figure 9 on the next page.

In the standing position, the spring is at its maximal length and in the fully relaxed position, as shown at **Point C**. During the process of walking or standing, the knee joint can undergo minor rotation, which of course affects the expansion of the piston, and therefore the compression of the spring. In order to compensate for this without applying a force on the wearer when it may not be desired, the upper attachment point for the piston assembly is in a leeway slot that allows for variation in the functional length of the piston without affecting the compression of the spring; this is highlighted at **Point D**. In the standing position the spring holds the piston fully extended, and thus exerts no force on the wearer until the piston is contracted when the wearer enters the transition phase, moving towards sitting.

Once the wearer moves into the transition phase, and eventually into the sitting state, the piston is contracted and the spring fully compressed. This is shown at **Point B** and **Point A**. This forces the piston's upper attachment point to the rear of the leeway slot and applies the required upward-pushing force to the wearer's thighs.

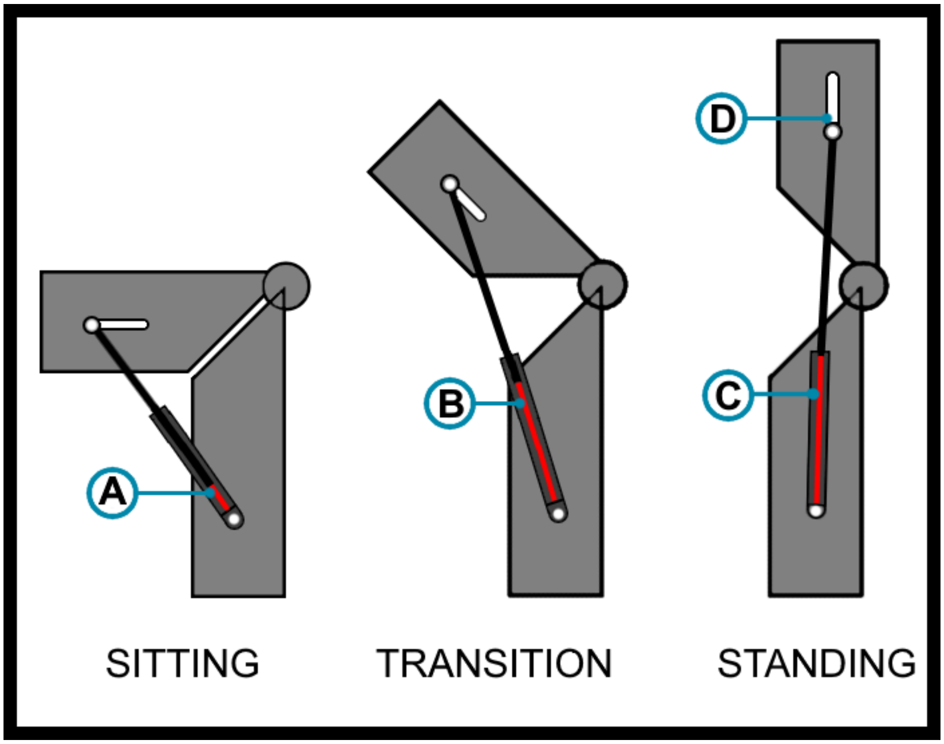


Figure 9: Design 1: Compressed-force Spring with Rigid Piston Arm

This design was rejected early in the brainstorming phase due to the rigid piston assembly creating an obstruction to the wearer's normal sitting stance. The inclusion of this piston alters the device's sagittal profile from two perpendicular rectangles to a triangle, thus increasing the size of the obstruction it provides. In order to avoid this in future designs, a flexible loading vector, such as a cable, would need to be substituted in place of the rigid piston assembly.

4.2.2 Actively Spooled Cable

Using an active mechanism was considered something to be avoided during the design process due to the inherent complexities that an active component introduces to the device. In spite of this hesitancy, this initial design does use an active cable spooling mechanism. This concept served as a means of exploring the use of a flexible loading vector, as opposed to a rigid, piston-like loading vecotr like the one used in the Compression-Force Spring Piston concept. A diagram of the overall truss assembly is shown below in Figure 10 on the following page, though it does not detail the operation of the active spooling mechanism itself.

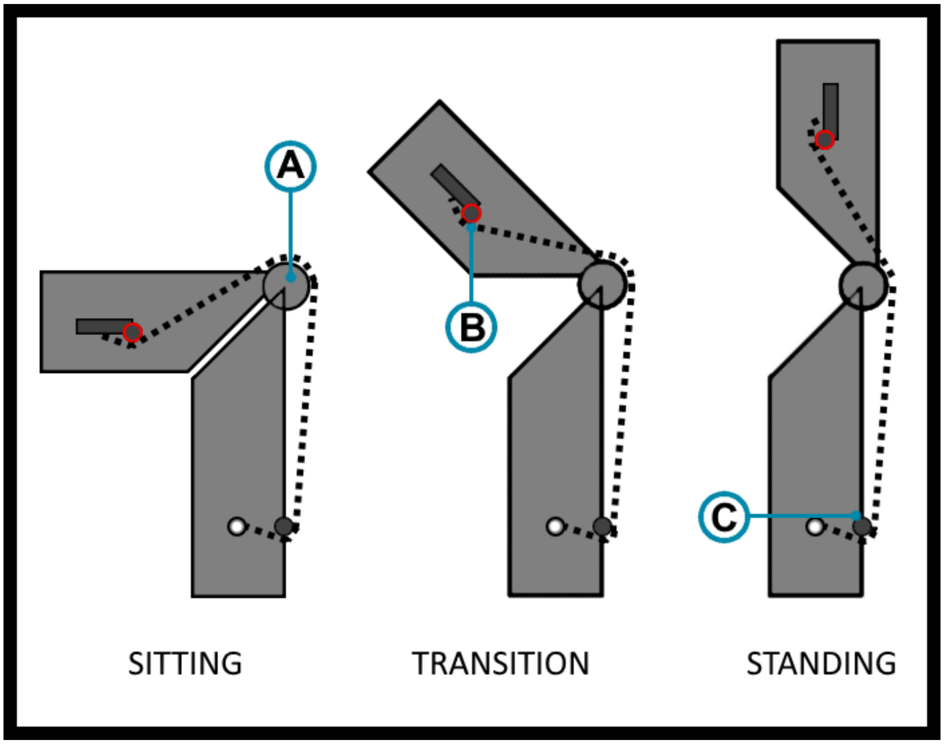


Figure 10: Design 2: Active Spooled Flexible Cable and Pulley Assembly

The active gear, highlighted at **Point B** and shown in red, uses teeth or another high friction surface to drag the cable forward or backward; unlike every other pulley shown in the diagram, the cable can neither freely rotate or slip over the active gear. As the gear spins, it pulls the cable inward and coils it in a container or on a spool, denoted in the diagram as the dark grey box behind the active gear. This lengthens or shortens the length of cable that runs through the rest of the pulley system, and therefore affects the angle of the overall truss structure.

In order to maximize the moment that the cable can apply about the knee-joint of the truss, the cable is passed over a pulley at the main joint in the truss structure. As shown in Figure 8 on page 23 and **Point A** of the above diagram, the main truss joint is offset from wearer's knee joint. This offset allows the cable to apply a moment-force on the wearer's knee: the magnitude of a moment is measured as the product of the force and the perpendicular offset of the force's vector line from the joint axis, and therefore increasing either will increase the magnitude of the moment. In this case the force's vector line is colinear with the cable itself, as the cable is also the loading-medium of the force, and so the moment about the knee is directly related to the distance that the pulley is offset from the knee joint.

Further, **Point C** highlights a force redirection pulley which alters the direction that the cable's force-vector is applied to the lower portion of the truss. This force redirection pulley, like the main joint pulley, is free rotating and spins with minimal resistance as the cable moves over it. By routing the cable over this pulley the superior and anterior components of the cable's force are resolved into two separate forces and each is applied at the force redirection pulley and the cable-truss mounting point, respectively. The result of this is that the superior component of the cable's force is loaded on the force redirection pulley, while the anterior component pulls on the truss at the cable's mounting point. This further increases the moment about the knee, as the perpendicular offset of the force is the distance from the main joint pulley to the force redirection pulley, the later of which is coincident with the newly created anterior force's vector.

Upon review, this design was rejected based on two of its attributes: as previously indicated, a fully passive mechanism would result in a lighter, simpler, and more user friendly device, as it forgoes the need for batteries, motors, and other electrical components. Second, the placement of the coil assembly on the upper portion of the truss structure inadvertently caused the direction of the moment about the main joint to be inverted from the optimal direction of rotation.

4.2.3 Extension-Force Spring Cable

The final iteration to be derived in the initial design stage incorporates elements from each of the previous design candidates, but uses an extension-force spring inline with the cabling as its mechanism. The mechanical assembly for this device, shown in Figure 11 on the following page, is a flexible cable routed over a freely rotating pulley at the main joint of the truss assembly and attached to an extension-force spring on the lower section of the truss assembly. This spring alters the functional length of the cable, and thus pulls on the truss assembly. This device is based on the same mechanic by which the patella allows the biological knee joint to function[23].

During the transition from sitting to standing the functional length of the cable is decreased by the spring, highlighted in red, as it contracts. In the sitting position the spring is under tension and expanded to its maximum length, as depicted at **Point A**. As the wearer enters the transition phase the spring applies a pulling force on the cable which has the effect of applying a lifting force on the upper portion of the truss and a moment about the knee.

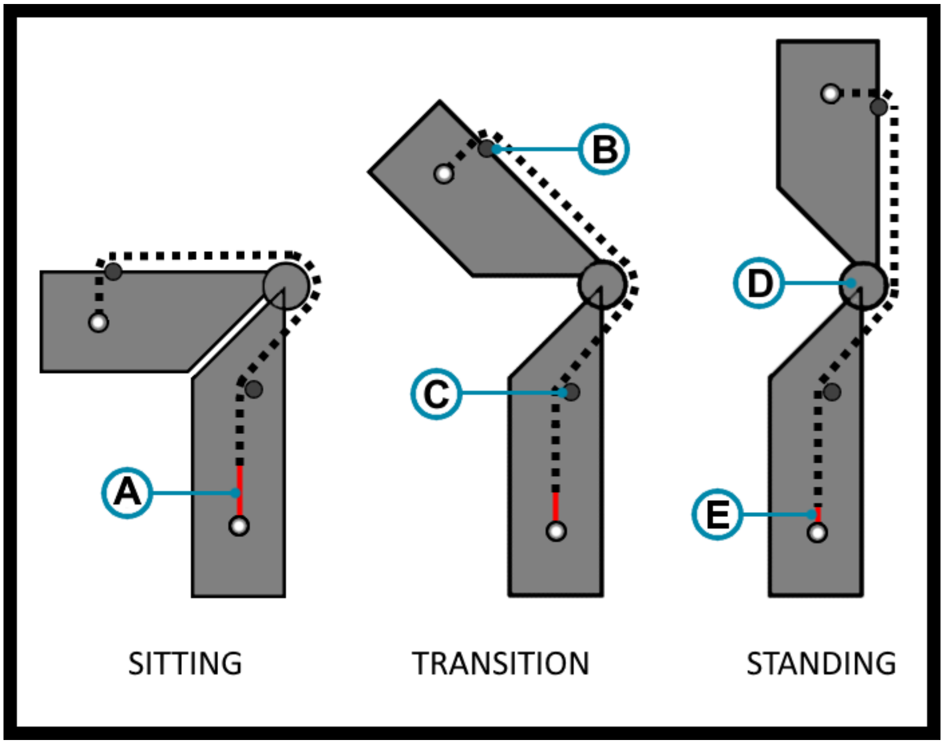


Figure 11: Design 3: Extension-Force Spring with Flexible Cable

As discussed in the previous section, the moment about a joint is the product of the magnitude of the force being applied and the perpendicular offset from the joint axis to the vector of the force. In order to maximize this value, and thus the magnitude of the moment, a freely rotating force redirection pulley is placed at **Point B** so that the force in the cable is applied to the truss structure perpendicular to the cable; this makes the force vector's offset equal to the distance between **Point B** and **Point D**, the upper force redirection pulley and the main joint pulley, respectively. Similarly, a second force redirection pulley is placed at **Point C** so that the spring's mounting point on the truss does not need to rotate, thereby reducing the points of movement and the potential points of failure.

As the wearer reaches the full standing position the spring reaches the fully contracted, and therefore fully relaxed, position and the force applied to the cable approaches zero; this is shown at **Point E**. It is important to note where the length differential in the cable between the sitting and standing states comes from: as the user transitions from sitting to standing, the cable is in contact with less and less of the main joint pulley, at **Point D**. That is, in the sitting position the cable wraps around approximately 120°of the main joint pulley, while approximately only 30°when in the standing position. This change in length is exactly equal to the length differential in the extension-force spring, and thus can be used in spring load calculations using Hooke's Law.

The layout of this design is the one used in the final prototype presented in this project, though with several refinements. Chronologically in the development process, this design was conceived after the creation of Prototype 1, which was based largely on the Actively Spooled Cable design. This will be covered in greater detail in Section 4.3, but after the mechanical shortcomings of the Actively Spooled Cable concept were further explored in Prototype 1, this Extension-Force Spring concept was adopted for use in the final design.

4.3 Prototype 1

The first prototype for this project's ultimate design was never physically constructed, but instead was modeled in SolidWorks©2016 Student Edition©for conceptual evaluation and mechanical assessment. The principle construction of this assembly was based on the Actively Spooled Cabling design described in Section 4.2 on page 24, though it was in itself a further iteration as it incorporates several other components not included in that initial concept:

- Instead of using an active spooling mechanism, Prototype 1 uses an extension-force spring to vary the length of the cabling. This idea was later incorporated into the Extension-Force Spring Cable design, also described in Section 4.2 on page 24.
- Prototype 1 provided an opportunity to perform a proof-of-concept design of a spring-driven ratcheting piston. While the implementation shown in Prototype 1 was not used in the final design, the same concepts were applied.

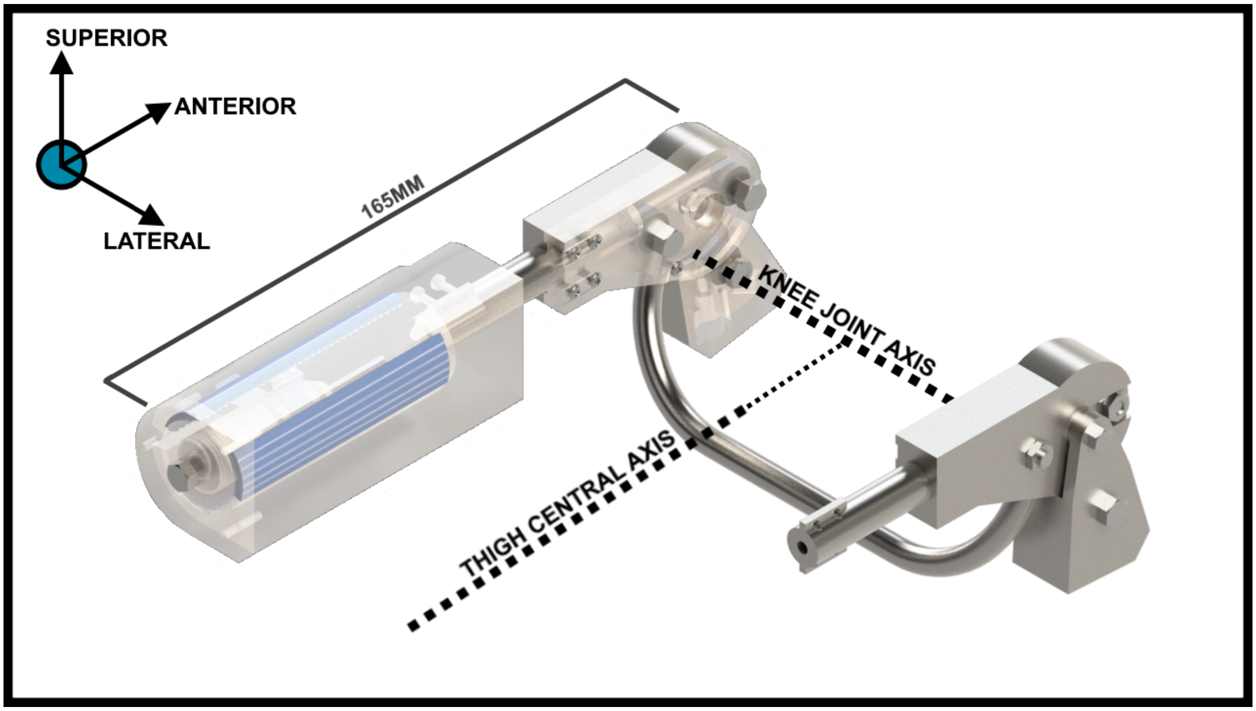


Figure 12: Prototype 1 Isometric Overview and Reference Axes

The primary isometric-view depiction shown in Figure 12 shows the entirety of the prototype SolidWorks© model created at this stage. Shown is the lower portion of the truss assembly and mechanism for one leg. The mirrored portion on the righthand side of the figure was only partially implemented as it is an exactly inverted version of the assembly shown in the lefthand portion of the figure. If fully implemented, the device would be mounted to the wearer so that the knee joint faces the anterior direction and the horizontal cross bar is pressed against the wearer's popliteus muscle. Figure 13 on the next page shows a cross section of the right side of the full assembly in order to depict the cable's path (highlighted in red) and the components of the mechanism.

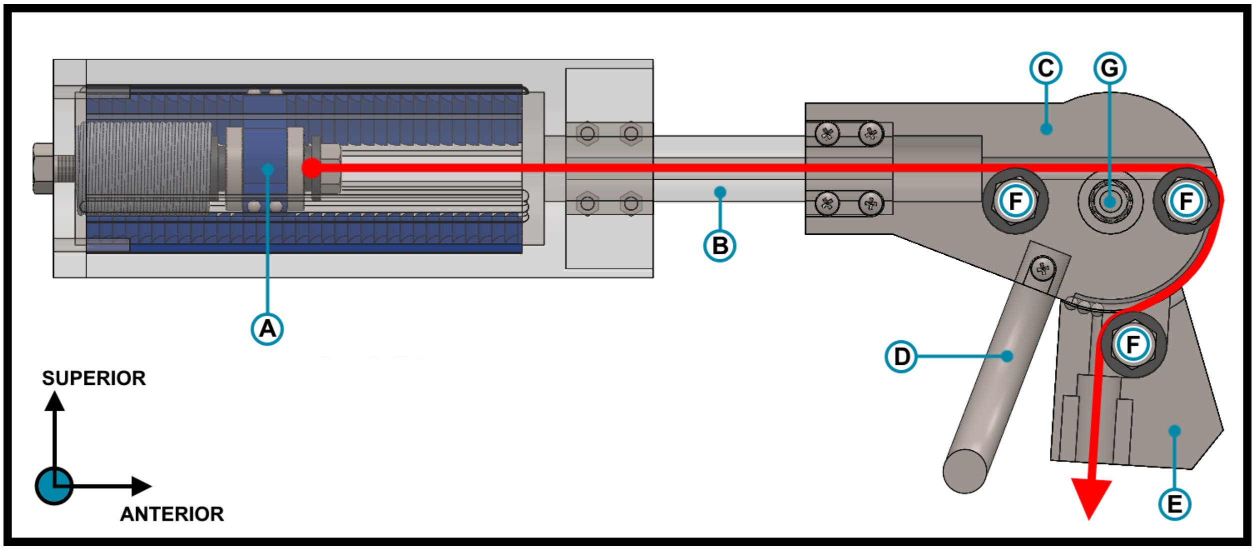


Figure 13: Prototype 1 Profile and Interior Mechanism View

- **A:** The spring-driven piston assembly, with the spring itself located to the left. This assembly is explored in detail in Figure 14 on the following page.
- **B:** Load bearing inter-component connector; bridges the joint assembly and the piston assembly.
- **C:** Upper main joint component; provides a path for the cable over guidance pulleys, and connects the upper truss assembly to the lower truss.
- **D:** Horizontal cross bar; a component of the upper truss assembly, this provides vertical support for the wearer's thigh as well as being a point of static connection between the left and right joint assemblies.
- **E:** Lower main joint component; the mounting point for the lower truss assembly, it can rotate freely around Point G.
- **F:** Guidance and force redirection pulleys; the lowermost pulley is the most critical, as it redirects the force in the cable to be directed perpendicular to the cable itself.
- **G:** Main joint bearing and attachment point; this point is coincident with the knee joint axis and is the point of attachment between the lower and upper truss assemblies.

Spring-Driven Piston Assembly

The spring-driven piston assembly is the most pertinent component of Prototype 1 that is carried through into the final design. This mechanism allows the spring to be extend as the wearer transitions from standing to sitting, but to not exert any contracting force on the mechanism until the wearer triggers it. This is accomplished by employing a ratcheting mechanism that prevents the spring from contracting once extended. Depicted in Figure 14 is a rear-on cross section of the piston assembly. Highlighted in red are the ratchet lever arms and the connecting pins that hold them to the piston arms.

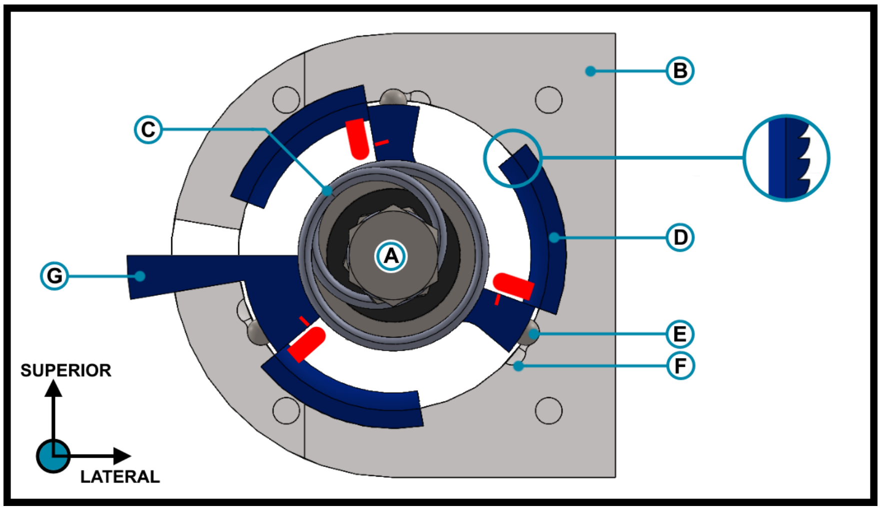


Figure 14: Ratcheting Spring-Driven Piston Assembly; Anterior facing view, depicts a cut-away of the internal mechanism

- **A:** Central axis of the piston and colinear with the attached cable (not shown).
- **B:** Housing; provides the piston bearing tracks and bears the static loading of the spring when extended and locked.
- **C:** Extension-force spring that pulls the piston, and by extension the cable, when released from the ratchet.
- **D:** Ratchet tooth insert; toothed panel that provides incremented hook, or purchase, points for the ratchet lever arms in order to hold the extended spring.
- **E:** Primary piston bearing track and bearing; allows the piston to roll smoothly forward and backward in the casing. In this position, the ratchet arms can catch on the tooth inserts.
- **F:** Secondary piston bearing track; allows the piston to roll smoothly, but is offset so that the ratchet lever arms cannot grab onto the tooth inserts.

- **G:** Piston rotation lever; allows the user to forcefully rotate the piston from the primary bearing track to the secondary, thereby releasing the ratchet.

In normal operation, the piston is in the state shown in Figure 14 on page 32. In this state the spring can be expanded, but the ratchet lever arms will catch and prevent it from contracting when the tension supplied by the wearer subsides. This provides two advantages: first, it means that when in the sitting position the device exerts no force on the wearer, thus removing the need for the wearer to manually keep the spring under tension. Second, during the normal walking process the spring will automatically extend to a point proportional to the stride of the wearer, thus preventing the device from exerting forces on the wearer during walking beyond the initial steps.

When the wearer wants to release the tension in the spring, in order to facilitate the transition to the standing position, the piston lever at **Point G** is raised upwards. This shifts the piston from the primary bearing track denoted at **Point E**, to the secondary bearing track denoted at **Point F**. This has the effect of offsetting the ratchet lever arms so that they no longer lock into the toothed inserts. Thus, the spring is able to contract and pull on the cable. The wearer depresses the lever, to move the piston back to the primary bearing track, in order to prepare the device for another loading cycle.

Prototype 1 Design Flaws

This design suffers from several critical flaws that caused it to be discarded during the design process. Chiefly among them, the positioning of the spring-driven piston assembly on the upper truss assembly reverses the polarity of the moment applied about **Point G**, which alters the operation significantly. While not completely ineffectual, this reversed moment causes the device to pull outward on the lower truss, rather than upwards on the upper truss. In practical terms, this means that the device is more likely to cause the wearer's leg to kick straight outwards than to assist the wearer in transitioning towards a standing state.

Similarly, the placement of the force redirection pulleys, located at the **F Points**, are not optimized in order to maximize the moment about **Point G**. The definition of a moment states: $M = F * d$; where F is a vector force, d is the perpendicular distance from the force vector to a point, and M is the magnitude of the resultant moment about that same point. It is a well established fact of mechanics that force vectors that pass through a point cannot cause a moment about that point; this is also apparent from the moment definition, as this condition would result in $d = 0$, and therefore $M = 0$. Because of this the only point in Prototype 1 that exerts a desirable moment is the lowermost **F Point** force redirection pulley; the cable's anterior force component is exerted here when the cable is pulled by the spring. The offset of this force's vector is equal to the distance from **Point G** to this **F Point**, which is a small proportion of the overall length of the device. Placing this force redirection pulley, and therefore the point that the force is applied, farther away from **Point G** would result in a greater force vector offset, and thus a larger moment.

Further, the construction of the Spring-Driven Piston Assembly is insufficiently sturdy for this design. This model calls for the ratchet arms, highlighted in red in Figure 14 on page 32, to have a surface area of contact with the ratchet teeth inserts equal to approximately two square millimeters. These ratchet arms are responsible for bearing the entire force of the extended spring when the device is in use, meaning that each ratchet arm is responsible for bearing $1/6$ of the total force stored by the device. The detailed spring and force calculations need not even be considered to determine that the pressure on these contact points would be large enough to cause the mechanism to fail catastrophically; if only fifty newtons of force were stored in the device, each ratchet arm would experience over two million pascals of pressure.

4.4 Prototype 2

The second prototype for this project's ultimate design was never physically constructed, but instead was modeled in SolidWorks© 2016 Educational Edition for conceptual evaluation and mechanical assessment. Similar to Prototype 1, this design was based on the Actively Spooled Cabling layout described in Section 4.2 on page 24. Prototype 2 aimed to correct on several of the flaws that were identified with Prototype 1:

- Prototype 1 placed the spring driven piston assembly on the upper truss, and therefore resulted in the generated moment acting to kick the lower-leg out to a horizontal position, rather than lifting the thigh up to a vertical position. Prototype 2 addresses this by placing the spring and piston assembly on the lower truss, below the knee joint.
- Prototype 2 was designed with an optimized distribution of both machined and 3D printed materials. The primary loadings on the device, created by the spring, are isolated to the machined metal components while the protective coverings are manufactured using a 3D printer and ABS filament.

- After a review of the metal components in Prototype 1, it was determined that the manufacturing process for several of them would be excessively complex or impossible with the tools available. Prototype 2 was designed with this in mind, and each metal component is explicitly designed to be optimized for ease of manufacturing.

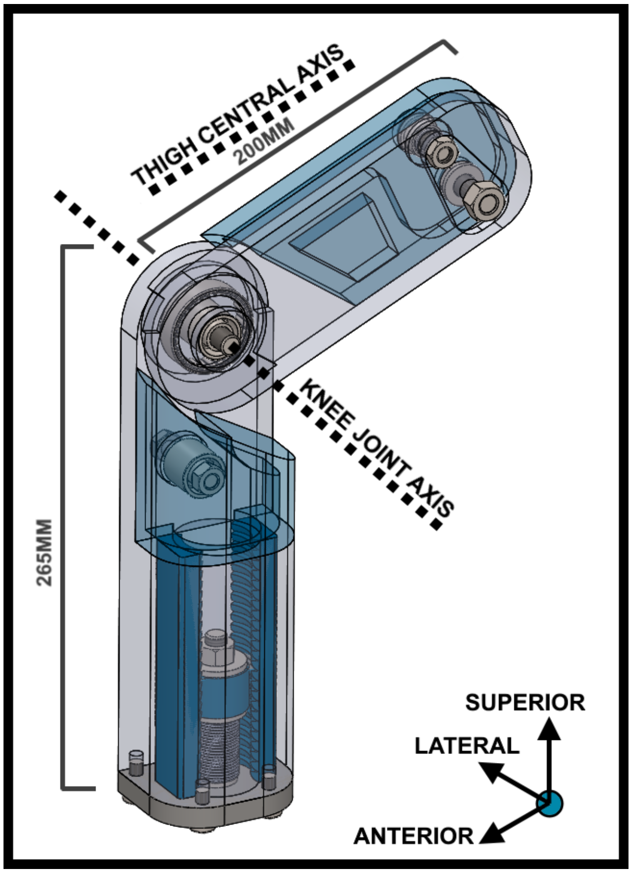


Figure 15: Prototype 2 Isometric Overview and Reference Axes

The isometric view shown in Figure 15 shows the model halfway between sitting and standing, with both the 3D printed cover pieces and machined backing plates set to partial transparency in order to allow viewing of the interior. Unlike the Prototype 1 model shown in Figure 12 on page 30, this only shows one side of the mechanism: the full assembly for one leg would have two of these devices, the second being a mirrored version and mounted on the far side of the line labeled Thigh Central Axis in the figure. Similar to Prototype 1, the upper and lower truss assemblies that attach directly to the wearer's legs are not depicted.

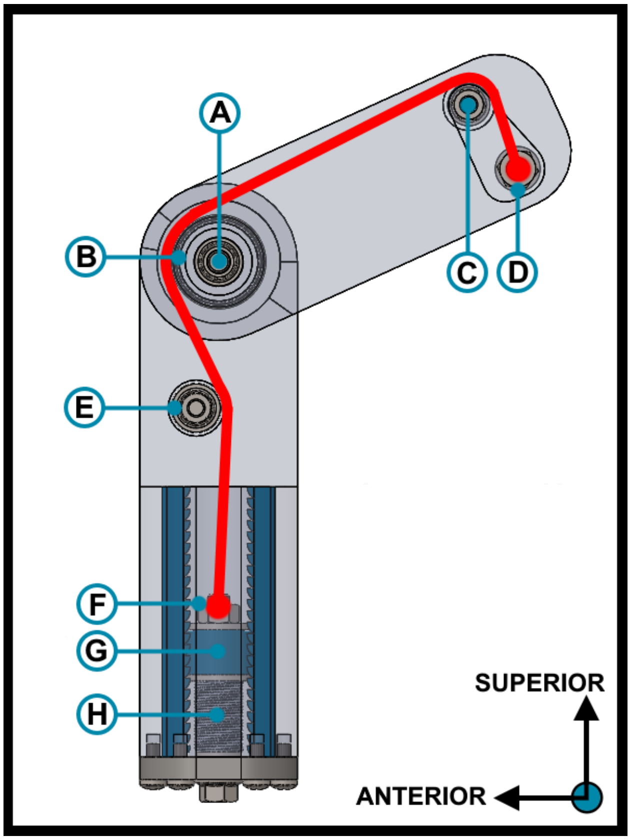


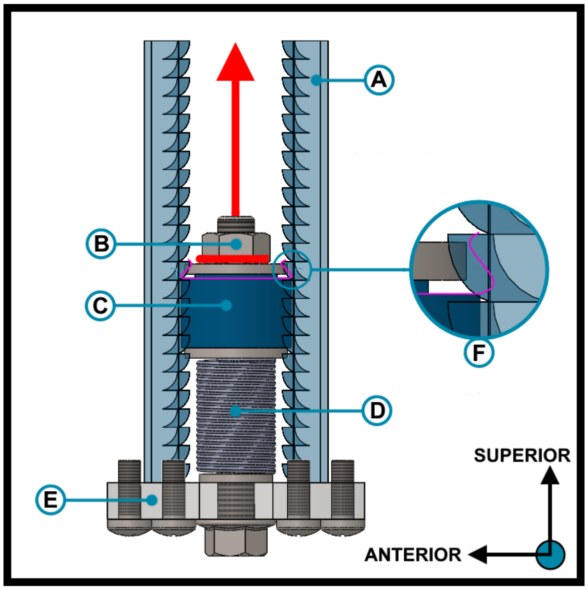
Figure 16: Prototype 2 Profile and Inteior Mechanism View

- **A**: Knee joint axis rotational ball bearing; the sole connection point between the upper and lower device sections.
- **B**: Outer rotational ball bearing and cable pulley; offsets the cable from the main joint axis and allows the cable to move around the joint independently of the joint rotation.
- **C**: Upper force redirection pulley; redirects the force of the cable 90°in order to induce the desired moment about the knee.
- **D**: Upper cable attachment point; attaches the cable to the upper assembly and bears the entirety of the force that the cable exerts on the device.
- **E**: Lower force redirection pulley; redirects the force from the offset main joint cable pulley so that the cable does not exert any lateral forces on the spring or piston.
- **F**: Lower cable attachment point; attaches the cable to the lower ratcheting piston.
- **G**: Ratcheting piston; attaches to the cable and the drive spring while also providing the mounting point for the ratchet tooth mechanism.
- **H**: Drive spring, shown here in the fully relaxed state.

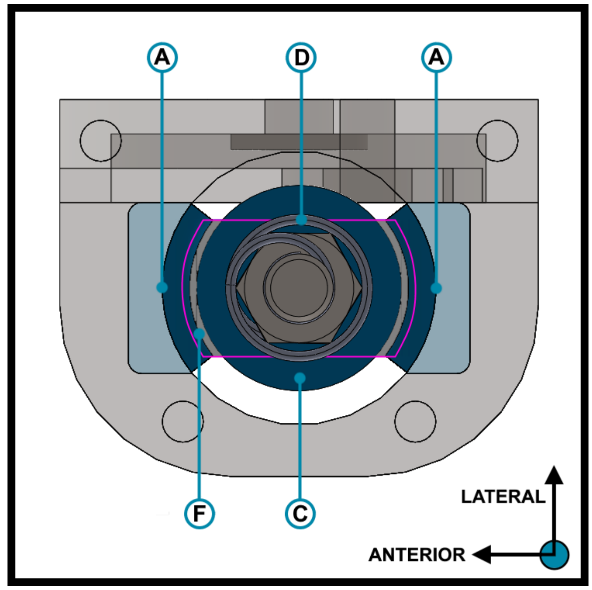
The design of Prototype 2 is vastly simplified when compared to Prototype 1. It is comprised of only three custom-machined parts, compared to the seven in the previous design, and these components require far less operations to create than any of the parts in the previous design. While this prototype was never actually assembled during the prototyping process, these optimizations and simplifications would have drastically reduced the needed construction time. Prototype 2 makes use of standardized parts wherever possible in order to further reduce construction time and cost: on Prototype 1 only the assembly bolts and corresponding nuts were standard sizes, while on Prototype 2 the pulleys, ball bearings, washers, and screws have all been standardized as well. This means that Prototype 2 includes only seven custom parts, of which only two cannot be 3D printed, representing a dramatic improvement over Prototype 1 which was comprised of fourteen custom parts, only four of which could be 3D printed.

A further improvement in this design is the placement of the drive spring on the lower assembly and the use of force redirection pulleys to maximize the applied moment about the knee. The force redirection pulley at **Point C** is the most notable improvement: by redirecting the cable's force so that it pulls on the upper assembly perpendicularly to the knee-joint axis, the moment is set equal to $M = F*d$ where d is the distance between **Point C** and **Point A**, or $0.138m$. Thus, in order to attain the desired moment of $0.2N * m/kg$ about the knee joint, **Point A**, the device requires a drive spring capable of delivering $1.45N/kg$.

The intended release mechanism is for the entire piston assembly to be rotated 90°either clockwise or counter clockwise; as shown in Section 4.4 on the next page, the ratchet tooth inserts at **Point A** only cover half of the total circumference of the piston cylinder. Thus, in normal operation the drive spring at **Point D** is extended and the piston is pulled upwards causing the thin aluminum to snap back and forth, locking into each subsequent ratchet tooth as it moves; rotating the piston 90° causes the aluminum insert to no longer be in contact with the ratchet teeth, and the piston, and subsequently the cable, is pulled by the spring until the spring is fully contracted. The thin curved aluminum sheet that serves as the ratchet lever is highlighted in pink in both Section 4.4 on the following page and Section 4.4 on the next page and is mounted to the piston body between **Point B** and **Point C**.



Prototype 2 Spring-Driven Ratcheting Piston Mechanism, Cutaway Profile View



Prototype 2 Spring-Driven Ratcheting Piston Mechanism, Top-Down View

Figure 17

Design Flaws

This design was ultimately rejected due to several critical flaws that rendered it unusable. The two primary reasons for this design's rejection were the lack of a simple release mechanism for the ratchet mechanism and the small size requirements for the drive spring. Other problems included a bulky size, making it impractical for mounting on a leg brace, and a very small offset of the main joint pulley from the main joint axis.

One of the most apparent problems with this design is the lack of a functional release mechanism for the ratchet mechanism. As shown in **Callout F** of Section 4.4 the ratchet mechanism is a simple shaped piece of aluminum that elastically deforms when the piston moves upwards and then snaps into place when the next ratchet tooth is reached. This presents two key problems: first, the constant bending of the thin aluminum will eventually lead to plastic deformation and failure of the ratchet mechanism; second, the usage of a semi-rigid aluminum sheet for the ratchet lever makes it impossible to externally release the ratchet mechanism. This second issue is caused by the structure of the spring-driven piston assembly: because the piston is mounted completely inside of the metal piston housing, adding a user accessible control to provide the needed 90° rotation to release the ratchet is not possible. This flaw was realized very late in the conception of this design and ultimately could not be resolved, leading to the design's rejection

4.5 Prototype 3

The third design prototype represents a fundamental shift in the structure of the project: as described in Section 3.5 on page 21 the project's scope was shifted to focus exclusively on the mechanism component of the device. Prototype 3 represents the first design candidate to be developed after this adjustment, and as a result it omits the truss attachment points for the cabling and a method for mounting the mechanism to the wearer's leg. In addition to the design changes that resulted from the scope adjustment, Prototype 3 also sought to improve on several flaws identified with both Prototypes 1 and 2:

- Both Prototype 1 and Prototype 2 used a spring-driven ratcheting piston assembly to attach the drive spring to the cabling system; Prototype 3 instead uses a ratcheting cam mechanism directly attached to the cables in order to avoid the complexity of releasing an engaged ratchet mechanism from inside an enclosed piston housing.
- Both Prototype 1 and Prototype 2 use a single continuous cable to attach the upper truss assembly to the lower, while Prototype 3 uses two separate cables to pull on the ratcheting cam; this allows the ratchet mechanism to be located at the knee joint rather than on the upper or lower truss assembly.
- By localizing the complexity of the mechanism to the knee joint, instead of spread across the entire truss, the design allows for advanced customization of the design of the truss in order to suit a wide variety of needs and uses.
- The force loading on this mechanism is distributed across many ratchet teeth, thereby greatly reducing the necessary strength requirements for the material. For this reason, this design can be entirely manufactured out of 3D printed materials.

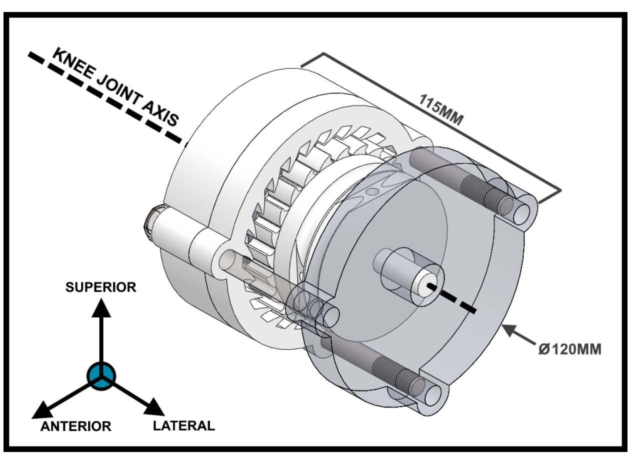
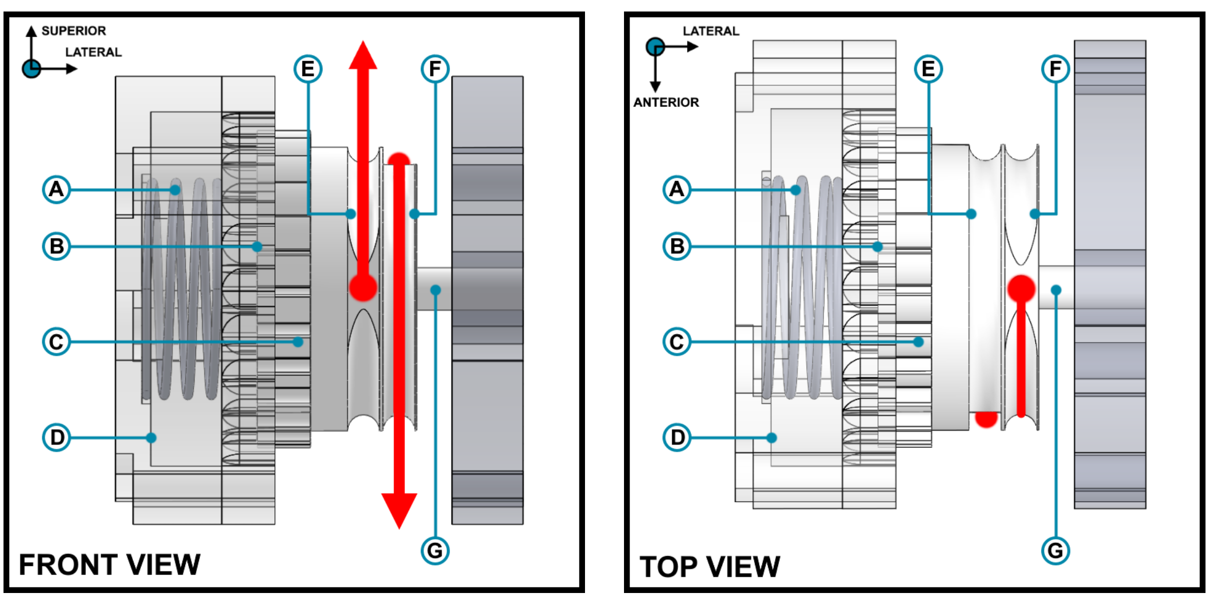


Figure 18: Prototype 3 Isometric View, Scale, and Reference Axes

Many of the problems that were encountered in Prototypes 1 and 2 were caused by the usage of the spring-driven piston assembly, originally introduced in Section 4.3 on page 29: both previous designs used a variant of this design, and as a result caused the surface area of the ratchet mechanism to directly detract from the accessibility of the mechanism from the outside. That is to say, for a piston casing of a constant size, the more surface area dedicated to the ratchet mechanism, the less area is available to provide a button, lever, or other interface for the user to release the ratchet. However, by using a rotational ratchet mechanism located at the joint the need for a linear piston is completely avoided. This also has a secondary advantage of making the design more compact.

Not pictured in the figures in this section are the drive spring and the force redirection pulley. The drive spring is connected to the lower truss and the lower truss attachment cable, which itself connects to the cam disk at **Point E** in Figure 20 on page 42. The upper truss attachment cable connects to the cam disk and is statically affixed to the upper truss at the other end, after being run across a force redirection pulley in order to attain the angled force required to generate the moment; this feature is taken directly from the upper truss assembly of Prototype 2.

Device Operation



Prototype 3 Cam Disk Ratchet and Release Mechanism, Front View

Prototype 3 Cam Disk Ratchet and Release Mechanism, Top View

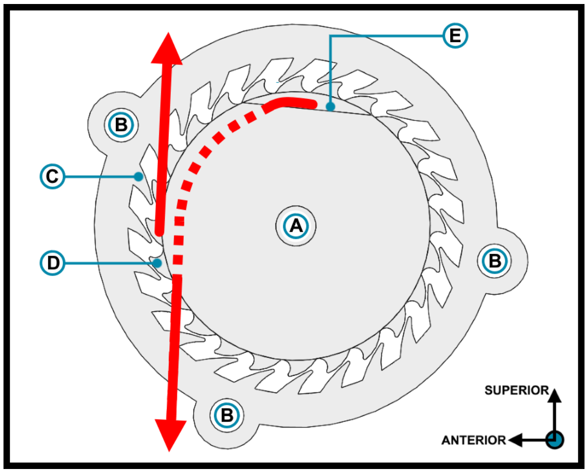
Figure 19

- **A**: Ratchet release compression spring; when the cam disk is pressed in to release the ratchet mechanism this spring provides a resistive force so that the cam disk is forced back into a position where the ratchet can engage.
- **B**: Outer ratchet teeth; mounted on the outer casing and designed to deform when pressed by the rotating inner ratchet teeth on the cam disk.
- **C**: Inner ratchet teeth; mounted on the cam disk.
- **D**: Hard stop for the sliding cam disk during ratchet release.
- **E**: Left cable run track; used for guiding the upper truss attachment cable as it wraps around the cam disk during sitting or standing.
- **F**: Right cable run track; used for guiding the lower truss attachment cable as it wraps around the cam disk during sitting or standing.
- **G**: Central shaft; mounted in a linear bearing (not shown) in order to allow the cam disk to slid freely in the lateral direction in order to release the ratchet mechanism.

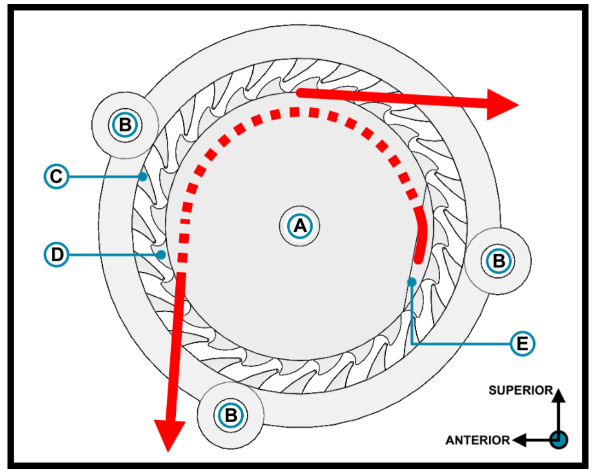
The front view of the model shown in Figure 19 on page 40 shows the attachment of both the upper truss attachment cable through the left cable run (**Point C**) and the lower truss attachment cable through the right cable run (**Point D**). The figures depict the mechanism in the standing position, but when in the sitting position the upper truss attachment cable pulls on the cam disk so that the it rotates 90°. This pulls the lower truss attachment cable 90°as well, thus placing the drive spring under tension.

Once the cam disk rotates, the ratchet mechanism engages. The outer ratchet teeth are shown at **Point B** of Figure 19 on page 40 and **Point C** of Figure 20 on the following page. The casing component with the outer ratchet teeth is intended to be printed out of PLA, the elastic properties of which will allow the outer teeth to deform as the harder inner teeth, printed out of ABS, press against them. The inner ratchet teeth, which are part of the cam disk, are located at **Point C** and **Point D** of Figure 19 on page 40 and Figure 20 on the following page respectively.

The release mechanism for the ratchet is shown in Figure 19 on page 40: the shaft at **Point G** is mounted in a linear bearing (not pictured) and allows the entire cam disk to move in the anti-lateral direction when the end of the shaft is pressed by the wearer. Resistance to the wearer pressing the shaft is provided by a compression spring, shown at **Point A**, and a hard stop at **Point D** prevents the shaft from being depressed so far as to slip out of the linear bearing. The inner ratchet teeth on the cam disk and the outer ratchet teeth on the casing part are offset such that moving the cam disk 15mm will allow the cam disk to spin freely without engaging the ratchet mechanism.



Prototype 3 Ratchet Mechanism with Cable Paths in Standing Position



Prototype 3 Ratchet Mechanism with Cable Paths in Sitting Position

Figure 20

- **A**: Central shaft; mounted in a linear bearing (not shown) in order to allow the cam disk to slid freely in the lateral direction in order to release the ratchet mechanism.
- **B**: Structural bolt holes; M10 standard size bolt holes that pass through all the outer casing parts so that they can be bolted together for final assembly.
- **C**: Outer ratchet teeth; mounted on the outer casing and designed to deform when pressed by the rotating inner ratchet teeth on the cam disk.
- **D**: Inner ratchet teeth; mounted on the cam disk.
- **E**: Mounting point for the lower truss attachment cable; flattened portion of the cable run guide with a screw hole so that the cable can be wrapped around and then held in place by the screw.

Design Flaws

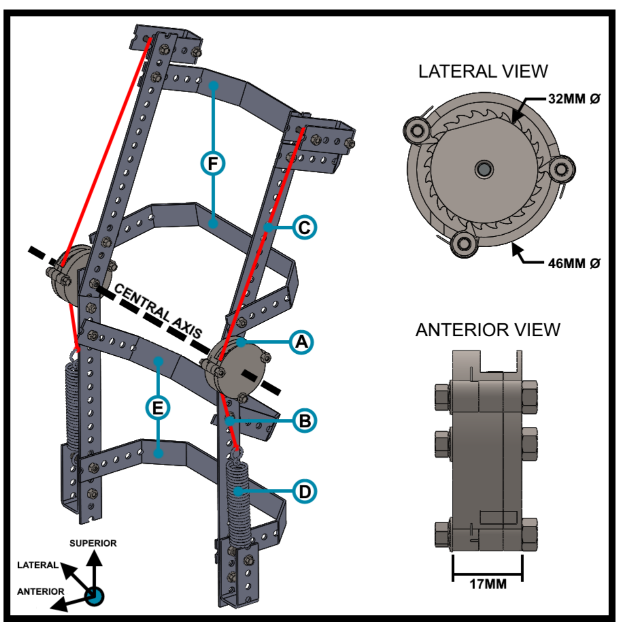
This model formed the basis for the final resultant design, however it is not without flaws. During the course of evaluating this design two primary problems were identified and corrected in the final design: the usage of semi-elastic PLA plastic for the outer ratchet teeth and then allowing them to be repeatedly and regularly deformed adds a significant risk of material failure; the thickness of the mechanism in the lateral direction, 115mm, makes it impractical for mounting on a wearer's knee in a convenient and unobstructive manner.

The first problem with this design was caused by designing the ratchet mechanism to use deformation for the locking component. This was done in an effort to avoid using torsion springs in a load bearing capacity and to maximize the amount of load bearing surface area on the ratchet teeth for maximum load distribution. However, an assessment of the mechanism by Professor J. Stabile of WPI Mechanical Engineering indicated that the deflection on the outer teeth during rotation to the next ratchet position would be significant enough to incur permanent damage and eventual failure. After a brief consideration of alternative materials in an unsuccessful attempt to identify a 3D printable material with lower modulus of elasticity and higher yield strength, it was agreed that an alternative outer ratchet tooth design would have to be created.

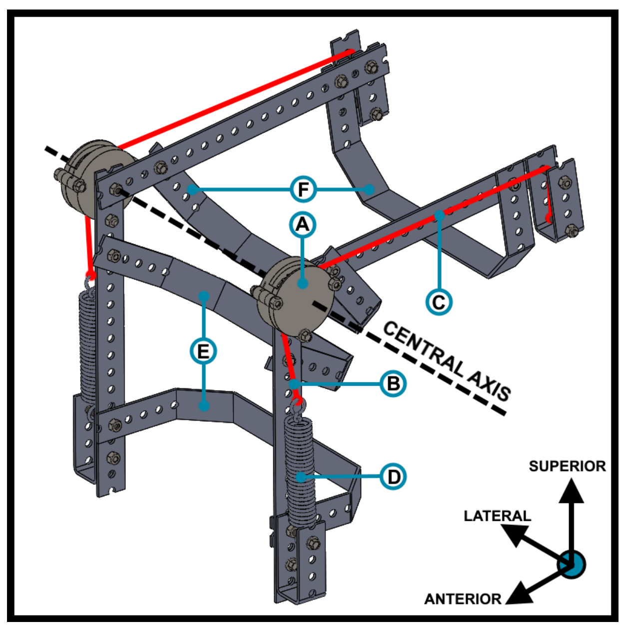
The second issue was a byproduct of the project scope reassessment detailed in Section 3.5 on page 21: with decreased attention paid to the needs of the end user, the size of the device was optimized for mechanical performance and not practicality. This problem was not identified until the printing of an initial prototype based on this model, at which point the large size became obvious immediately. For the mechanism to have any practical application, the thickness would need to be reduced considerably, to between 25mm and 40mm.

5 Final Design Documentation

The final proposed design of this MQP is a fully passive mechanism that delivers a moment about its central axis. The device is intended to be mounted on a two-part truss structure that is itself mounted to an individual's leg with a flexible joint at the knee to allow for natural knee movement. When mounted in this way the proposed device would capture the potential energy that is naturally expended during the stand-to-sit transition process so that it can be released as an assistive force during the Sit-To-Stand Transition (STST) process. The mechanism does not make use of any electronics, actuators, or batteries; instead, all the necessary potential energy is captured using a purely mechanical system comprised of a ratcheting cam and an extension spring. The mechanism is arranged so that the primary extension spring, also referred to as the drive spring', is easily replaceable with a spring with different properties in order to adjust the device for different individual requirements. The complete assembly, including the mechanism, trusses, drive springs, and leverage cables, is depicted in Figure 21a and Figure 21b; however it should be noted that the proposed device design only encompasses the cam and ratchet mechanism, shown in Figure 22 on page 46.



(a) Standing (Relaxed) Position



(b) Sitting (Tensioned) Position

Figure 21: Final Design, Full Assembly Including Truss, Spring, and Mechanism Assemblies; tether cables highlighted in red

- **A:** Spring-Driven Ratchet Mechanism assembly, shown in profile and portrait in the two detail views in Figure 21a on page 44; final design of the project.
- **B:** Lower Truss Tether cable; affixed to the rotating cam disk component of the mechanism and the drive spring.
- **C:** Upper truss tether cable; affixed to the rotating cam disk component of the mechanism and the upper truss assembly.
- **D:** Drive spring; provides the assistive force to the mechanism, and is kept outside of the mechanism for ease of maintenance and customization.
- **E:** Lower truss assembly; comprised of two primary steel bars, two cross-leg bars, and two folded sections for affixing the drive springs.
- **F:** Upper truss assembly; comprised of two primary steel bars, two cross-leg bars, and two folded sections to redirect and attach the upper truss tether cables.

5.1 Overview

The initial parameters for this design project called for a complete design of a final, marketable, product including the truss assembly. However, as discussed in Section 3.5 on page 21, the final design only includes the knee rotation cam and ratchet mechanism, as well as the specifications for the drive spring. The full truss assembly and final components are included in Figure 21a on page 44 for clarity, but the truss assembly itself has not been evaluated to ensure that it meets design requirements, beyond basic dimensioning. The mechanism shown in Figure 22 on the next page is the entirety of this project's final design and has been evaluated to ensure that it meets the design parameters. The full dimensions and material information for each individual component can be found in Appendix A on page A-1.

When the wearer is in the standing position, the device is in the position shown in Figure 21a on page 44. In this state the spring is in the fully relaxed position and the loading on the system is minimal. During the transition from standing to sitting, the upper truss cable pulls the central cam disk 90°, causing the lower truss cable to extend the drive spring. As this is done, the central cam disk rotates and displaces each of the three ratchet levers until the three torsion springs cause the levers to snap into the next tooth on the cam disk. The device is shown in the sitting position in Figure 21b on page 44. The result of this is that the drive spring is kept extended by the ratchet, but the spring does not exert a force on either the upper truss cable or the wearer's leg. The internals of the ratchet mechanism are shown in detail in Figure 22 on the next page.

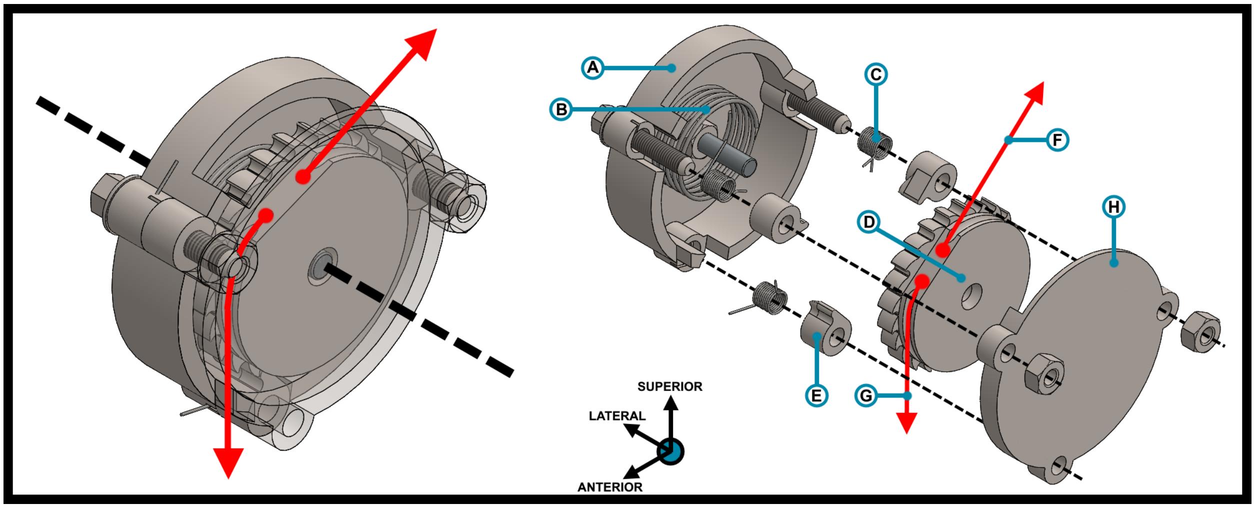


Figure 22: Final Design of Spring-Drive Ratchet Mechanism, with Labeled Components Visible in Exploded View of Internal Workings; tether cables highlighted in red

- **A:** Mechanism base; mounts the mechanism to the truss assembly and provides structural support for the other mechanism components.
- **B:** Compression spring; compressed when the cam disk (**D**) is pressed in the lateral direction when releasing the mechanism from the locked position. This spring then forces the cam disk back into the interfering position.
- **C: (x3)** Torsion spring; mounted inside of the ratchet levers (**E**), these springs force the ratchet levers to the fully extended position. When the cam disk (**D**) pushes the ratchet levers out of the way, these springs force them back into interference position.
- **D:** Cam ratchet disk; the upper and lower truss tether cables are mounted to this component, which can rotate freely about the central axis and slide laterally along the central axis. Rotation is inhibitted by interference from the ratchet levers (**E**), and lateral movement is inhibitted by the compression spring (**B**).
- **E: (x3)** Ratchet lever; mounted along the assembly-bolt axes to interfere with the cam disk (**D**). The force applied by the cam disk is transferred into these components which in turn brace against the mechanism base (**A**).
- **F:** Upper truss tether cable; affixed to the cam disk (**D**): when the cam disk is rotated this tether is pulled, when the upper truss is lowered this tether rotates the cam disk.
- **G:** Lower truss tether cable; affixed to the cam disk (**D**) and drive spring: when the cam disk is rotated this tether is pulled and the drive spring extended, when the cam disk rotates freely the drive spring pulls this tether and rotates the cam disk.
- **H:** Mechanism cap; covers the mechanism and acts as the forward brace for the cam disk's (**D**) lateral motion.

The central cam disk has a linear ball-bearing firmly inserted along its central axis. This bearing is in turn mounted on a stainless steel shaft that is mounted along the lateral axis of the mechanism, thus allowing the entire central cam disk to slide along its length. A compression spring, mounted to the rear cap, forces the central cam disk as far along the positive lateral axis as the front cap allows for. To allow the central cam disk to rotate freely and release the force of the drive spring, the wearer of the mechanism pushes the central cam disk along the negative lateral axis until the disk's teeth no longer interfere with the ratchet levers. Once the wearer releases the central cam disk, the compression spring forces the disk back along the positive lateral axis so that the ratchet levers again can hold the disk in place.

5.2 Operation

The mechanism used by the device is a ratcheting cam mounted on a central shaft. This central cam disk can rotate freely about the central axis of the device, while the ratchet teeth are mounted to the outer casing and are statically affixed to the lower truss assembly. The primary drive spring is affixed to the lower truss assembly at one end and an inelastic cable at the other, which is itself connected to the cam disk. Similarly, the upper truss is also attached to the cam disk via an inelastic cable; however, this connection is not bridged by a spring as on the lower truss. Both of the truss tether cables are connected to the cam disk on the outer perimeter of the circular disk. The lower truss and upper truss are joined together by a bearing, with the axis of rotation being collinear with both the central axis of the ratchet mechanism and the knee joint of the individual wearing the device.

Starting from the vertically aligned position, as when the individual is standing, the spring is in the relaxed, shortest, state and there is a slight slack on both of the truss tether cables. When the upper truss begins rotating about the central axis the upper truss tether cable pulls on the cam disk, causing it to rotate. This, in turn, pulls on the lower truss tether cable, which extends the drive spring. As the upper truss stops its rotation and the force that caused the rotation is removed, the drive spring pulls on the cam disk in an attempt to return to its relaxed state. However, the ratchet teeth interfere with the disks rotation and hold the drive spring extended and therefore under tension. When held in this manner, the upper truss is free to rotate with no stress placed on either it or the upper truss tether cable.

When the mechanism is arranged in such a way, with the drive spring extended, the cam disk's rotation locked, and the upper truss at roughly a right angle to the lower truss, the individual wearing the device can release the force contained in the drive spring at will. This is achieved by moving the cam disk horizontally along the central axis. By moving the cam disk in this way, the teeth on the cam disk no longer interfere with the ratchet teeth on the mechanism casing, which allows the cam disk to spin freely. The drive spring is then allowed to relax, which rotates the cam disk and pulls the upper truss tether cable. The upper truss tether cable is attached to the upper truss at the highest point of the truss, and perpendicularly to the main truss beams. This means, in effect, that the force applied by the tether to the truss is not directed towards the knee joint, but rather perpendicular to it. This allows the drive spring to generate a moment about the knee, which serves as the assistive force for the individual wearing it. Once the drive spring is fully relaxed again the individual wearing the device can release the cam disk, at which point the compression spring underneath the cam disk will push it back into a position where its teeth will interfere with the ratchet teeth on the mechanism casing.

5.3 Construction

The spring-driven ratchet mechanism is comprised of six custom parts, three bolts, three nuts, four springs, and a stainless steel shaft; a full bill of materials can be found in Appendix B on page A-10. The six custom parts are machined or cast from stainless or alloy steel for the final assembly. However, in the interests of time and resource availability, the final assembly was never produced in the course of this project. Instead, a prototype was constructed with the following adjustments: the custom parts were 3D printed from ABS filament using a Dimension SST 1200es rapid prototyping machine; the mechanism was scaled up by 60% to account for the printing resolution of the machine; the drive spring specifications were calculated to provide only half the required force. The specifications for both the prototype and final design components can be found in Appendix A on page A-1.

In addition to the components that comprise the mechanism itself, the upper and lower truss assemblies are comprised of several different items. The main truss structures are comprised of simple steel bars with pre-punched holes at regular intervals. This allows the bar components to be mounted to each other and to the mechanisms themselves.

5.3.1 Spring Calculations

The drive spring is the source of power for this mechanism. During the sitting process it is extended, thereby storing spring energy, and it is the release of this energy that provides the assistive force to the individual wearing the device. For these reasons, ensuring that the properties of the drive spring are properly calculated is essential to ensure proper functionality of the device. A spring that delivers too much force could injure the individual, and a spring that does not deliver enough force would fail to generate the required moment and thus make the device ineffectual.

The drive spring property equation for this mechanism is derived from several universal spring equation, and several constants that result from the design of the device itself. The design constants, as well as the unknowns, are tabulated in Table 4.

Table 4: Spring Calculation Constants, Known Values and Symbol Definitions

Description	**Symbol**	**Value**
Moment about the knee	M	$0.2Nm/kg$
Average mass of an adult	W	$70kg$[11]
Max. elongation of the spring	L_1	$0.025m$
Max. extended length of the spring	L_2	$0.2m$
Max. relaxed length of the spring	L_3	$L_2 - L_1$
Number of active spring coils	n	L_1/D_w
Diameter of the spring wire	D_w	To be calculated
Outer diameter of the spring coil	D_o	To be calculated
Modulus of rigidity for the spring material[5]	G	$7.7 * 10^{10}$

The equation used for the drive spring calculations is derived from Hooke's Law, the definition of the spring constant, and the definition of a moment. The derived equation is below, and repeated with the known constants applied:

$$W * \frac{M}{L_2} = L_1 * \frac{G(D_w)^4}{8n(D_o - D_w)^3}$$

$$70 * \frac{0.2}{0.2} = 0.025 * \frac{7.7{*}10^{10}(D_w)^4}{8{*}(\frac{0.2-0.025}{D_w})(D_o - D_w)^3}$$

After solving out the above equation using an approximate constraint for the outer wire diameter based on the physical size of the truss assembly a solution was determined, as shown in Table 5. It should be noted that this is only one of several different solutions that would yield properties for an adequate spring. Further, this solution has been calculated using the average mass of an adult[11], and as such the equation can be adjusted to accommodate individuals with different masses, both higher and lower than the average.

Table 5: Spring Property Calculation Results

Constant	**Symbol**	**Value**
Number of active spring coils	n	58
Diameter of the spring wire	D_w	$0.0018m$
Outer diameter of the spring coil	D_o	$0.0198m$
Total relaxed spring length	L_s	$0.104m$

From this equation, it is possible to determine the necessary specifications for a drive spring that supplies the necessary force to the mechanism in order to provide an assistive moment to the individual. This is important because it allows the calculation of the spring properties from the required output, rather than the other way around.

The result of these calculations are the details of a drive spring with a relaxed length of $104cm$ and a diameter of $19.8cm$, that is capable of delivering $70N$ of force when extended by $25cm$. This force is sufficient to generate a moment of $14Nm$ about an axis that is offset from the force vector by $200cm$, as the upper truss tether cable is in the device assembly. These calculated properties are sufficient to specify a spring for manufacture or order from a retailer.

5.3.2 Prototype Assembly

The prototype model was constructed mostly to the specifications detailed above. The custom components were printed by the Dimension printer to well within acceptable margins of error, and the springs were ordered from an online hardware retailer called The Spring Store. The remaining components, including truss bars, bolts, nuts, cabling, and central shaft, were acquired from the online retailer McMaster Carr and the hardware store Home Depot. The total cost of the components, including the 3D printing charges for filament and machine time, came to approximately $250.00 USD.

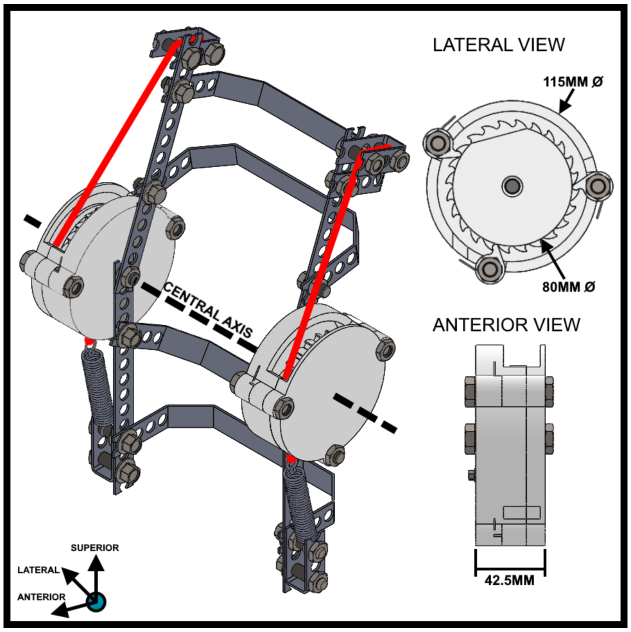
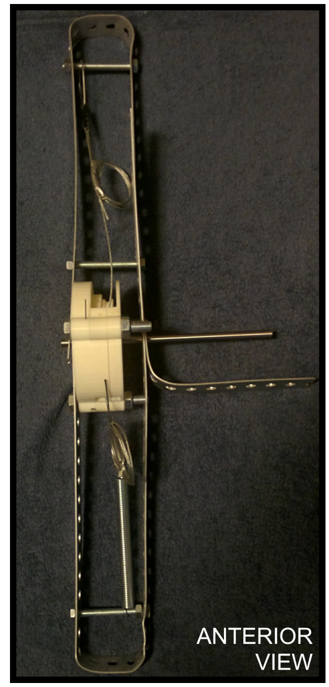


Figure 23: Prototype Design Using

Enough parts were ordered from the various retailers to assemble two of the prototype mechanisms, however due to time restrictions on the Dimension 3D printer only one final mechanism could be built. To accommodate this, the original plan of constructing the full two-mechanism mirrored truss as shown in Figure 23 was abandoned. Instead, the truss would be constructed around a single mechanism assembly, with the mechanism itself mounted between the two truss bars; this updated design is shown in Figure 24 on the next page. Because the purpose of this prototype is to test the mechanical operation of the spring-driven ratchet mechanism, the modification of the truss assembly does not diminish the usefulness of constructing the prototype.

(a) Lateral View



(b) Anterior View

Figure 24: Photograph of Assembled Prototype Design Using 160% Scaled Mechanism Components and Half-Strength Spring

The final prototype assembly functioned mostly as expected, though with some notable flaws. Chiefly among these flaws was the high coefficient of friction between the various ABS filament components. This was caused in part by the rough finish of the components that results from the 3D printing process, but was also contributed to by the lack of proper clearances between the various interfering components. This excessive friction presented resistance to the operation of the ratchet mechanism that could make normal operation difficult. Further, the unexpectedly high friction between the parts made the transition from the ratchet-locked state to free spinning cam disk, and back again, difficult: the mechanism continually became stuck when sliding back into the interference position.

Based on the experience of assembling and testing the prototype, it is expected that manufacturing the mechanism out of machined steel should solve these problems. Further, by scaling the cam disk to 38.5% of its prototype size, rather than the 40% scale applied to all other custom components, the clearances between the cam disk and the ratchet teeth are sufficiently increased to prevent the jamming problems observed in the prototype.

5.4 Simulation Results

The SolidWorks 2016 Education©edition makes a portion of the SolidWorks Simulation©package available for usage. Unfortunately, the cyclical loading and fatigue study tools are not included in the Educational Edition Simulation package, and a license for SolidWorks 2016 Premium©could not be secured for this project; the one simulation tool that is available in the Educational Edition is the Static Loading analysis study.

One operational cycle of the device is defined as the full transition from the spring-relaxed standing state, through the transition into the sitting state with the system under stress, and finally through the final transition back to a relaxed sitting state. Each stage presents different potential points of failure for the mechanism, but the state with the highest static loading, and thus the highest potential for spontaneous failure, is the sitting state when the spring is extended and held in place by the ratchet mechanism. This state requires the system to bear the highest loading for an indeterminate amount of time ranging from under thirty seconds to several hours. Due to the high stress on the system in this state, it is an ideal position in the device's cycle to simulate and investigate potential points of failure.

The key loading under investigation in this simulation will be the load applied to the three ratchet levers by the cam disk when under torque from the drive spring. The ratchet levers are braced against the casing base component, and so can be treated as static relative to the dynamic cam disk. Because of this allotment, a number of simplifications can be made to the model in order to isolate the components and forces that are of greatest interest.

For instance, only the spring-driven ratchet mechanism assembly will be included in the simulation profile, and even many parts of this assembly can be suppressed in order to simplify the simulation calculations further. Because the area of interest is the interference between the ratchet teeth and the cam disk, the casing base and casing cap can be removed. Subsequently, the ratchet springs and nuts on the primary assembly bolts can be suppressed as they do not bear any of the load that is being investigated. This has the added benefit of greatly reducing the complexity of simulation meshing calculations and removing the need for simulating springs.

Once the model has been simplified, the forces and fixture points for the simulation can be defined. There are four fixed points in this model; fixed here meaning static relative to the lower truss assembly. These four fixture points are the three axes of rotation for the ratchet levers, and the central axis of rotation for the assembly. To improve the accuracy of the simulated strain, the fixture type is set to Bearing to allow for rotational movement about these fixed axes. It is important to note, however, that the bearing fixtures are applied to the primary bolts and the central axis shaft, not the ratchet teeth or cam disk. This allows them to rotate about their respective axes during the simulation's calculation, as they would in a physical model. The only force on the system will be a torque applied directly to the cam disk about the central axis of the mechanism. The magnitude of this torque can be taken directly from the spring calculations in Section 5.3.1 on page 49:

$$\tau = L_3\left(\frac{M}{L_3}\right) = 0.2m * \frac{70kg}{\left(\frac{0.2Nm}{0.2m}\right)} = 14Nm$$

Displacement and strain graphs of the mechanism after running the resultant simulation are shown below in Figure 25 and Figure 26 on the following page, respectively.

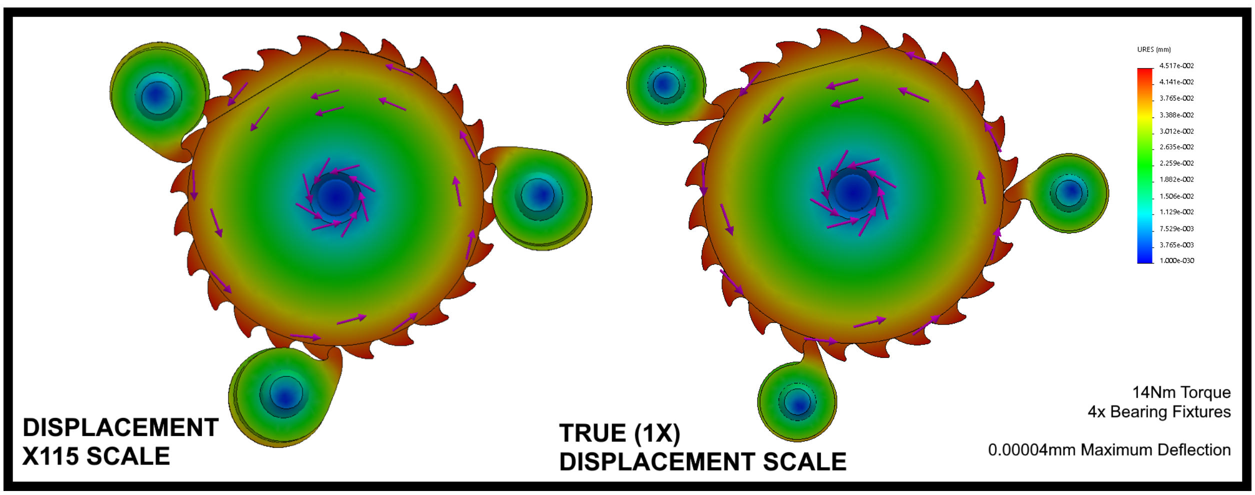


Figure 25: Displacement Result Graph from Simulation of Final Design Under Static Loading

The maximum calculated displacement in the simulation occurred at the predicted place in the mechanism: the interference between the ratchet levers and the cam disk. However, the maximum calculated displacement is less than $0.05mm$, or 0.34% strain. This indicates that the mechanism is capable of bearing this loading with relative ease, as these results indicate that the deformation as a result of the load is so small as to be negligible.

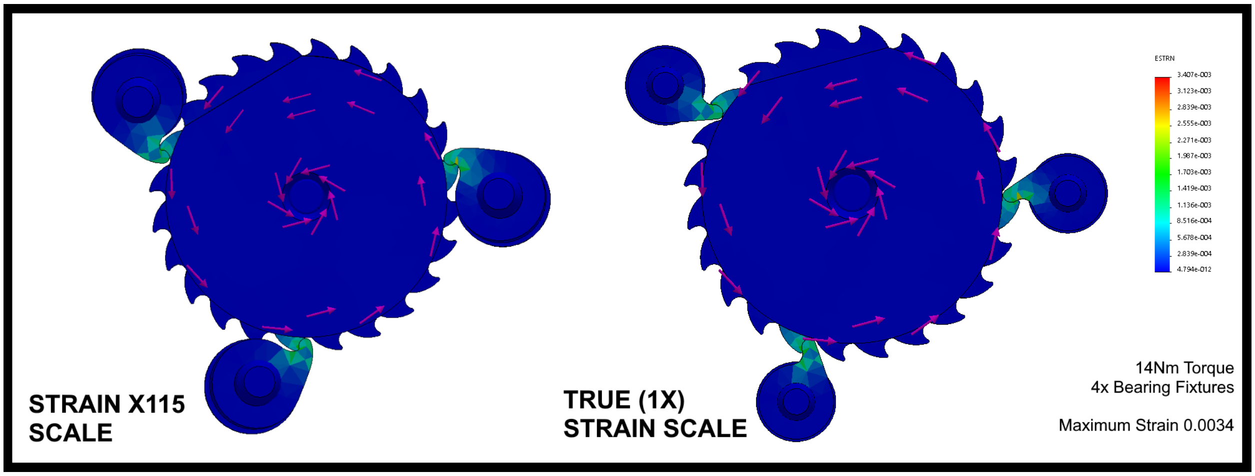


Figure 26: Strain Result Graph from Simulation of Final Design Under Static Loading

This completes the design testing, as it verifies the one attribute that the prototype construction was not designed to test: the ability to withstand the prescribed load. Due to the reduced spring force in the prototype to account for the reduced strength of the construction material, the prototype served only to verify the mechanical operation of the mechanism. The reduced load and different material invalidated any loading tests that could have been done. The simulation results, however, have been conducted on the final design model and therefore can be taken as accurate for the final stainless-steel mechanism, rather than the prototype.

6 Conclusion

This project originally set out to design a complete, end-user ready product that would provide assistance to geriatric individuals that experience difficulty completing the Sit-to-Stand Transition (STST). However, after approximately a third of the project had been completed, a joint decision was made by the team and advisor to limit the project's scope to focus solely on the mechanism itself, rather than on creating a final product. As a result, the end product of the project is a less complete product design than what was originally intended, but the core mechanism has been analyzed and tested with a much higher degree of confidence than would have been possible otherwise.

The mechanism that has been designed in the course of this project addresses the primary goal of providing an assistive force for the STST. The original project specifications called for a device that provides a moment of at least 0.2 Newton-meters about the subject's knee per kilogram of the subject's mass. This requirement is met by the final design, and in fact also offers the capability to make fine adjustments: because of the drive spring is isolated from the ratchet mechanism, and is easily detachable from the truss assembly, springs with different properties can be easily swapped into the device in order to adjust the resultant moment. This makes the device easily adjustable and customizable, which gives it another advantage over competing solutions.

However, a consequence of the refocusing of the project's priorities is that there remains substantial work required to turn this design into a market-ready product. The original project goals laid out in the **Capstone Design Intent** section operated under the premise of creating a complete product, and as such have not been fully addressed in this project. Specifically, the Safety and Lifestyle Integration and Economic Viability goals have yet to be addressed in the current design. These two goals could be adopted as the primary goals in a new project, potentially at the MQP level, in order to complete the development of this idea and make it market-ready.

Further, there exists the potential for a manufacturing project in relation to this design, with the goal of optimizing the manufacturing process and material usage of the mechanism and truss assembly. During the design process, attention was paid to the practicality of manufacturing the necessary components of the mechanism through common sense simplification and minimizing the usage of custom parts; the actual feasibility and requirements for manufacturing the custom components, however, has not been verified through practical testing. The development of a manufacturing method, both for the initial construction of a single device and for eventual mass-production, will be needed in order to move this design into the next phase of development.

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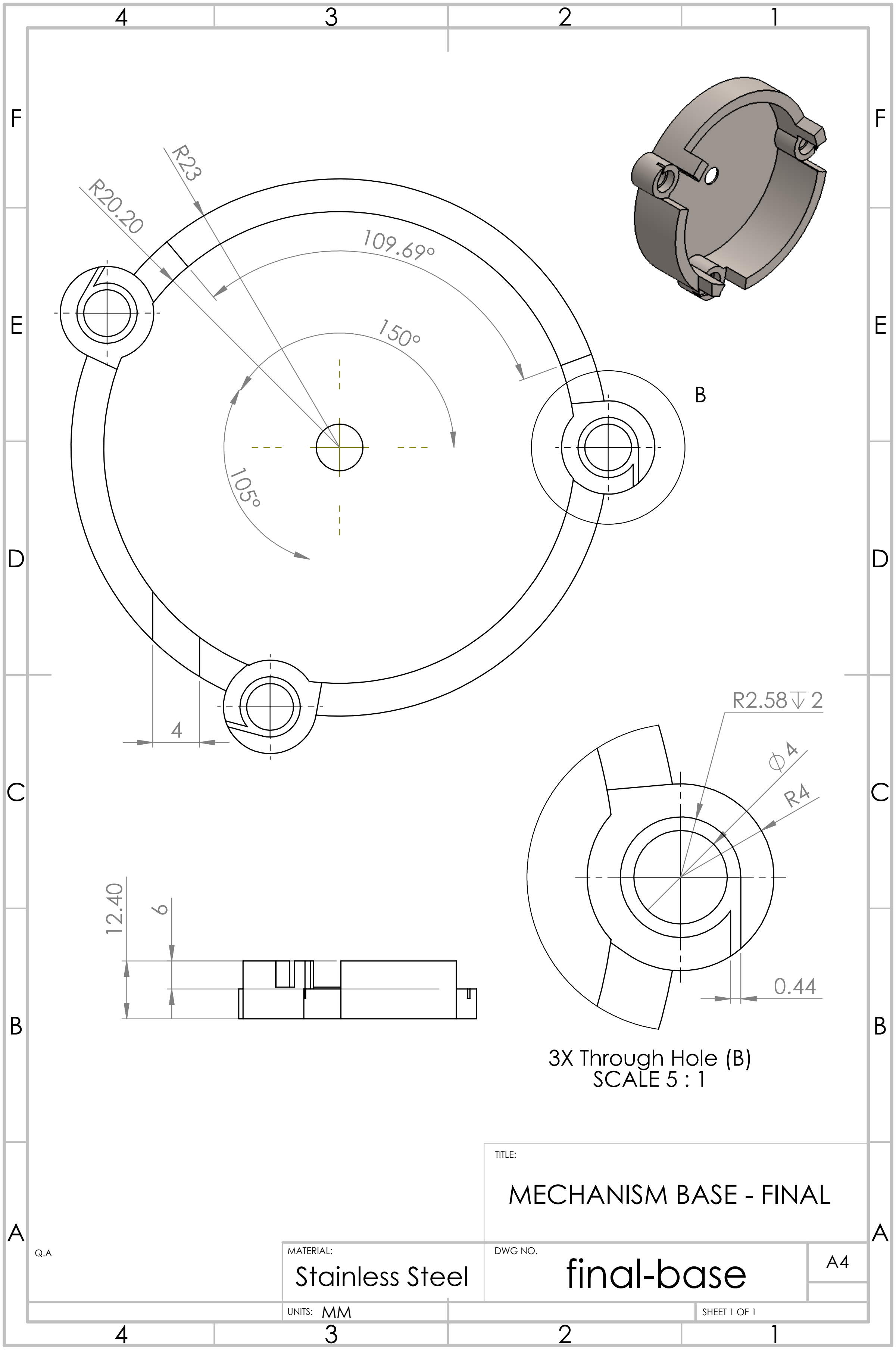
A Final Design, Mechanism Component Documentation

Appendix Contents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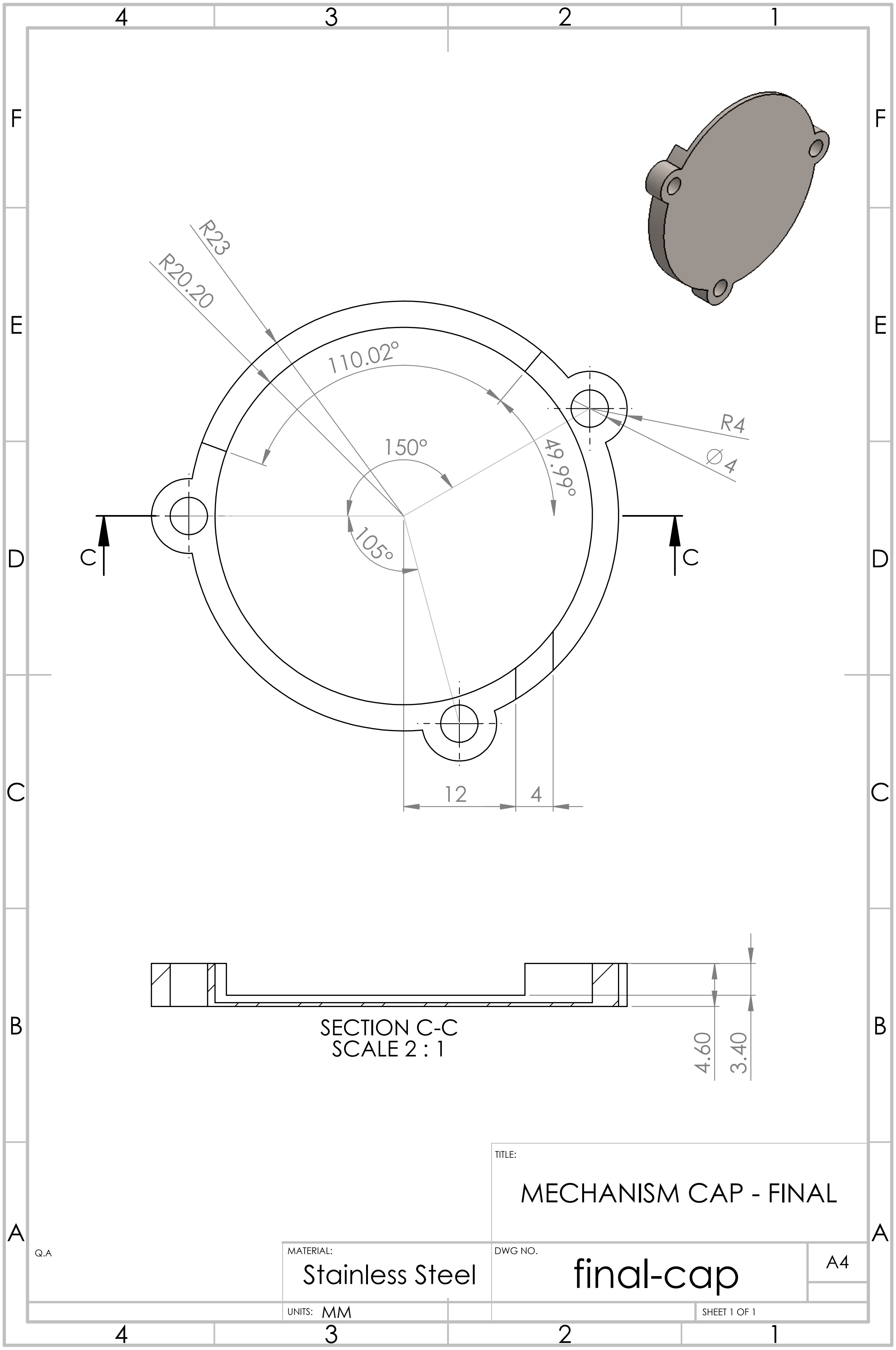
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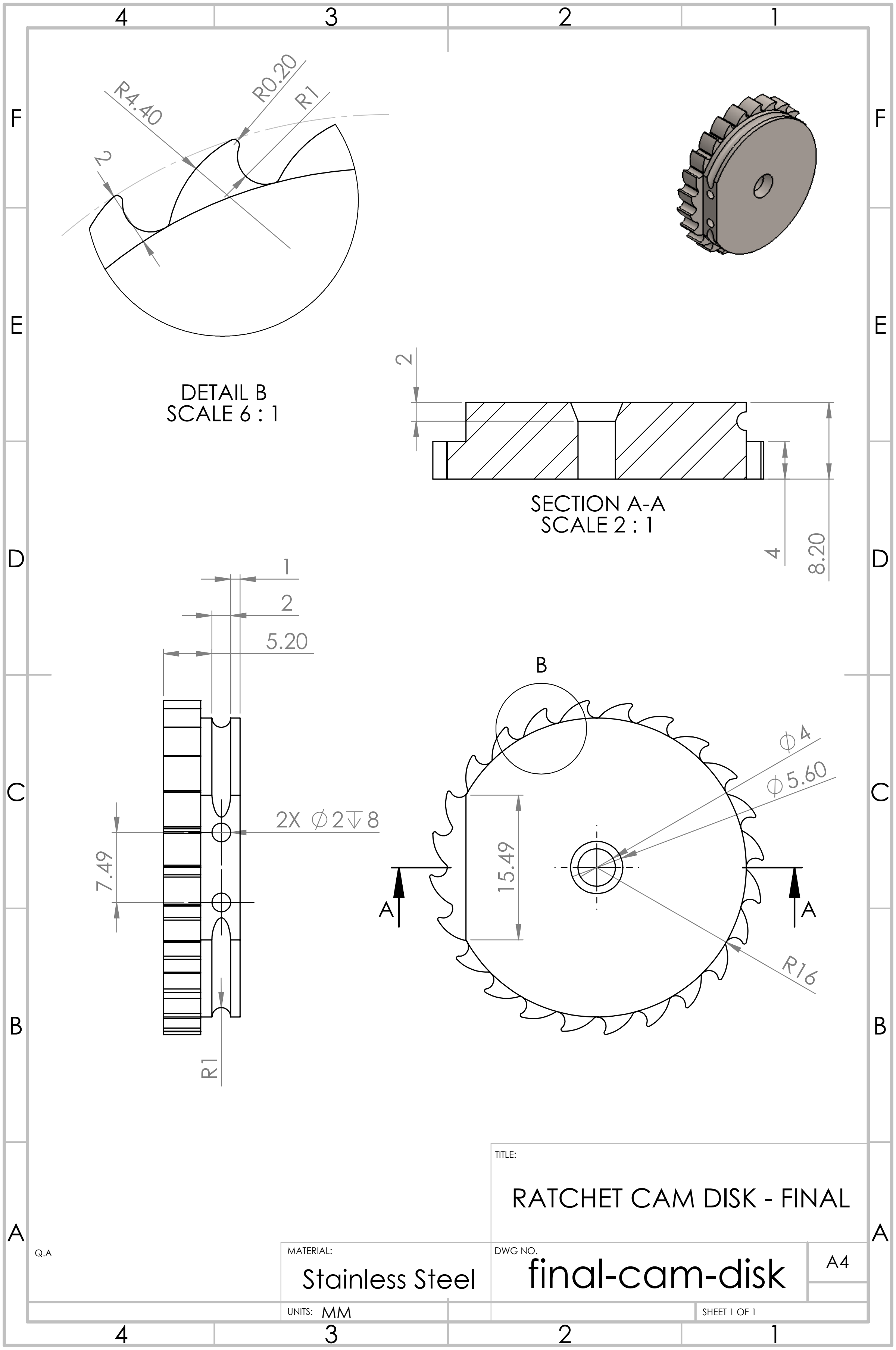
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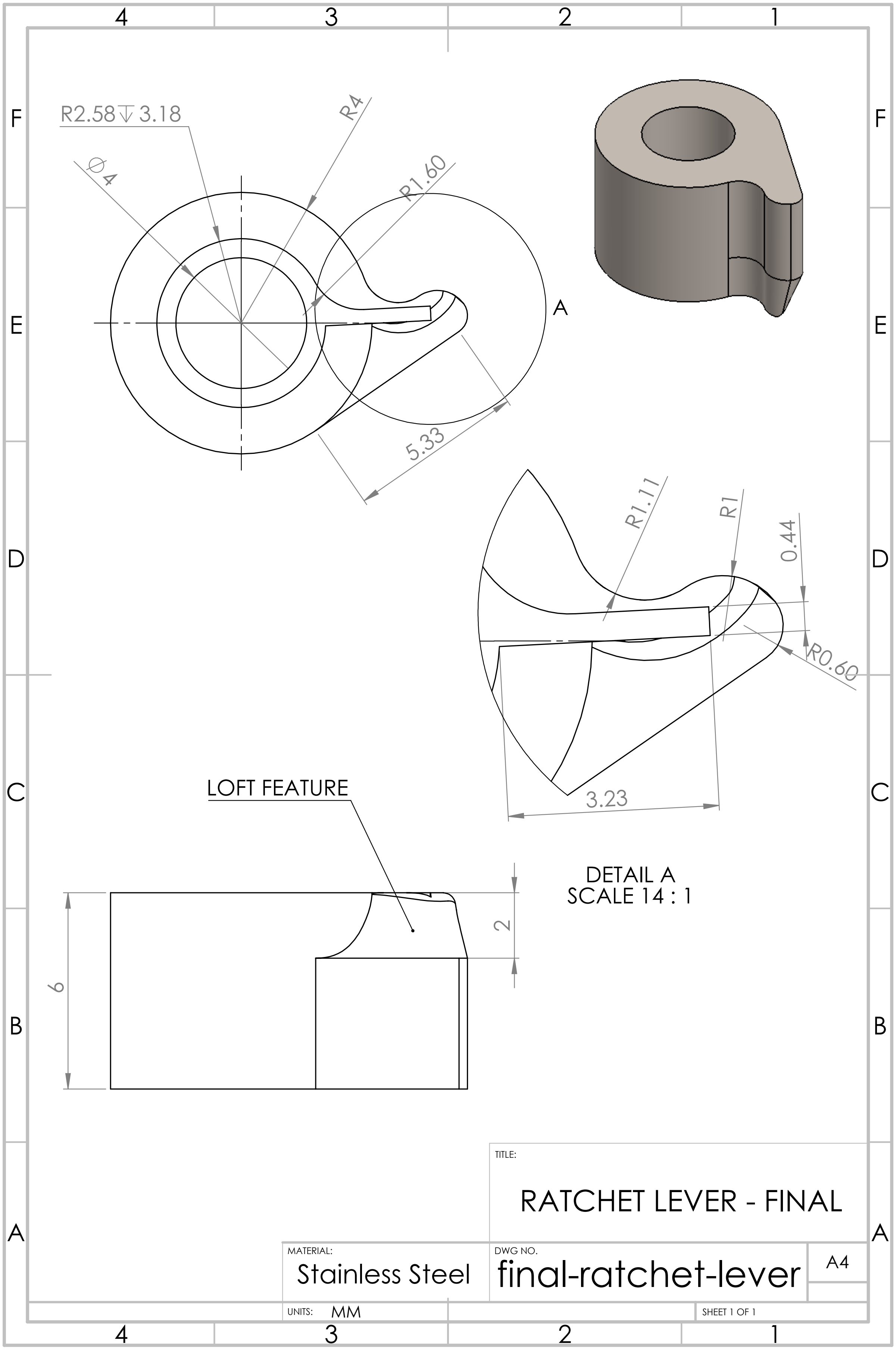
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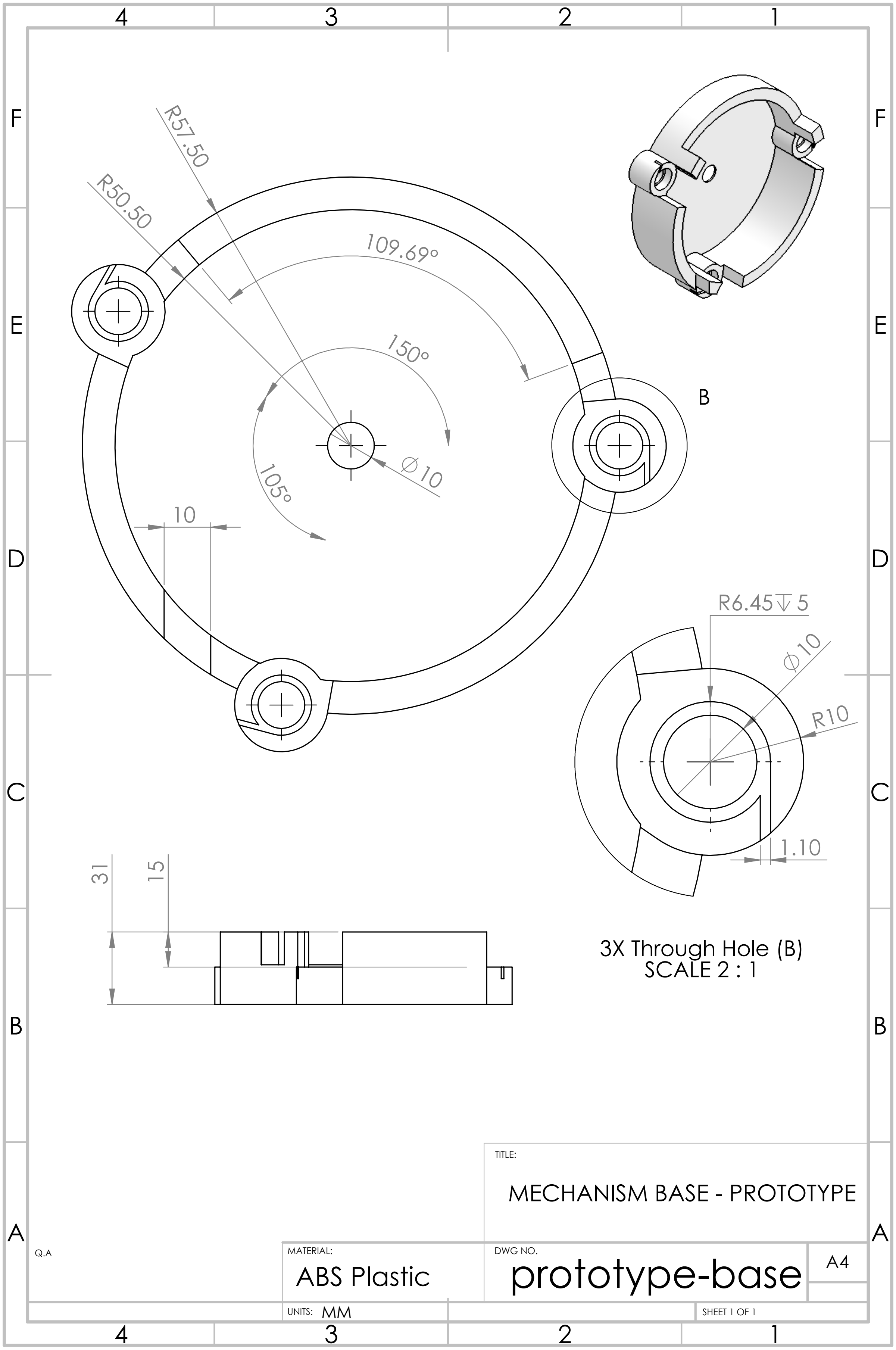

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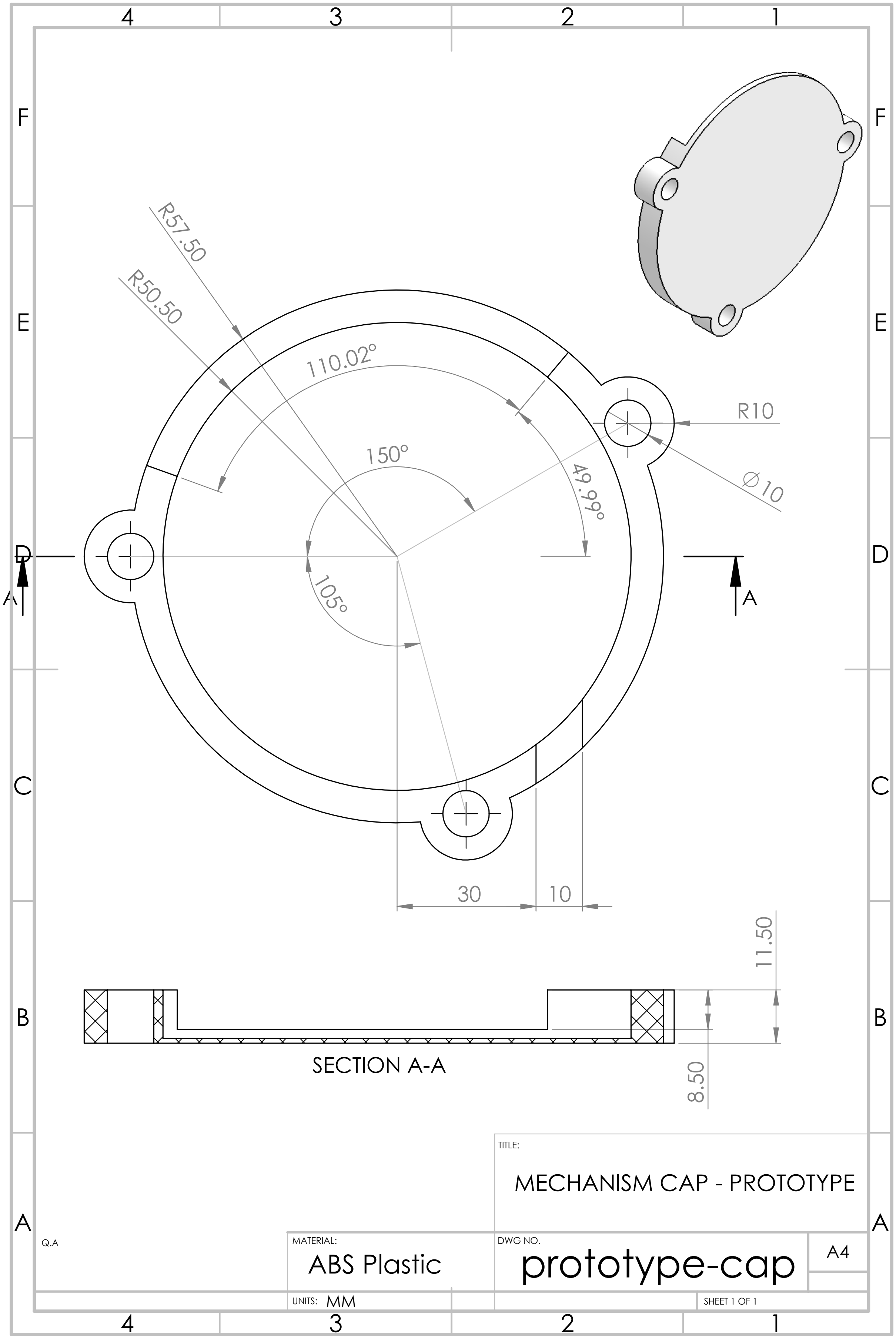
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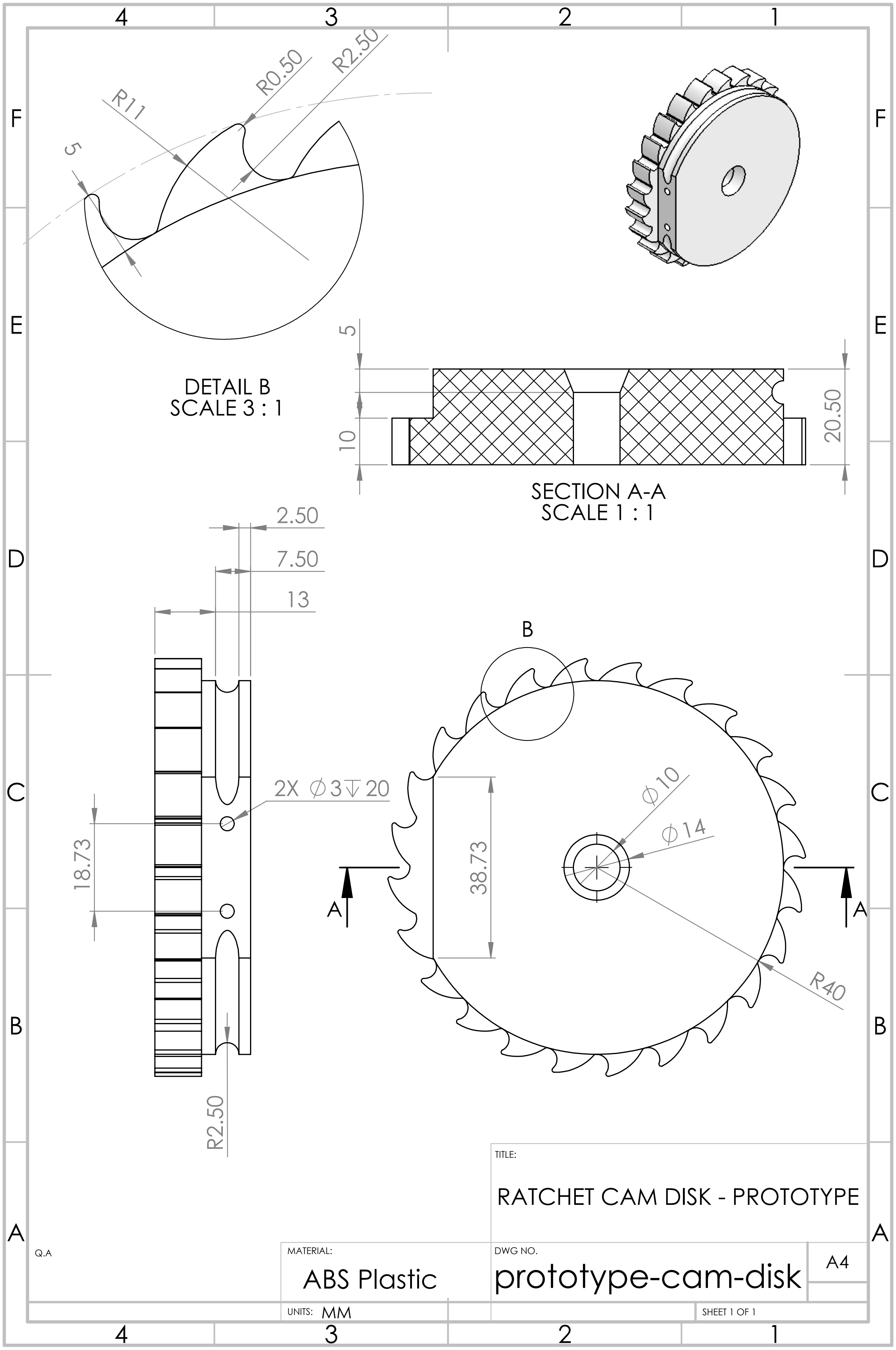
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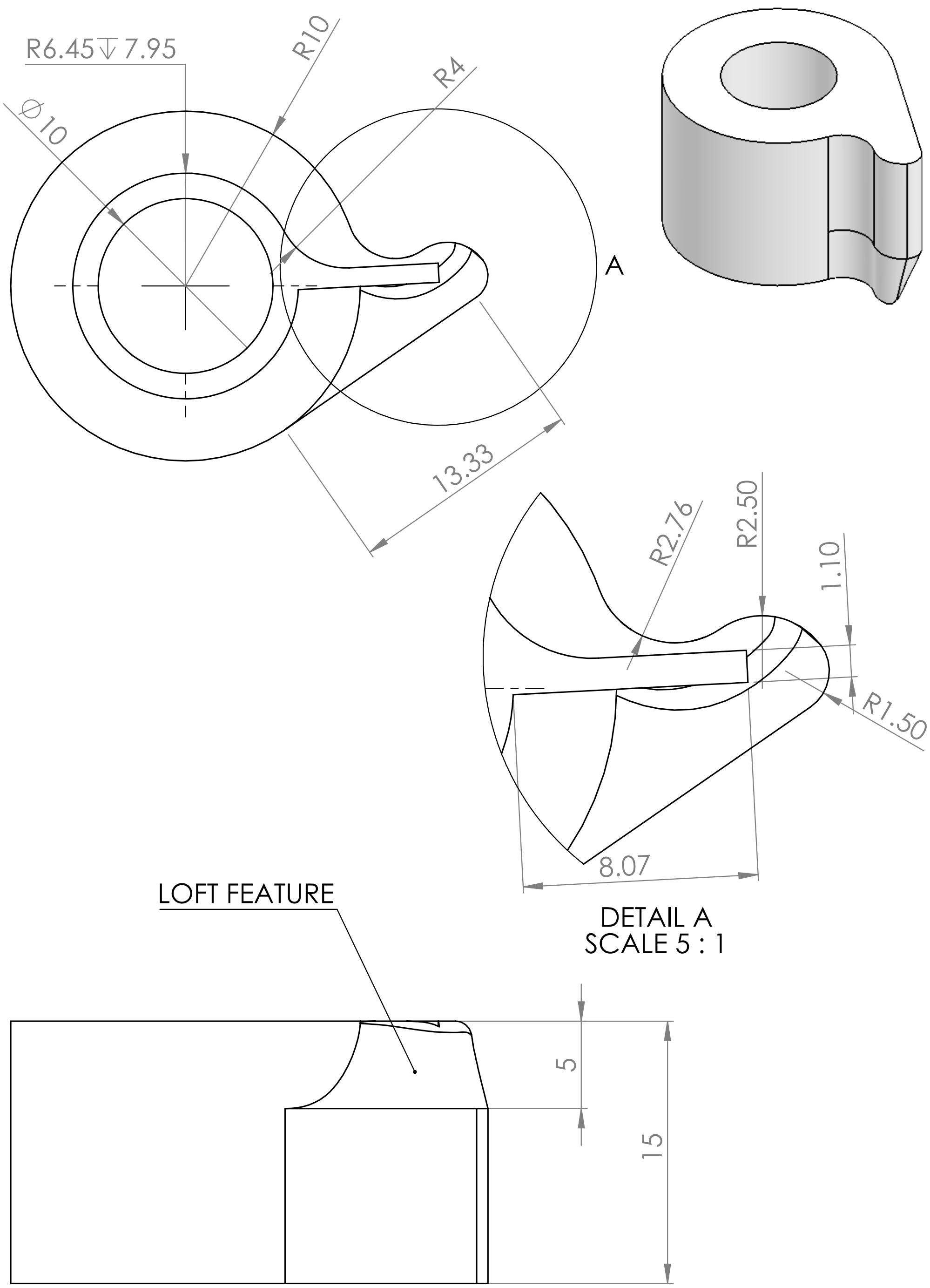

TITLE:

RATCHET LEVER - PROTOTYPE

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UNITS: MM		SHEET 1 OF 1

B Bills of Materials

Final Mechanism Design Bill of Materials

Item	Description	Material	Count	Details
Custom Parts				
Cam Disk	Cam and rotating ratchet mechanism	Stainless Steel	1	$51.93g$
Base	Mounting and structural component for the mechanism	Stainless Steel	1	$34.55g$
Cap	Cover and endplate of the mechanism	Stainless Steel	1	$15.73g$
Ratchet Lever	Load bearing tooth for the ratchet	Stainless Steel	3	$1.79g$
Springs				
Torsion Spring	Ratchet lever force spring	Steel	3	$D_o = 4.8mm$ $D_w = 0.8mm$ $L = 8.32mm$
Compression Spring	Cam disk lateral force spring	Steel	1	$D_o = 21.8mm$ $D_w = 0.838$ $L = 19.05mm$
Drive Spring	Primary force supply spring	Steel	1	$D_o = 19.8mm$ $D_w = 1.8mm$ $L = 104mm$
Misc				
Assembly Bolt	Securing nut for assembly bolt	Cast Steel	3	$M4x20$
Fastening Nut	Securing nut for assembly bolt	Cast Steel	3	$M4$
Central Shaft	Central rotation axis and lateral shaft	Stainless Steel	1	$L = 25mm$ $D = 4mm$
Tether Screws	Secures tethers to cam disk	Cast Steel	2	$M2x6mm$

Prototype Mechanism Design Bill of Materials

Item	Description	Material	Count	Details
Custom Parts				
Cam Disk	Cam and rotating ratchet mechanism	ABS Plastic	1	$105.81g$
Base	Mounting and structural component of the mechanism	ABS Plastic	1	$70.05g$
Cap	Cover and endplate of the mechanism	ABS Plastic	1	$31.9g$
Ratchet Lever	Load bearing tooth for the ratchet	ABS Plastic	3	$3.62g$
Springs				
Torsion Spring	Ratchet lever force spring	Steel	3	$D_o = 12.9mm$ $D_w = 1.02mm$ $L = 20.8mm$
Compression Spring	Cam disk lateral force spring	Steel	1	$D_o = 21.8mm$ $D_w = 0.838$ $L = 19.05mm$
Drive Spring	Primary force supply spring	Steel	1	$D_o = 19.8mm$ $D_w = 1.8mm$ $L = 52mm$
Misc				
Assembly Bolt	Mounting bolt for the mechanism	Cast Steel	3	$M10x45mm$
Fastening Nut	Securing nut for assembly bolt	Cast Steel	3	$M10$
Central Shaft	Central rotation axis and lateral shaft	Stainless Steel	1	$L = 55mm$ $D = 10mm$
Tether Screws	Secures tethers to cam disk	Cast Steel	2	$M3x15mm$