ABSTRACT

Designing, Constructing, and Testing a Second-Generation
Prototype Mechanical Hippotherapy Horse

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The use of horses as a means of therapy has been documented for some time. To determine why this type of therapy works and to provide a means of expanding its accessibility, a mechanical horse has been developed. Data collected on the movement of live horses during a previous study was used as a target motion in the development of a prototype mechanical horse. This mechanism was designed to be capable of reproducing that motion. For this prototype, the base remains stationary and a suspended saddle seat moves in a pattern replicating that of a live horse. The saddle is suspended by eight cables which are displaced by eight distinct cams. The cam set can be exchanged for various cam sets which correspond to different prescribed movements. Testing revealed good agreement between the motion of the prototype and the target, but improvements can be made in the measure of z-translation.

Designing, Constructing, and Testing a Second-Generation Prototype Mechanical Hippotherapy Horse

by

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A Thesis

Approved by the Department of Mechanical Engineering

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

## LIST OF ABBREVIATIONS

AC – Alternating Current

AHA – American Hippotherapy Association

ANSI – American National Standards Institute

BABS – Brunel Active Balance Saddle

BES – Baylor Electromechanical Systems

BU – Baylor University

COG – Center of Gravity

DOF – Degree of Freedom

IRB – Institutional Review Board

LED – Light Emitting Diode

NARHA – North American Riding for the Handicapped Association

SD – Standard Deviation

URC – University Research Committee

# PREFACE

This thesis is submitted in partial fulfillment of the requirements for a Master of Science in Biomedical Engineering Degree from Baylor University. It documents work done from June 2009 to May 2011. Advisors for the project include Dr. Brian Garner and Dr. Carolyn Skurla.

In January of 2009, my advisor first introduced me to the mechanical horse concept. During the course of the next 4 months I worked as part of a team of undergraduate students to develop our first prototype mechanical horse. After considering the results of the project, we resolved to build a second generation prototype mechanical horse that would operate by different mechanical means. Since June of 2009 I have been working to realize this prototype. It is our greatest hope that this prototype will not only provide a means of comparison for research into how hippotherapy works, but also will be a therapy tool that can be used in hippotherapy and physical therapy clinics around the world. It has been designed with manufacturing and maintenance concerns in mind, in hopes that it will be inexpensive and easily producible.

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their love and support, without which I would never have made it this far.  Thank you for everything.

# DEDICATION

To everybody whose love and support has given me the foundation to achieve whatever dreams may come. Without you I am lost, for you are the home to which I run.

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# EPIGRAPH

"Without courage, wisdom bears no fruit" –Baltasar Gracian

# CHAPTER ONE

## Introduction

### *History of Horse and Man*

During the last 6,000 years man and horse have been companions in labor, warfare, trade, health, and friendship [1]. Even now, in this age of modernity, where technology evolves more swiftly than ever before and the progression of our society has rendered a good many things once honored and revered for their usefulness as obsolete, do we still employ our timeless companion, the horse, to the benefit of mankind. What was once taught as an essential part of day-to-day life in the sleepy times of yesteryear, we now administer as therapy for the disabled. Horseback riding, though primarily conceived of for its usefulness in labor, transport, trade, and warfare, has been found to be a therapeutic exercise unlike any other [1]. Its benefits have long been noted. Even wise old Hippocrates, father of medicine, briefly made note of its potential and obvious benefit [2]. As the centuries ticked by, further notice of the horse as a therapeutic tool continued, and in the $17^{th}$ century therapeutic riding, as we know it today, began to take form [3]. By the $18^{th}$ century it was commonly counted among other medical treatment modalities of the time.

> Treatment with the use of the horse is not a recent invention, but rather an ancient therapeutic method. Later it became part of empirical medicine and as such has been included in the annuals of medical science since the $18^{th}$ century [4].

Therapy by way of horse, though beneficial in the treatment of many afflictions, is not without its own risks and limitations. Such limitations and the desire to objectively understand why therapeutic horseback riding is so effective have given rise to our goal of building a mechanism capable of creating the same three dimensional motion as a horse. Walking is a very complex mechanism. It involves the activation and coordination of numerous muscles, tendons, ligaments, and bones, which are all directed by biofeedback received through the nervous system. To be able to define such complex motion and reproduce it by way of mechanical design rather than natural, biological function is a fascinating and challenging task.

### *Purpose*

Though equine therapy has long been established, it is still largely unknown as to what aspects of horseback riding are therapeutic. Since this form of therapy is relatively new, and there is still much to be learned about the mechanisms of its benefit. There is no definite conclusion as to whether the benefit of therapeutic horseback riding is derived from the physical, emotional, or psychosocial aspects associated with equine therapy. One way to test this is to take the horse out of therapeutic horseback riding and to conduct experiments on patients riding a mechanical horse. To date, there have been a limited number of studies completed which utilize a mechanical horse in an attempt to standardize test variables and simulate therapeutic horseback riding sessions [5, 6]. There are also a limited number of mechanical horses available on the market today, most of which are marketed toward healthy, able-bodied persons to be used as exercise equipment. Inventors of some of these mechanical horses claim that they move in a fashion similar to a live horse, but they fail to specify what kind of horse (*i.e.*, therapy horse, dressage horse, warmblood, coldblood, breed, size) or gait (*i.e.*, walk, trot, canter, gallop) is being replicated. Little information or comparison with motion data collected from live horses is available.

Building a mechanical horse could potentially improve the quality of life of prospective equine therapy patients around the country by increasing its accessibility. There are potentially thousands of patients around the country who are either too weak, allergic, or fearful to ride live horses or who live in cities where equine therapy is not available. All of the aforementioned could benefit from the creation of a mechanical therapy horse. For those too weak to ride, a mechanical therapy horse could be used as a complementary therapy tool to increase their physical ability and strength to the point that they could eventually benefit from riding a live horse. For those afraid of riding a live horse, the mechanical horse could be used to introduce the patient to riding until they become more comfortable on horseback. The mechanical horse would also provide the physical benefit of equine-therapy to those allergic or not living near a therapy center, and who would otherwise not be able to experience any form of equine therapy. After all, a mechanical horse is better than no horse at all.

### *Thesis Overview*

This thesis project was completed in compliance with the requirements for the Master of Science in Biomedical Engineering Degree at Baylor University. To begin the project, background research was conducted on equine therapy, specifically hippotherapy, and that information is presented in Chapter Two. Chapter Three discusses background information regarding the historical and present designs of existing mechanical horses. With an understanding of the applications of and techniques used in equine therapy in mind, construction on a first prototype mechanical horse was commenced. The design, construction, and disadvantages of this first prototype are presented in Chapter Four. Chapter five illustrates the methods of design, construction, and testing of the second prototype mechanical horse. The results of the construction phase and testing of the prototype are presented in Chapter Six and discussed in depth in Chapter Seven. Concluding remarks are given in Chapter Eight.

# CHAPTER TWO

## Background

### *The Medicinal Use of Horses*

Smaller animals, such as cats and dogs, often come to mind when speaking of animal-assisted therapy, although larger animals such as horses are equally capable in terms of therapeutic capacity. Horses are eager to please, unconditionally accepting, generous in affection, and loyal in companionship [7, 8]. They are inherently social animals, eager to partake in a bond of friendship with their human counterparts. According to Engel, "[t]he horse accepts people on their responsive level and does not discriminate against a person's sex, nationality, disability, or form [9]." The horse, however, has a great advantage over other therapy-animals in that it can support a rider upon its back. From the long-past times of ancient Greece to the present, the horse has been recognized for its applicability in therapy and the wide range of benefits it can bestow upon its riders [10].

The prescription of horseback riding for medical and therapeutic purposes first occurred in Europe sometime in the 17$^{th}$ century [10]. It was during this time that people began to take an interest in the unique experience of horseback riding, the distinct motion generated by the horse, and the direct affect that it could have on health. Today there are a number of different types of equine-assisted therapies, all of which address different goals through various means and applications of horseback riding. Equine-assisted therapies include therapeutic riding, hippotherapy, riding for the disabled/handicapped, remedial educational sport-riding and vaulting, and equine-facilitated/assisted mental health [11]. The phrase "therapeutic riding" is both commonly used as an umbrella term to incorporate all types of therapy in which a horse is employed and also as a term for a specific type of therapy conducted on horseback with the intentions of teaching horsemanship. These therapies are a type of animal-assisted therapy in which specific goals are set out for the patient, and the horse is used as a therapeutic tool to reach these goals. In the United States, equine-assisted therapy has been a viable means of physical therapy since 1969, when the first American riding center was opened [3, 12]. Since then, the American Hippotherapy Association (AHA) and the North American Riding for the Handicapped Association (NARHA) have been founded. These organizations provide information and guidelines about hippotherapy and also function to certify therapists for hippotherapy.

Of the various types of equine-assisted therapies, hippotherapy is the only one which is specifically considered to be medicinal [13]. As a recognized branch of alternative medicine, it is prescribed by a physician or therapist, administered by a licensed therapist, and is usually covered by insurance [11, 14, 15]. Under the guidance of these highly experienced therapists, "the horse becomes a living physiotherapeutic apparatus [13]."

Hippotherapy employs licensed physical, occupational, and speech-language therapists in the treatment of neuromusculoskeletal impairments through the application of motion generated by a horse [14]. During the administration of hippotherapy, a therapist transitions a specific motion pattern from the horse to the client. The client sits on the horse while passively allowing the motion of the horse to affect his or her body, specifically to move the trunk and pelvis in a symmetrical and cyclic manner through a 3-

dimensional space [16]. According to Debuse, "[t]he user does nothing to actively influence the movement of the horse; on the contrary, the user is moved by the horse and responds to the horse's movement [17]." As the motion of the horse is translated to the patient, he or she will subconsciously make active responses to his or her change in position in an attempt to stay balanced upon the horse [13]. This subconscious participation in therapy as a reflex mechanism is thought to be essential in the rehabilitative process of hippotherapy [18].

### *Indications and Contraindications*

Hippotherapy is a versatile form of therapy and is recommended in the treatment of a broad range of diseases and disabilities. Most commonly it is prescribed for the treatment of cerebral palsy and autism, though it is also used to treat paralysis, Down syndrome, epilepsy, Alzheimer's disease, multiple sclerosis, stroke, scoliosis, lumbago, limb deformities, spinal deformities, circulatory disease, muscular dystrophy and atrophy, mental retardation, traumatic brain injury, post-traumatic stress syndrome, and spina bifida [11, 13, 19, 20]. Many of these ailments involve the impairment of similar physical functions and are manifested as gait disorders, muscle spasticity, asymmetric muscle tonicity, gross motor control deficiencies, fine motor control deficiencies, joint immobility, lack of head and trunk coordination, and postural imbalance [12, 15, 21, 22]. Developmental disorders which can affect the progression and use of cognitive and behavioral functions, such as cerebral palsy and autism, can also be addressed by hippotherapy in its documented benefit to articulation, speech, language, learning, behavioral, sensory, and cognitive disabilities [3, 7, 17, 23-26].

It is important to address such disorders early on in their onset and also to find a method of therapy which the patient will be able to and willing to participate in for a potentially great length of time. Inaction, inattention, or ineffective therapy will leave the physical problems of the disease or disorder to grow as the patient does so.

> Physical growth in the face of long-term sensory and motor impairments combined with postural asymmetries often leads to increasingly severe disability. Muscle imbalance, in particular, may lead to uneven bone growth, contractures, spinal deformities, scoliosis, imbalances in weight bearing, hip dislocation, chronic pain, and increasing difficulty with performance of basic motor skills such as sitting, standing, and walking [3].

It has been claimed that hippotherapy has the ability to stop the progression of the disability and in some cases to improve the condition. This is done through the application of cyclic, symmetric motion which may strengthen and proportionally develop the body, thus preventing escalation of the disability [27]."

Though hippotherapy has a variety of uses, there are a few contraindications against the use of hippotherapy. These include uncontrolled seizures, excessive lack of head control, excessive lack of trunk control, and excessive lower extremity spasticity [15, 28]. Lower extremity spasticity or hypertonicity of the hip adductors and internal rotators preclude the ability of a patient to straddle the girth of the horse [15, 28]. Head and trunk control are essential to being able to sit independently and ride safely [15]. Excessive lack of control can lead to further injury through the jarring accelerations sustained during each phase of the horse's gait.

### *Comparison with Alternative Therapies*

There are a number of therapies and surgeries that have been implemented to address the above-mentioned diseases and disorders. However, many of these procedures are invasive, painful, and require considerable rehabilitation time. Procedures commonly prescribed for such patients include tendon release surgical procedures, selective dorsal rhizotomy, injection of botulinum toxin into the affected muscles, baclofen, osteotomy, hamstring lengthening, Achilles tendon lengthening, hip osteotomies, femoral hip resection, adductor release, ventricular peritoneal shunt, and prescription of systemic muscle relaxing drugs [3, 29, 30].

Alternatively, there are many forms of physical and occupational therapies available that are noninvasive and have less associated risk. These various forms of therapy have been shown to be effective, but they are often described as painful. Patients are often described as being unwilling to participate or cooperate. Benda states that "the repetitive and often painful necessity of life-long therapeutic work challenges the physical therapist to find strategies that will address specific impairments and enhance functional improvement while simultaneously sustaining the child's interest and enthusiasm [3]."

Regardless of the patient's willingness or enthusiasm in participating in such physical therapy, there is also an issue of the physical demand placed on the therapist, especially when working with nonambulatory clients. Working to improve gait and daily functional capacity often requires the improvement of balance and control of body and appendages. This often places a substantial demand on the therapist, as he or she must assist the patient in bearing, balancing, and directing their own body weight [18].

Many therapy clinics use devices such as bolster swings and therapy balls to move a patient and stimulate a response [29, 31]. According to Casady, "[t]herapy balls are commonly used as a dynamic surface to develop postural control in lying or sitting positions. Therapists move the ball and thus provide the direction, speed, and magnitude of postural displacement [12].” However, there are inherent limitations on the movement patterns which can be facilitated through the use of a ball or swing. Furthermore, these treatment modalities are dependent upon the strength and stamina of the therapist alone. This limits the amount of time that therapy can be delivered directly to the patient, as the therapist may become exhausted. It also limits the quality of the therapy as the therapist is busy controlling the devices instead of focusing complete attention on the patient.

“Hippotherapy gives [therapists], if you will, a hairy, olfactory-stimulating, warm, four-legged Bobath ball platform on which a trained therapist can capitalize on motor control, stretching, and equilibrium [14].” When considered as a therapeutic device, the horse is similar to therapy balls, bolster swings, and floor mats commonly found in therapy clinics [23, 27, 31]. However, unlike therapy balls, bolster swings, and other therapeutic modalities, the use of the horse does not require any physical demands on the therapist and frees the therapist to consistently observe the patient. With the use of the horse, it is no longer necessary for the therapist to support the weight of the patient or to use his or her strength to repetitively move a ball or swing under the patient’s weight, which may lead to longer and higher quality therapy sessions. Hippotherapy is also almost limitless in the amount of various stimuli that can be applied through both the act of riding and the sensory stimulation of being on horseback. The variability of a horse's gait gives the therapist an opportunity to manipulate the motion that is being transferred to the patient through the manipulation of speed, direction, and cadence, thus changing the type and degree of stimulation the patient is receiving [12]. This makes the horse, as part of therapy, a very unique and powerful tool, as many patients and therapists claim "that no other piece of equipment or physiotherapy method is able to produce such even, and prolonged three-dimensional movement stimulation as a horse, while at the same time being able to produce such finely-tuned variations of movement in terms of speed and direction [32]."

### *Hippotherapy Staff*

Hippotherapy sessions are usually conducted with several staff members, as seen in Figure 1. In every session there is a licensed therapist who outlines the goals for the session, conducts activities and exercises with the patient, and implements adjustments in the speed, gait, and direction of the horse [17]. The hippotherapist will often walk behind or beside the horse to observe movement in the patient and decide how the therapy session can be enhanced in such a way as to best suit the patient [33]. The hippotherapist may also ride along with the patient in order to ensure that the patient is stimulated correctly [31]. Also on the therapy team is an experienced horse handler who leads the horse and puts into effect any requests by the therapist for change in motion of the horse [27]. Depending upon the strength and skill of the rider, there may also be one or two side-walkers present who will provide support to the rider and assist the rider in conducting exercises when necessary.

Figure 1: Hippotherapy Team and Patient [34]

*Professional Licensing and Certification*

Certification for practicing hippotherapy includes three years of experience within a therapy field, one hundred hours of hippotherapy experience, written examination, continuing education, and scholarly activity [35]. Therapists must be licensed as physical therapists, occupational therapists, or speech-language pathologists [12].

*Horse Selection and Training*

The selection of horses for use in hippotherapy is somewhat rigorous. Horses are selected for gentle temperament, symmetrical gait, trainability, obedience, health, girth and height [4, 11]. Therapy horses are subject to extensive training, during which they are instructed in tolerance with unbalanced riders, acceptance of sudden distraction, loud noises, and unusual objects, and ease of transition in gait [4, 11]. Horses are generally on the scale of 14.0-15.2 hands [11, 15]. Heine contends, "[s]maller horses or ponies can be used, but they must have a strong back that is broad enough to act as a support surface. Very tall horses represent a safety risk, as their height renders it difficult to adequately support and/or position a patient from the ground [15].”  The height, girth, breed, and gait of the selected horse can have significant impact on the frequency, amplitude, and magnitude of stimuli received by the patient [11].

### *Hippotherapy Facilities*

Hippotherapy clinics are often found in rural settings as they require space for stables, arenas, covered arenas, pastures, and walking trails.  Currently there are around 800 NARHA centers operating in the United States and of those over 200 of them offer hippotherapy [36].  These NARHA centers employ over 6,000 horses, ponies, miniature horses, donkeys, and mules and over 6,000 employees, half of whom are certified instructors.  Together the NARHA clinics serve over 40,000 patients a year [36].

### *Hippotherapy Sessions and Administration*

Typical hippotherapy sessions last anywhere from twenty minutes to an hour and are usually administered one to three times a week.  While the patient is riding, the therapists may require the patient to perform various tasks.  These tasks may include identifying shapes or colors, catching objects, playing games with rings, balls, or beanbags, reaching across midline to touch the horse, holding an object, such as a stick, at a particular orientation, giving commands to the horse, using the reins to direct the horse, or performing some form of exercise as shown in Figure 2 below [14, 29, 37]. Mackey-Lyons notes, “[t]hese exercises included arm swings, leg swings, trunk rotation flexion and side flexion [38].”  Having the patients participate in games and exercises with the purpose of improving strength, balance, and tonicity allows the patient to become actively involved in their rehabilitation in an enjoyable and recreational way [31].

Figure 2: Reach Exercise (Left) [39], Coordination Exercise (Center) [40], Balance Exercise (Right) [40]

In addition to strengthening and stretching through performance of activities, the therapist may place the rider in various positions on the horse such as prone, side-lying, side-sitting, or sitting. Frequently used sitting positions are shown in Figure 3. In many cases, the therapist and rider will ride together so that the therapist can facilitate the movement or desired response as needed [27, 31]. These different positions allow the targeted strengthening of various muscle groups and provide different sensations useful as stimuli for balance input. In hippotherapy sessions, the rider typically rides on sheepskins, saddle blankets, or soft pads rather than a saddle. This allows the rider to sit in a greater variety of positions, the movement of the horse to be transferred directly to the patient, and the warmth generated by the horse to reach the rider [14, 27]. Brudvig suggests that "[t]he lack of a saddle also made the child work equally harder to maintain his/her balance and equilibrium [23]."

Figure 3: Demonstrations of Various Sitting Positions (Left) [27], Example of Side-Sitting (Right) [41]

During the session the therapist will also modify the terrain on which the horse walks, the pattern and/or direction of walking, the gait, and the pace. Changing the terrain will affect how the horse walks. On a flat and easy terrain, the motion of the horse will be more systematic and cyclic, while on rocky and changing terrain the motion of the horse will change with each step as the horse adjusts its gait in order to keep its footing. Walking trails are frequently used to supply changing terrain for the horse, as well as varying environmental stimuli for the patient. While conducting hippotherapy sessions in an arena, the pattern of walking can be changed. Commonly used patterns are circles, figure eights, straight lines, serpentine patterns, and cone weaving [11, 20, 42]. These patterns can be used to affect balance and target strengthening on muscles in one side. The velocity and acceleration of the horse can also be manipulated through the application of gentle or abrupt starts and stops, changes in direction, and changes in gait [11].

*The Mechanics of Hippotherapy*

It is not yet completely understood how and why hippotherapy works. There have been a number of studies conducted in an attempt to answer this question, but many of them lack large sample sizes due to the diversity of hippotherapy patients and limited accessibility, making the results hard to generalize to a large population. Another common problem is the inability to duplicate testing variables. A universal claim is that the three-dimensional motion experienced by a rider atop a walking horse is very similar to healthy, normal human gait [3, 12, 14, 15, 18]. In fact there have been a few studies that show similarities between normal human gait and the movement sustained during horseback riding [43, 44]. The "alternating forward and downward movement of the horse as the horse first drops one hip and then the other in an undulating motion [13]," drives the body, and particularly the hips, of the patient in a pattern that is similar to the natural motion of healthy human gait [3, 30, 31, 45].

Many of the patients treated with hippotherapy have little to no experience with smooth, rhythmic, symmetric motion, such as a normal walking gait [13, 14, 46]. It is such that their disabilities prevent them from completing daily functional tasks, such as walking, dressing, and reaching. The horse provides a symmetric and rhythmic pattern of motion to the rider in a repetitious manner that drives the patient's body in a pattern that their disability would have previously prohibited. The horse is capable of providing 90-150 impulses per minute, and over the length of a hippotherapy session this can total anywhere from 1000-5000 three-dimensional impulses [12, 20, 22, 33, 47, 48]. Such a large number of impulses provide an ample amount of practice and exercise for the rider. It has been shown that patients are successful in generating self-righting equilibrium reactions that minimize pelvic and trunk displacement in response to the movement of the horse [12, 49]. Biery states that "[r]esponse to the horse's movement is unconscious and it is that unconscious process that helps to retrain the malfunctioning muscles [13]." Both the numerous repetitions of movement generated in a single hippotherapy session and the fact that the movement is rhythmic allows the patient to begin to predict how their body will be displaced and account for that to increase efficiency in balance and movement. Casady asserts that "[p]ractice and experience are believed to lead to the modification and reorganization of the central nervous system [12]." Hippotherapy also requires the patient to actively engage in the therapy session, as the surface of the horse is dynamically changing [12]. This requires the patient to respond and adapt to the movement of the horse and to think about maintenance of posture and balance. The rhythmic motion of the horse causes the rider to constantly anticipate and compensate for changes in their position and center of gravity. This challenges their ability to balance and coordinate muscle control, which is thought to benefit control of posture, gait, and motor function [3, 12, 30]. As the patient becomes more confident and skilled on the horse, the patient will begin to relax and subconsciously increase the amount of pressure applied on the horse through the saddle or blanket [47]. This allows for the patient to experience more of the natural equine motion, as tension in their own muscles will no longer inhibit passive movement or active reflexes [47]. Riding on the horse also creates the sensation of moving forward through space unrestricted, which is a novel sensation to many of the patients who are normally confined to wheelchairs or impeded by other obstacles [38].

Another aspect of hippotherapy is the slow stretch of the muscles of the legs and hip, which results from sustained, cyclic pressure on the muscles from the motion of the horse, the action of sitting astride the horse, and the warmth generated by the body of the horse [14, 20, 27]. Stretching of the muscles coupled with muscular activation during riding increases muscle contraction in hypotonic muscle and relaxes muscle contraction in hypertonic muscle [3, 45]. This allows symmetric development of the muscular system and normalization of muscle tonicity. The warmth and motion generated by the horse also improve blood circulation [29].

The final aspect in the mechanics of hippotherapy is its activation and integration of multiple sensory systems, including the sensory, muscular, skeletal, limbic, vestibular, ocular, cognitive, tactile, and olfactory systems [17, 50].

> The interaction of the continuously changing environment of the moving horse, the challenging and motivating task of sitting astride, and the intense multiple influences on the patient’s sensory, motor, cognitive, and limbic systems facilitate the emergence of new movement strategies that are not developed through traditional treatment strategies [3].

The integration of therapy into such a stimulating environment reflects more closely the environment often experienced while learning new tasks during developmental years, in comparison to attempting to learn new tasks in a clinic setting.

### *Physical Benefits*

Hippotherapy provides a variety of physical benefits to the patient suffering from any one of the previously mentioned disorders. The physical benefits are listed in Table 1 below. Improvements seen in one or more of these areas, especially balance, ambulation, and head and trunk control, are likely to result in functional carryover and increase the chance that patients will be able to advance their efficacy in successfully completing daily tasks. For example, increased balance control could improve the ability to walk effectively and in turn lead to improvements in strength, energy expenditure, and self-confidence. Positive development of one functional disorder can cascade into multiple benefits, in a self-perpetuating positive feedback cycle.

Table 1: Physical Benefits of Hippotherapy

| Benefit | Reference |
|---|---|
| Balance and Equilibrium Stability | [16, 20, 23, 25, 31] |
| Improved Gait Speed and Cadence | [18, 38] |
| Increased Stride Length | [18, 30, 38] |
| Independent Ambulation | [18] |
| Reduced Lower Limb Impairment | [18] |
| Independent Weight Bearing | [27] |
| Improved Posture | [25, 31] |
| Trunk Stability | [23, 25] |
| Head Control | [25] |
| Strength | [25] |
| Flexibility | [25] |
| Gross Motor Control | [30, 51] |
| Muscle Activity Symmetry | [3] |
| Improved Muscle Tonicity | [31] |
| Improved Muscle Spasticity | [23, 52] |
| Improved Energy Expenditure | [30] |

There is also thought to be a reorganization of muscle memory and an increase in motor-planning capacity as a result of passive reaction to the rhythmic and dynamically changing surface of the horse's back [18]. The incredible amount of stimulation received during one session and the patient's passive postural adjustments and balance responses make "it possible to reorganize the behavioral stereotypes, which have still not been strongly fixed, and change them for new, more correctly organized behavioral skills [53]."

*Cognitive Benefits*

There are cognitive benefits that result from hippotherapy. Benefits commonly documented include critical thinking and decision making skills and improvement in speech and language learning [24]. These benefits as well as stimulation of the sensory and cognitive systems activated during riding may improve speech, respiration, and concentration [3]. Improvements in speech may also result from an improvement in respiration, making the act of speaking much more achievable. There is also some evidence to support increased attention span and focus [28].

*Emotional Benefits*

The companionship developed between the horse and patient and also between the patient and the staff and other riders provides an opportunity for emotional benefit. Documented emotional improvements include increased motivation, volition, self-esteem, and self-confidence [7, 17, 23-26]. The increased sense of motivation translates into an increased desire to participate in therapy and an increased level of confidence in attempting new tasks [17]. Fear of moving and performing functional activities is reduced and quality of life is increased [31]."

Hippotherapy also provides social and emotional stimulation, and as horseback riding is generally thought of as a "fun" activity it provides motivation for completing therapy [3, 28]. Successfully riding a horse may also benefit the patient's level of confidence and self-esteem [28, 45]. One theory regarding the effect of hippotherapy on confidence and esteem level is that the perception of risk involved in horseback riding forces the rider to engage with, confront, and master a large and powerful force [13]. "The child also benefits from engaging in a sports-related activity with the perception of risk behavior, although the extremely low incidence of injury reflected by the low insurance rates required to operate a therapeutic riding center refute this theoretical concern [3]."  Hippotherapy sessions are also commonly described as fun and satisfying, which would insinuate that the patient may be receiving more benefit from the therapy by taking an active interest in the therapy and from the increased quality of the therapy as the therapist does not have to convince the patient to participate [24, 54].

### *Social Benefits*

The relationships built between the horse, staff, and patients provide an opportunity for social engagement.  Lessons are learned in social behaviors such as cooperation and teamwork, trust, communication and authority [7].  There is also "the psychological enhancement of moving freely through space astride a powerful animal without the constraints of assistive devices [3]."  It has been documented that this ability to move freely gives the disabled the sensation of finally being able to achieve equal participation with able-bodied people.  Also, the simple act of sitting high on top of the horse means that people will be looking up to the rider instead of down at the patient, many of whom are confined to wheelchairs [38].  This simple act gives a sense of equality and social well-being.  These social benefits have been implicated in improved social interaction at home and in school.

### *Limitations of Hippotherapy*

Hippotherapy is not without risks.  The therapy sessions are performed on a live horse and as such may be dangerous.  There is a risk that the rider could fall from the horse, or that the rider may be thrown from the horse if the horse is spooked [28, 55].  An excessive amount of fear can increase the patient's stress level, which can manifest itself as increased hypertonicity [28]. Hippotherapy may also be limited by possible allergic reactions of the patient to the horse. Common allergens, such as animal dander, hay, and dust are plentiful in the environment of the arena and stables. Hippotherapy is also limited by the availability of clinics and therapy horses. Since hippotherapy horses are to be used in therapy with disabled patients, the horses must undergo substantial training. Only a few horses are capable of being therapy horses as they must not only have a gait sufficient for therapy, but must also be of a calm and gentle temperament [28]. The cost of boarding, grooming, feed, equipment, arena, and training of both horse and handler eliminates hippotherapy as a therapy method for many physical therapy clinics. Hippotherapy is also limited by time and space. Horses require a substantial amount of space, and hippotherapy arenas are large in comparison to environments for other types of therapy. This often prohibits hippotherapy centers from being located in urban settings and means that travel time to and from the hippotherapy center could increase for the patient, caretaker, and therapist [55]. Weather also plays a role in the ability to administer hippotherapy sessions, as cold, wet, stormy, or excessively hot conditions may prohibit outdoor intervention. Hippotherapy may also be limited by finances. Not all insurance companies extend coverage to hippotherapy because it is still considered an experimental form of treatment [56]. Some insurance companies may cover a few hippotherapy sessions but may limit the number of paid sessions within a certain amount of time.

*Advantages of a Mechanical Horse*

The development of a mechanical horse capable of reproducing the motion of a living therapeutic horse may be helpful in expanding access to hippotherapy and eliminating the limitations associated with hippotherapy. A mechanical horse would eradicate potential risks associated with horseback riding because the motion is predictable and controlled. The height of the saddle is also shorter than that of a horse, improving both safety and accessibility to the patient. Allergies would no longer be problematic, as the mechanical horse does not produce dander and can be used in a clean clinical setting. Because the mechanical horse is relatively small and mobile, it could be used in clinics, offices, and homes throughout every region of the country and can be used indoors year-round, eliminating the adversities of unpredictable or disagreeable weather conditions. Such a device may generate some of the same benefits of horseback riding without the additional costs of grooming, training, tack, feed, facilities, and maintenance. Additionally, the mechanical horse could be used as a companion therapy tool. Such a device would allow the evaluation of new hippotherapy patients without the risks associated with evaluating them on horseback. A mechanical horse could also be used as an exercising and training device to ready patients for the challenging task of riding a live horse.

There is also a need to develop a mechanical horse so that the mechanics of hippotherapy can be properly tested and so that we can discover how and why particular aspects of hippotherapy work. This will lead to an increased ability to prescribe appropriate hippotherapy exercises, durations and frequencies of sessions, and achievable goals for specific types of disorders. Currently "[r]esults of hippotherapy are difficult to measure objectively due to a lack of valid and reliable instruments [14]."  The development of a mechanical horse will allow us to separate out different variables, such as type of gait, speed, movement through space, weather, environmental setting, warmth, and psychosocial aspects and to determine what role each of these variables have in achieving functional improvement.  Research on hippotherapy can help establish its place in the ranks of medicine, improve treatment, and institute criteria for insurance coverage.

# CHAPTER THREE

## Mechanical Horses

### *Prior Efforts in Mechanical Horse Design*

The idea of creating a machine that can reproduce the motion of a horse is not new. In fact, the first documented horse machine was built in 1735 by Professor Samuel Theodor Quellmalz. It was an implementation of a swing in which a horse-shaped body was suspended from above by several ropes [4]. An image of the design is shown in Figure 4 below.

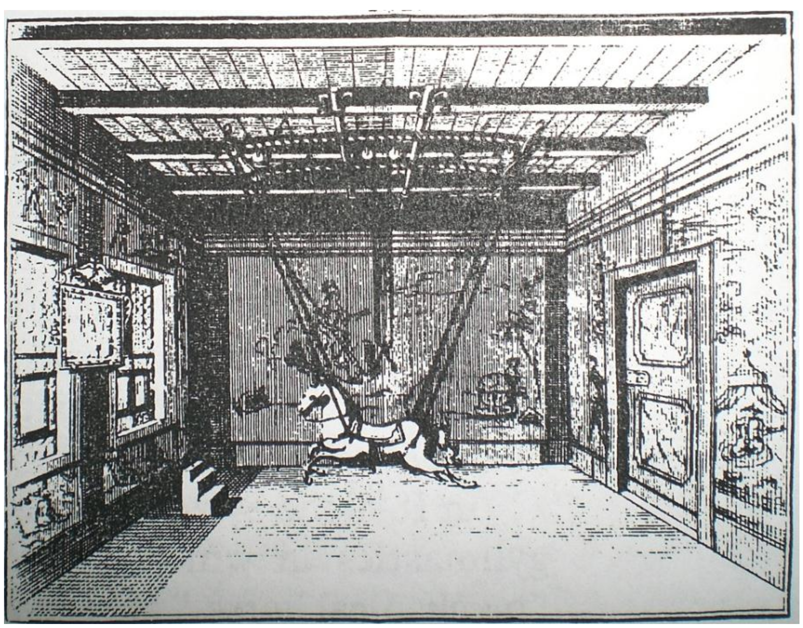


Figure 4: Quellmalz's Mechanical Horse [4]

By 1890 further attempts were being made to design more compact and efficient horses, and G. Zander developed a machine capable of tilting in several directions in succession while simultaneously moving up and down at 180 cycles per minute. The machine included a saddle shaped seat and a steering rod that could be used to direct which direction the seat would tilt [4]. In 1936 a mechanical horse complete with an entire horse body, legs, neck, and head and capable of producing 5 different gaits was introduced in Popular Mechanics Magazine, though no additional information could be found [57]. Images of both the Zander Horse and the horse presented in Popular Mechanics are provided in Figure 5. Horses such as these were developed to compete against the expense of owning a live horse and also to broaden the ability to receive the beneficial effects of horseback riding in any location [2]. In fact, the mechanical horse developed by Zander was placed in many gymnasiums of the time period including the White Star Line's RMS Titanic and RMS Olympic, thus making the benefits of horseback riding available at sea for the first time.

Figure 5: Girl Riding Zander's Mechanical Horse (Left) [58], Zander's Mechanical Horse (Center) [59], Popular Mechanics Magazine Horse (Right) [57]

## *Various Uses of Mechanical Horses*

### *Mechanical Horses in Entertainment*

From the late 1800's through the present day there have been a number of user-propelled mechanical horses. These are usually propelled through pedaling action, as on a bicycle, or through rocking action of the body [60-62]. Designs have ranged from ambulating quadruped machines and horse-shaped bicycles to stationary rocking mechanisms. These horses are generally used for childhood exercise and entertainment [60, 63]. Examples of various designs are given below in Figure 6.

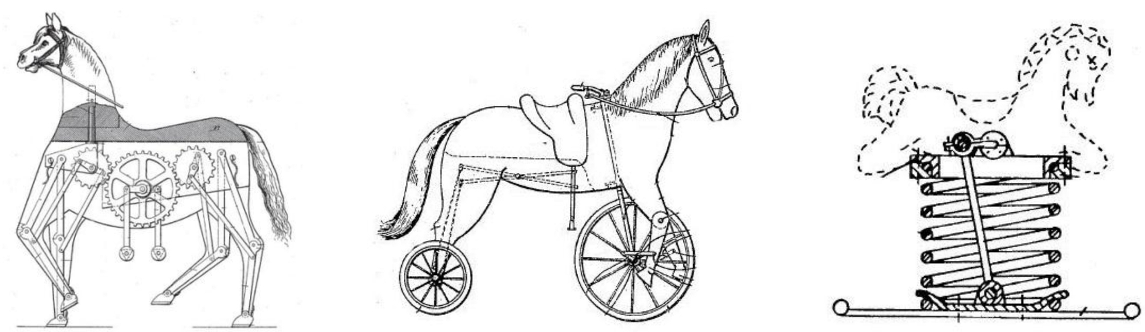


Figure 6: Pedal Horse Patent (Left) [64], Bike Horse Patent (Center) [65], Rocking Pedal Horse Patent (Right) [66]

There have also been several motorized mechanical horses that have been created for amusement's sake. These include machines that have been designed as hobby-horses or rocking horses for children's entertainment. Similar designs have appeared in rodeo devices used in the challenge of remaining atop a bucking animal for either practice or amusement [67, 68]. These generally consisted of a horse or bull shaped seat or a simple barrel shaped seat and were operated through various combinations of gears, planar four-bars, cams, pulleys, crank-arms, and springs [69, 70]. Examples as these designs are presented in Figure 7 below.

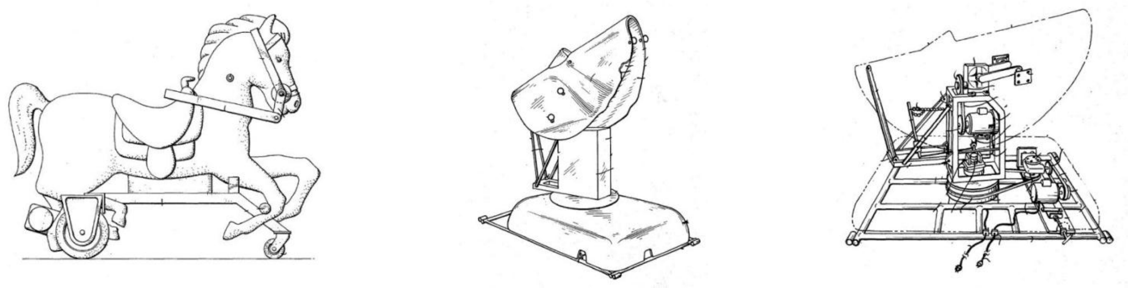


Figure 7: Motorized Rocking Horse Patent (Left) [71], Mechanical Bull (Center) [67], Mechanical Bull Internal Components (Right) [67]

Also within the realm of mechanical horses developed for entertainment purposes are riding simulators used in video gaming, as shown in Figure 8. These systems utilized a moving horse-shaped seat in combination with a virtual reality system, having used computers in the video game console and sensors in the seat to give instant feedback that directed the progress of the game and the movement of the seat. Some systems controlled the movement completely, such as the case of the bucking bull. Others required rocking movement input by the user to supplement any movement from the device itself, such as in jockey games where the rocking of the horse affected one's success in the game [72, 73]. Games were commonly rodeo or bull-riding games or horse jockeying racing games. Planar four-bars, and cams were the most common means of implementation.

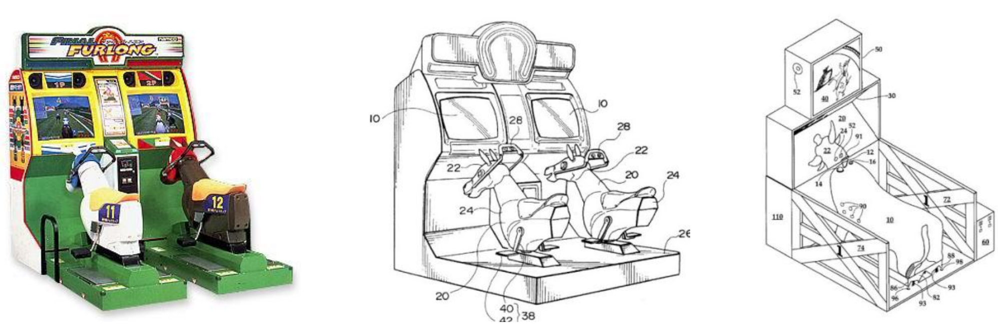


Figure 8: Jockey Video Game (Left) [74], Jockey Video Game Patent (Center) [73], Bull Riding Video Game (Right) [72]

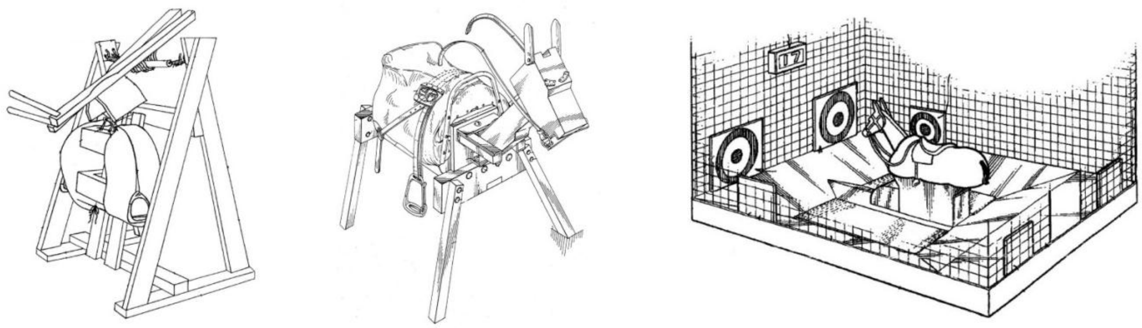


Figure 9: Split-Seat Saddle (Left) [78], Training Horse with Sensors (Center) [75], 9c: Polo Training Apparatus (Right) [77]

*Mechanical Horses in Training and Conditioning*

Mechanical horses have been developed to supplement training in competitive horseback riding, dressage, horsemanship skills, and jockeying, which allowed the rider to practice additionally without risk of injuring or tiring the competition horse. These designs have included a horse body, complete with the head, neck, body, and sometimes legs. Bits and/or reins were attached to the horse and were either connected to a sensor or some other electro-mechanical component that could control the movement of the horse (*i.e.*, gait, speed, direction), while also giving instant feedback to the rider [71, 75]. Some of the designs required the user to drive the motion by rocking or by other means, and were useful in strength and postural training in relation to certain gaits. Some of the designs were stationary and rigid, some were stationary but the seat may have moved and/or the horse head in relation to the seat may have moved, and some were capable of moving through space in response to the rider's directional control [76-78]. There were also horsemanship training devices that have been paired with virtual systems in which the arena, terrain, saddle type, gait type, skill level, sporting event, or riding discipline could be chosen, and where data measured by sensors on the horse, such as center of gravity, leg position, body position, etc. was displayed [79, 80]. Examples of various designs are given above in Figure 9.

*Mechanical Horses in Exercise*

As these types of mechanical horses have become more popular and common, some industrious companies have developed mechanical horses to be used as passive exercise machines for building core strength, postural strength, and balance. Examples of these devices are given in Figure 10. These machines, much like Zander's mechanical horse of the late 19$^{th}$ and early 20$^{th}$ centuries, consisted of a stationary base unit and a mobile seat unit connected by a mechanical driving system capable of moving the seat unit in a prescribed and predictable manner [81]. As exercise equipment, the structures of each have been minimized and the speeds are variable and correspond to different workout intensities. Generally these devices operated by means of planar four-bar, crank-arms, gear systems, eccentric cams, pivot shafts, and worm gears [82-86]. Many of these exercise-oriented mechanical horses have "the capability of giving a horse-riding experience that is a combination of the three-effective motions… which is a combination of a rectilinear reciprocating motion in a forward and backward direction of the seat, a first pivotal reciprocating motion about a first axis extending in a horizontal direction substantially perpendicular to the forward and backward direction, and a second pivotal reciprocating motion about a second axis extending in the forward and backward direction [87]." Improvements to these designs over the years introduced inclination angles of the seat and a rotating disc on which the saddle was mounted that allowed rotation about the vertical axis [84, 88]. Some of these devices might have been able to achieve full six degree-of-freedom motion, but may have lacked the same magnitude and pattern seen in the gait of a live horse.  Also, there has been no verification or comparison of these generated motions to that of live horse motions.

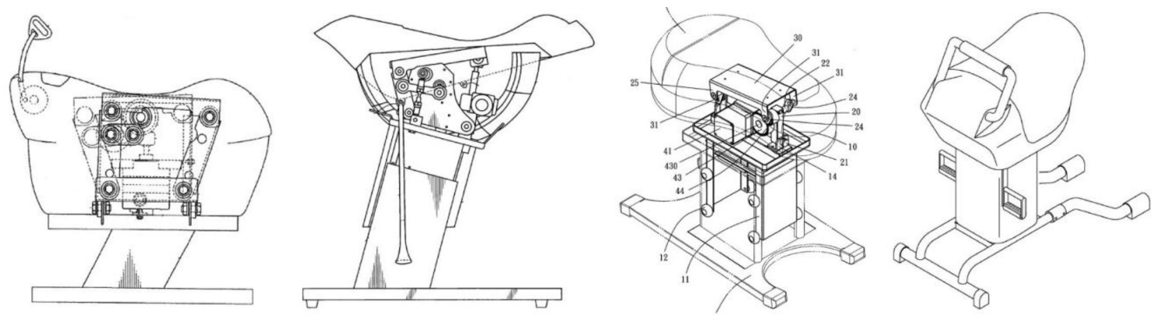


Figure 10: Various Exercise-Oriented Mechanical Horse Models [82, 83, 85, 86]

*Mechanical Horses in Therapy and Rehabilitation*

Mechanical horses may be useful in hippotherapy clinics or other physical therapy clinics, when riding live horses is impossible for a patient.  They may also be useful in initial training of the patient, so as to gradually introduce the patient to the process of riding or to treat a patient who is too weak or fearful to ride on a live horse.  To date, there have been a very limited number of horse machines that have been developed specifically for use in therapy settings.  These machines have tended to have larger sitting surfaces to accommodate disabled users, the use of saddles, and possibly two concurrent riders.  Implementation of designs intended to generate horse-like motion has been varied, as shown in Figure 11.  The Ettenhofer Therapy Saddle (Figure 11: Left) was a seat surface, similar in shape to that of the back of a horse and capable of supporting a saddle that was suspended by a series of springs.  Motion was generated only through external force supplied by the therapist [89].  The Jung Horse Apparatus, shown below in Figure 11: Center, used a series of four-bars and crank-arms to achieve a forward-backward and up-down motion that was similar to a horse, but did not truly produce the three-dimensional movement of a horse [90]. In 2008 one mechanical horse was developed in China for exercise and therapy that utilized a crank-rocker and four-bar system (Figure 11: Right). However, the research team claimed that it was “not meaningful to research walking,” and instead focused on the motion of running [91]. The Li Horse moved generally in an up and down direction, with very little, if any movement longitudinally or transversely and therefore was not apt in recreating the motion of a horse.

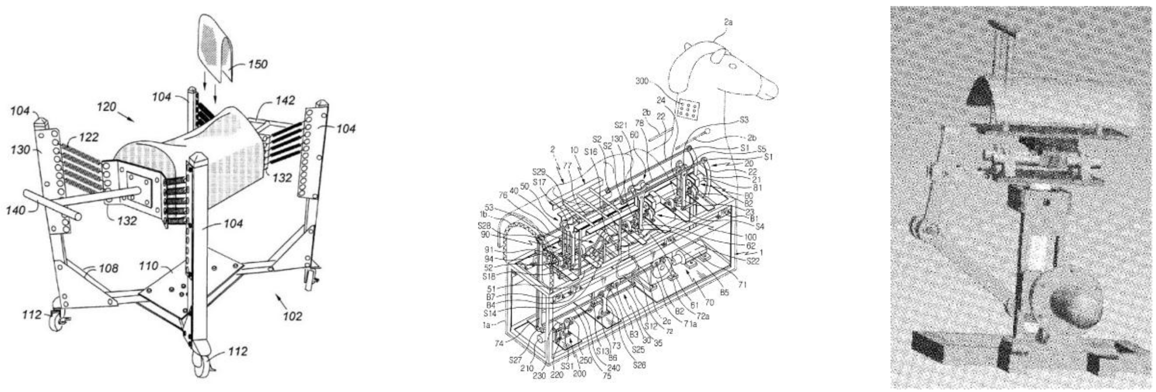



Figure 11: Ettenhofer Therapy Saddle (Left) [89], Jung Horse Apparatus (Center) [90], Li Horse (Right) [91]

The BABS model was designed to replicate the motion of a horse that was filmed by the Brunel Institute, but data is not available to verify the motion. Since the BABS model was built for use in hippotherapy, it functioned to improve balance, gait, posture, and range of motion [6, 92]. This horse however, was relatively small in comparison to a live horse and is no longer available for purchase.

The Nalty Hippotherapy Simulator was a motorized mechanical horse designed specifically for use in hippotherapy. The preferred implementation of the design is shown in Figure 12. The device was driven by a set of cams and springs. This patent claimed that the machine was capable of producing a six-degree-of-freedom motion that replicated the motion of a horse exactly [55]. This is the only patent that provided data regarding how and what information was gathered from actual horses and how it was used in the development of the motion generated by the machine. The cam system allowed the user to change out the cam system for a different set representing a different motion. It used a split-seat to generate accurate motion [55]. To date, no information can be found on whether or not this horse machine was ever constructed or whether it will ever be made commercially available.

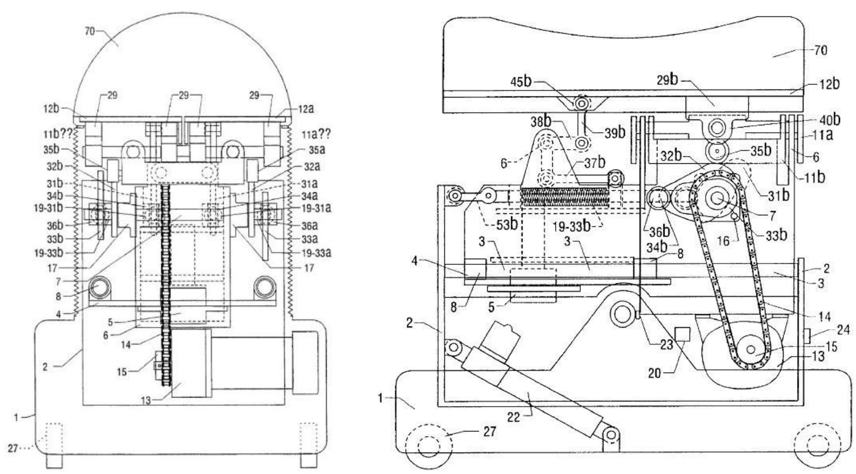


Figure 12: Nalty Hippotherapy Simulator Front View (Left) [55], Nalty Horse Simulator Side View (Right) [55]

*Robotic Horses for Research, Exercise, and Therapy*

There have been several robotic horse machines developed in Japan, China, and France, though none of them have become commercially available. Development of two quadruped robots with the intention of replicating horse gaits occurred from 1997-2003 [93, 94]. The machine designed by Makita *et al* is shown in Figure 13. These might be useful for transporting heavy loads or in construction or military applications, but are not yet useful for therapy applications.

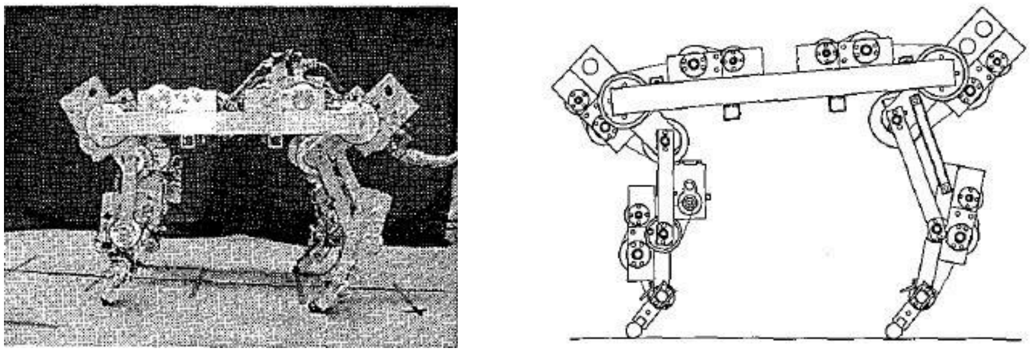


Figure 13: Quadruped Horse (Left) [93], Drawing of Quadruped Horse (Right) [93]

The development of stationary robotic horse machines which use some configuration or variation of a Stewart Platform started in 1995. These machines have all been intended for use in exercise and therapy applications, though none have been made available to the public. Three of these robotic horses all operated by means of six linear actuators arranged after the fashion of a Stewart Platform, in which there was a bottom platform and a top platform and between which the actuators connected the two platforms in an alternating diagonal fashion, as shown in Figure 14: Left. Mounted to the top platform was a mobile horse-shaped body, usually a hard plastic replica of a horse form including the torso, neck, and head capable of accommodating a saddle and supporting up to 150 kg [95-98]. Data was collected from living horses and translated into code, then transmitted to the computer-controlled platform. Real-time manipulation of the motion was possible [95-98]. In 2009 the 6-PSS Bionic Parallel Machine Horse, which used six linear actuators arranged orthogonally to one another to achieve full six degree-of-freedom range of motion, was developed. It is shown in Figure 14: Center. These actuators were all connected to a central mobile horse body. This machine was also equipped with several sensors capable of reading signals from the body, such as heart rate and blood pressure, allowing it to interpret this information and make adjustments to the speed and motion of the horse in real-time. Various factors such as length of actuators, interference concerns, and range of rotation on end effectors limited the range of the workspace in which the horse machine was free to move [99]. No data is available to confirm how closely the 6-PSS Bionic Parallel Machine mimicked a horse.

Figure 14: Stewart Platform Mounted Horse (Left) [96], Bionic Parallel Robotic Horse (Center) [99], Karakuri Horse (Right) [100]

There have also been two distinct horse machines integrated with virtual reality systems. The horse developed by Shinomiya *et al* in 1997 operated on the same Stewart Platform concept as the previous horses and was developed with medical research and therapeutic applications expressly in mind. It used two computer systems to control both the motion of the horse and the virtual world which responded to activation of sensors strategically located on the horse, thus allowing the rider to control the speed, gait, and direction. Control of the horse was simulated by signaling sensors with rein, leg and hip control. The virtual reality system incorporated such data and used it to change the scenery and sounds of the virtual reality display system and also to control the gait, speed, and tilt of the horse, thus making the system fully interactive. The horse was covered in suede to have a realistic feeling, and included saddle, reins, and stirrups [98].

The second virtual reality machine was the Karakuri Horse developed by Kijima *et al* in 1999. This horse is shown in Figure 14: Right above. This horse had a virtual reality system much like the previous one, in which the virtual reality system displayed changes in scenery, sounds, and motion of the horse in response to user control. However, this horse operated by completely different means, as it is part of traditional Japanese Karakuri, in which a single craftsman utilizes complex designs and limited actuators to realize the motion goal. The process of Karakuri is unique to the individual and "it is difficult to reproduce the product and mass-production is almost impossible [100]." This mechanism used four motors to drive the motion of each foot separately and contained over 70 links and components in each leg. Like the previous horse, this machine was also covered in fur and was modeled to be similar in size and shape to a real horse.

### *Modern Mechanical Horses*

Mechanical horses that have become available on the market in recent years include the Panasonic Joba, the Human Touch iJoy Ride and iJoy Twist, the OSIM iGallop, the Equicizer, and the Ridemaster Pro Dressage Simulator. While the Joba, iJoy Ride, iJoy Twist, and iGallop horses may appear to have horse-like motion, there has been no evidence to verify or check how closely the motion generated by these machines comes to that of a live horse, nor do all of these mechanisms move in all six-degrees of freedom. These mechanical horses are shown in Figure 15.

Figure 15: Joba (Left) [103], iJoy Ride (Center-Left) [104], iJoy Twist (Center-Right) [105], iGallop (Right) [106]

The motion that they generate in some directions tends to be smaller in magnitude or out of phase with that of a live horse. “One movement cycle of the Joba fitness apparatus consists of a set of back and forth swing/slide of the saddle, swaying left and right and returning to the initial position [101].” Some of these horses use a simplified movement to simulate the up and down motion of a horse in order to cause the rider to bend forward and straighten up [102]. This is because these horse-like models tend to be for exercise rather than for therapy. The machines contain complex internal parts, including four-bars which require high tolerances for machining in order to achieve proper operation. The rigid internal components provide no laxity, which may result in a jerky movement that is not smooth such as real horse motion.

The Equicizer is not self-powered, but is driven by the motion of the user or the external application of force by a helper (Figures 16: Left and 16: Center-Left). The Ridemaster Pro Dressage Simulator (Figures 16: Center-Right and 16: Right) is capable of producing different motions based on various gait patterns of living horses, but there is no evidence to show how close these motions come to that of a living horse. This machine is priced in the range of $50,000-$70,000 and includes an interactive virtual reality system, complete with sensors “in the mouth, head, and neck [that] measure the amount of tension in the reins and regulate pace [107].”  There are also sensors on the sides and bottom of the horse body that regulate the position of the legs and the rider’s weight distribution [107].

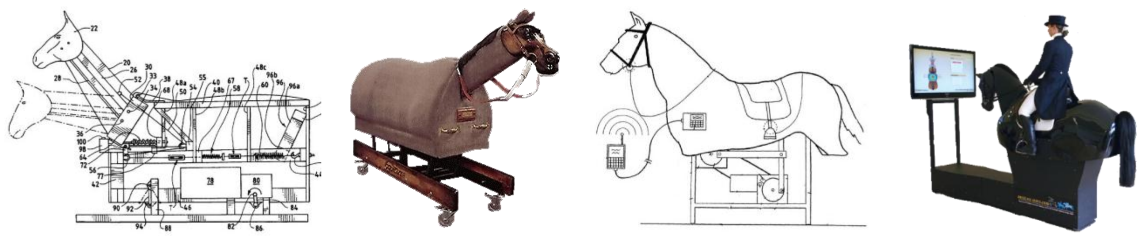


Figure 16: Equicizer Internal Components (Left) [76], Equicizer (Center-Left) [108], Dressage Simulator Internal Components (Center-Right) [80], Dressage Simulator (Right) [109]

*Literature Review: Studies Conducted with Mechanical Horses*

“Skepticism, due to its unconventionality and lack of evidence-based research, hinders a broad acceptance of hippotherapy [110].”  The majority of hippotherapy studies that have been conducted generally have small sample sizes so that broad-reaching implications seen in the research cannot be established.  The experimental conditions are never repeatable, and the most common method of assessing hippotherapy is by performing standardized testing before and after the therapy to look for changes in balance, strength, and functionality.  A few experiments have been conducted with mechanical horse apparatuses, as follows.

In 1998 Quint *et al* conducted an investigation in which participants either spent 10 minutes riding the Brunel Active Balance Saddle or sitting on a static saddle over the duration of 4 weeks.  “The development of a mechanical saddle – the Brunel Active Balance Saddle (BABS) – enabled us to test whether horse riding did facilitate pelvic movement [6].”  BABS was chosen because it was the only commercially available mechanical horse.  Quint *et al* believed the mechanical horse to be advantageous over the use of a live horse because it made it possible to exactly reproduce riding sessions because the BABS had a consistent cyclic motion, the speed could be adjusted and fine-tuned, it could be used in various locations (including indoors where weather would not be a potential problem and locally so that transportation would be reduced), and because it "require[d] less manpower than conventional horse riding to maintain and operate, and thus [was] cheaper to run [6]." Quint *et al* concluded that participants riding the BABS had experienced a greater increase in passive range of antero-posterior pelvic tilt compared to their stationary saddle counterparts.

In 1999 Kuczynski *et al* performed an experiment in which study participants rode a mechanical saddle for a duration of three months. They used the BABS, stating that the "movements are 3D and mimic the horse's walk [111]." They concluded that mechanical horseback riding led to an improvement in balance and postural stability.

In 2003 Benda conducted a study in which participants were asked to sit astride a barrel for eight minutes or sit astride a horse during a hippotherapy treatment for 8 minutes. "Eight minutes of hippotherapy, but not stationary sitting astride a barrel, resulted in improved symmetry in muscle activity in children with spastic cerebral palsy. [3]." Benda *et al* concluded that increases in symmetric muscle activation were the result of the application of movement of the horse [3].

In 2007 Lechner *et al* conducted a study that compared the effects and benefits of hippotherapy with those achieved by sitting on a rocking stool or sitting astride a stationary Bobath roll [112]. Pictures of the rocking stool and Bobath roll are provided in Figure 17. The rocking stool was intended to mock the rhythmic stimulus of horseback riding and possibly improve balance, coordination, and strength. The Bobath roll was intended to mimic sitting astride a horse and potentially improve spasticity and tonicity by passive and sustained stretching. The subjects were subjected to four weeks of each intervention. Lechner *et al* concluded that hippotherapy and not either of the other two interventions was successful in reducing spasticity and improving mental-wellbeing.

Figure 17: Bobath Roll (Left) [112], Rocking Stool (Right) [112]

In 2008 Zurek *et al* designed a study in which participants received 10 minutes of mechanical horseback riding while data was collected on the temperature of the limbs before and after the intervention. Zurek *et al* claimed that mechanical horseback riding had "the advantage of being possibly performed on a regular basis and [was] weather-independent [113]." It was found that skin temperature decreased in both disabled and healthy patients after the intervention. No note of what mechanical horse was used in the study was made.

In 2009 Shurtleff *et al* conducted an experiment during which disabled children received hippotherapy over the duration of a 12-week period. They gathered video motion capture data both before and after hippotherapy by having the subjects riding a mechanical barrel that moved in one translational direction only and processed the results of head and trunk stability compared to data collected from healthy children of the same ages. The mechanical barrel enabled the exact replication of testing conditions and also made experimental observation easier by moving the testing facility and apparatuses from the arena to the laboratory [22]. "Laboratory testing [was] likely to reduce testing variability because the mechanical barrel produce[d] precisely the same challenge perturbation every movement cycle, whereas it has been reported that kinematics (*i.e.*, tempo and stride length) of the same horse's gait very substantially even at the walk [22]." Shurtleff concluded that hippotherapy was effective at improving trunk coordination [22].

In 2009 McGibbon *et al* conducted a study in which participants received either a 10 minute hippotherapy session or 10 minutes sitting astride a "55-gal drum approximating the girth of a horse, covered with a fleece pad, and mounted on supports at the approximate height of an average horse [114]." The children were also shown a video about horses to maintain their attention during the 10 minute interval. EMG data was recorded during walking from electrodes placed on the upper thigh [114]. "After intervention, the hippotherapy group demonstrated significantly less adductor muscle asymmetry than the barrel-sitting group [114]."

In 2010 Hosaka *et al* conducted a study to determine the effect of mechanical horseback riding on insulin sensitivity and resting metabolism in diabetes patients. The Panasonic Joba was used to simulate horseback riding. "By repeating a synchronized, three-dimensional movement pattern, the riding simulator continuously and rhythmically impose[d] unconscious muscular reactions on the user to maintain both balance and upright posture [101]." Hosaka *et al* concluded that riding the Joba improved insulin sensitivity, improved basal insulin resistance in diabetic patients, and increased the resting metabolic rate. An advantage of using a mechanical horse was that exercises could be performed on a daily basis at home.

In 2010 Herrero *et al* also used a Panasonic Joba to study possible therapeutic effect of mechanical horseback riding, citing the ability of the horse simulator to produce repetitive and identical movement patterns as the main advantage of its use [5]. Participants were asked to sit on the Joba for 15 minutes with it switched either on (moving) or off (stationary). Results from the study have not yet been published.

## *Conclusion*

The mechanical horses currently available leave room for improvement in both design and function. The majority of these mechanical horses are not practical in a therapeutic setting due to both their size and lack of safe, stable seating and due to their fast-paced, jarring motion. Many of these mechanical horses are also unavailable for purchase, and are therefore unable to impact the field of hippotherapy. We see a distinct need for the development of a machine that moves identically to a horse and that is safe, economical, robust, and practical for therapeutic use. "Even if one could invent a machine to do all this, one could never duplicate the warmth and the sensory stimuli, not to mention the tremendous boost to the ego, afforded by the horse [13]."

It should be made clear that the goal of building a functional mechanical horse is not to replace hippotherapy but to improve accessibility to it and to supplement it in anyway necessary. Such a mechanical horse would expand access to hippotherapy to patients and clinics currently unable to perform hippotherapy due to a lack of facilities. This mechanical horse would also negate the effects of weather and allow hippotherapy intervention to continue through perilous and stormy weather or through the extreme heat and chill of summer and winter.  This mechanical horse would also supplement hippotherapy by enabling the training of weak, inexperienced, or fearful patients by helping them achieve the capability to ride a living horse.

Furthermore, the development of a dependable, economic, and readily available horse capable of accurately recreating the motion of any therapy horse would be a valuable tool in applications to research.  This would allow the many variables and aspects of hippotherapy to truly be tested, and research could be conducted that would help to determine what kinds of motion and what lengths of session duration are most beneficial.  Research on how and what aspects of hippotherapy work towards promoting a therapeutic goal could also be conducted.

# CHAPTER FOUR

## Mechanical Horse Prototype #1: Mr. Ed

In 2009 the Baylor University Department of Engineering requested that a group of fifteen senior engineering students develop a prototype therapeutic mechanical horse intended for use in the rehabilitation of injured or disabled persons. The motion of the mechanical horse was required to accurately imitate the motion of a live therapeutic horse's gait, as provided by Dr. Garner. The mechanical horse was designed to be capable of moving a maximum user load of 250 lbs. in a cyclic, three-dimensional translational and rotational pattern imitating equine walking gait. This was achieved through the development and construction of a complex system of mechanical linkages all powered by a single AC motor. This prototype is referred to as Mr. Ed.

The first prototype therapeutic mechanical horse consisted of three major subsystems. The first subsystem was made up of a seat, grips and handles, a base with casters, and shielding. Together these components provided a structure for the horse body, a housing for its internal components, saddle seat for the user, and a protective boundary between moving parts and users. The second subsystem consisted of three devices that together produce equine motion at the saddle. There was one planar four-bar mechanism located in the middle section of the horse, which restricted one degree of freedom. There were two spherical four-bar mechanisms, one located at the anterior end and one at the posterior end of the horse, which together restricted five degrees of freedom. The final subsystem included all electrical components and power transmission devices.  This included a motor, gearbox, speed-controller, chain, and sprockets which were all used to turn the motion devices simultaneously.

### *Equine Motion Data Collection*

The pattern of motion that Mr. Ed followed was based on data obtained from previously conducted motion-capture studies performed at a local hippotherapy clinic on living therapy horses [44].  This data was collected in accordance with an approved Baylor IRB protocol.  To achieve this three-dimensional motion, it was necessary for Mr. Ed to have six-degrees of freedom.

A four-camera video motion capture system was used to record the movements of both a horse and rider during a simulated hippotherapy session.  During each session, a horse and mounted rider were led by a trained hippotherapist at a slow walking pace through a predetermined, calibrated observation space.  Three light-emitting markers were adhesively attached to distinct points on a western-style saddle.  Three more light-emitting markers were adhesively attached to the left iliac crest, right iliac crest, and L1 process of each rider's pelvis.  The motions of several therapeutic horses and several volunteer riders, ages 8-12, were recorded.

The data from the video was manually tracked and smoothed using SimiMotion (SIMI Reality Motion Systems GmbH, Unterschleissheim, Germany).  The data was then normalized in time so that the gait cycle between the various horses could be directly compared.  After subtracting out the forward motion of the horse, computer models simulating the motion data from each trial were built.  Data from one particular trial of one particular horse was chosen for its symmetry and was used as the target motion for the Mr. Ed prototype. Testing of several mechanisms revealed that a spherical four-bar was best suited to replicating our target motion [115].

### *Design and Construction*

Design and construction of the mechanical horse project were accomplished by a senior design team of 15 engineering students, advised by Dr. Garner. Design of the mechanical horse device was divided into three major subsystems: a structural system including the base, saddle, and support structures, the motion system including three motion-delivery mechanisms, and the electronic system including all power and transmission components, as shown in Figure 18 below. Operation of the mechanical horse was achieved by turning three separate linkage mechanisms that were permanently

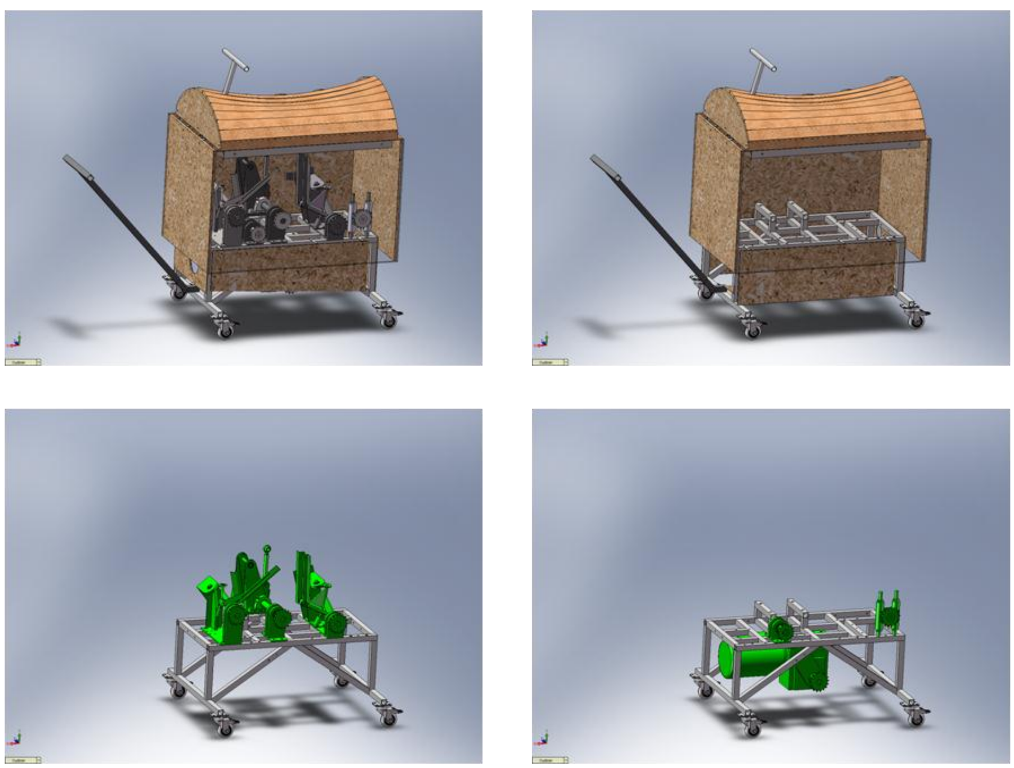


Figure 18: Mr. Ed Prototype (Top-Left), Structural System (Top-Right), Motion Driving System (Bottom-Left) and Electronic System (Bottom-Right)

mounted to a rigid base structure. Prescribed motion from each mechanism was translated to three distinct points fixed to the rigid saddle platform structure.

The structural system included the stable base of the device, grips and handles, external shielding, and a saddle platform intended to comfortably support a rider. The base of the device provided a supporting infrastructure to which all other mechanisms were mounted and was designed for stability by considering the user's center of gravity, which would be suspended above the device. The base structure and component mountings are shown in Figure 19. The grips and handles simply provided handholds for transporting the mechanism or for maintaining balance when riding the horse. The shielding was designed to ensure the safety of users from internal moving parts without inhibiting the function of any component or the mechanism as a whole. The saddle of Mr. Ed was modeled after the anatomical features of a live horse and was designed to approximate the size, shape, and curvature of the back of a typical horse, as can be seen in Figure 19 below. The saddle platform also accommodated the use of a western saddle and was intended for use by two riders simultaneously, as might be required with patients who are unable to maintain their own posture. The saddle platform was suspended above the base by way of the three rigid connection links, each mounted to a specified point on one of each of the four-bar mechanisms in the motion system.

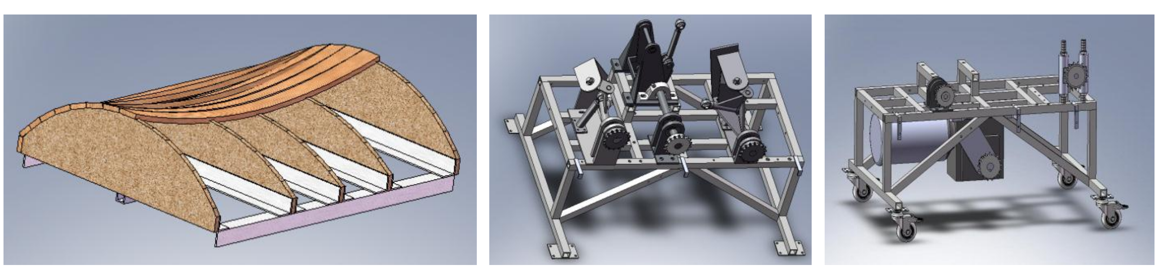


Figure 19: Seat Structure (Left), Mechanism Mounting (Center), Power Transmission Mounting (Right)

The motion generated by Mr. Ed was driven by three carefully designed four-bar mechanisms, which together drove the seat structure in a specified pattern while the bottom support structure remained stationary. Of the three mechanisms, one was a planar four-bar and the other two were spherical four-bars (spherical mechanisms). The parameters considered for the design of each mechanism included the geometric dimensions and the potential for physical implementation of the base, crank, coupler, and rocker links. Also considered were the attachment locations of each coupler link (attachment from coupler end effector to saddle frame). Each linkage geometry was optimized using custom software to reproduce the target motion. These mechanisms converted the rotational motion generated by a motor into a variety of motions, in this case into elliptical and infinity-shaped patterns, and translated it to the saddle through the designated connection points.

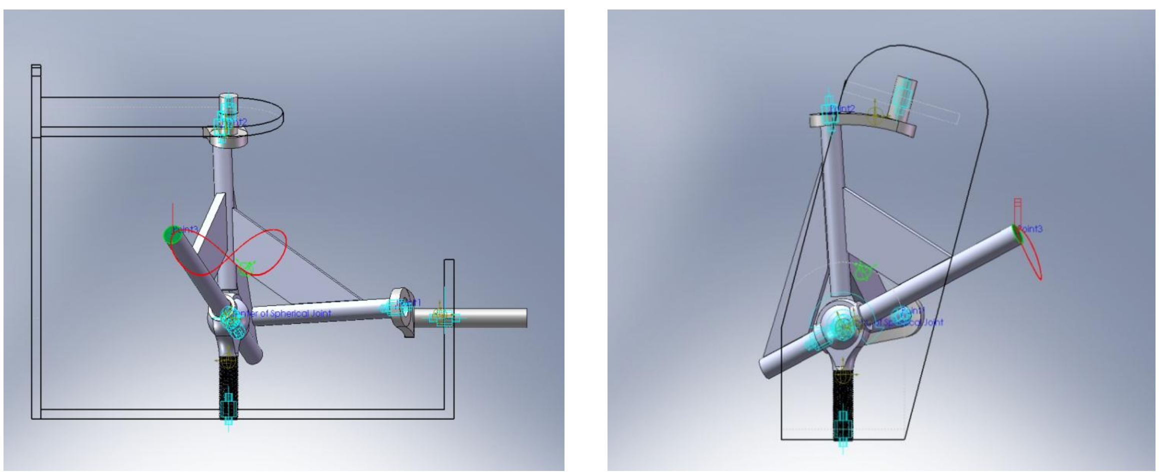


Figure 20: Motion Path of Back Spherical Mechanism

An example of one of the four-bars is given in Figure 20. The red line demonstrates the path of one of three prescribed motion patterns. In all cases, the coupler link was used for the end-effector as it provided the greatest variety of motion pattern possibilities. Physical construction of these linkage mechanisms followed designs derived from the computer simulations to recreate the target motion patterns.

The two spherical mechanisms together accounted for the primary pitch and yaw motion of the mechanical horse, and the planar mechanism provided the primary rolling motion of the horse. Each mechanism is shown in Figure 21 below. The spherical mechanisms were located medially, with one anterior and one posterior. The planar mechanism was positioned centrally and laterally. Two spherical mechanisms theoretically defined the necessary six degrees of freedom, however because they are both fixed with respect to each other there is a redundancy on the line between the end effectors of the two mechanisms. The planar mechanism was used to resolve this redundancy and to provide a better means of creating the roll motion needed to replicate the motion of a live therapeutic horse’s gait cycle. The end effector of the planar mechanism was connected to the saddle platform point by way of a pivoting rod to avoid over-prescribing the saddle motion.

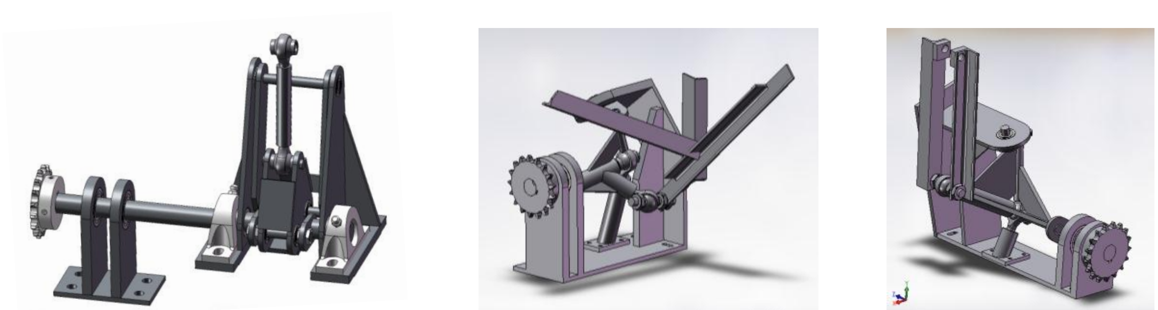


Figure 21: Planar Mechanism (Left), Front Spherical Mechanism (Center), Back Spherical Mechanism (Right)

These four-bar mechanisms were driven and controlled by the electronics system, which included a 1.0 hp AC motor, 40:1 reducer gearbox, and 1.0 hp AC drive speed-controller, as well as power transmission components. The motor was connected to the gearbox in order to reduce the output rotational speed of the motor from 1800 rpm to 45 rpm. A single chain connected the drive shafts of each mechanism to the drive shaft from the gearbox, as can be seen in Figure 22. Various idler sprockets and tensioner sprockets were used to maintain a sufficient number of teeth on all drive shaft sprockets, to direct which side of the driveshaft sprocket to turn (direction), and to maintain the appropriate tension in the chain. This arrangement enabled all mechanisms to be powered by a single motor and, thereby, kept each mechanism in sync with the others.

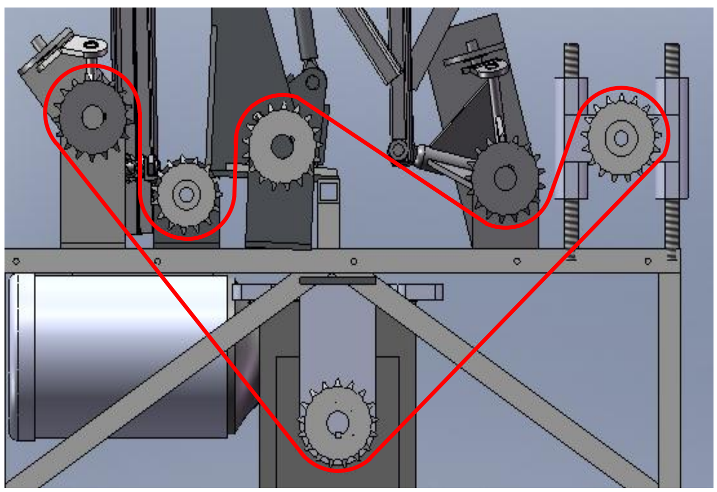


Figure 22: Power Transmission Subsystem

*Results and Limitations of Mr. Ed*

The video motion capture system was used to record motion of the mechanical horse and compare it to the target motion derived from the live horse. Examples of the motion of Mr. Ed and the target data are shown in Figures 23 and 24. Graphs of the translations and rotations in other directions are available in Appendix D. For these graphs, x-translation corresponds to forward-backward motion, y-translation to upward-downward motion, and z-translation to leftward-rightward motion. The x-, y-, and z-rotations correspond to list, twist, and tilt about their respective axes. The Mr. Ed prototype was successful in recreating the same general trends in magnitude and three-dimensional patterns of motion that were seen in the target data. However, at some instances during the gait cycle, the motion of Mr. Ed was out of phase with the target motion, which resulted in deviations from the target data of several centimeters. There is opportunity to improve motion accuracy, increase symmetry, and reduce noise in future prototypes.

The results of this design project indicated that the mechanisms which drove the motion of Mr. Ed required a precise degree of machining and assembly. The concept had inherent limitations in that, to achieve the desired motion, the back spherical mechanism was at a leveraged disadvantage. It could slip into a singularity when standard operational loads located over the posterior end of the horse caused the rocker link to rock past its normal limits and to begin rocking 180 degrees opposite of its correct location. This singularity caused the back spherical mechanism's coupler link to trace an arched path instead of an infinity pattern, which caused operation of the horse to bind up and come to an abrupt stop. Because of this essential design flaw, Mr. Ed could only support about 130 lbs. positioned on the front-half of the saddle. Ideally it needed to be able to support the user loads of both the patient and an instructor or one full-grown, large patient, about 250-300 lbs.

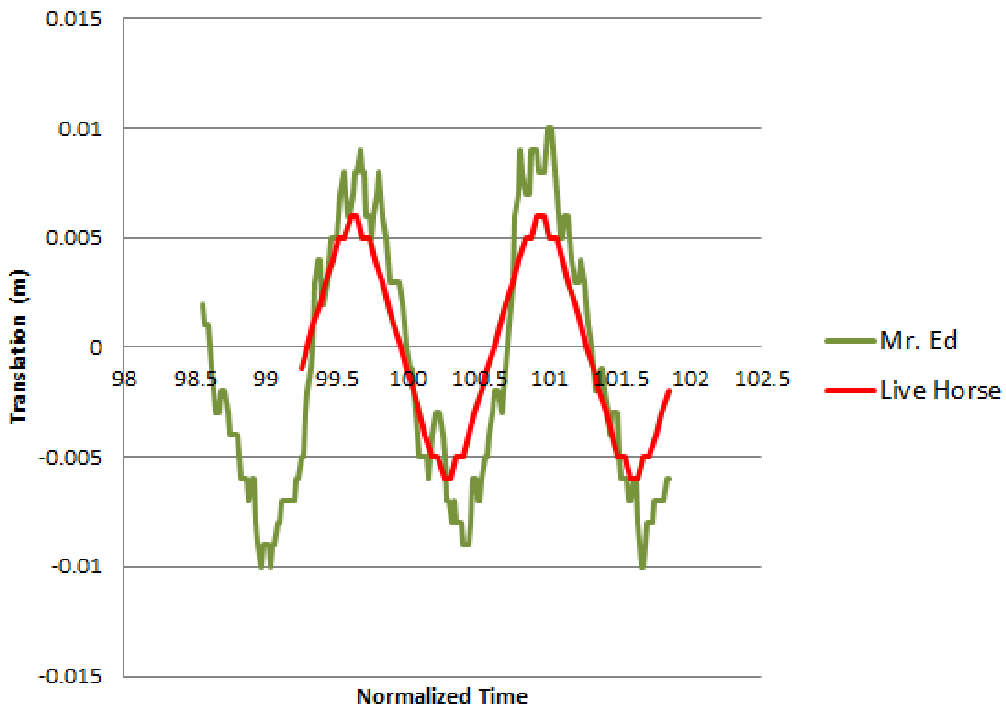



Figure 23: Mr. Ed Prototype Y-Translation

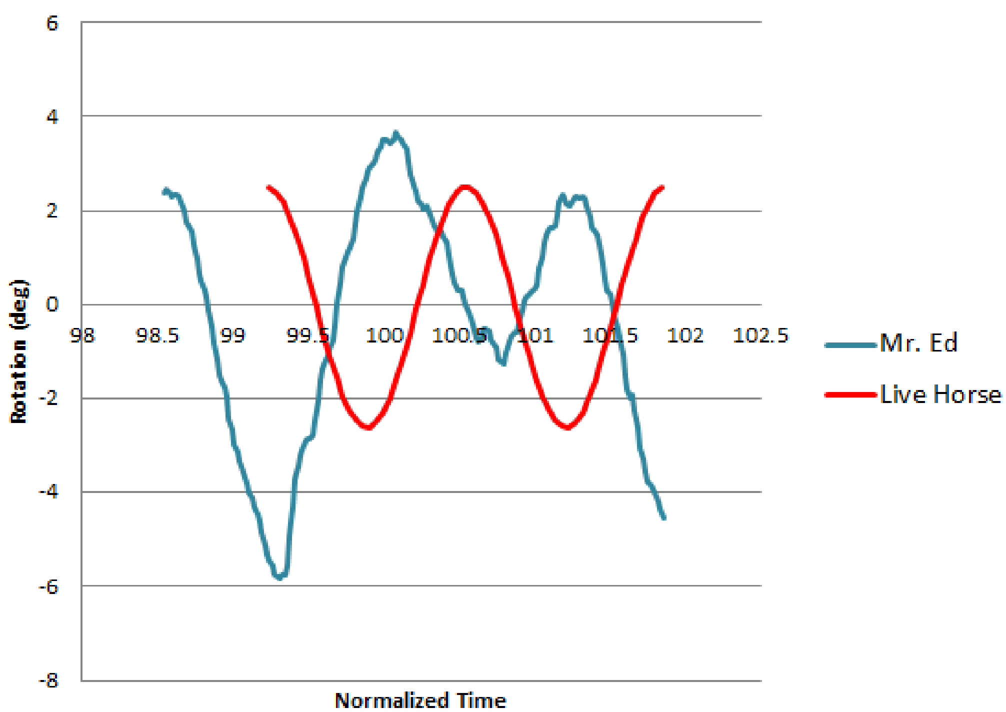



Figure 24: Mr. Ed Prototype Z-Rotation (Pitch)

*Second-Generation Development*

Mr. Ed was limited to one gait pattern. The cycle speed could be varied but would not correspond to the way a horse's gait would change at different speeds. This meant that Mr. Ed was not capable of a trot or gallop but only a walking gait. A new design concept is desirable in which internal mechanisms will be interchangeable and allow for a variety of gaits and speeds, corresponding to different therapy horses, different walking patterns, tempos, cadences, and different terrains.

Figure 25: Mr. Ed Prototype

There is also room for improvement on several of Mr. Ed’s components. The shielding design would be safer if the entire perimeter of the mechanism was covered. This would prevent injury by making it impossible for users to reach inside the internal compartment of the horse. Also, the shielding was previously mounted on the saddle platform as shown in Figure 25 and, as such, moved with the saddle. It occasionally interfered with the base structure. This was problematic, inefficient, and loud. A new shielding design, in which the shielding is mounted to the base structure would be preferred.

The large force being carried by the planar mechanism caused it to periodically and abruptly drop, which caused an undesirable jolt in the motion of the horse.  To dampen this abrupt and undesired noise in the motion, a compression spring could be added in close proximity to the planar mechanism.  The addition of such a spring could help the planar mechanism to carry its load during the upward phase of its rotational motion.  For instance, the compression spring would exert an upwards force on the saddle as the planar mechanism also moves the saddle upwards, thus reducing the load on the planar mechanism.  However, during the downward phase of the planar mechanism's rotational motion, the force of the spring would be acting in direct opposition to the planar mechanism.  In this case, the compression spring would be compressed as the planar mechanism moves the saddle downwards.  As the spring is compressed, the upward force it exerts on the saddle increases and, thereby, increases the load on the planar mechanism.

To remedy the possibility of the mechanism falling into a singularity, two large springs could be installed at the posterior end of the horse.  These springs would be located in the internal compartment of the horse, just behind the back spherical mechanism.  As the saddle is pulled downward by the mechanisms, the springs will push upward on the rear of the saddle, forcing the back spherical mechanism into the correct position.  Other options for preventing the singularity include redesigning the entire mechanism and adjusting linkage dimensions.

# CHAPTER FIVE

## Methods and Prototype Design

### *Design #1*

#### *Introduction*

After the discovery of the problems encountered with the first prototype, we decided to design a second prototype based on a completely new design concept. It occurred to us that we might be able to use compression springs to support and suspend the saddle and user, while still allowing for flexibility in the range of movement. However, the springs would need to be arranged in a way so as to fully drive all six degrees of freedom of the saddle. The use of compression springs would require the implementation of a tensioned cable system in order to provide a resistive force that could be applied against the springs. A cam system could then be attached to the tensioned cables and drive the desired saddle motion. It was decided that an arrangement commonly used in robotics, referred to as a Stewart Platform, would suit our needs. A Stewart Platform is traditionally made up of six linear actuators, which work together to drive a platform with six degrees of freedom [116]. Each of the linear actuators is connected on one end to a base platform and on the other end to a mobile platform [116]. Connections between the actuators and platforms are formed by ball-and-socket or gimbal joints [117]. The linear actuators are usually arranged so that six distinct connection points on both platforms form regular or semi-regular hexagons [117]. The base platform remains stationary. The mobile platform can move three-dimensionally within a set range of motion. The range of motion is limited by the length of actuation displacement in the linear actuators, limits on the desired minimum distance between the platforms, and the range of rotation available in the joints connecting the linear actuators to the platforms [117].

*Design Concept*

The theory of operation behind our design was based on the use of a Stewart Platform in which the six linear actuators were a combination of compression springs and tensioned steel cables. The system was arranged so that a tensioned cable ran parallel to and through the central axis of each of six compression springs, as shown in Figure 26:

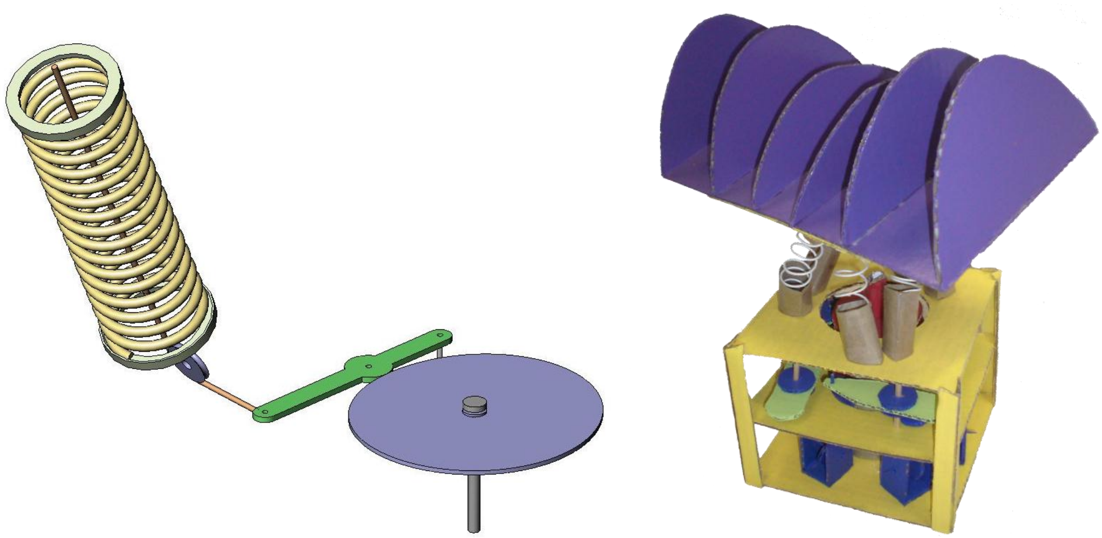


Figure 26: Spring, Cable, and Cam Design Concept (Left), 1/5 Scale Cardboard Model (Right)

Left. When in operation, the compression springs would resist any compressive force created by the weight of the user and saddle while the cables, which were to be controlled by a cam-system, would independently pull the saddle towards the base and thereby control the motion. The cams were to be designed so that one complete rotation of the camshaft would correspond to one full gait cycle of the horse. A quick 1/5 scale cardboard model was constructed to help identify geometrical constraints and is shown in Figure 26: Right.

*Computer Models*

From June 2010 to August 2010, computer models of the design were built using SolidWorks (SolidWorks Education Edition 2009 SP4.0, Dassault Systèmes SolidWorks Corp., Concord, Massachusetts), as shown in Figure 27. The computer models were built at a 1/5$^{th}$ scale so that a scale model could be built to test and validate the design concept.

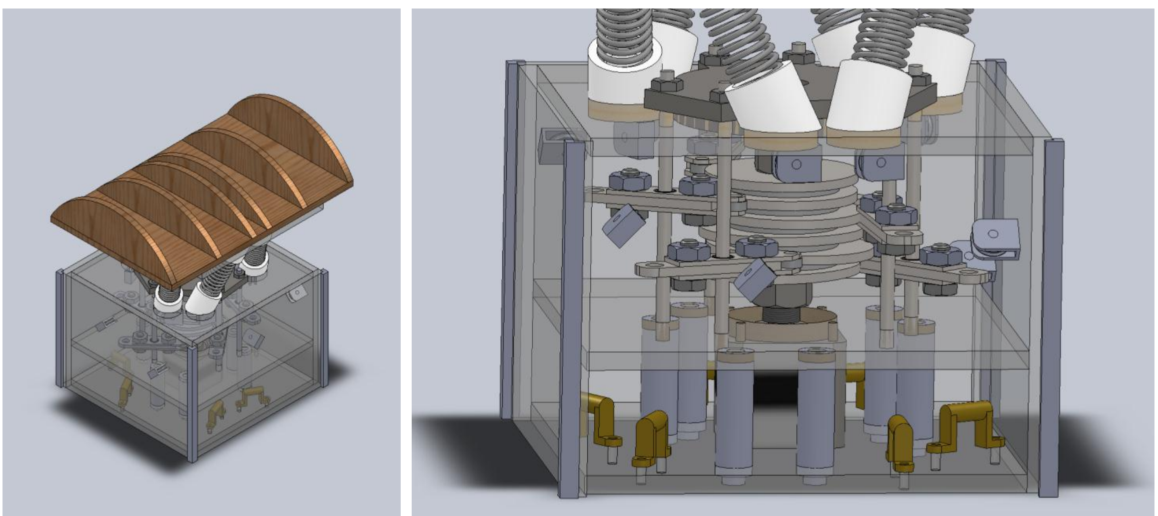


Figure 27: 1/5 Scale Computer Model (Left), Close-Up of Internal Components (Right)

The design consisted of four unique functional levels, as shown in Figure 28. Starting with the uppermost level, the levels were the saddle platform (Figure 28: Left), the spring platform (Figure 28: Center-Left), the cam platform (Figure 28: Center-Right), and the tensioner platform (Figure 28: Right). Each platform was named for the functional components mounted to it.


Figure 28: Bottom View of Saddle Platform (Left), Top View of Spring Platform (Center-Left), Top View of Cam Platform (Center-Right), Top View of Tensioner Platform (Right)

The saddle platform was directly mounted to the saddle seat and also contained spring and cable mounting components. The saddle was designed to imitate the contour and size of a horse's back. On the underside of the saddle platform, a removable plate was attached. This plate can be seen as feature A in Figures 28: Left and 29: Left. Mounted on the removable plate were six hollow, cylindrical receptacles that were intended to hold the compression springs in place while still allowing them to rotate freely about their central axes. The receptacles were also designed to align and incline the springs at a specified angle. One receptacle is circled in Figure 29: Left. In the center of each spring receptacle and mounted to the saddle itself were eye-bolts intended as the attachment site for the cables.

The spring platform was located approximately 3 inches below the saddle platform, was 6 inches square, and had a 3 inch diameter hole located centrally. Six more cylindrical spring receptacles were mounted to the spring platform in order to secure the opposing ends of the springs, as shown with feature B in Figure 29: Left. On both the base platform and the saddle platform, the spring receptacles were arranged in three pairs equally spaced around a circle with a 3 inch diameter. Also mounted on this platform was an end support for a camshaft that spanned the space of the 3 inch central hole. A bearing was installed in this end support to allow for free rotation of the camshaft. The end support is circled in Figure 29: Right.

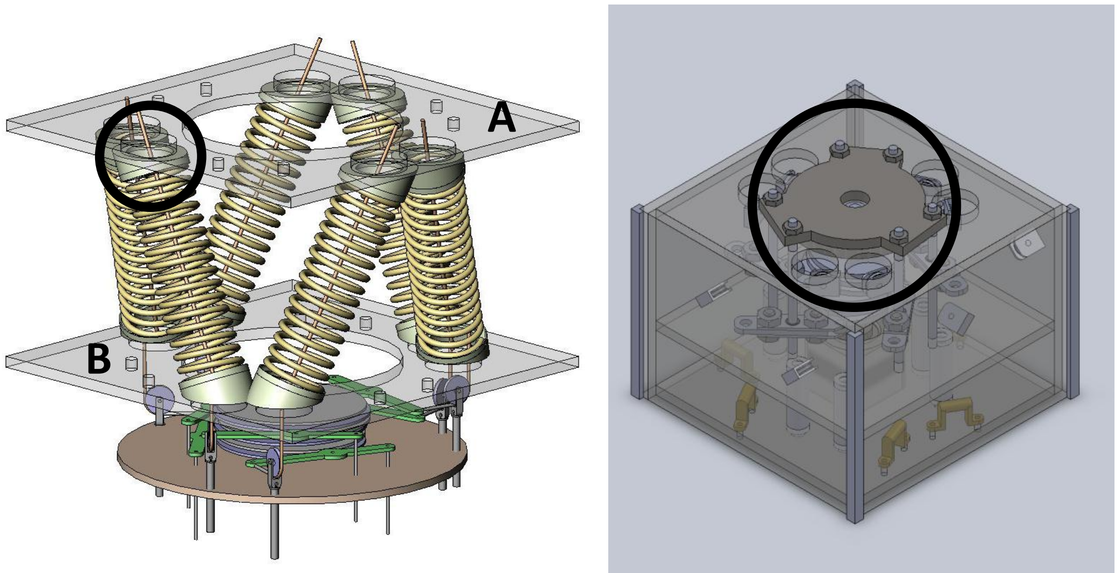



Figure 29: Spring Platform on Model (Left), Spring Platform with Springs (Right)

The cam platform was located 3 inches below the spring platform and was also 6 inches square. The platform contained a 1 inch central hole for the camshaft, six 1/2 inch holes for mounting the tensioners below, and six 1/8 inch holes located circumferentially to the central hole (Figure 28: Center-Right). Between the cam platform and the spring platform was housed a camshaft positioned in the center and oriented along the vertical. Six cams were mounted on the camshaft. These cams are shown as feature A in Figures 30: Left and 30: Right. In contact with each cam was the corresponding central end of a cam-follower. Cam-followers are shown as feature B in Figures 30: Left and 30: Right.

Six cam-follower axles were paired and spaced circumferentially about the center of the platform. Cam-follower axles are labeled as feature C in Figures 30: Left and 30: Right. The cam-followers were designed to resist bending and also to accommodate the use of a roller bearing for contact with the cam. The cam-followers consisted of three structural components: one central 1/8 inch thick steel link and two 1/16 inch thick steel external links. The central link was shorter than the external links and had a hole in the distal end used as the attachment site for the cable. The external links extended past the central link and supported a roller bearing. A central hole allowed the insertion of a bearing for rotation about the cam-follower axle and two holes through all components allowed the cam-follower to be bolted together. In order to have space for each cam-follower to move freely, they were positioned in pairs equally spaced around the central cam axis. The pairs were as follows: cam 1 and cam 4 (lowest cam, upper-middle cam),

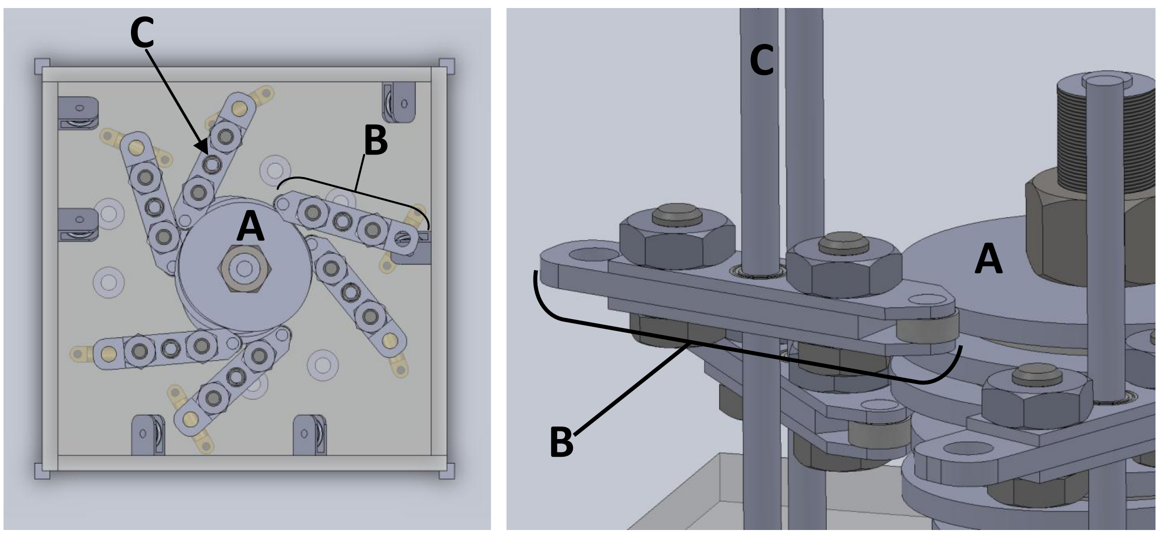



Figure 30: Cam-Follower Arrangement Top-View (Left), Close-Up of Cam-Follower (Right)

cam 2 and cam 5 (second lowest, second highest), and cam 3 and cam 6 (lower-middle cam, highest cam) in order to provide the maximum amount of space between each follower and its neighbor. This cam arrangement is shown in Figure 31. The cam-followers pivoted about a midpoint and translated motion through each end. The distal end of the cam-follower was attached by way of swaging to a steel cable. The cable was then relayed by means of two pulleys to the top of the spring platform, through the inside of a corresponding spring, and finally attached to the saddle. The pulleys were mounted to side panels running vertically between the tensioner platform and the spring platform. Pulleys were arranged so that interference between components would be minimized.

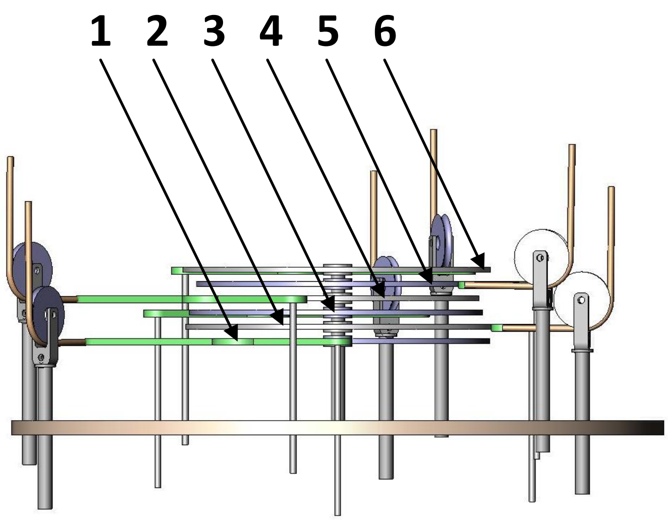



Figure 31: Vertical Arrangement of Cams and Followers

The final level was the tensioner platform. On this level the motor was housed directly below the centrally located camshaft, as shown in Figure 32: Left. Six tensioning devices were located on this level so that each cable could be separately tensioned as required. These are shown as feature A in Figure 32: Right. The tensioning devices were simply cylindrical rods mounted vertically between the tensioner platform and the cam platform in such a way that they would maintain the ability to rotate freely. A groove was added to a bottom projection, extending past the tensioner platform, so that each tensioner rod could be turned with a flathead screwdriver. The cables were relayed through the distal end of each cam-follower, down through the cam platform, and swaged to the middle of the tensioning rod. Rotation of the rod resulted in spooling of the cable around said rod.

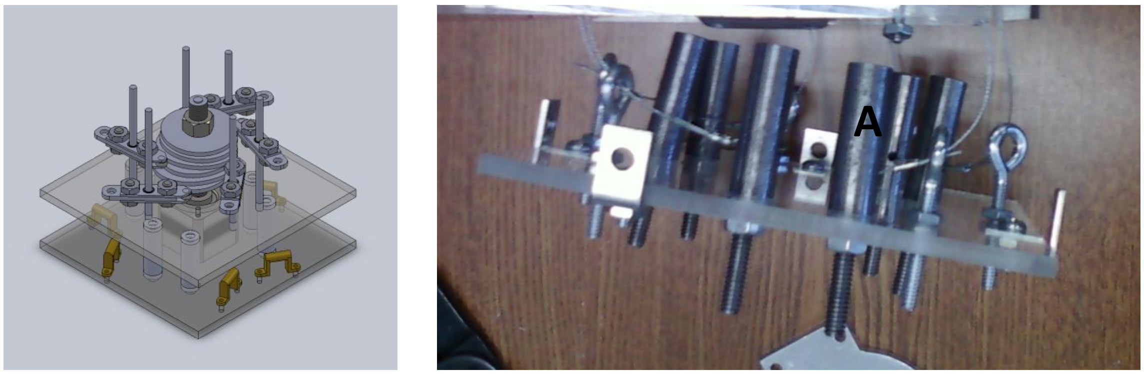



Figure 32: Tensioner Platform on Model (Left), Tensioner Platform and Tensioners (Right)

*Scale Model*

From August 2010 to October 1, 2010 I finalized the design and built the 1/5$^{th}$ scale model. The model accurately represented the dimensions and forces that would be seen in a life size prototype. The springs and motor were purchased. All other components, including the cams, cam-followers, pulleys, saddle, unit housing, and tensioners were manufactured in the Baylor Engineering Machine Shop. The pulleys were an assembly of 0.38 inch pulley wheels, bolts, and stock aluminum u-channel. The pulleys are shown in Figure 33: Left. The cam-followers were designed to accommodate the use of 1/8 inch miniature bearings for both the central end contact surface and the central bearing used in pivoting about the cam-follower rod. Cam-followers are shown in Figures 33: Top-Right and 33: Bottom-Right. Both the cams and cam-followers were machined with a CNC mill.

Figure 33: Pulley (Left), Cam-Follower (Top-Right), Cam-Follower Unbolted (Bottom-Right)

As the model was built, it became increasingly obvious that the springs were quite large and stiff in comparison to the rest of the system. Problems with the stiffness of the springs and alignment of the pulleys made it impossible to tension the model to the appropriate level. Images of assembly and of the completed model are given in Figure 34 below.

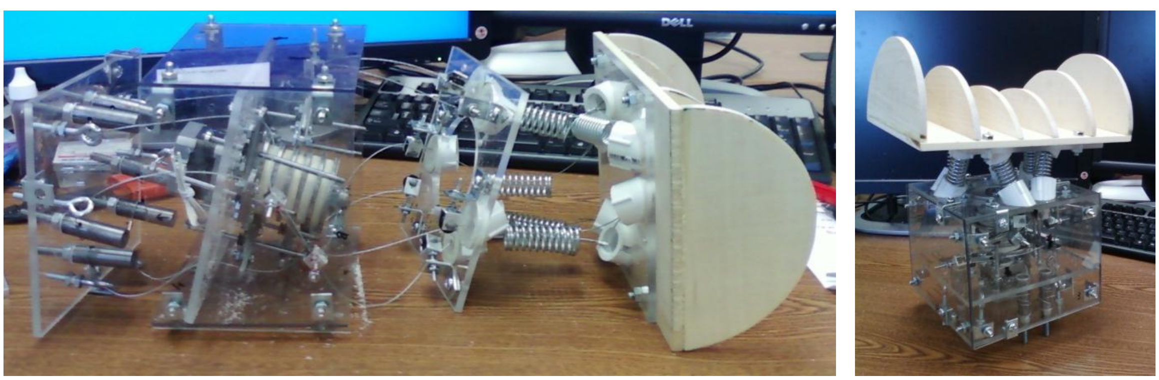


Figure 34: Assembly of Scale Model (Left), Completed Scale Model (Right)

*Disadvantages*

In order for this design to be operational, the springs would have to be pre-compressed in order to support the weight of any user upon their mounting the mechanical horse. Each spring would also have to be compressed to an initial level wherein the spring would be able to both compress and relax up to three inches. This proved to be a complex design problem, as the theoretical potential energy stored in each spring was quite large and had the potential of being dangerous during operation and maintenance. Even if the potential energy had not been a design concern, there was still the issue of compressing the springs before installation in the spring receptacles, as the fully extended springs would be misaligned with them and unable to be mounted in receptacles on both platforms simultaneously. Another major disadvantage of this design was the task of tensioning the cables. The cables would need to be tensioned so that, at the equilibrium position, the cables pulled the saddle with the same force being applied to it by the springs, thereby causing the saddle to be stationary. The cables would also need the capability of incremental tensioning for fine-tuning before operation. Practical implementation of the design was impossible to achieve.

*Design Conclusion*

After results of the scale model were less than convincing and after careful analysis of the forces and dimensions that would be required by the springs, we decided to find new springs that would be less stiff in order to decrease the potential energy and therefore the potential danger. However, using a less stiff spring also meant that we would have to find a longer spring in order to be able to pre-compress them far enough to support the user load. The reduction in potential energy came from requiring a smaller force to be used during operational displacement. Unfortunately, the necessary length plus the clash length of the spring meant that we would need a spring approximately two feet long. Such a spring would have made the mechanical horse taller than desired. Ultimately we abandoned the idea and proceeded to develop a second conceptual design.

## *Design #2*

### *Introduction*

Still utilizing the idea of the Stewart Platform arrangement, we endeavored to invert the roles of both the cables and the springs. We were now considering a system in which the tensioned cable would be pulling the saddle up and away from the base while tension springs would be pulling the saddle down towards the base. This concept proved to be advantageous in a number of ways. First, it eliminated the need for large, stiff springs. Instead we would now be able to use small, comparatively flexible tension springs. Second, the cables no longer had to play the role of compressing the springs, nor did they need to be aligned with the springs. Third, this design proved to be more efficient in comparison to the past design, in that this new concept was designed to work best with an increasing user load. The past design operated most efficiently with little or no user load.

### *Scale Models*

Still unconvinced that this idea would prove to be any more practical or realistic once physically implemented, it was decided to build scale models of both the original and the new conceptual design systems. Figure 35 shows the models, where design #1 models the first conceptual design using compression springs and design #2 models the second conceptual design using tension springs. Both scale models were comprised of two platforms, an elevated bottom platform and a top platform suspended above the other. The bottom platform represented the would-be stationary base of a mechanical horse and the top platform represented the would-be saddle. For the design #1 scale model, spring receptacles were mounted on both platforms and small, flexible compression springs were installed. Nylon string was run between each corner of both platforms and hung below the bottom platform so that simulation of the operation of the device could be achieved by pulling on the string. For the design #2 scale model, three rods were mounted to each platform and projected toward one another. They were positioned so that they would be equally spaced about a 3 inch circle, and the arrangement between each platform was shifted by 180 degrees. Small eye-bolts were mounted to the end of each rod and nylon string was run from an eyebolt mounted to a top platform rod and through an eyebolt on a neighboring bottom platform rod. Eyebolts were also mounted on the distal end of each top platform rod to which small, flexible tension springs were attached. Though not proportionally to scale, it was easy to discern from the models that design #2 was physically feasible.

Figure 35: Design #1 Scale Model (Left), Design #2 Scale Model (Right)

*Computer Models*

Initially the concept of this design was that there would be three structures mounted to the saddle equally spaced around a circle of a set diameter and projecting down towards the base and from which the terminal ends of two cables would attach on opposing sides and then be directed off into opposing directions. Three structures would then also be mounted to the base shifted 180 degrees out of phase with the structures projecting down from the saddle and project up towards the saddle. The cables would run from the structure on the saddle to the structure on the base and then be directed toward a cam-follower where it would terminate. With this design, the original idea of the Stewart Platform was still preserved, and the linear actuators (cables) were positioned and implemented in the same way as in the initial design. Images of the progression of the design are given in Figure 36 below. In Figures 36a and 36b, a six-actuator system is shown. The camshaft was originally intended to be in-line with the gearbox (Figure 36a), but space constraints forced the use of a right-angle gearbox (Figure 36b). After extensive computer modeling and additional scale model construction, it was decided that two additional cable actuators would be added. This might eliminate the need for the tension springs altogether. In Figures 36c and 36d, the cams were directly connected to the gearbox, the cable actuator connection points were moved to the outside corners of the saddle, and the saddle was designed to overlap the base. In Figures 36e through 36h, the cams and gearbox were separated in order to enable different cable and cam-follower configurations. Projecting the cable actuator saddle connection points down into the base from the saddle (Figures 36e through 36h) simplified the design and construction of the saddle and its components. This also allowed the saddle to be suspended above the base, which provided more clearance between moving components. Further modifications to simplify the base, saddle, camshaft, and mounting components were done and the final design is presented in Figures 36g and 36h.

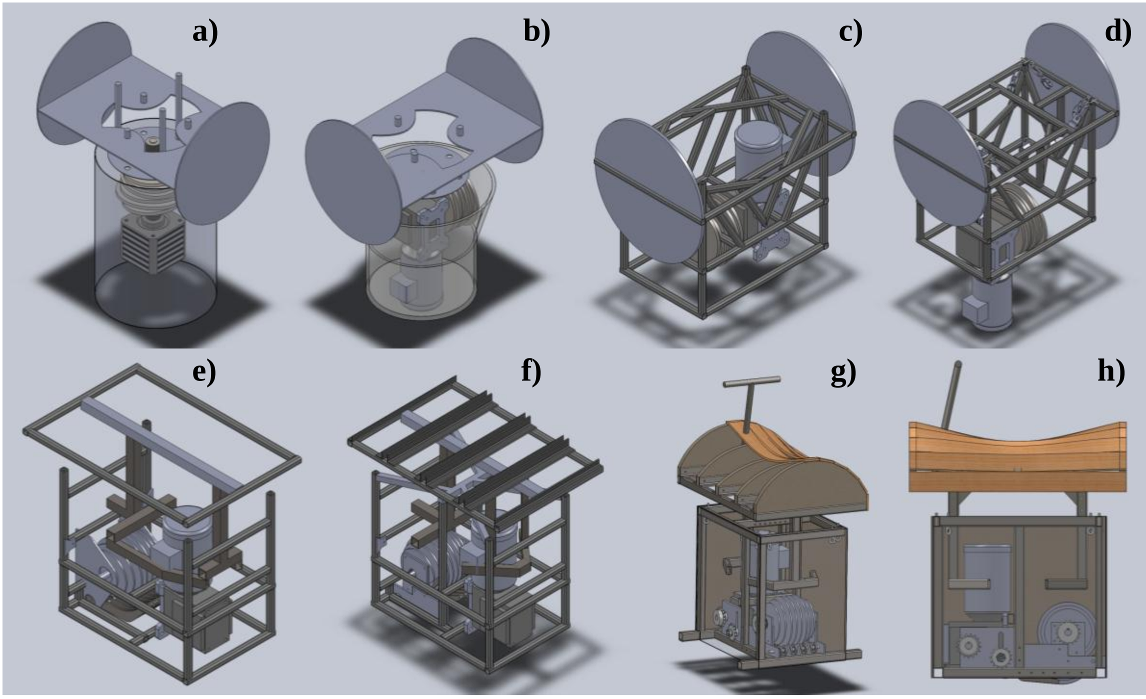



Figure 36: Progression of Design

## *Final Design: The Wild Bill Prototype*

In the final design, we settled on a modified arrangement inspired by the operational ideals of the Stewart Platform while still utilizing the cam system for motion generation. Eight cable actuators were to be connected from cam-followers mounted on the base to projections reaching down from the saddle. Connection to the cam-followers would displace the cable, causing the saddle to be either raised upward by the exertion of force from the motor or dropped downward by the force of gravity. The mechanical horse was made up of four basic subsystems: the saddle, the base, power transmission, and motion transmission.

### *The Base Subsystem*

The base was built entirely of A36 structural steel tubing. Our materials were 1”x1.5”x14 gauge rectangular tubing and 1.5”x1.5”x14 gauge square tubing. The base was 17 inches wide, 25 inches long, and 24 inches tall. The structure of the base is shown in Figures 37: Left and 37: Center. It was designed so that it would fit through a standard size doorway, be easy to move during transportation, and remain upright and stationary during operation. Two rigid and two locking swivel casters enabled mobility and maneuverability of the device during transportation and provided stability during operation. The top of the base structure was designed to be strong enough to support the mounting of two pulleys in each of its four corners and eight pulleys in the middle of the mechanism. Mounting bars were added to provide a surface for mounting the gearbox. The inside of the base structure was purposely left void to allow room for structures projecting down from the bottom surface of the saddle (Figure 36g and 36h). Three shaft supports were located on an external bottom member of the base (circled in Figure 37: Center). These supports provided support to the shaft on which the cam-followers would pivot. There was also a support bracket containing a 1.125 inch roller bearing through which the motor shaft passed. On the opposite end of the support bracket there was a 5/8 inch vertical slot. This bracket provided support for the motor shaft in bending and also served as the housing for a tensioning device. Finally, the base had mounting plates bolted onto the inner surface of the bottommost structural members that ran half the length of the device. The mounting plates are represented as feature A in Figure 37: Right. These mounting plates provided a way to easily align and mount the camshaft in the device while still allowing for the camshaft to be removable. This exchangeable camshaft allowed quick installation of multiple cam sets representing different motion patterns. The camshaft is identified as feature B in Figure 37: Right. There was also wood shielding mounted to the flush surfaces of the outside of the base by magnets. The shielding was added in order to protect the user and any passersby from the danger of the internal moving components.  Magnetic adhesion enabled the shielding to be quickly and easily installed or removed.


Figure 37: Base Front-View (Left), Base Side-View (Center), Base with Hardware and Components Mounted (Right)

*The Saddle Subsystem*

The saddle consisted of four different parts: the frame, the contour arcs, the seat surface, and the projections.  The frame was made out of A36 structural steel 1.5"x1.5" angle iron, 1"x1.5"x14 gauge rectangular tubing, and 1.5"x1.5"x14 gauge square tubing. The frame was designed to have the approximate width of an average horse and is 22 inches wide.  The frame was a rectangle with a beam running longitudinally through the middle.  The frame is shown as feature A in Figure 38: Left.  A handle was welded to the middle beam of the frame to provide support to the user.  The handle is represented as feature B in Figure 38: Left.  Braces, shown as feature C in Figure 38: Left, were made by positioning pieces of angle iron so that the angle sides opposed one another and were 1 inch apart.  Five such braces were equally spaced and welded across the top of the frame.  These braces provided a place to mount each wooden contour arc.  The contour arcs, shown as feature D in Figure 38: Left, were designed to approximate the shape of a horse's back.  They allowed for the attachment of wooden planks, which formed the surface of the seat.  These wooden planks are shown in figure 38: Center-Left.  The seat surface was covered with carpet padding and upholstered with suede, as shown in Figures 38: Center-Right and 38: Right.


Figure 38: Saddle Internal View (Left), Wooden Frame (Center-Left), Carpet Padding (Center-Right), Complete Saddle (Right)

Mounted to the beam running through the middle of the frame were two projection units.  The projections were made from the same A36 rectangular and square tubing.  A 22 inch square tube descended directly down from the bottom surface of the saddle and projected into the inside area of the base.  At the terminal end of each projection was a crossbar with two pieces of rectangular tubing angled in towards the center, as shown in Figure 39.  These members provided a surface for mounting the terminal ends of the cables.  Each projection supported four cable connections.  At the interface between the projection and the saddle surface there was a coupling member that bolted to both the projection and the saddle and allowed for lateral adjustment of the projection unit.

Figure 39: Saddle Projections Front-View (Left), Saddle Projections Side-View (Right)

*The Power Transmission Subsystem*

The power transmission subsystem was made up of a motor, gearbox, speed-controller, tensioner, chain, and sprockets. The motor (MTC-001-3BD18 Ironhorse, AutomationDirect, Cumming, GA) was a 1.0 hp general AC motor with a maximum output rotational speed of the motor shaft at 1800 rpm. The gearbox (WG-262-040-R, AutomationDirect, Cumming, GA) was a heavy-duty, single-stage worm gearbox. It had a 40:1 gear ratio which converted an 1800 rpm input from the motor to a 45 rpm output. The speed-controller (GS2-11P0, AutomationDirect, Cumming, GA) was an AC microdrive capable of adjusting the speed of the motor from 0 to 1750 rpm (corresponding to a range of 0 to 43.75 rpm output from the gearbox). Table 2 provides the operational frequency of the speed-controller and the corresponding motor shaft and gearbox shaft rotational speeds for several commonly used speed settings. The period of one complete cycle of the saddle corresponding to various speed-controller settings are provided in the column on the right. Horse gait tends to be between 1.2 s/cycle and 1.8 s/cycle, so a setting of 45-60 Hz on the speed-controller would be most realistic. Power was transferred from the motor to the camshaft by a chain and sprocket. The chain (7265K415, McMaster-Carr, Atlanta, GA) was an American National Standards Institute (ANSI) 50 heavy duty chain with a 5/8” inch pitch. The sprockets (6280K942, McMaster-Carr, Atlanta, GA) were also ANSI 50 with 5/8” pitch. One sprocket was located on the end of the gearbox shaft and one was on the camshaft. A tensioner was located medially and enabled adjustment of the tension in the chain when the camshaft was being exchanged. The tensioner consisted of an idler sprocket (6663K52, McMaster-Carr, Atlanta, GA) and a 5/8” shoulder bolt (26374, Fastenal, Winona, MN).

Table 2: Operational Speeds

| Actual Speed-Controller Operating Frequency (Hz) | Estimated Motor Shaft Rotation (rpm) | Estimated Gearbox Shaft Rotation (rpm) | Corresponding Saddle Cycle Period (s/cycle) |
|---|---|---|---|
| 0 | 0 | 0.000 | n/a |
| 5 | 147 | 3.675 | 16.327 |
| 15 | 437 | 10.925 | 5.492 |
| 20 | 583 | 14.575 | 4.117 |
| 30 | 875 | 21.875 | 2.743 |
| 35 | 1020 | 25.500 | 2.353 |
| 40 | 1166 | 29.150 | 2.058 |
| 45 | 1312 | 32.800 | 1.829 |
| 50 | 1458 | 36.450 | 1.646 |
| 60 | 1750 | 43.750 | 1.371 |

*The Motion Transmission Subsystem*

The motion transmission subsystem consisted of all of the devices used to transmit the motion information from the surface of the cams to the saddle structure. These included sixteen pulleys (02048, Southwest Wire Rope Company, Houston, TX), eight steel cables (Southwest Wire Rope Company, Houston, TX), sixteen cable swages (71514005331, Home Depot, Atlanta, GA), eight cam lobes, eight cam followers, sixteen eye-bolts (22211, Lowe’s Home Improvement, Mooresville, NC), eight U-bolts (22249, Lowe’s Home Improvement, Mooresville, NC), eight turnbuckles (43010, Fastenal, Winona, MN), and eight yoke ends (BTC-250L, Midwest Control Products Corporation, Bushnell, IL).

Figure 40: Pulleys Mounted on Center-Bar (Left), Pulleys Mounted in Corner (Center), Pulley, Swivel, and Eye-Bolt (Right)

The pulleys were 1.5” inch block single-sheave swivel pulleys capable of supporting a working load of 600 lbs. The pulleys had to be able to swivel so that the cables could align themselves to the path of least resistance. The mounting arrangement of the pulleys is shown in Figure 40. Eight of the 5/16” x 3.25”eye-bolts were used to connect the pulleys to the corners of the base. The remaining eight eye-bolts were used to mount the rest of the pulleys to the middle crossbar. The 1/4” x 3/4" x 2.5” U-bolts were used to mount the swaged cables to the saddle projections.

The cable was 3/16” steel cable capable of supporting 4200 lbs. With cable terminations, the cable’s safe working load drops to 750 lbs., which exceeded our design needs. The 3/16 inch cable swages were used to terminate both ends of the cable. Each swage was compressed four times. Swaging was chosen because it is a technique used to permanently terminate cables and is capable of achieving up to 100% of the strength of the cable.

The cam lobes were designed such that eight cams turning in sync would cause the saddle to recreate the motion of a horse. They were designed to be no more than 9 inches in diameter so that they would remain small enough to be easily exchangeable and to be no more than 1/4 inch in thickness in order to minimize the weight of the cam unit. Seven 3/4 inch thick foam spacers with 2 inch diameter aluminum insets were used to position the cams and to dampen noise.

The cam-followers were designed so that they would pivot on one end, make contact with the cam at 1/3 its length, and attach to a swaged cable at the opposite end. This arrangement was chosen because it multiplied the motion created by the cam by a factor of three. The cam-followers each contain two bearings. On the distal end of each cam-follower (feature A in Figure 41), a 1.125 inch bearing (EE4S2RSC3, Applied Industrial, Cleveland, OH) was press-fit into the cam-follower. This bearing allowed the cam-follower to pivot about an axle mounted to the base structure. Aircraft control bearings (KP4A, AST Bearing, Montville, NJ) were used to make contact with the cam surface and act as roller followers. These were mounted 1/3 of the cam-follower length from the distal end (feature B in Figure 41). The bearings were mounted to the cam-follower with 1/4 inch shoulder bolts (1126302, Fastenal, Winona, MN). These bearings were capable of supporting loads of over 1,500 lbs. and were chosen for their high load capacity and small size. Small plastic spacers are used to position each cam-follower.

The cables were attached to the cam-followers through the use of turnbuckles, which have the advantage of enabling tensioning of each cable individually. Yoke-ends

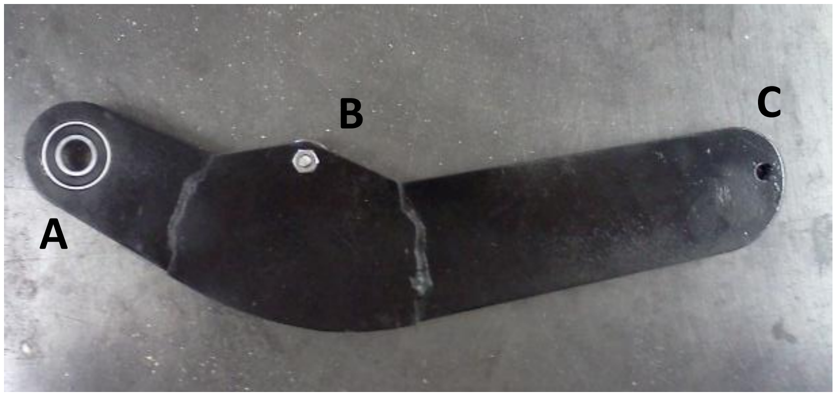



Figure 41: Cam-Follower

were mounted to the attachment site of the cam-follower (feature C in Figure 41). The yoke-ends (Figure 42: Left) were threaded into the turnbuckle through the use of modified hex bolts (Figure 42: Center-Left), as shown in Figure 42: Right. Threaded at the opposite end of the turnbuckle was an eye-bolt through which the cables were swaged, as shown in Figures 42: Center-Right and 42: Right.

Figure 42: Yoke-Ends (Left), Modified Bolts (Center-Left), Turnbuckles (Center-Right), Assembled Turnbuckles (Right)

*Prototype Construction*

After months of building computer models, deliberating, and double-checking everything, and with no small amount of good-faith, we began construction on a full scale prototype. No major problems were encountered during the construction phase.

Construction began in February, and the project was completed on May 3, 2011. See Appendix A for complete drawings.

Before operation of the device, it was necessary to tension all of the cables while the saddle rested in its equilibrium position, at which the x, y, and z axes of the saddle align with the x, y, and z axes of the base, with the origin point located 3 inches above the top of the base. The equilibrium position occurred when all cams are 8 inch diameter circles. For preliminary tensioning an 8 inch diameter cylindrical, wooden block was made and installed, as shown in Figure 43. With the saddle firmly secured in this position, each turnbuckle was adjusted until the tension on each cable was observed to be approximately the same.

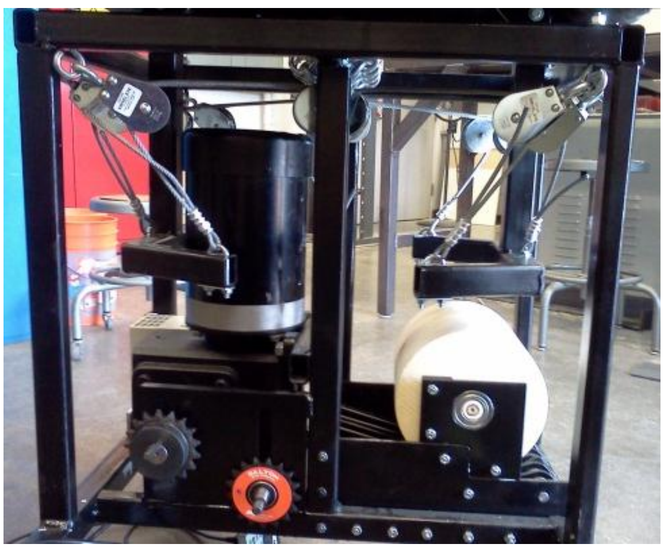


Figure 43: Assembled Prototype and Wooden Tensioning Block

After completion of the construction phase and initial testing, it was determined, that when a rider was mounted, the saddle was unstable and that tension springs should be added to prevent the cables from going slack and to prevent the saddle from tipping over. The added springs are circled in Figures 44: Left and 44: Right. Five eye-bolts

(209222, Lowe's Home Improvement, Mooresville, NC) were added to the top longitudinal members of the base and to the median beam of the saddle structure, allowing for adjustment of springs as needed.  In total, eight tension springs (9432K125, McMaster-Carr, Atlanta, GA) were added to the design.

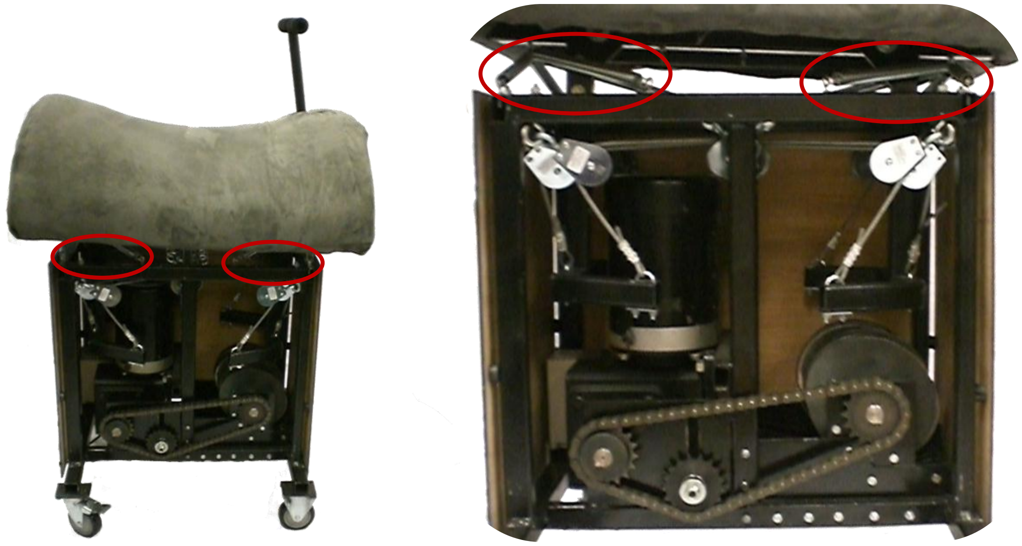


Figure 44: Completed Wild Bill Prototype (Left), Close-Up of Internal Components (Right)

*Motion Capture Testing*

Two healthy subjects, one male and one female, participated in a series of motion capture trials conducted at Baylor University.  This study was conducted in accordance with the Baylor University Institutional Review Board's (IRB) policy regarding pilot studies.  Informed consent was given verbally by both subjects.  Motion capture experiments were conducted with a three camera system.  Reflective markers were used to identify landmarks on human subjects and to establish a reference frame for the saddle. SimiMotion tracking software was used to synchronize, import, and record the video data in real-time.  All tracking of the reflective markers was completed in SimiMotion.  Once tracking was complete, the information was used to calculate the three-dimensional data for each marker.

*Human Subjects*

Two subjects completed a series of motion capture trials conducted atop the mechanical horse at three different speeds. Subject 1 was a 45 year-old, healthy male. Subject 2 was a 23 year-old, healthy female with scoliosis. Neither of the subjects reported any pain or illnesses immediately prior to or during testing, nor were either on any medication regimens. Subject 1 had very little riding experience, and Subject 2 had some significant riding experience during her developmental years.

*Data Collection*

We used a three camera (Canon Optura XI, Canon U.S.A., Inc., Lake Success, NY) motion capture lay-out to capture the movement of reflective markers on the saddle of the mechanical horse and on the pelvis and spine of the subjects riding the mechanical horse. LED lights were mounted on each camera and were the only light-emitting sources in the room during testing. The observation space was calibrated using Sputnik (Sputnik, Peak Performance Technologies, Englewood, CO) and was arranged so that the calibrated volume would include the area in which Prototype #2 would be positioned as well as the space above the seat in which the rider would be seated. Sputnik was arranged so that six of eight calibration arms were used, thereby allowing us to calibrate the entire volume of space required for the motion capture trials. Calibration of the space was performed by ensuring that each calibration point on Sputnik was visible in at least two cameras. Results of the calibration in each camera revealed that error measurements were between 0.05 and 0.78 with a standard deviation of 0.21, indicating that accuracy of results would not be affected, as all error was under the 1% limit of SimiMotion.

Two separate test sessions were conducted. For Test Session #1 the saddle without springs was evaluated under different load and speed conditions. Nine trials were performed, including no rider at speeds of 15, 20, and 30 Hz, Subject 1 riding the horse at speeds of 15, 20, and 30 Hz, Subject 2 riding the horse at speeds of 15, 20, and 30 Hz, and stabilization of the saddle (achieved by applying a light downward force on the saddle projections or the saddle) at 15 and 30 Hz. For Test Session #2 the saddle with springs was evaluated under various load and speed conditions. Twelve trials were conducted, including no rider at speeds of 15, 30, 35, 40, 45, and 50 Hz, Subject 1 riding the horse at speeds of 15, 30 and 45 Hz, and Subject 2 riding the horse at speeds of 15, 30, and 45 Hz. The speed settings used during testing correspond to the operational frequency displayed by the speed-controller, as previously listed in Table 2. Video data was synchronized, imported, and recorded in real-time with SimiMotion motion capture software to a computer in our lab.

*Protocol*

Adhesive reflective markers were placed approximately on the L2 and T8 processes of the spine and on the two distal ends of an elastic pelvis belt that was worn around the pelvis of each subject. Three reflective markers were also mounted to the mechanical horse. One was mounted on the top, anterior surface of the horse and was placed alongside the handle. The remaining two markers were mounted bilaterally on the top, posterior surface of the horse about six inches removed from the midline.

Data was captured from the horse and both subjects at speeds ranging from 15-50 Hz. Time was allowed for the mechanical horse to reach operational speed before recording commenced, and at least three complete gait cycles were recorded for each trial. Subjects were instructed to respond passively to the mechanical horse's movement and to not actively influence the motion of the saddle.

*Data Processing*

Before exporting position data of each of the markers from Simi Motion, gaps in data due to arms swinging in front of the anterior marker of the mechanical horse were filled using built-in functions in the software. The speed setting was used to calculate the time required to complete one full gait cycle, and this information was confirmed by visual comparison with the videos and graphical results. The data was then processed using custom software to align the forward, vertical, and lateral motions of the mechanical horse to the x, y, and z axes of the observation space, respectively, and to normalize the time taken to complete one gait cycle. The average value for each measure of each trial was subtracted from the data in order to center it about its respective axis. In order to calculate deviation from the target, it was necessary to repopulate the data so that each measure of each trial had the same number of data points. This was accomplished by importing the data into MATLAB (R2009a Student, The MathWorks, Natick, MA), fitting a $16^{th}$ degree polynomial curve to the data, sampling the curve from 0 to1 at intervals of 0.004, and exporting the data to Microsoft Excel (32-bit Professional Plus 2010, Microsoft Corporation, Redmond, WA).

*Graphs*

From the data collected, graphs were generated for the x, y, and z translations and rotations of the saddle both with and without riders, with and without springs, and at various speeds. These data were compared to motion data of another mechanical horse (Panasonic Joba) and the target of motion of the live therapeutic horse on which Prototype #2 was modeled. Two-dimensional graphs representing the front, side, and top views of the translations and rotations of the saddle where generated for some of the trials. Deviation from the target data was calculated and graphed using the distance equation to find the distance between each measure of each trial and each measure of the target motion. Data ranges were calculated and graphed by finding the minimum and maximum for each measure of each trial and subtracting the minimum from the maximum.

# CHAPTER SIX

## Results

Construction of the mechanical horse proceeded in accordance with the final design concept. Supplies, materials, and components were ordered and materialization of the project began. A few minor problems developed during construction. First, we discovered that the base was about 2 inches too narrow to accommodate all eight pulleys being mounted on the center-bar without there being some interference in their ability to swivel. This issue was not resolved, as it was hoped that the interference would be negligible because the pulleys would not need a significant swivel range. Second, bolts used to mount the gearbox to the base interfered with the movement of the turnbuckles, cables, and cam-followers. This was resolved by manufacturing custom nuts at half the thickness of a standard nut. Third, no turnbuckles could be found that fit snuggly around the cam-follower, were the correct length, were rated to an appropriate working load, and fit within our budget. This was resolved by purchasing yoke-ends and turnbuckles separately, modifying hex bolts in-house, and assembling the unit so that the yoke-end connected the cam-follower to the turnbuckle and ultimately to the cable.

Initial results of the construction phase were exciting. The mechanical horse ran effectively, quietly, and supported loads of at least 250 lbs. Upon further testing, we discovered that, when a rider was mounted, the saddle seat was more unstable than originally anticipated. The cause for this is unknown, though it is suspected that there may be geometrical differences between the physical implementation of the design and computer models of the design significant enough to affect the operation of the unit during computer simulation. This instability could also be due to the collision of the pulleys, as it could be causing the cables to go slack when the pulleys are not able to properly align themselves. In order to resolve this issue, eight tension springs were added between the top of the base and the bottom of the saddle. Springs were selected for their ability to extend to an appropriate length and for a loading rate of less than 4 lbs./inch. Springs with loading rates of about 3lbs./inch were chosen so that the force applied by the spring would have minimal impact on the targeted motion of the saddle. This design change significantly reduced the instability, thereby making the horse safer to ride.

The scope of the motion capture study was to compare the motion of Prototype #2 to the motion of other mechanical horses and to the target motion. To test this, three experimental conditions (stabilization, speed, and load) were tested. Two separate tests with varied stabilization conditions were conducted, during which data was collected from several distinct trials. In Test 1 Prototype #2 was tested without the addition of any springs and for Test 2 springs were added between the base and saddle. Trials are preceded by either 1_ or 2_, designating which test session the trial was in (with or without springs). The speed at which the trials were conducted is signified by a number appended to the end of the trial name. The trial names also indicate the loading conditions under which the saddle was being tested. Subj1 or Subj2 indicate which subject was riding the horse, ProjStab indicates that the saddle was being lightly held down as it was moving (no rider), and Null indicates that there was no load on the saddle whatsoever (no rider, no interference). For example, 2_Subj1_30 would mean that the saddle was tested during Test Session #2 (with springs added), that Subject 1 was riding it during testing, and that the machine was set to a speed of 30 Hz, as indicated on the speed-controller. Trials conducted in Test 1 include 1_Subj1_15, 1_Subj2_15, 1_Subj1_30, 1_Subj2_30, 1_ProjStab15, 1_ProjStab30, and 1_Null30. Trials conducted in Test 2 include 2_Subj1_15, 2_Subj2_15, 2_Subj1_30, 2_Subj2_30, 2_Subj1_45, 2_Subj2_45, 2_Null15, 2_Null30, 2_Null35, 2_Null40, 2_Null45, and 2_Null50.

In the following section, x-translation represents forward and backward motion (Figure 45: Top-Left), y-translation represents upward and downward motion (Figure 45: Top-Center), and z-translation represents side-to-side motion (Figure 45: Top-Right). Accordingly, x-rotation is list about the x-axis (Figure 45: Bottom-Left), y-rotation is twist about the y-axis (Figure 45: Bottom-Center), and z-translation is tilt about the z-axis (Figure 45: Bottom-Right).

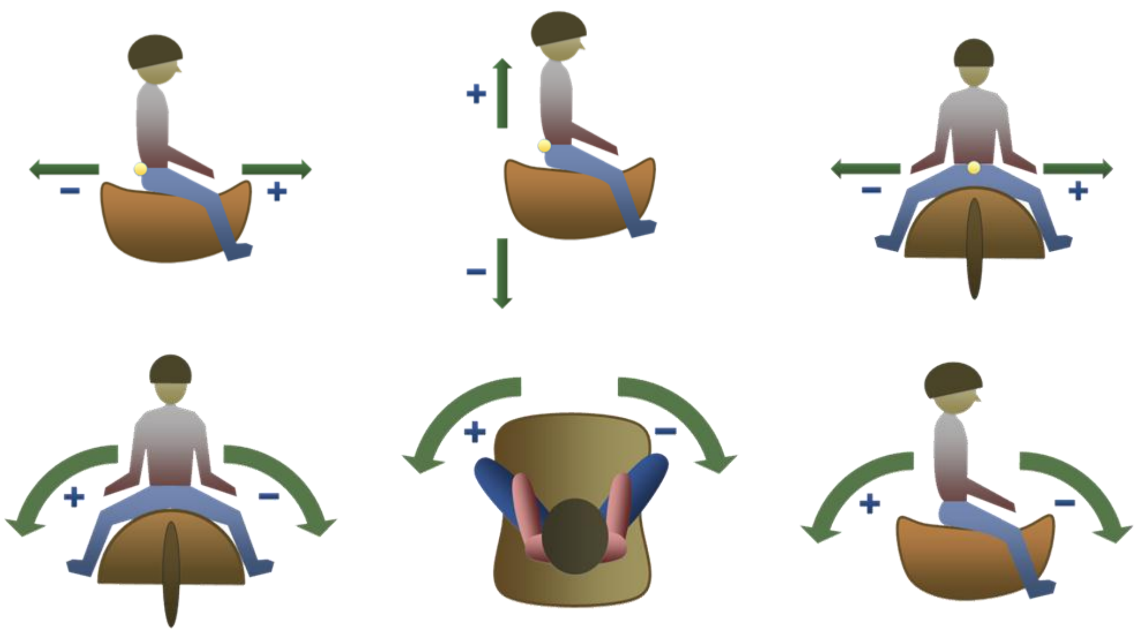


Figure 45: X-Translation (Top-Left), Y-Translation (Top-Center), Z-Translation (Top-Right), X-Rotation (Bottom-Left), Y-Rotation (Bottom-Center), Z-Rotation (Bottom-Right) [118]

*Graph Set 1: Effect of Stabilization*

The graphs in Figures 46-49 show how the addition of stabilization springs between the saddle and the base structure affect the motion of the saddle when no rider is present. These graphs are representative of the changes in motion seen between different measures (x, y, z translations and rotations) for the same testing conditions. Graphs of the measures not shown below can be found in Appendix C. In Figure 46, the y-translation motion data from trials conducted with no rider at speeds of 15 and 30 Hz (5.492 and 2.743 s/cycle, respectively) and either with or without stabilization are graphed against the target data. In this plot similar magnitudes and trends were observed between the curves for each trial. Translation in the y-direction is sinusoidal, with two local maxima and two minima occurring during one gait cycle. The deviation between each trial and the target data is graphed in Figure 47. Generally, the same trends can be seen between each curve. Maximum deviation from the target data was approximately 1.25 cm. Excepting trial 1_Null30, the greatest deviations correspond to the inflection points of the translation data.

In Figure 48 below, the y-rotation motion data for trials conducted with no rider at speeds of 15 and 30 Hz and either with or without the addition of stabilization springs are graphed against the target motion. Similar trends are observed between all trials except 1_Null30. At some instances there is a 1.5 cm difference in the range of motion between the experimental trials. Within one gait cycle there are three local maxima and three local minima for all trials but 1_Null30. For this particular trial there are four local maxima and four local minima. For the target data there is only one local maximum and minimum. The deviation between each trial and the target data is graphed in Figure 49.

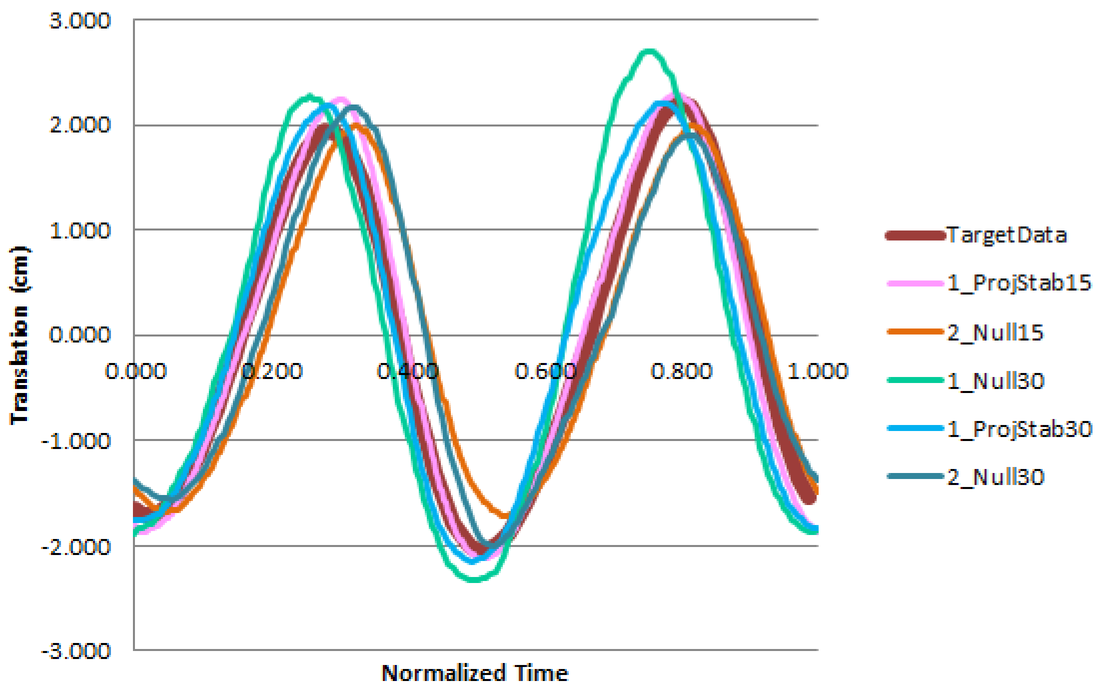



Figure 46: Effect of Stabilization Conditions at Speeds of 15 and 30 Hz (Y-Translation)

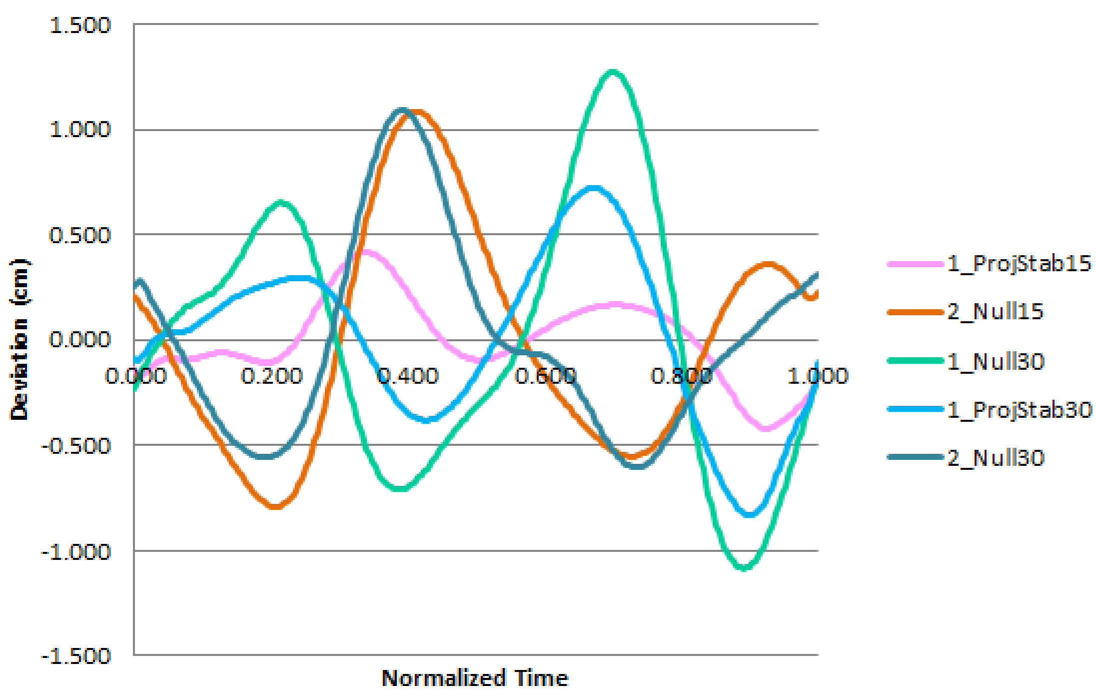



Figure 47: Deviation from Target Data (Y-Translation)

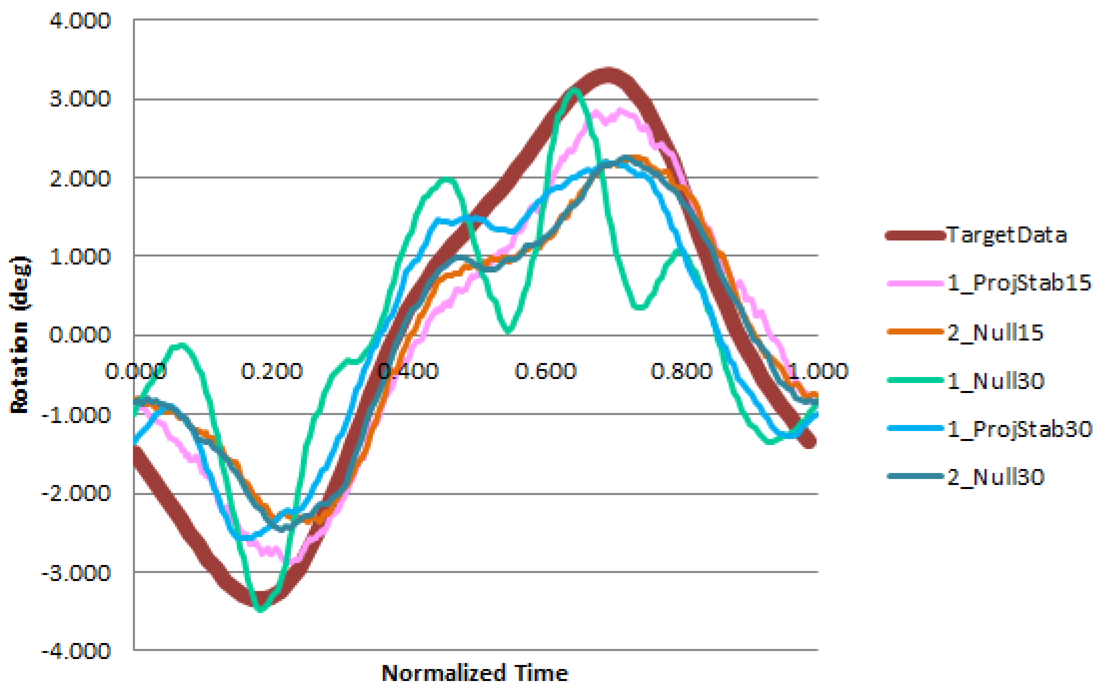



Figure 48: Effect of Stabilization Conditions at Speeds of 15 and 3 Hz (Y-Rotation)

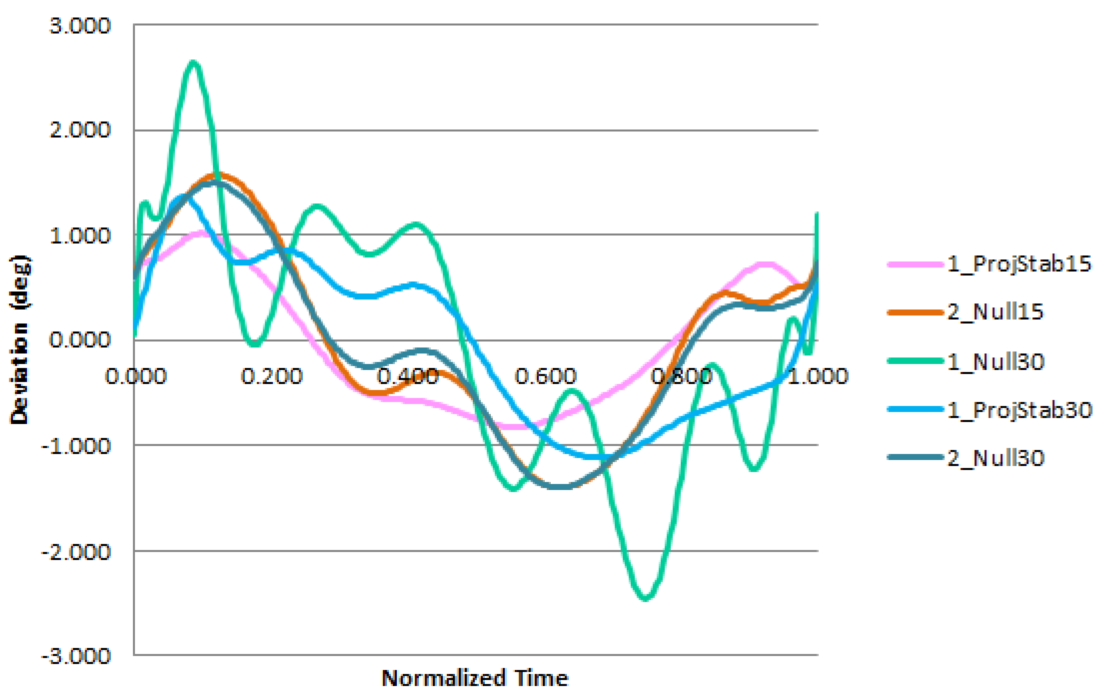



Figure 49: Deviation from Target Data (Y-Rotation)

The same general trend is observed between all experimental trials except 1_Null30. For these trials, deviation from the target remains less than 1.5 cm, while for trial 1_Null30 deviation reaches 2.5 cm.

### *Graph Set 2: Effect of Speed*

The graphs in Figures 50-53 show the average x, y, and z translations and rotations sustained by the Prototype #2 saddle when operated at different speeds. For these tests the stabilization springs were used and no rider or load was present on the saddle. Speeds tested corresponded to a speed-controller setting of 15, 30, 35, 40, 45, and 50 Hz, or periods of 5.492, 2.743, 2.353, 2.058, 1.829, and 1.646 s/cycle. The following graphs are representative of the resulting motions seen between different measures (x, y, z translations and rotations) for the same testing conditions. Graphs of the measures not shown can be found in Appendix C. In Figure 50, the y-translation motion data from the above trials is plotted against the target data. In this graph, similar trends were observed between each trial and the target data. Translation in the y-direction is sinusoidal with two local maxima and two local minima occurring during one gait cycle. The deviation between each individual trial and the target motion is shown in Figure 51. Similar trends and magnitudes are seen between the deviation curves for trials conducted at speeds 15 through 40. For these trials maximum deviation from the target data is just over 1 cm, and occurs at the inflection point. Trials 2_Null45 and 2_Null50 have similar trends and magnitudes, with the maximum deviation from the target being 0.5 cm.

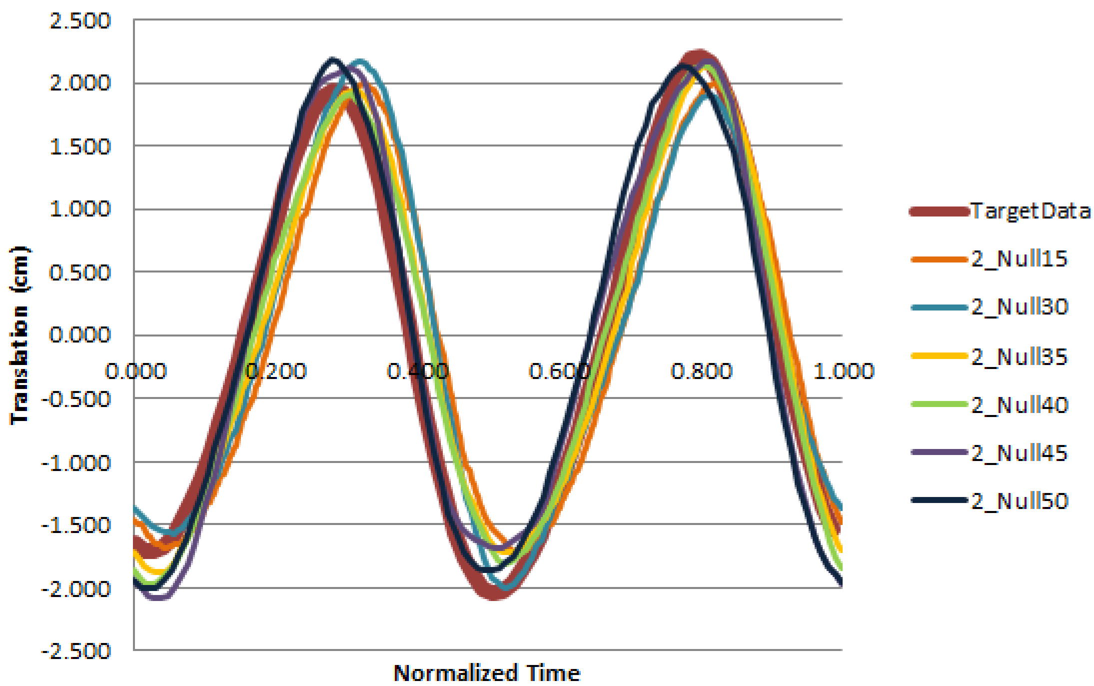



Figure 50: Effect of Speed Conditions with Spring Stabilization (Y-Translation)

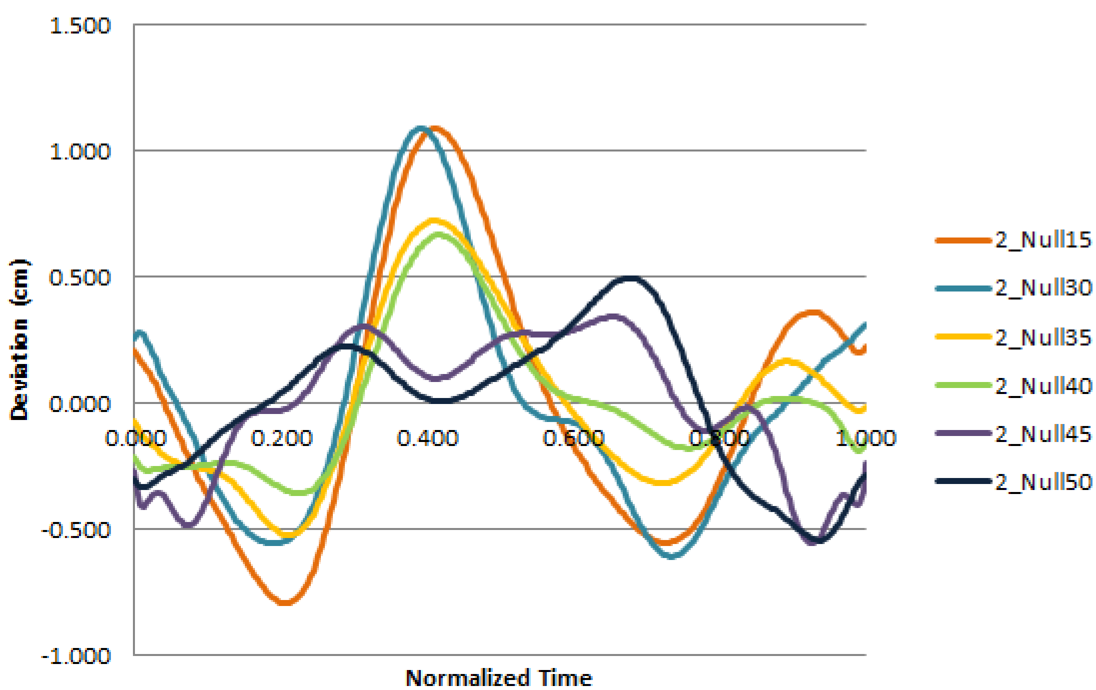



Figure 51: Deviation from Target Data (Y-Translation)

In Figure 52 below, the z-translation motion data for each of the experimental trials are graphed against the target data. Similar trends are seen between each of the experimental trials conducted at a speed less than 45 Hz, but there is a substantial difference from the shape of the target data. The range of motion for these trials is about 12 cm more than the range of motion achieved by the target motion. For trials 2_Null45 and 2_Null50 there is a noticeable change in the shape of the curve when compared to the shape of the target data. The deviation between the trials and the target motion is shown in Figure 53. The same general trends and magnitudes are observed for trials conducted from 15 to 40 Hz. The maximum deviation of these trials is approximately 4.5 cm. Trials 2_Null45 and 2_Null50 have a similar shape, but different magnitudes of deviation. Trial 2_Null50 has deviation magnitudes similar to the trials conducted from 15 to 40 Hz, while trial 2_Null45 deviates from the target by up to 6 cm.

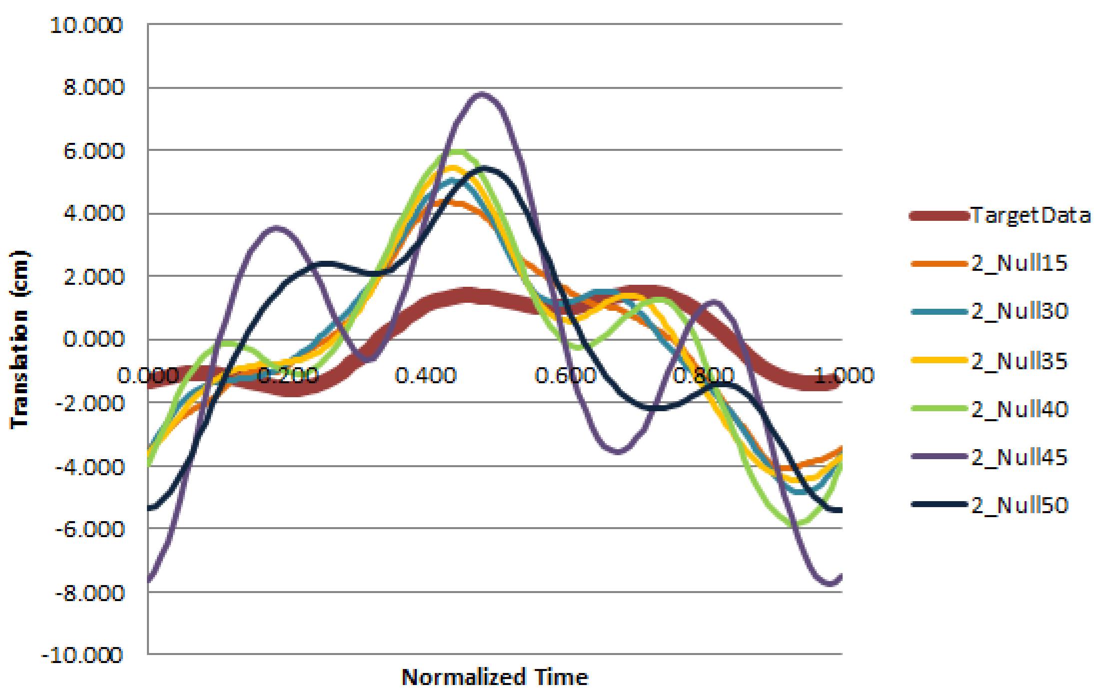



Figure 52: Effect of Speed Conditions with Spring Stabilization (Z-Translation)

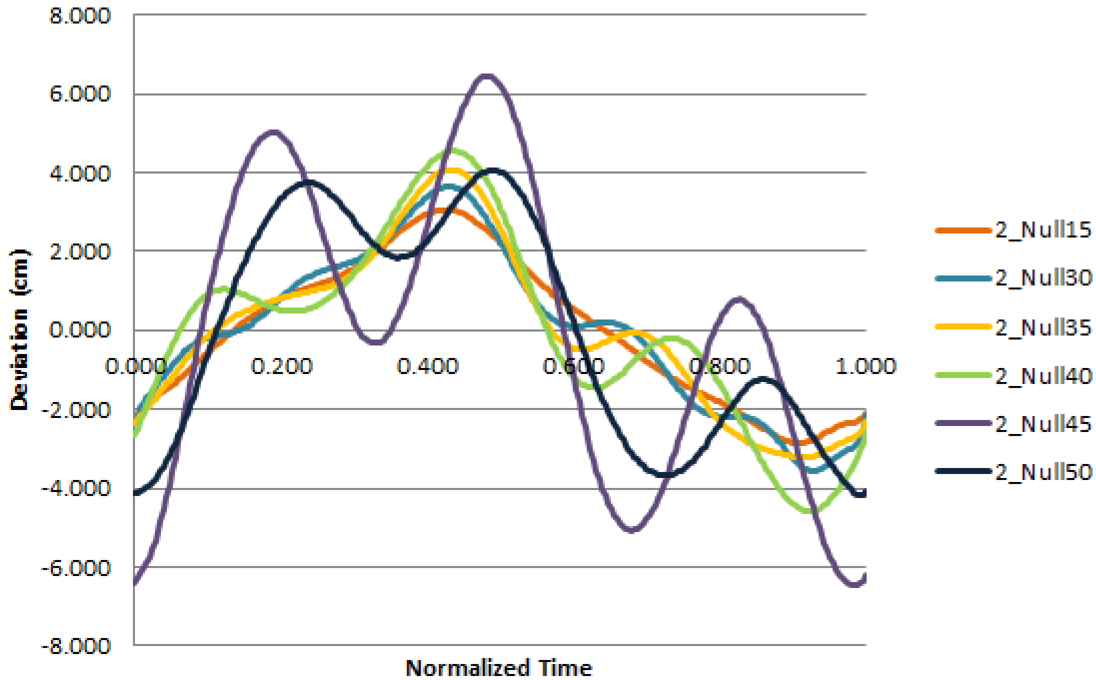



Figure 53: Deviation from Target Data (Z-Translation)

*Graph Set 3: Effect of Load*

The graphs in Figures 54-57 show how the motion of the saddle of Prototype #2 is altered by the load on the saddle and by the addition of springs. These graphs show data recorded at a speed of 30 Hz (period of 2.743 s/cycle), with or without stabilization, and with either no rider, Subject 1 riding, or Subject 2 riding. The measures graphed in the following figures are representative of the results seen for these particular trials. Figures of the measures not shown can be found in Appendix C. In Figure 54, the x-translation data is plotted alongside the target data. In general, the trends and magnitudes of trials 2_Subj1_30 and 2_Subj2_30 are similar. The shape of the curve of the trial 2_Null30 data does not match the shape of the target motion. Translation in the x-direction is sinusoidal, with two local maxima and two local minima occurring during one gait cycle. For trials 2_Subj1_30 and 2_Subj2_30 there is a delay on the declining side of each

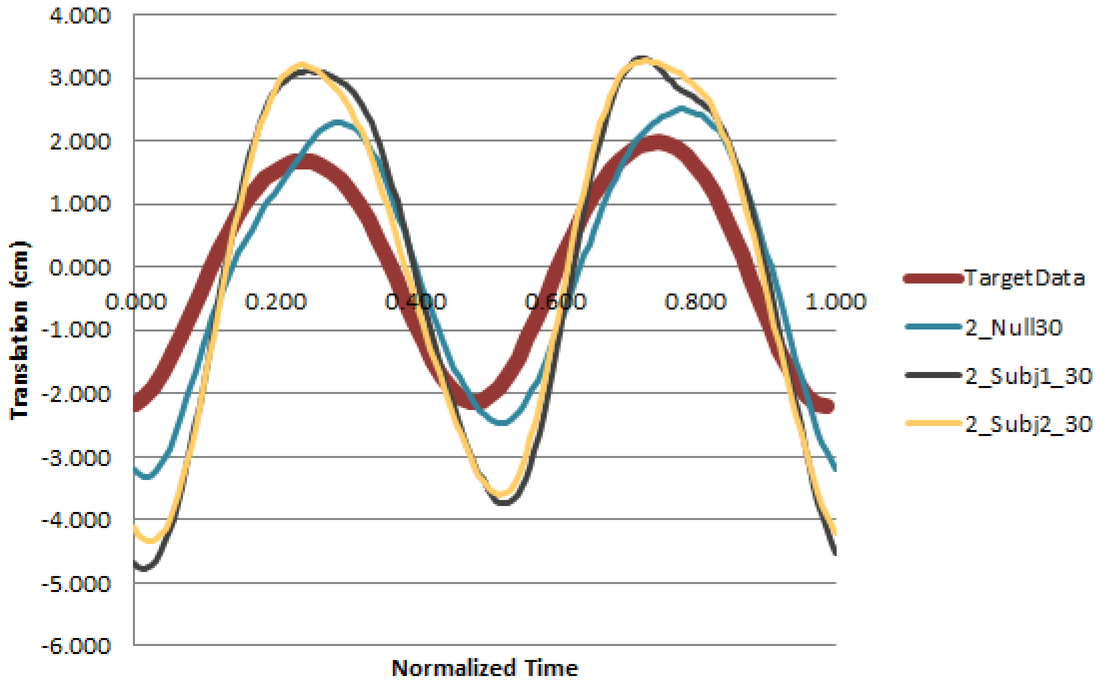



Figure 54: Effect of Loading Conditions at Speed of 30Hz with Spring Stabilization (X-Translation)

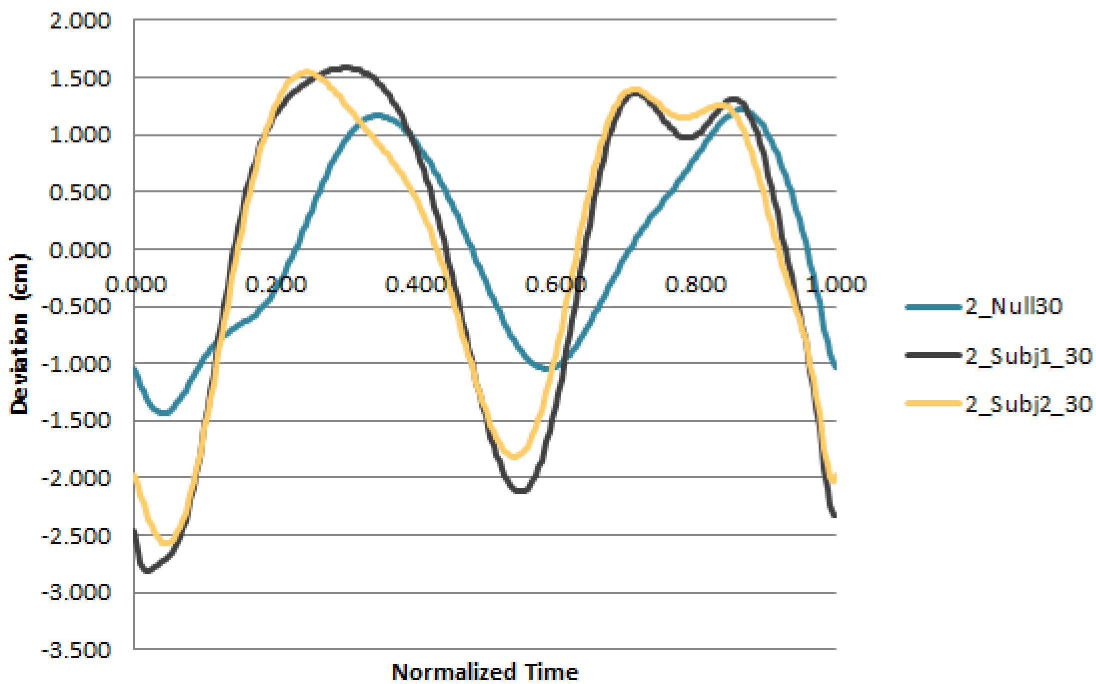



Figure 55: Deviation from Target Data (X-Translation)

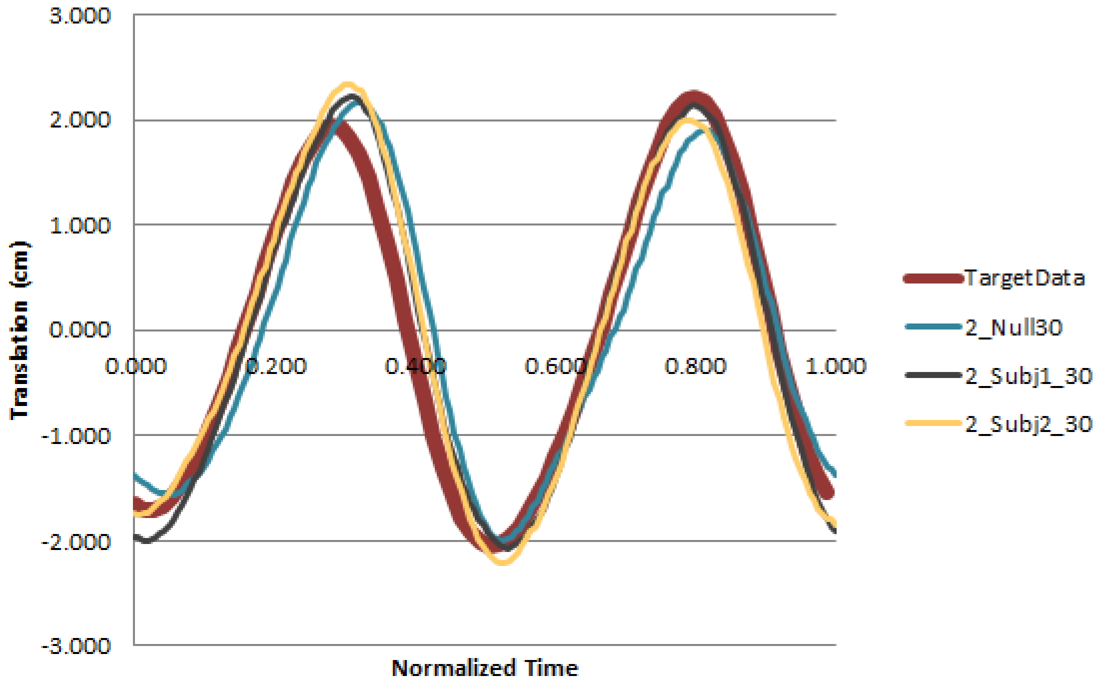



Figure 56: Effect of Loading Conditions at Speed of 30 Hz with Spring Stabilization (Y-Translation)

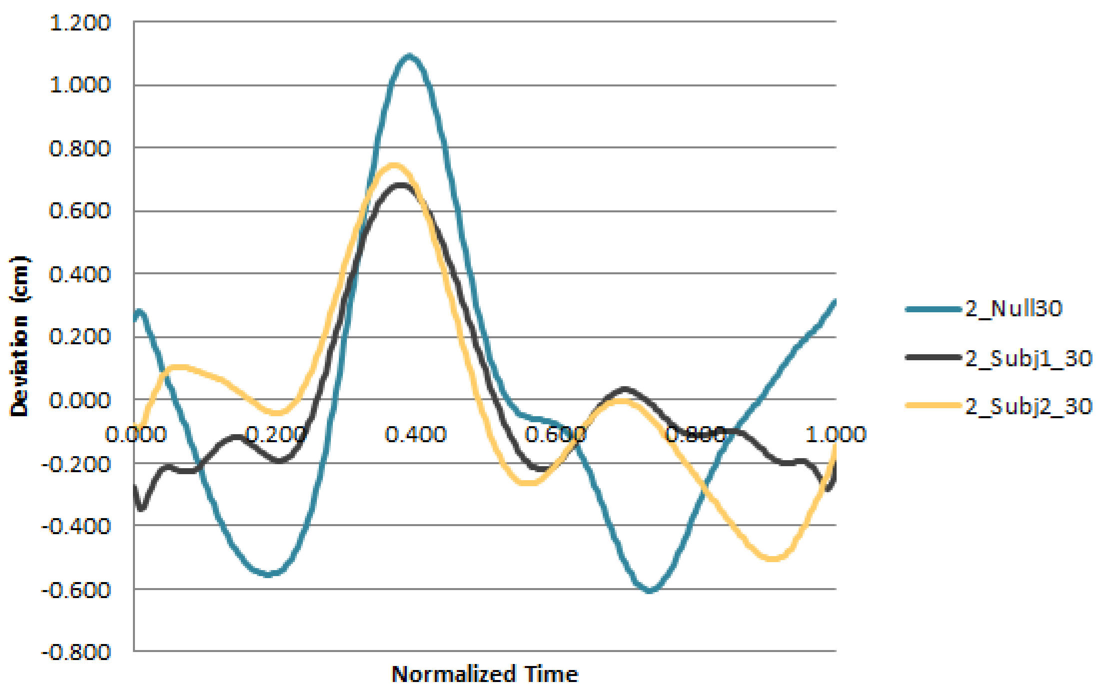



Figure 57: Deviation from Target Data (Y-Translation)

maxima.  For trial 2_Null30 the delay occurs on the inclining side of the maximum.  Such a delay is not seen in the target data.  The deviation between each trial and the target data is graphed in Figure 55.  The trends and magnitudes are similar for trials 2_Subj1_30 and 2_Subj2_30, with the maximum deviation from the target being almost 3 cm.  For trial 2_Null30 deviation from the target is less than 1.5 cm.

In Figure 56, the y-translation motion data for the aforementioned trials are graphed against the target data.  In this plot similar magnitudes and trends were observed between the curves of each trial.  Translation in the y-direction is sinusoidal throughout the gait cycle, with two locally occurring maxima and two minima.  The deviation between the trials and the target data is given in Figure 57.  Similar trends and magnitudes are seen between the deviation curves for trials 2_Subj1_30 and 2_Subj2_30.  Maximum deviation from the target for these two trials is about 0.7 cm.  The maximum magnitude of deviation for trial 2_Null30 is 1.1 cm.  For all three trials, the maximum deviation corresponds to the y-translation inflection points.

*Graph Set 4: Prototype #2, Target Motion, and the Panasonic Joba*

Figures 58-75 compare the x, y, and z translations and rotations of the motion of Prototype #2 to the target motion (live horse data) and to the motion of the Joba (existing mechanical horse data).  In the following graphs the Prototype #2 trials shown are the trials with projection stabilization and no rider, with spring stabilization and Subject 1 riding, and with spring stabilization and Subject 2 riding.  Each of these trials was conducted at a speed of 30 Hz (period of 2.743 s/cycle).

Figure 58 shows that average translation in the x-direction is sinusoidal, with all trials, the Joba, and the target motion having two maxima and two minima during one gait cycle. The Prototype #2 trials show a delay on the declining side of each peak, while the Joba and the target curves do not include this feature. The deviation between each of the trials and the Joba from the target motion is shown in Figure 59. The Joba and experimental trials generally have the same trend. The Joba deviates from the target data by 1.5 cm in some instances, while the trial data deviates from the target by almost 3 cm. The ranges of motions are shown in Figure 60. In the x-direction, the range of translation for the target data was 4.25 cm. Joba's range was 6.25 cm and Prototype 2 ranged from 7.5 to just over 8 cm.

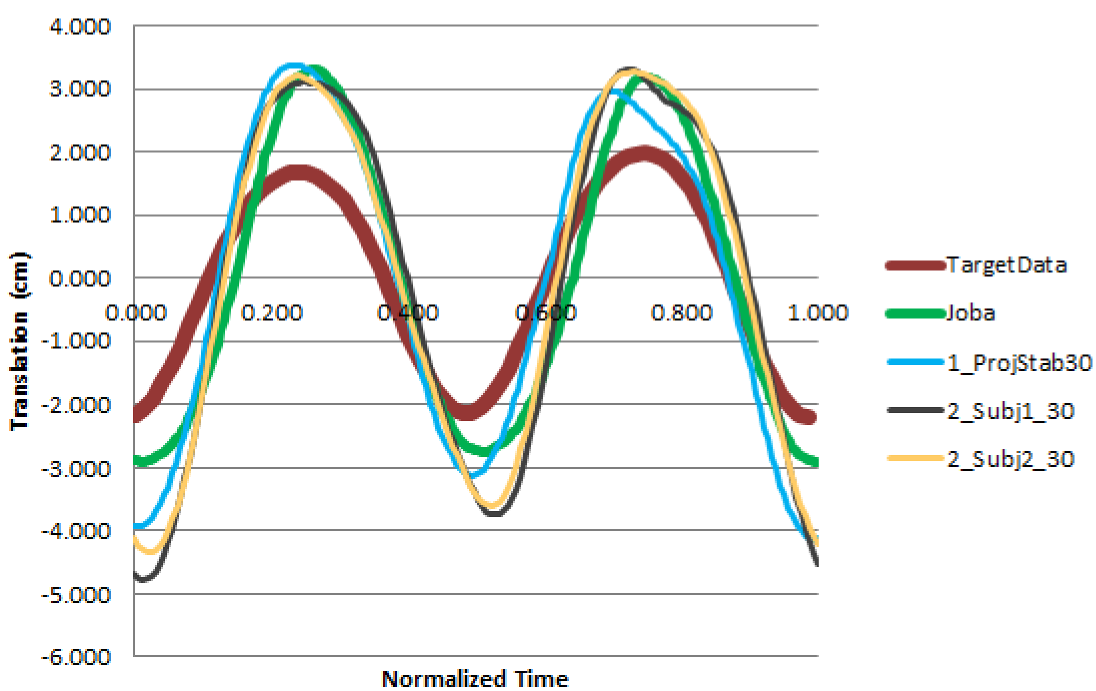



Figure 58: Comparison with Joba at Speed of 30 Hz with Various Spring Stabilization and Loading Conditions (X-Translation)

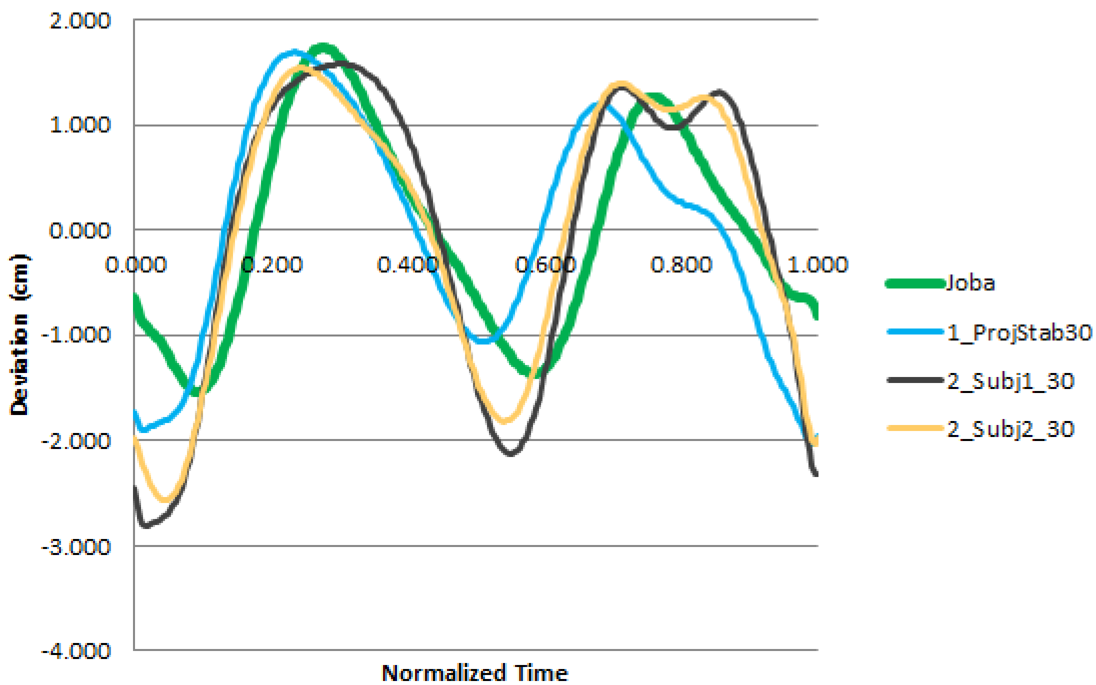



Figure 59: Deviation from Target Data (x-Translation)

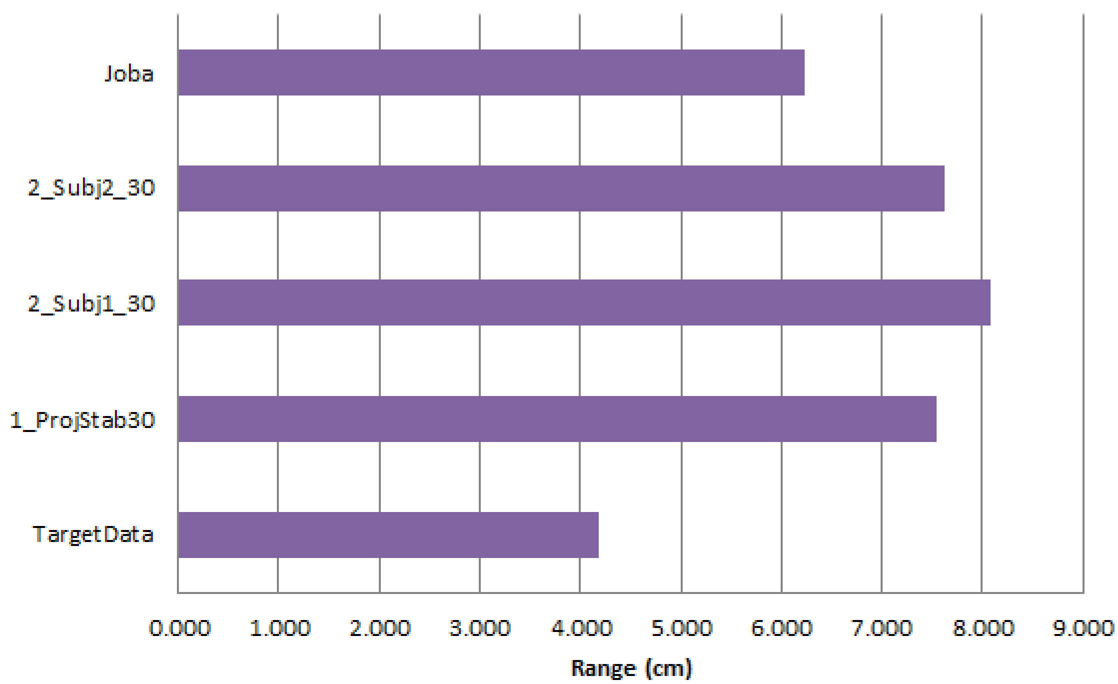



Figure 60: Range of Motion of Target, Joba, and Wild Bill Prototype (X-Translation)

Figure 61 shows that average translation in the y-direction is sinusoidal, with all trials, the Joba, and the target motion having two maxima and two minima during one gait cycle. The experimental trial data and the target data are observed to have similar trends and magnitudes, while the Joba has a substantially reduced magnitude. The shape of the Joba does not match the shape of the target and trial data in that the peaks are less steep than displayed in the target and trial data. The deviation between each of the trials and the Joba from the target motion is shown in Figure 62. Trials 2_Subj1_30 and 2_Subj2_30 generally have the same trend and deviate from the target data by 0.75 cm at the y-translation inflection points. Trial 1_ProjStab30 also deviates from the target data by about 0.75cm, but has a different trend. The deviation curve of the Joba appears sinusoidal, reaching a maximum deviation of 1.25 cm from the peaks of the target data.

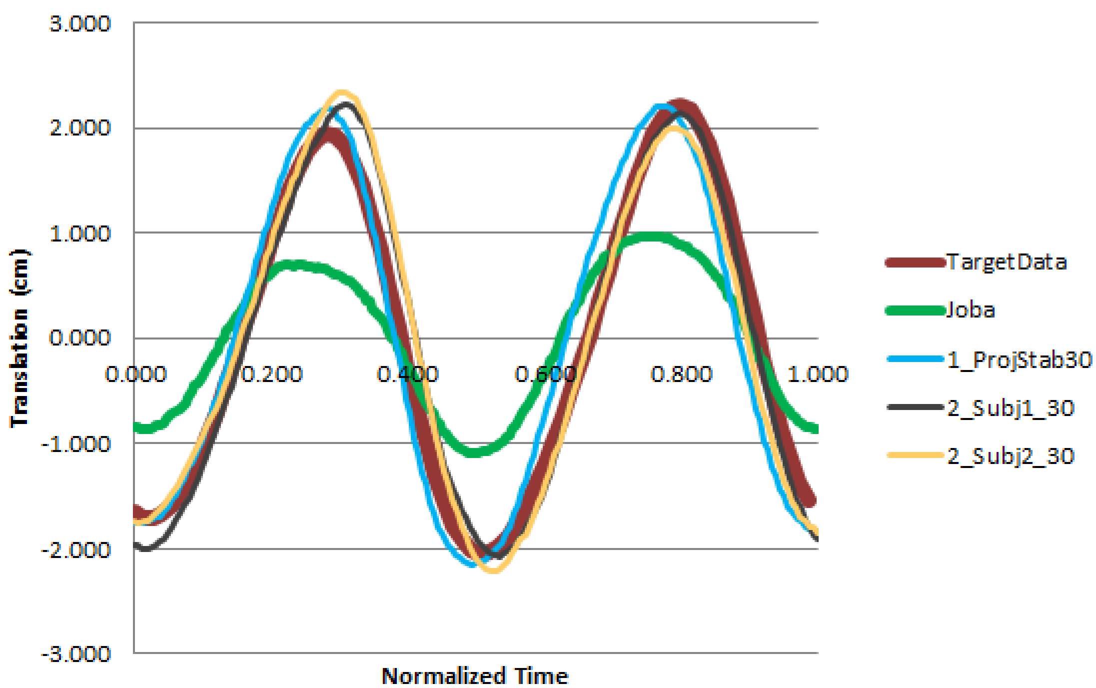



Figure 61: Comparison with Joba at Speed of 30 Hz with Various Spring Stabilization and Loading Conditions (Y-Translation)

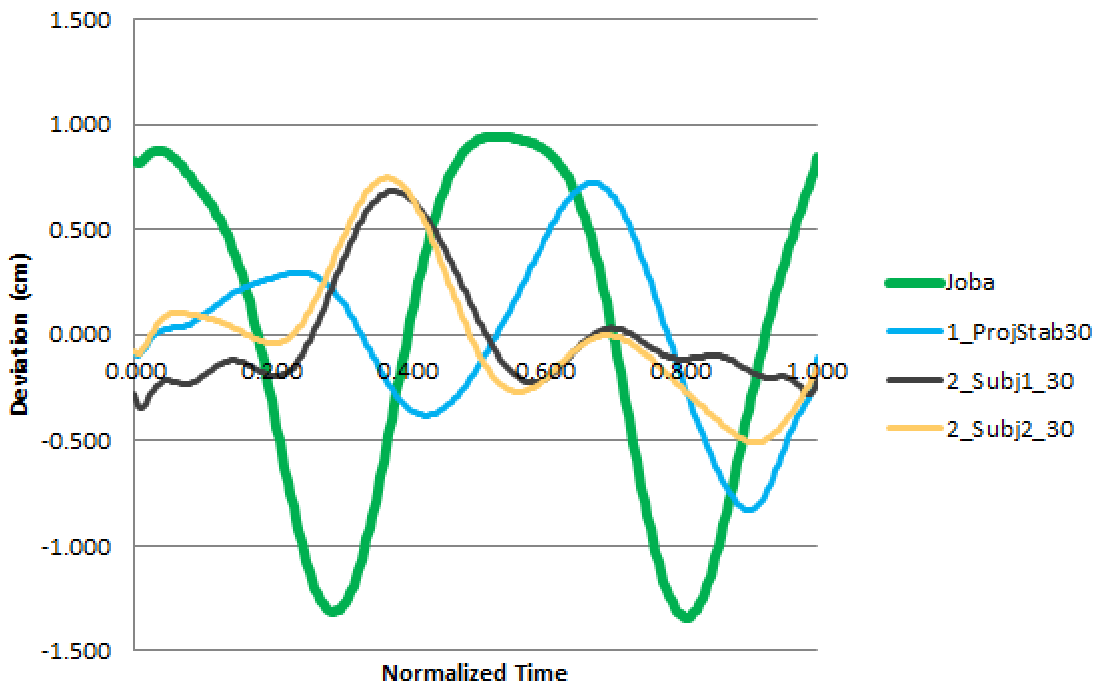



Figure 62: Deviation from Target Data (Y-Translation)

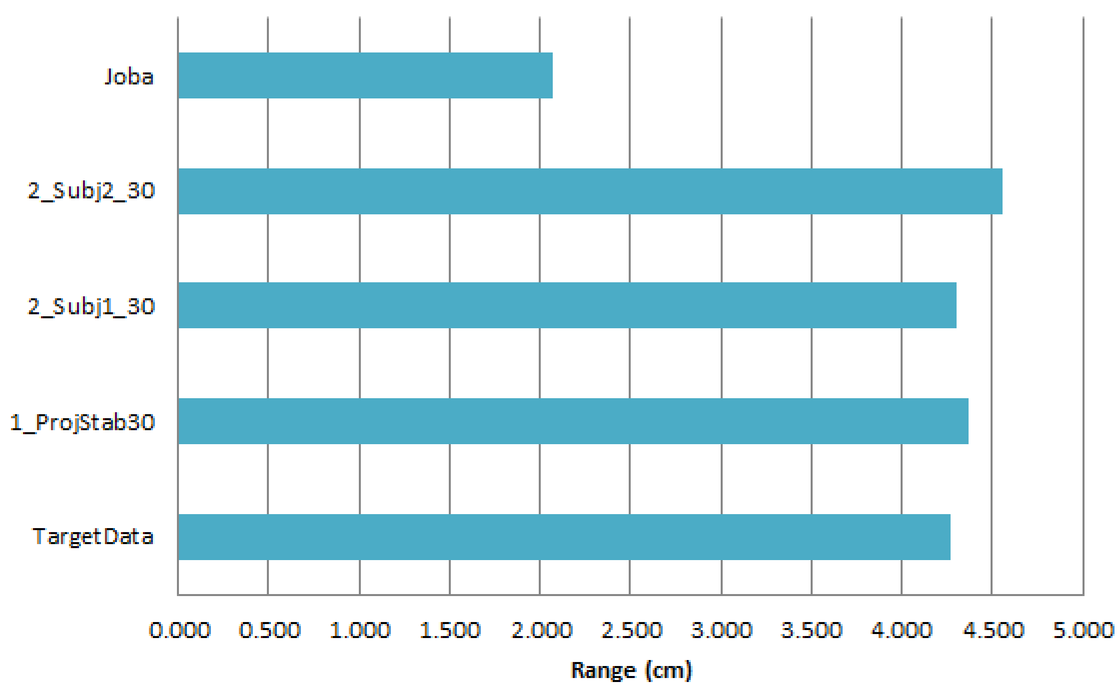



Figure 63: Range of Motion of Target, Joba, and Wild Bill Prototype (Y-Translation)

The ranges of motions are shown in Figure 63. In the y-direction, the range of translation for the target data was 4.25 cm. Joba's range was just over 2 cm and Prototype 2 ranged from 4.25 to just over 4.5 cm.

For translation on the z-axis there are three local maxima and three minima during one gait cycle for the target and 1_ProjStab30 trial, as shown in Figure 64. The experimental trials generally have the same trend, but with 1_ProjStab having slightly more pronounced features and a greater magnitude. For the Joba there is only one maximum and one minimum, and the data is out of phase with the target and trial data. The deviation of the trials and the Joba from the target is plotted in Figure 65. The experimental trial data have similar trends. Trial 1_ProjStab30 has a maximum deviation of 6 cm, while the other two trials have a maximum deviation of 4.5 cm from the peaks of

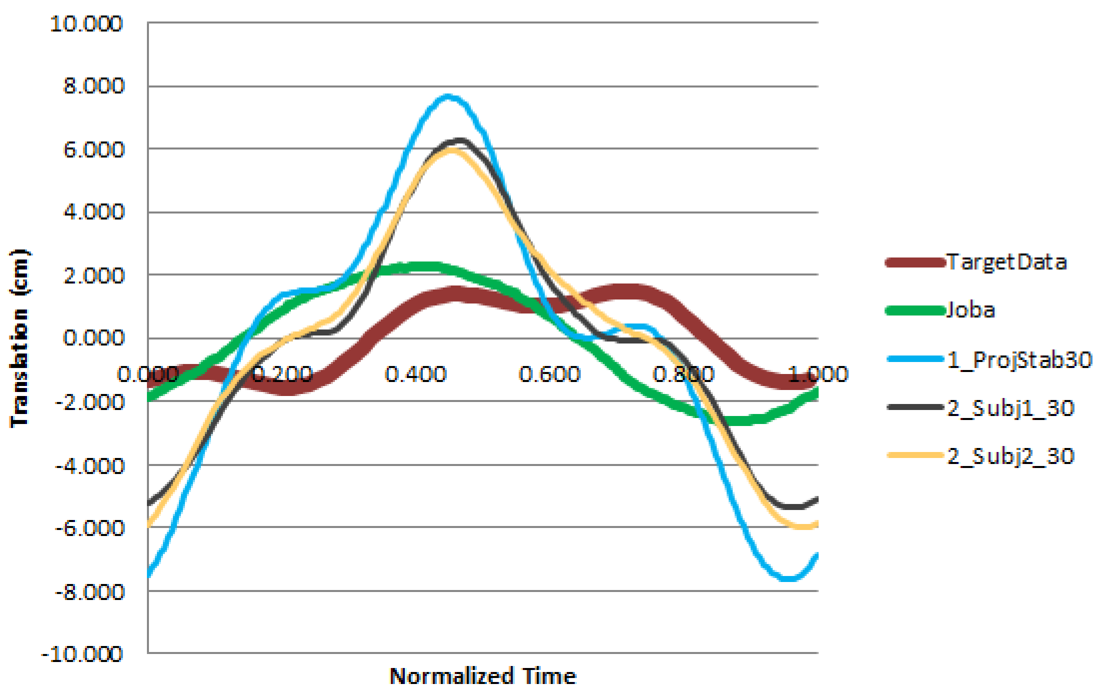



Figure 64: Comparison with Joba at Speed of 30 Hz with Various Spring Stabilization and Loading Conditions (Z-Translation)

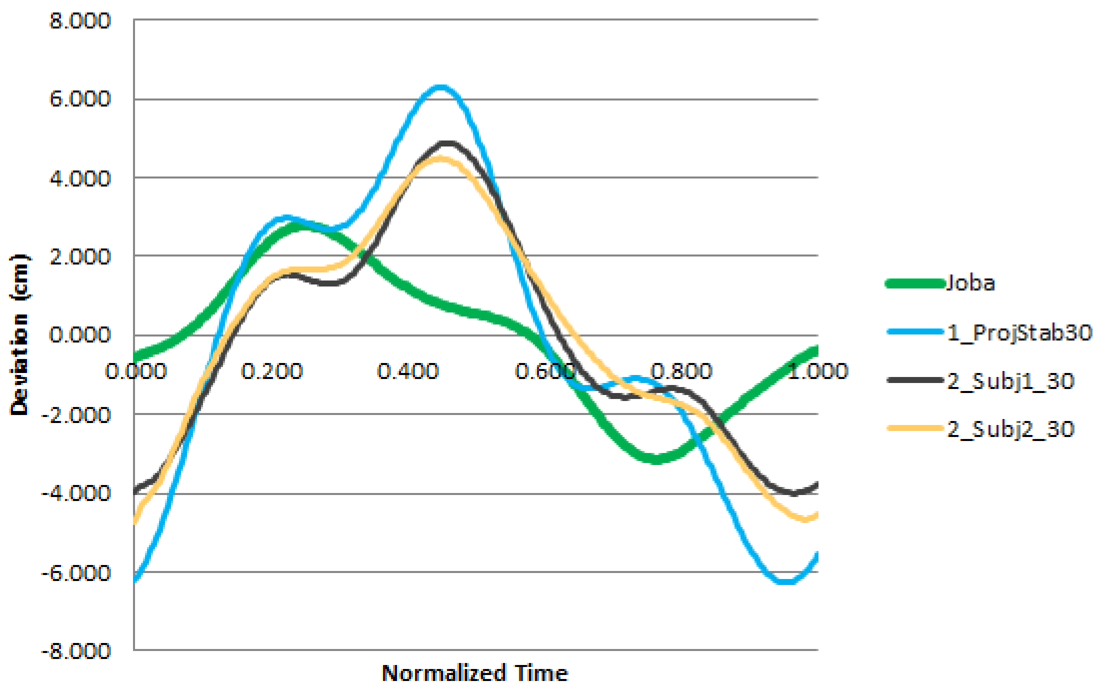



Figure 65: Deviation from Target Data (Z-Translation)

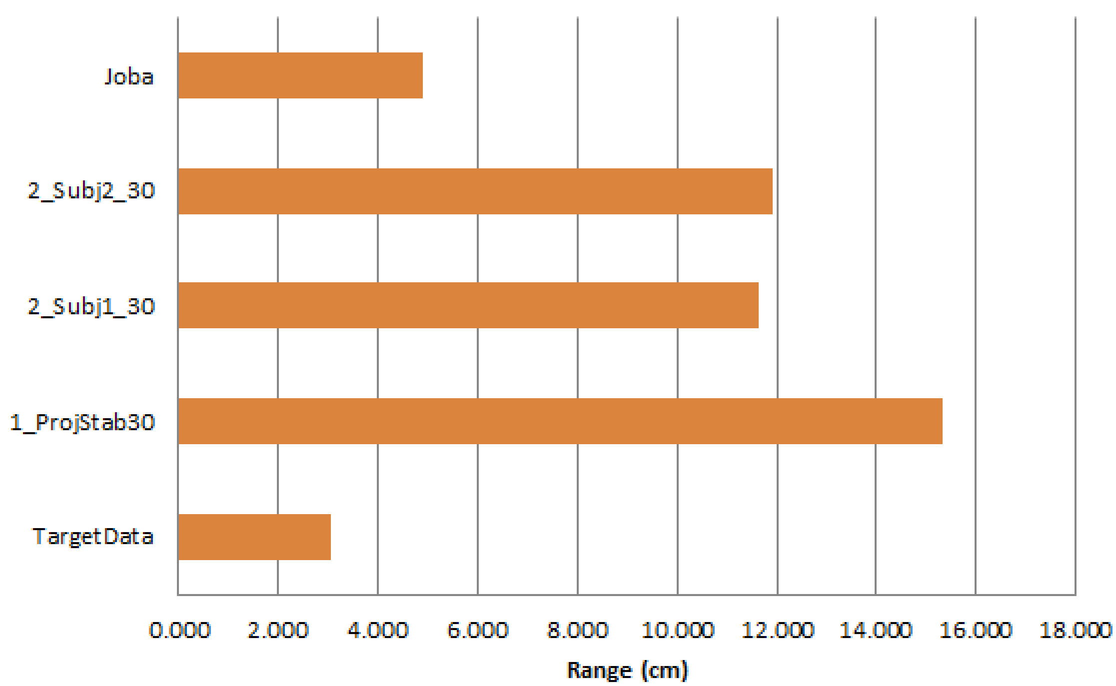



Figure 66: Range of Motion of Target, Joba, and Wild Bill Prototype (Z-Translation)

the target data. The trend of the Joba is dissimilar and reaches a maximum deviation of 3 cm. The ranges of motion are shown in Figure 66. The target data has a range of 3 cm, the Joba has a range of 5 cm, and Prototype #2 ranges from 11.5 to 15.25 cm.

Figure 67 shows average rotation in the x-direction. For each trial, the Joba, and the target motion there is one maximum and one minimum during one gait cycle. The trends and magnitudes of the target data and the Joba are similar. The Prototype #2 data has a shape similar to the target data, but has an increased magnitude. The deviation between each of the trials and the Joba from the target motion is shown in Figure 68. The experimental trials with subjects riding generally have the same trend and magnitude. The Joba deviates from the target data by almost 2 cm in some instances, while the trial data deviates from the target by about 3 cm. The ranges of motions are shown in Figure

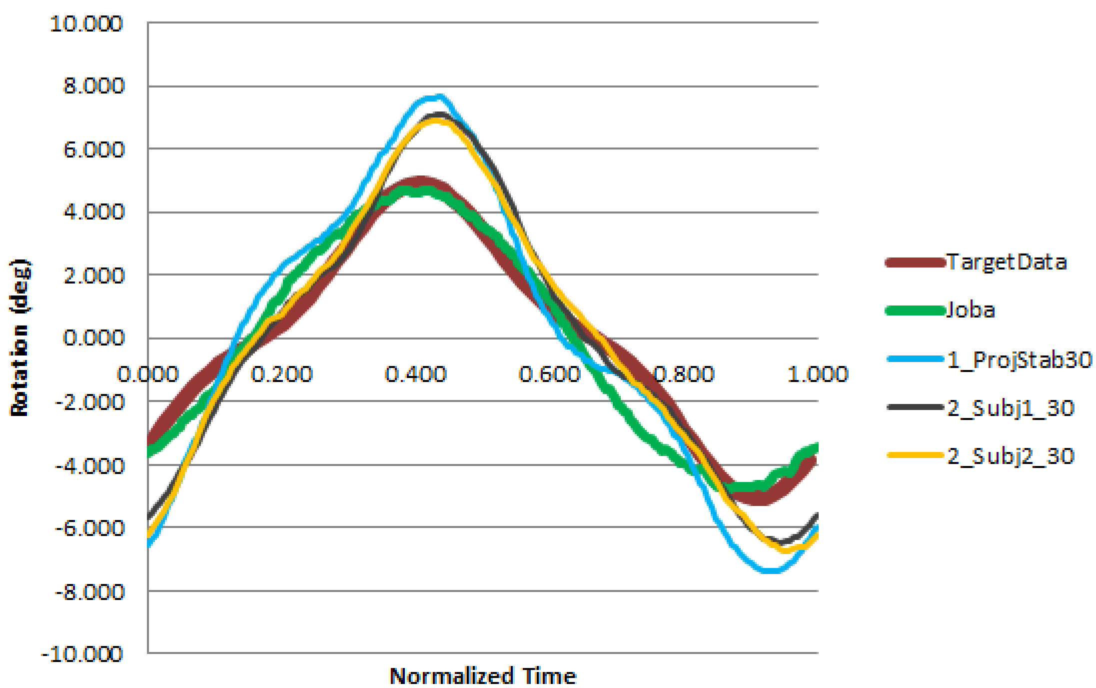



Figure 67: Comparison with Joba at Speed of 30 Hz with Various Spring Stabilization and Loading Conditions (X-Rotation)

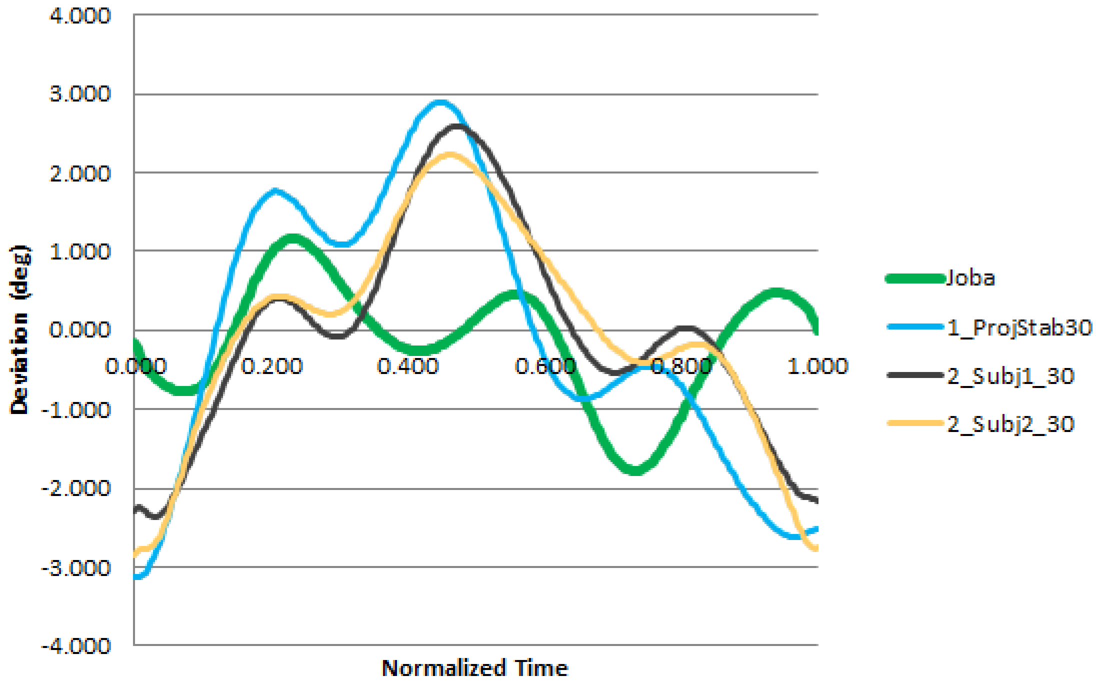



Figure 68: Deviation from Target Data (X-Rotation)

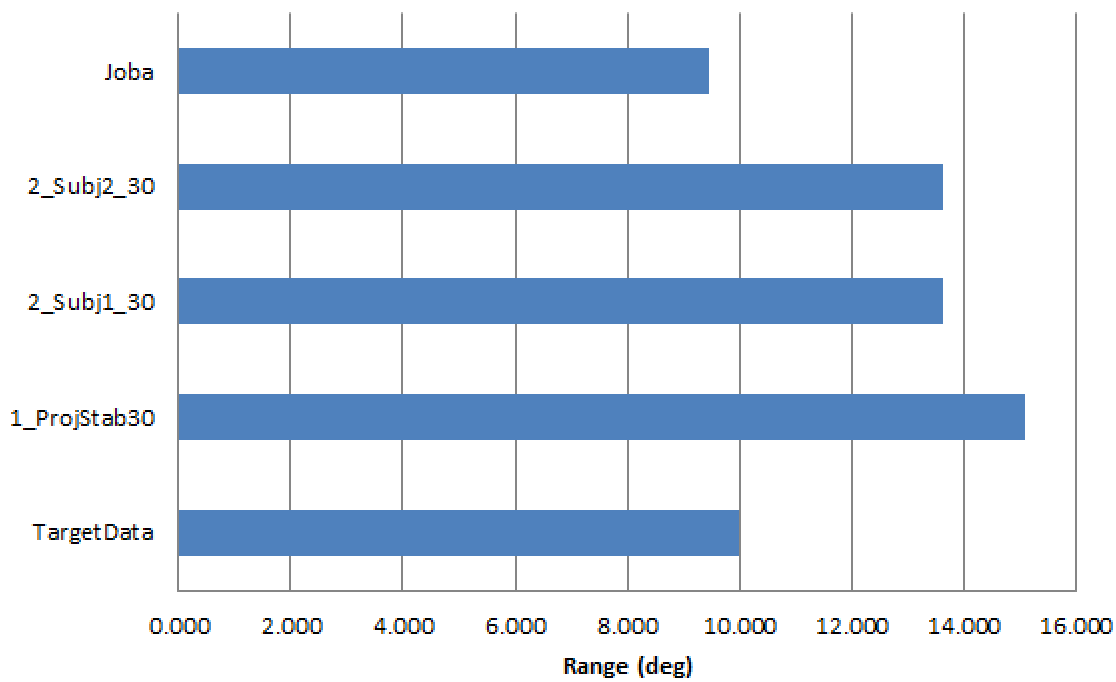



Figure 69: Range of Motion of Target, Joba, and Wild Bill Prototype (X-Rotation)

69.  In the x-direction, the range of rotation for the target data was 10 cm.  Joba's range was 9.5 cm and Prototype 2 ranged from 13.5 to 15 cm.

Figure 70 shows average rotation in the y-direction.  For the Joba and the target motion there is one maximum and one minimum during one gait cycle.  For the experimental trials there are three local maxima and three minima.  The trends and magnitudes of the trial data are similar.  The Prototype #2 data has a shape similar to the target data, but has an undulation in the peak not seen in the target data.  The curve of the Joba data is out of phase with the target and the trial data.  The deviation between each of the trials and the Joba from the target motion is shown in Figure 71.  The experimental trials have the same trend and magnitude.  Maximum deviation from the target data is about 1.25 cm.  The Joba deviates from the target data by about 4 cm in some instances.

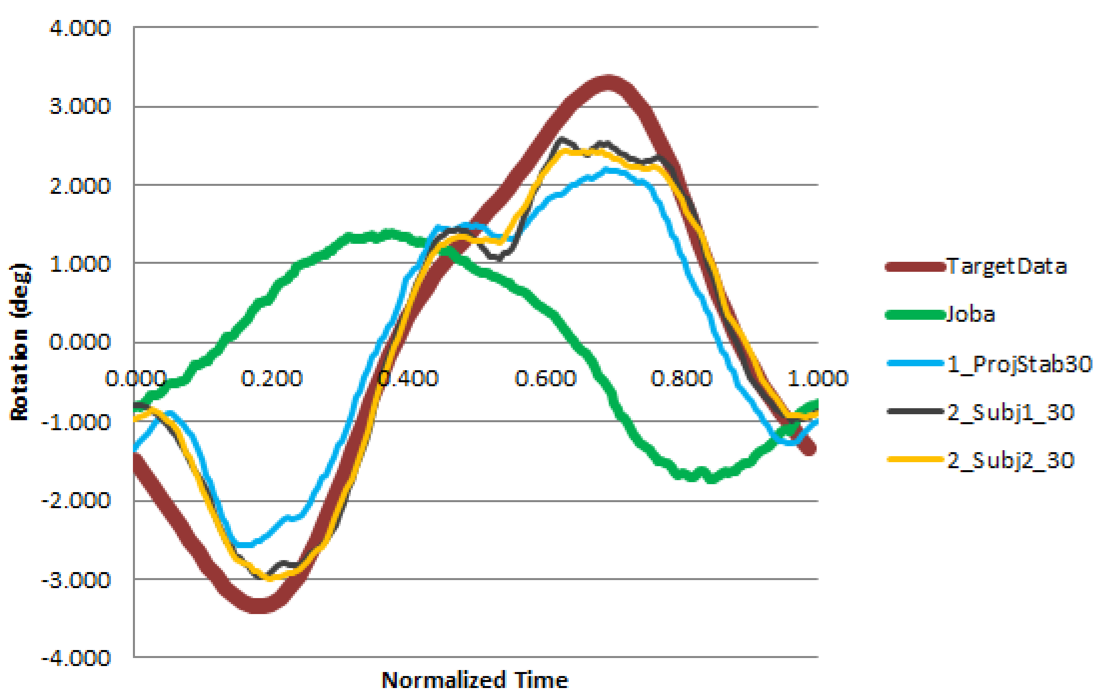



Figure 70: Comparison with Joba at Speed of 30 Hz with Various Spring Stabilization and Loading Conditions (Y-Rotation)

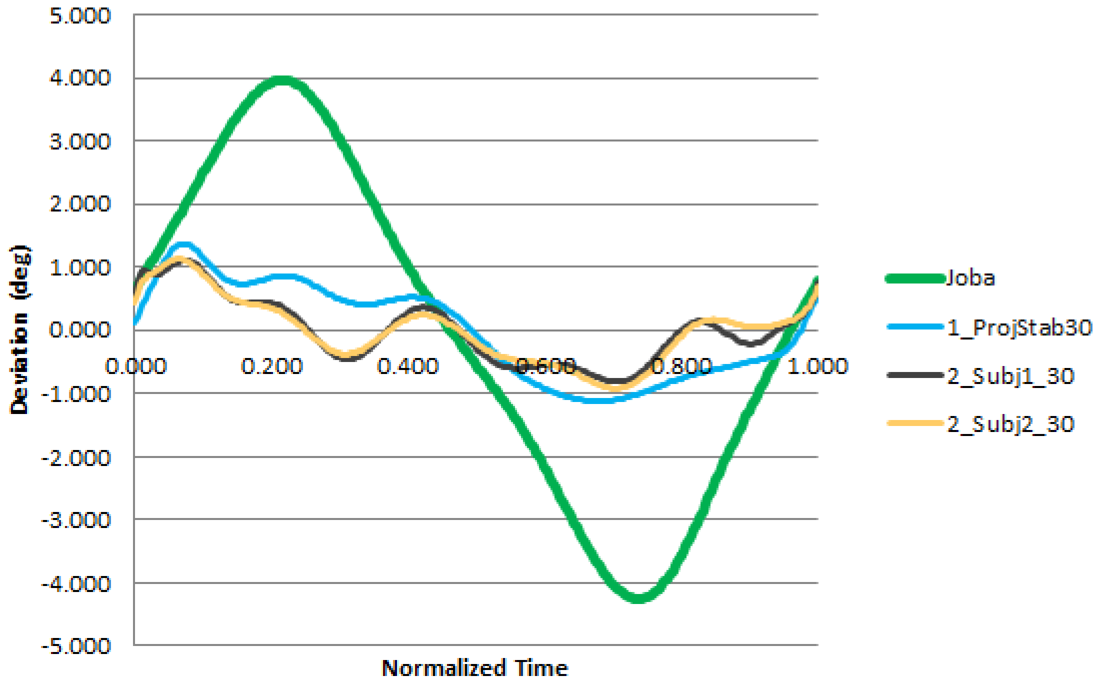



Figure 71: Deviation from Target Data (Y-Rotation)

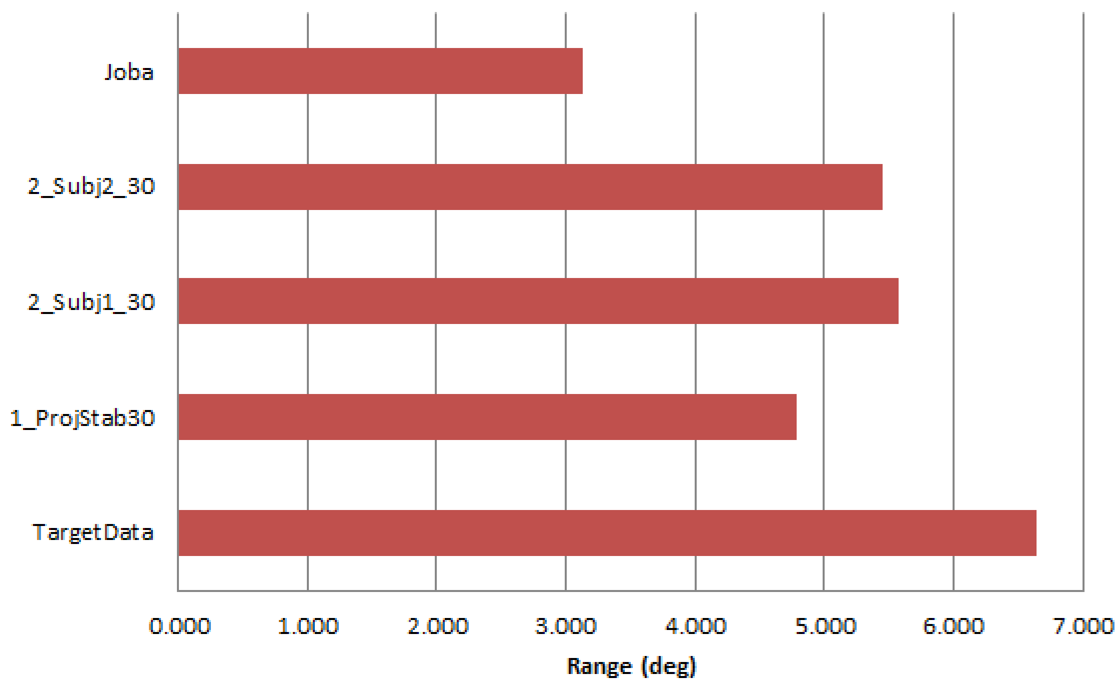



Figure 72: Range of Motion of Target, Joba, and Wild Bill Prototype (Y-Rotation)

The ranges of motions are shown in Figure 72. In the y-direction, the range of rotation for the target data was 6.5 cm. Joba's range was just over 3 cm and Prototype 2 ranged from 4.75 to 5.5 cm.

Figure 73 shows the average rotation in the z-direction is sinusoidal. For each trial, the Joba, and the target motion there is two maxima and two minima during one gait cycle. The trends and magnitudes of the target data and the trial data are similar. The Joba data has a shape similar to the target data, but has an increased magnitude. The deviation between each of the trials and the Joba from the target motion is shown in Figure 74. The experimental trials generally have the same trend and magnitude. The Joba deviates from the target data by almost 2.5 cm at the peaks of the data, while the trial data deviates from the target by as much as 1.5 cm. The ranges of motions are

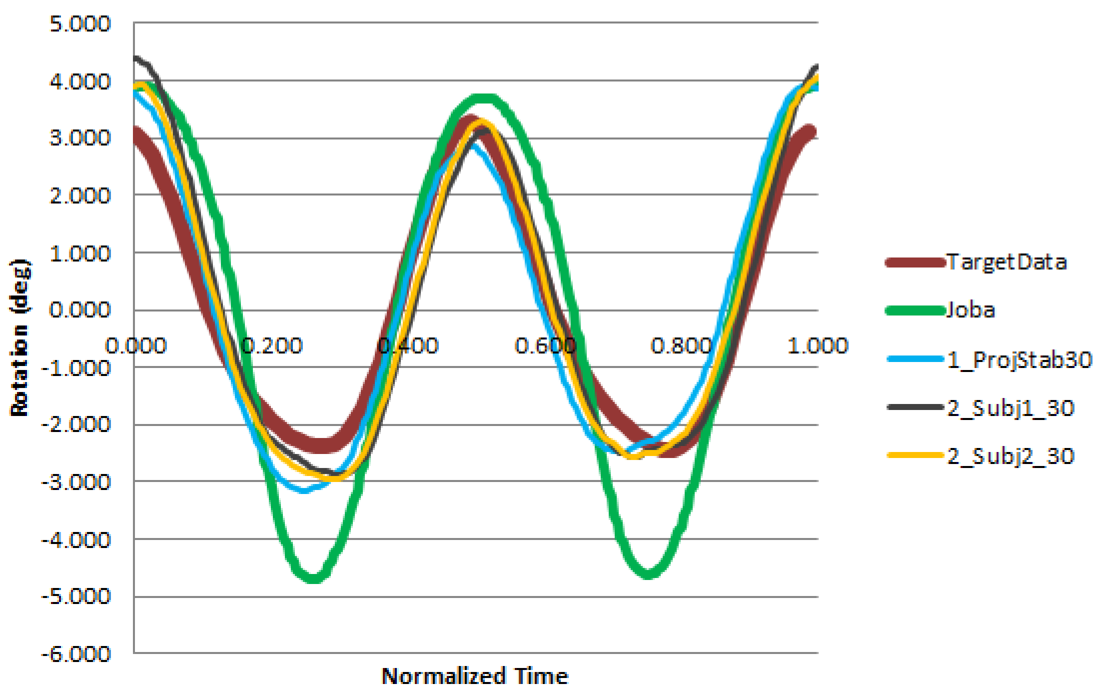



Figure 73: Comparison with Joba at Speed of 30 Hz with Various Spring Stabilization and Loading Conditions (Z-Rotation)

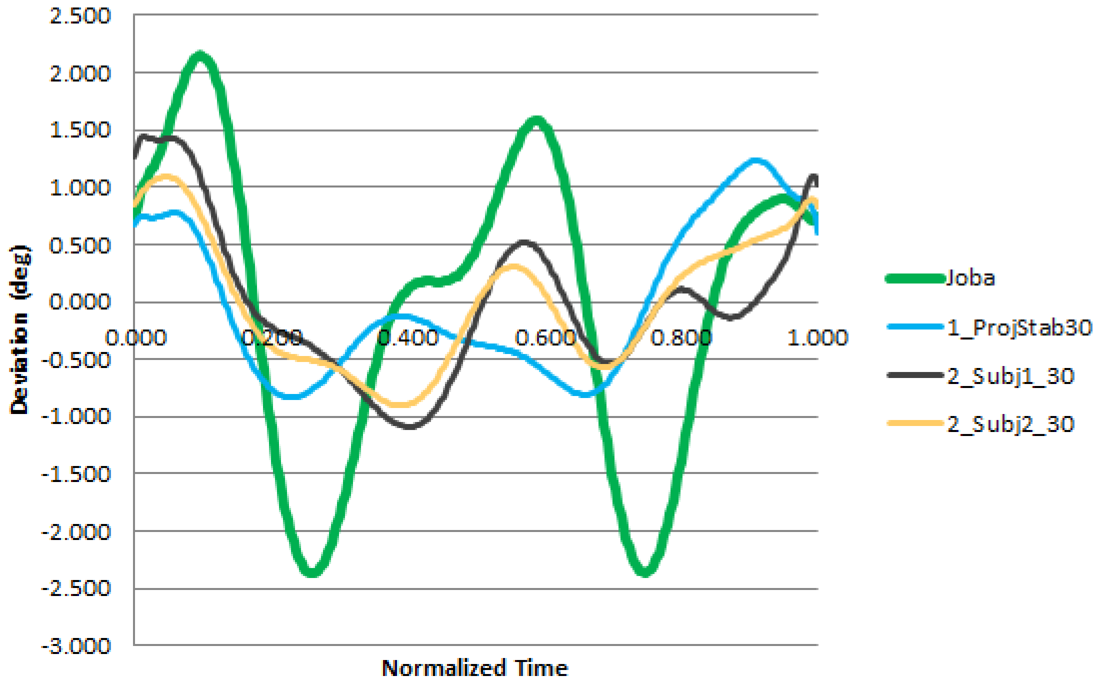



Figure 74: Deviation from Target Data (Z-Rotation)

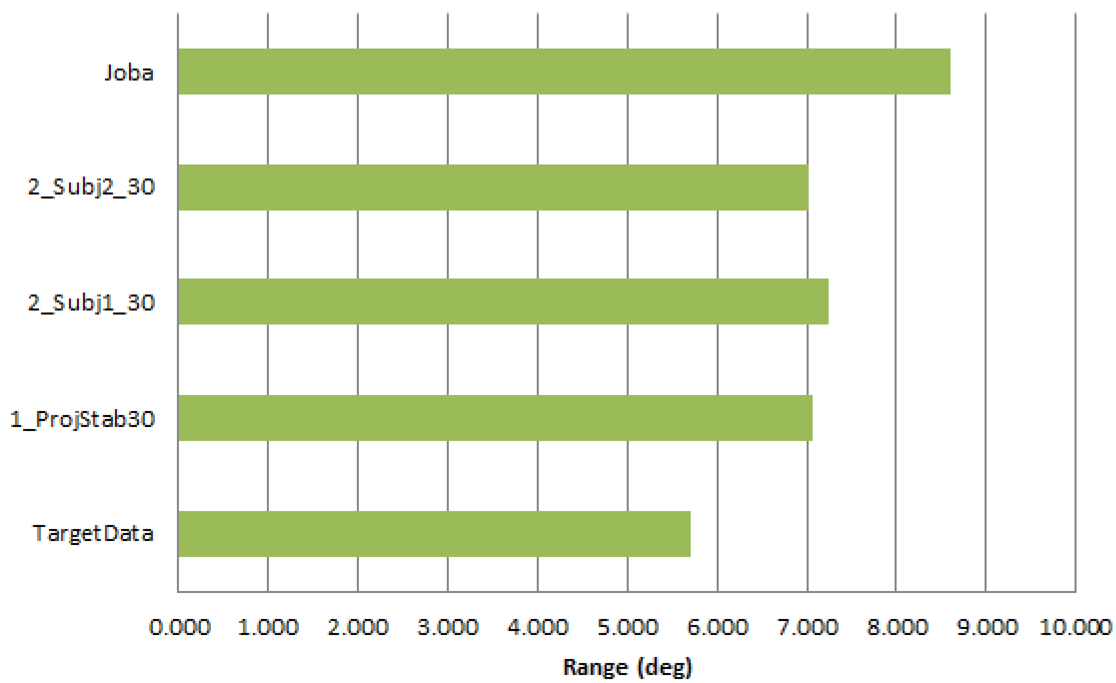



Figure 75: Range of Motion of Target, Joba, and Wild Bill Prototype (Z-Rotation)

shown in Figure 75. In the z-direction, the range of rotation for the target data was 5.5 cm. Joba's range was 8.5 cm and Prototype 2 ranged from 7 to 7.25 cm.

*Saddle Trajectories in the Principal Planes*

The following graphs show the translation of Prototype #2, the target motion, and the Panasonic Joba in two dimensions. Two-dimensional graphs of the rotations can be found in Appendix C. Figure 76 shows how the average saddle marker moves when looking on the saddle from above. Generally, all of the data exhibits an asymmetric figure-8 pattern. The motion of Prototype #2 has a larger range of side-to-side z-translation and larger range of backwards-forwards x-translation. The Joba has a similar range of motion, but does not match the trend of the target data. Figure 77 shows how the average saddle marker moves when looking at the saddle from the side. Prototype #2 trial data is similar to the target motion in both magnitude and trend. The Joba has a reduced range of upwards-downwards y-translation and does not have a trend similar to the target data. Figure 78 shows how the average saddle marker moves when looking at the saddle from behind. All of the data exhibit an infinity-shaped pattern. The Prototype #2 trials have a similar range of upwards-downwards y-translation as the target data, but have a greater range of side-to-side z-translation. The Joba has a reduced range of both y- and z-translation

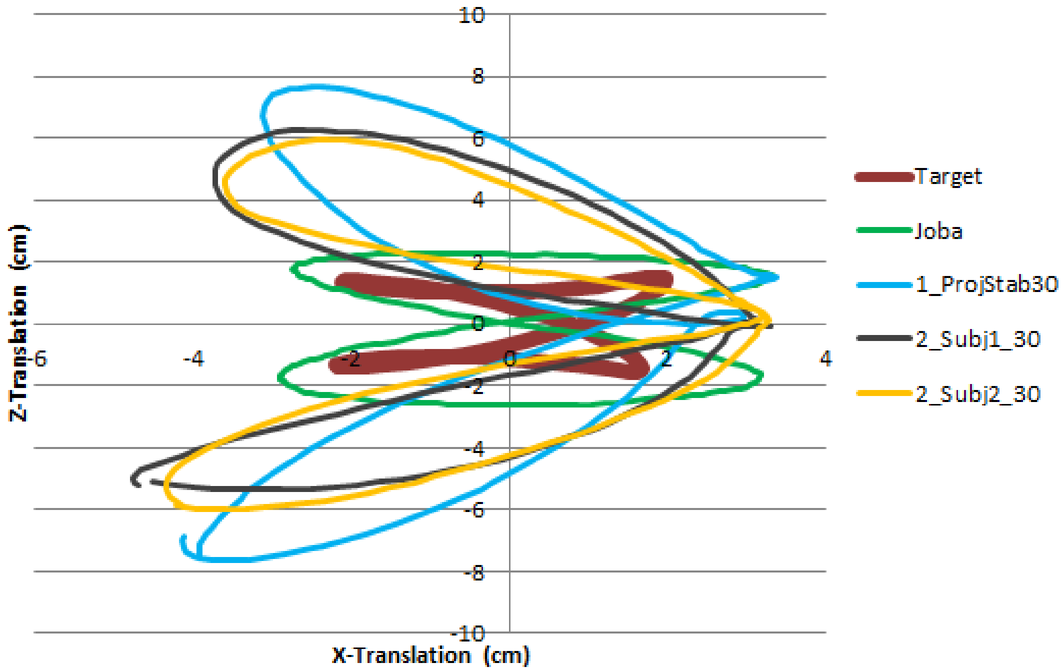



Figure 76: Comparison of X-Z Translation with Joba at Speed of 30 Hz with Various Spring Stabilization and Loading Conditions (Top View)

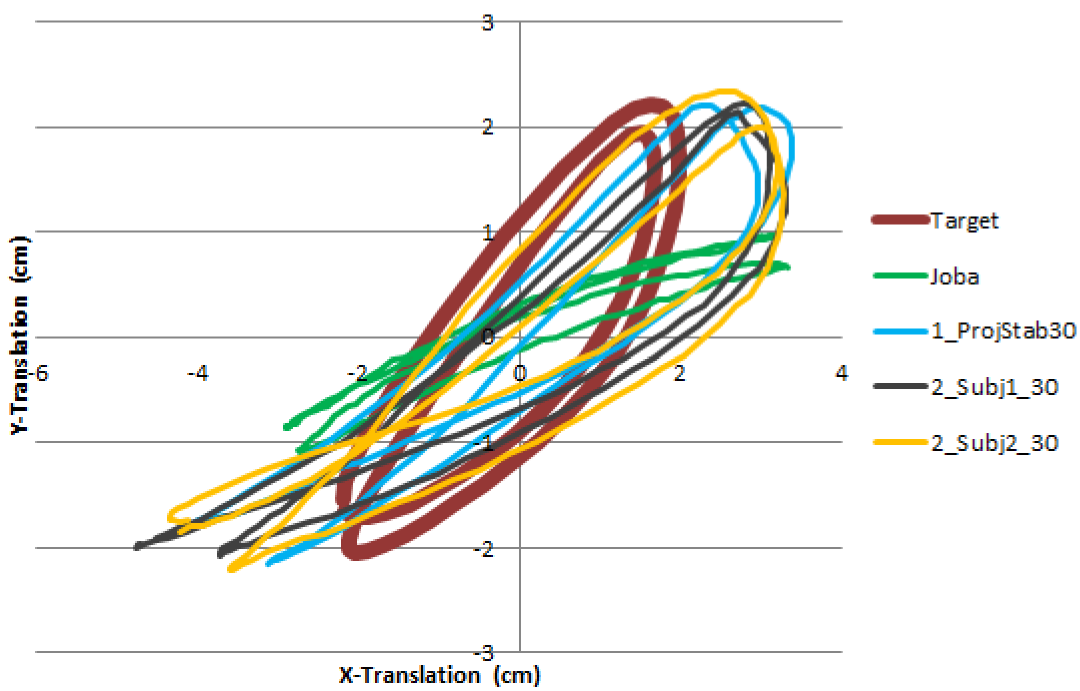



Figure 77: Comparison of X-Y Translation with Joba at Speed of 30 Hz with Various Spring Stabilization and Loading Conditions (Side View)

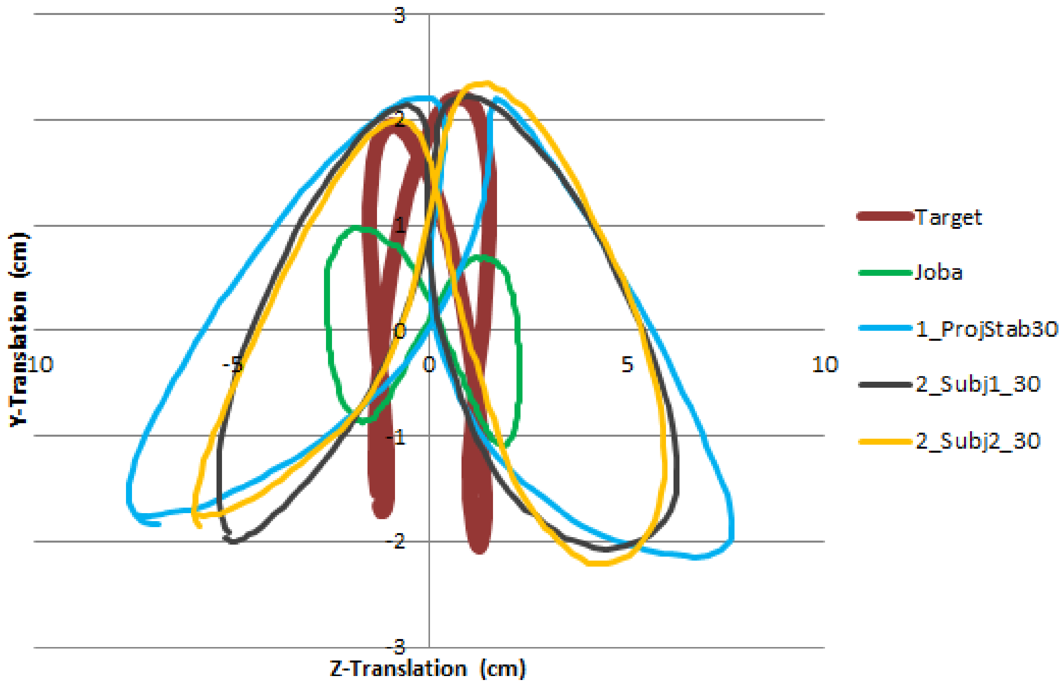



Figure 78: Comparison of Z-Y Translation with Joba at Speed of 30 Hz with Various Spring Stabilization and Loading Conditions (Back View)

# CHAPTER SEVEN

## Discussion

### *Significance*

The purpose of this study was to compare the motion generated by various trials of Prototype #2 to the target motion and to the Panasonic Joba. As shown in the previous chapter, many similarities between the patterns, magnitudes, and ranges of motion were evident. Motion of Prototype #2 was evaluated by comparing it to the target data and the Joba and testing the significance of stabilization, speed, and load upon the saddle.

As previously discussed, there is a need for a mechanical horse capable of reproducing the motions generated by living horses. Such a machine would be capable of improving hippotherapy accessibility and also of standardizing testing conditions for hippotherapy research. There are currently no such machines available. Increased accessibility could potentially open the option of hippotherapy to thousands of patients. Standardized testing conditions as well as the mechanical horse's ability to separate physical and psychosocial variables could potentially affect the quality of experimental results and increase the number of experimental variables that can be controlled. This could eventually lead to uniform treatment of specific diseases and disabilities, including the optimization of duration of session, type of gait, specific horse, pace, direction of walking, and environment. Consistent treatment criteria and evidence to support the usefulness of hippotherapy could also expand the practice of hippotherapy and enlarge the patient pool.

The exchangeable set of cams in Prototype #2 allows the user to change the motion of the horse, a feature not available in any other marketed mechanical horse. This would correspond to changes in type of gait or particular horse used. This feature would also allow therapists to design motion patterns themselves in order to target specific patient responses or to recreate the motion of one particular therapy horse. It is also thought that a cam set generating the motion of human walking may be valuable, as the premise behind the benefit of hippotherapy is that the gait of the horse is similar to human gait.

## *Analysis*

The results show that the Prototype #2 mechanical horse is capable of generating sustained, prescribed motion in all three dimensions. Changes in the stabilization conditions, speed of operation, and loading conditions can impact the motion of the saddle, as discussed below.

### *Effect of Spring Stabilization*

The addition of springs to Prototype #2 effectively changed the motion of the saddle, but did not prevent the saddle from replicating the general shapes and magnitudes of the target motion. This is ideal, as the springs were chosen so that they would add stability to the saddle without hindering or interfering with the desired motion of the saddle. As shown in Figure 46, the addition of the springs or stabilization of the saddle had little to no effect on the upwards and downwards translation of the saddle. The data collected without stabilization matched the target data, and the presence of springs or saddle stabilization did not prevent the saddle from moving in the intended way. The presence of the maximum deviation at the inflection point suggests that the discrepancies between the motion of the prototype and the target motion may be due to a phase shift resulting from imperfect operational timing rather than strict differences in the displacement of the data. However, Figure 48 shows that the springs were capable of generating enough force to change the motion of the saddle in other measures. For the measure of y-rotation (Figure 48) as well as the measures of x- and z- translations and rotations (Appendix C) the application of stabilization techniques reduced the error seen between the saddle motion without any stabilization and the target data. Addition of the springs dampened translation and rotation about the x and z axes, effectively reducing the range of motion generated along those axes and bringing it closer to the range of the target data. This is thought to occur because the springs are oriented at about 15 degrees from the horizontal when the saddle is in equilibrium position. This spring arrangement causes the load generated by the springs to be applied mostly in the x-z plane.

*Effect of Speed*

The speed at which the device was operating had some effect on the motion generated by the saddle in some measures. As shown in Figure 50, increasing the operational speed of the device had no effect on the upwards and downwards motion of the saddle. However, as shown in Figure 52, increasing the speed beyond 35 Hz can change the pattern of motion sustained by the saddle for side-to-side z-translation. For this measure and the measures of x-, y-, and z- rotation and x-translation (Appendix C), speeds faster than 35 Hz are capable of increasing the range of motion or of exaggerating curve features. At an operational speed of 45 Hz the machine seems to change motion, possibly as the result of operating at the machine's natural harmonic frequency. At an operational speed of 50 Hz the trend of the data changes motion patterns again, possibly indicating that the speed has superseded the harmonic frequency of the device and that the motion may return to a pattern closer to the intended motion. In Figure 51, deviations of the prototype y-translation motion from the target motion is likely due to a phase shift, possibly resulting from problems with syncing individual components in the device.

*Effect of Load*

Changing the loading conditions on the saddle can impact the motion produced by Prototype #2. As shown in Figure 56, placing an additional load on the saddle had no effect on the motion of the saddle. This may occur because gravity and the stabilization springs are already applying a downward force on the saddle substantial enough to eliminate any affects that would be caused by increasing the load or moving the center of gravity. Likewise, the addition of a user load has no effect on rotation about the x-axis (Appendix C). As shown in Figure 57, maximum deviations occur at the curve inflection points, thus indicating discrepancies are more likely the results of minor timing issue than absolute differences in data. Concerning the data shown in Figure 54, the prototype performed better when riders were not present. The increased inertia resulting from the addition of a user load caused the saddle's range of motion to increase, and in this case to move away from the target data. Likewise, in the cases of y-rotation and z-translation (Appendix C) the saddle also experienced an increase in range of motion, though for y-rotation this reduced the deviation from the target data. Also observed in Figure 54, the increased load seems to have rounded the peaks of the data, thus matching the shape of the target data more accurately. This also occurs for the measure of z-rotation (Appendix C). This is also likely a result of the increased inertia of the saddle.

*Comparison of Prototype #2, Target Motion, and the Panasonic Joba*

It can be seen from the data presented in Figures 58-79 that the Joba does not accurately produce the motion generated by a living horse in all measures. In Figure 58, both the Joba and the Prototype #2 trials generate similar motions, but these motions do not match the trend of the target motion. The target motion has a smaller range of motion and the peak and valley gradients are less steep. In Figure 61, the Prototype #2 trials match the target data, but the Joba does not. The inclines of both the target data and the trial data are steeper than those exhibited by the Joba. The Joba's limited range of 2 cm is not true to the realistic motion of a horse. From Figure 62, it can be observed that the maximum deviations of the prototype and the Joba occur at different instances during the gait cycle. For the prototype trials, maximum deviation occurs at the inflection points and indicates possible phase issues. For the Joba trials, maximum deviation occurs at the peaks and valleys of the data. This indicates the presence of discrepancies between the absolute motion data of the Joba and the target. For z-translation, the Joba matches the magnitudes of the target data but neglects the production of the undulations presents in the target data that could be indicative of realistic horse-like motion, as shown in Figure 64. The Prototype #2 trial data contains these features but in an exaggerated manner. As shown in Figure 65, the maximum deviation occurs at the peak of the data and suggests a discrepancy between the absolute patterns of the motion. It is likely that reducing the range of z-translation motion while keeping the same data trend would result in a highly realistic motion. Likewise, for the x-rotation data shown in Figure 67, the Prototype #2 trial data contains features not replicated by the Joba. These features are present in the target data and may improve the sensation of the motion. In Figure 70, it is shown that the motion of the Joba is out of phase with and has a smaller range than both the target and the trial data. The trial data matches the motion of the target, but exaggerates the delay on the increasing half of the peak. However, this motion is closer to realistic horse-like motion than the Joba. For z-rotation, the Prototype #2 trials closely match the target data. These trials have the same range as the target and also the same peak shape. The shapes of the peaks of the Joba data are sharper. The Joba also has an exaggerated range of motion. This difference may make Prototype #2 feel more realistic than the Joba. The various Prototype #2 trials show that the prototype is capable of producing a wide variety of motion, while still maintaining the general pattern generated by a walking horse. Since the cams can be replaced, future iterations of cam designs are likely to improve the quality of the motion and reduce deviation from the target motion.

### *Limitations and Errors*

Errors affecting the construction of the mechanical horse and the collection of motion capture data are inherent. Limited tolerances during machining may have effectually changed the active surface of the cams, and therefore the motion. The absence of a device able to read the tension being distributed through the cables rendered the tensioning of said cables to be done by estimation. Resulting differences in equilibrium position cable tension could affect the motion of the saddle. Uneven drilling or tapping of holes for mounting pulleys may have led to small geometrical differences between the simulated computer model and the actual physical model. Warping of components during welding may have led to misaligned axes, possibly affecting the delivery of power from the motor to the saddle.

Inherent errors in the motion capture system include the built-in errors of the calibration systems, inaccurate placement of markers on subjects, and displacement of markers during testing. The disruption of data for the anterior saddle marker (horn marker) caused by interference from the rider's arm obscuring the marker from one camera's line-of-sight resulted in the intermittent loss of data for the marker. Gaps in the data were filled using a built-in function in SimiMotion and could have introduced error by not modeling the actual motion of the marker.

Further error was added in the processing of the data used to generate graphs of error between the trials and the target motion. To create these graphs a MATLAB function was written that would import the original data into MATLAB, fit a $16^{th}$ order polynomial curve to the data, repopulate the motion data by sampling the curve at specified intervals, and finally exporting the data back out. Any discrepancies between the polynomial curve and the actual data would result in the addition of error into the original data.

# CHAPTER EIGHT

## Conclusion

A machine capable of accurately reproducing the motion of a living horse could be used for exercise, therapy, training, and research. Thus far, the mechanical horses currently on the market fall short of creating realistic movement in all six degrees-of-freedom. The prototype presented in this thesis implements design concepts for a machine capable of moving in all six degrees-of-freedom. The design is robust, efficient, inexpensive, and easily manufacturable. It provides a means for quickly exchanging the desired motion pattern and provides a large, stable saddle area ideal for use in therapy, two aspects not offered in any other currently available commercial mechanical horse.

The motion capture experiments conducted as part of this thesis validate the ability of the prototype to replicate sustained, three-dimensional motions similar to those of a living horse. In general, the data graphed in Chapter 6 show that the mechanical horse follows the same pattern of motion as the target data and that this motion is different from the Panasonic Joba. The measures analyzed included average x, y, and z translations and rotations of the saddle surface. The results provide quantitative and comparative evidence to support the notion that this prototype can produce the same quality of motion as a living horse.

### *Future Work*

The results show that this prototype can be successfully used to consistently generate motion through all six degrees-of-freedom. However, there is room for improvement.  Explanations for the discrepancies in motion need to be found and addressed.

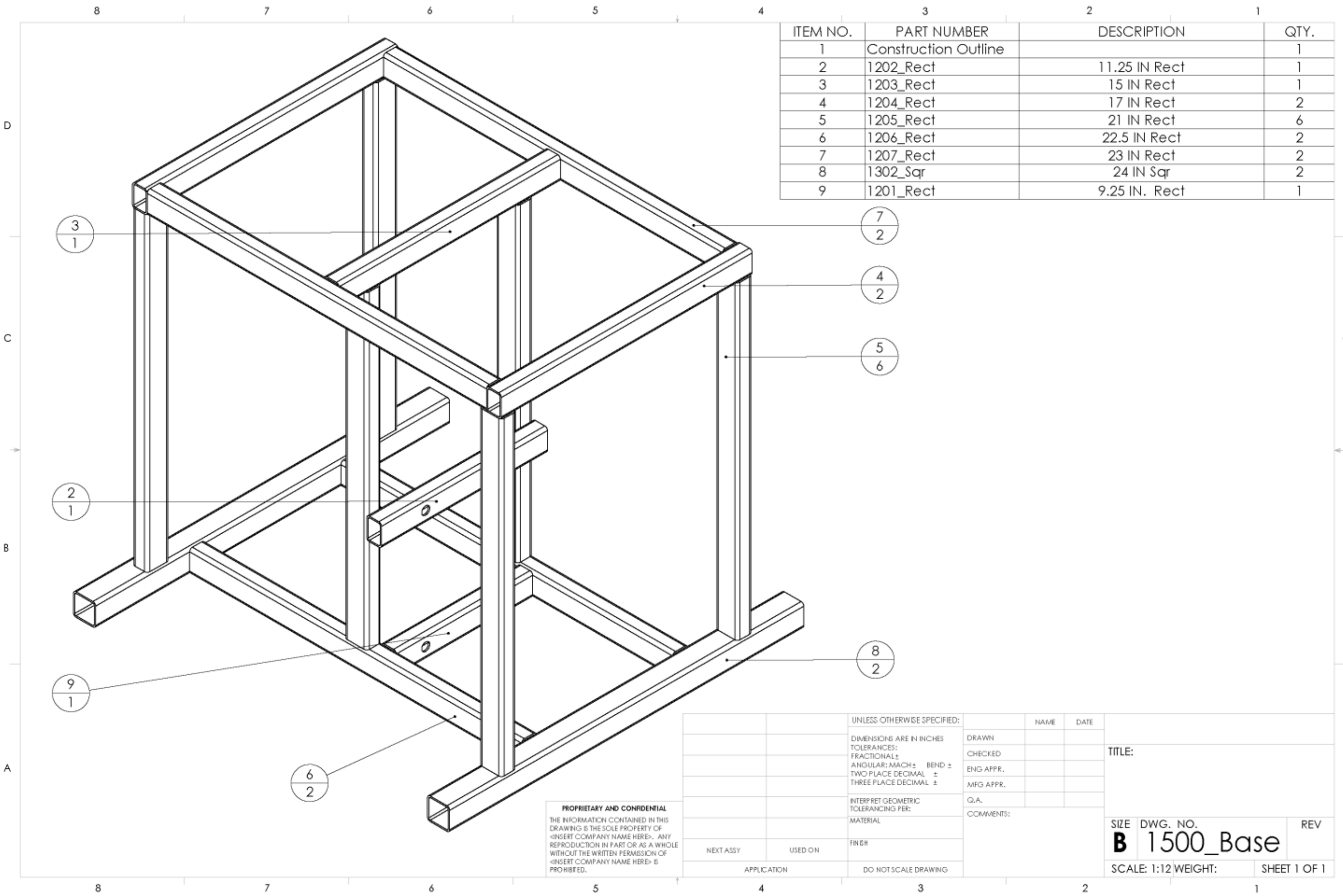
Future prototypes can expand on this model and incorporate improved or expanded functionality.  A heating pad could be installed under the first layer of padding in the body of the saddle seat in order to imitate the body warmth of living horses.  This could possibly improve flexibility through relaxation and stretching.  Lighter cables could be used to reduce the stiffness observed in the current cables, thereby reducing the chance of cables going slack.  Ideally, the cams could be redesigned to be smaller, thinner, and lighter so that exchange of cam sets is easier.  There is also need for an improved tensioner design.  The current tensioner requires the user to push-down on the device while simultaneously tightening a bolt to lock the tensioner in place.  Though the tensioner works as designed, it is difficult to apply the appropriate amount of tension to the cable by hand.  It is also difficult for only one person to operate the tensioner.  Ideally, the tensioner would have some mechanical component apply force to the chain and tensioner device and would be operable by only one person.  There is also a need to make the chain and camshaft sprocket permanent.  In the current design, exchange of the cam set requires slackening of the chain by release of the tensioner, removal of the camshaft sprocket, and unbolting of the camshaft supports.  Future designs should provide a support for the camshaft bearing permanently attached to the base so that the cam set can be exchanged without slackening the chain.  Use of a smaller motor and gearbox would open space in the body of the base, allowing for a wider range of saddle projections to be designed.  An automatic cable reel should be installed on the base of the mechanical horse to retract slack from the hand-held speed-controller.  The mechanical horse could be made shorter by dropping the mountings of the internal components by a few inches. The base should also be made wider to allow enough room for each pulley and cam-follower to move freely. Cam-follower spacers should be redesigned to traverse the length of the follower in order to reduce lateral motion made possible by laxity in the cam-follower bearings.

APPENDICES

# APPENDIX A

Construction Drawings for Prototype #2

*Base Subsystem*




| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | Construction Outline | | 1 |
| 2 | 1202_Rect | 11.25 IN Rect | 1 |
| 3 | 1203_Rect | 15 IN Rect | 1 |
| 4 | 1204_Rect | 17 IN Rect | 2 |
| 5 | 1205_Rect | 21 IN Rect | 6 |
| 6 | 1206_Rect | 22.5 IN Rect | 2 |
| 7 | 1207_Rect | 23 IN Rect | 2 |
| 8 | 1302_Sqr | 24 IN Sqr | 2 |
| 9 | 1201_Rect | 9.25 IN. Rect | 1 |

Figure A.1: Bill of Materials for Base Subsystem

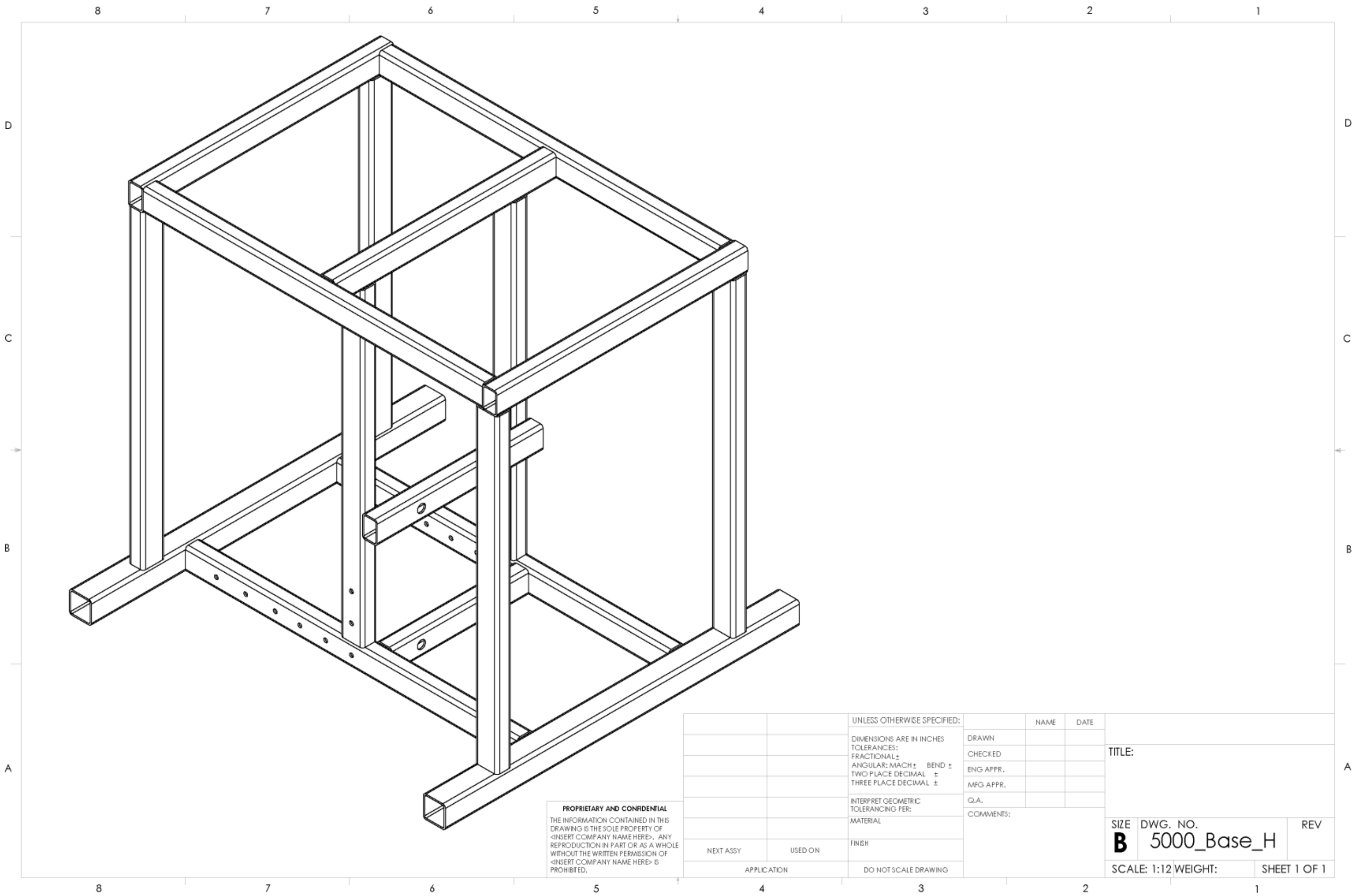



Figure A.2: Drawing of Base with Holes for Mounting Plates

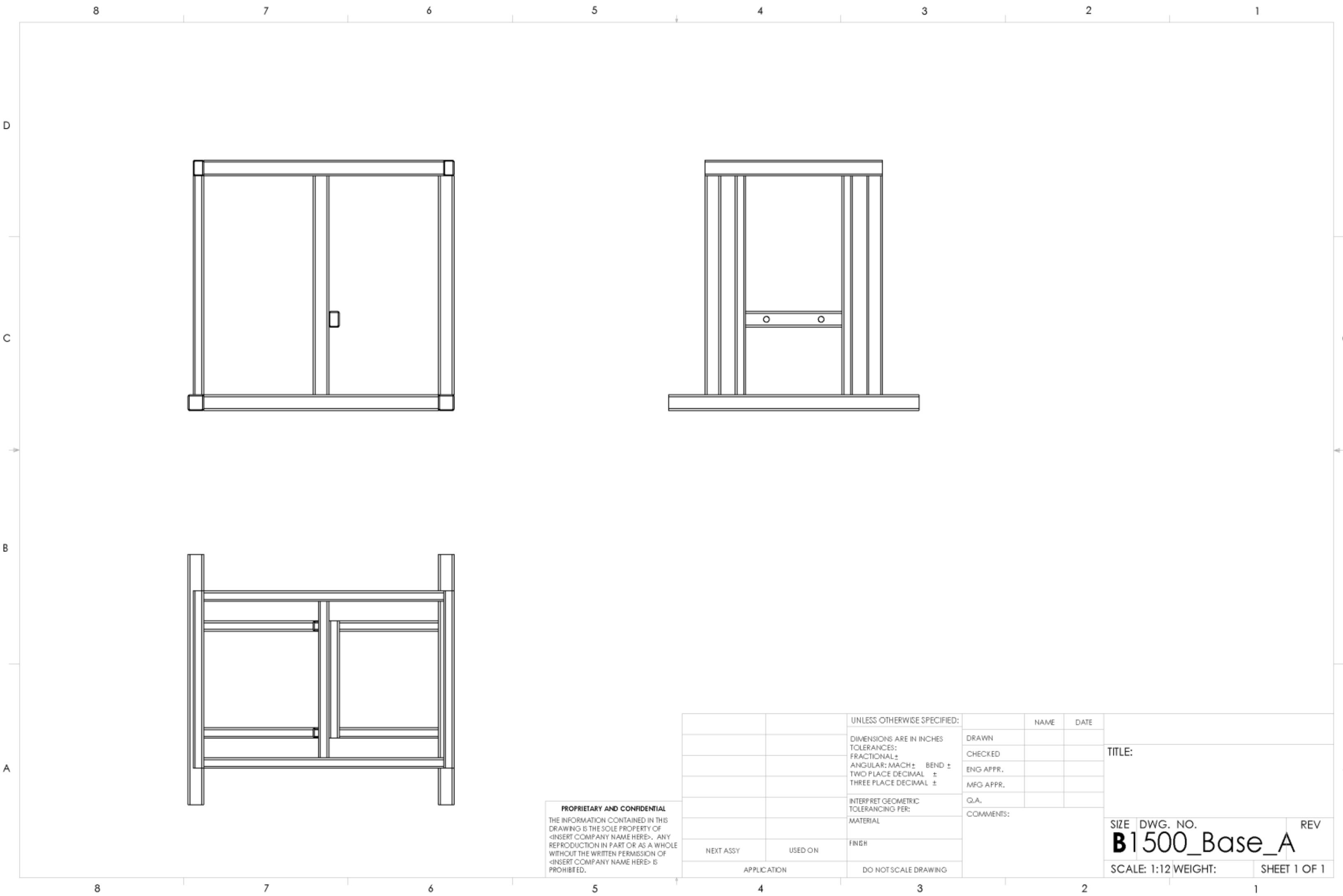



Figure A.3: Two-Dimensional Views of Base

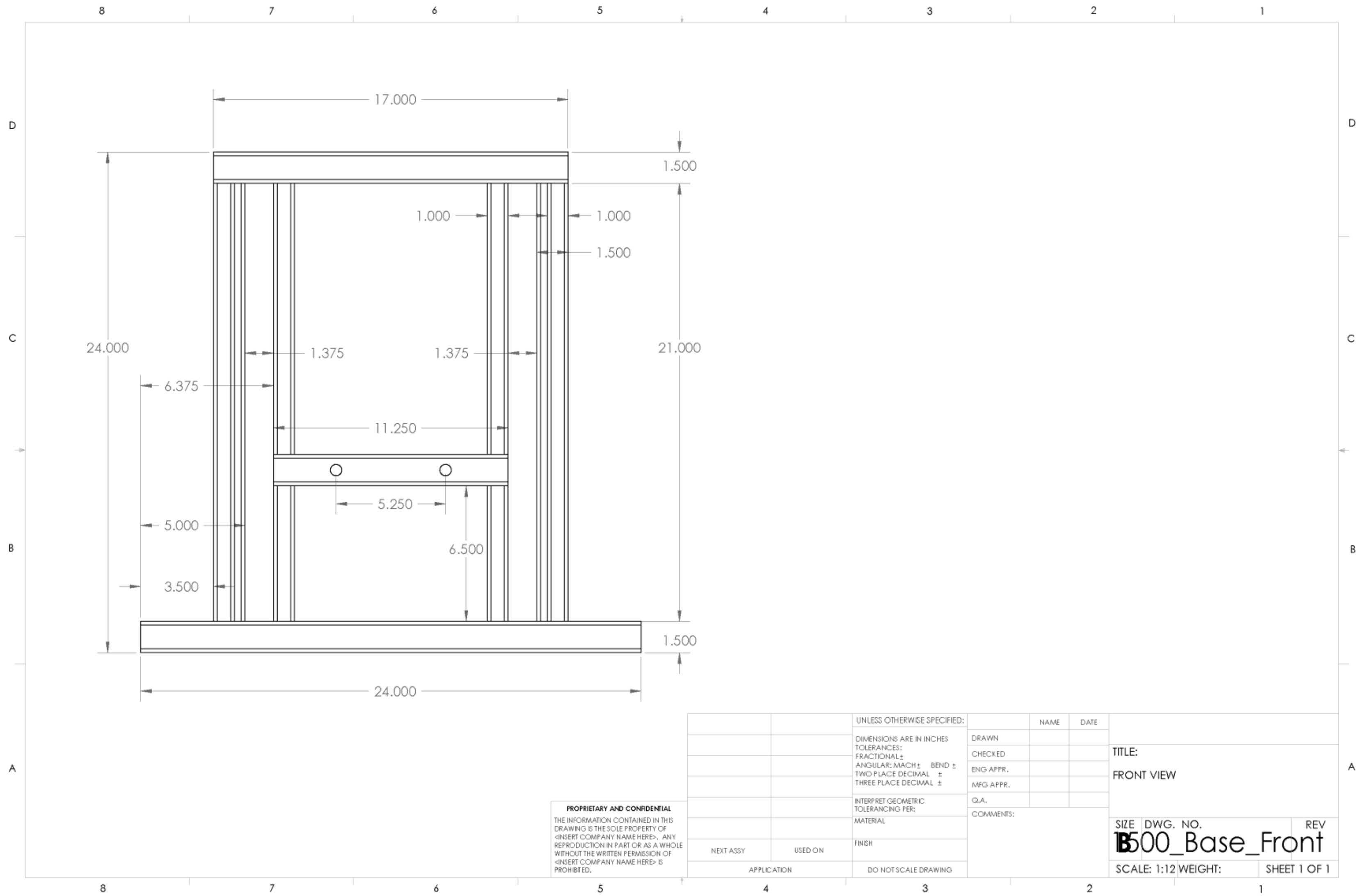



Figure A.4: Base Front View

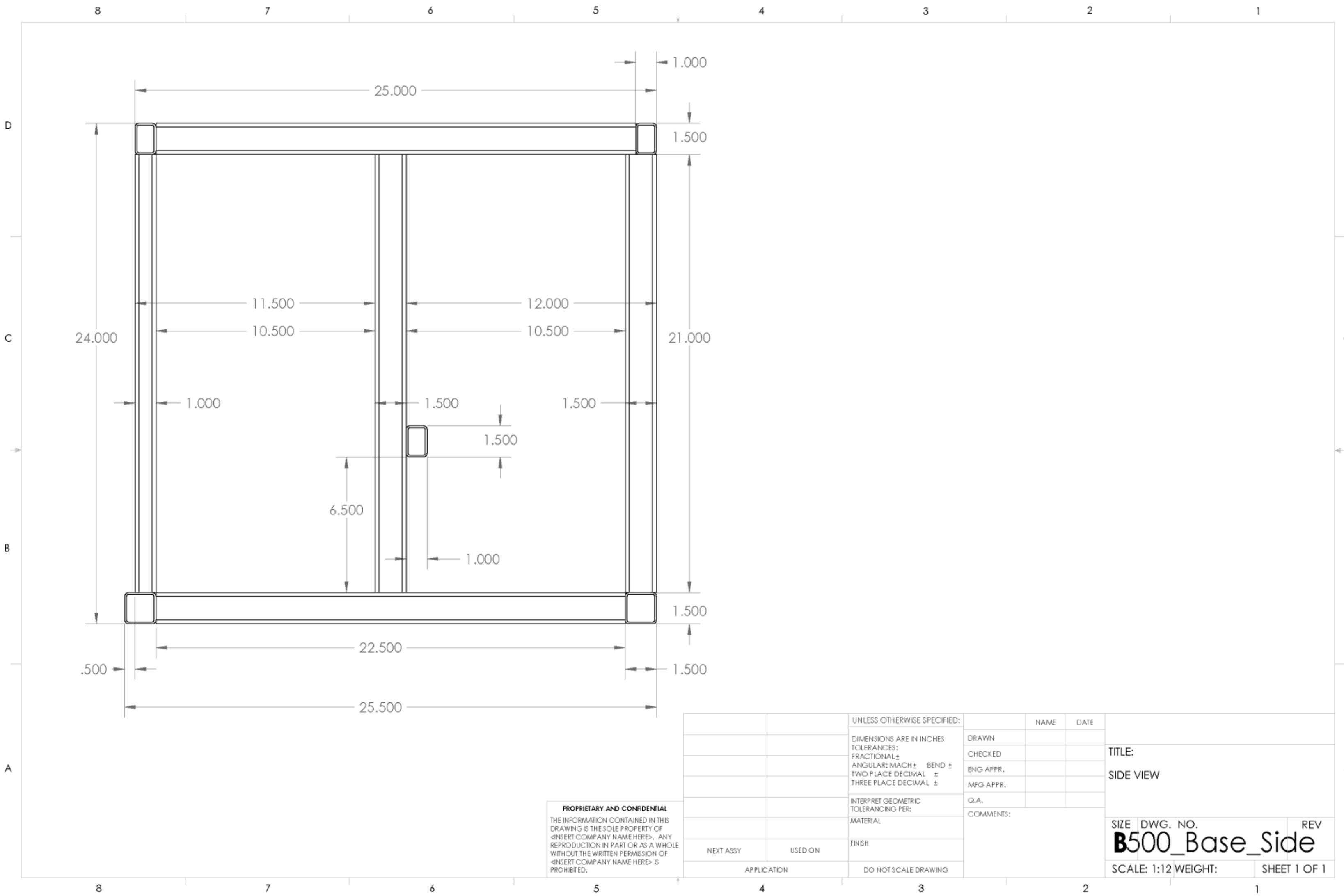



Figure A.5: Base Side View

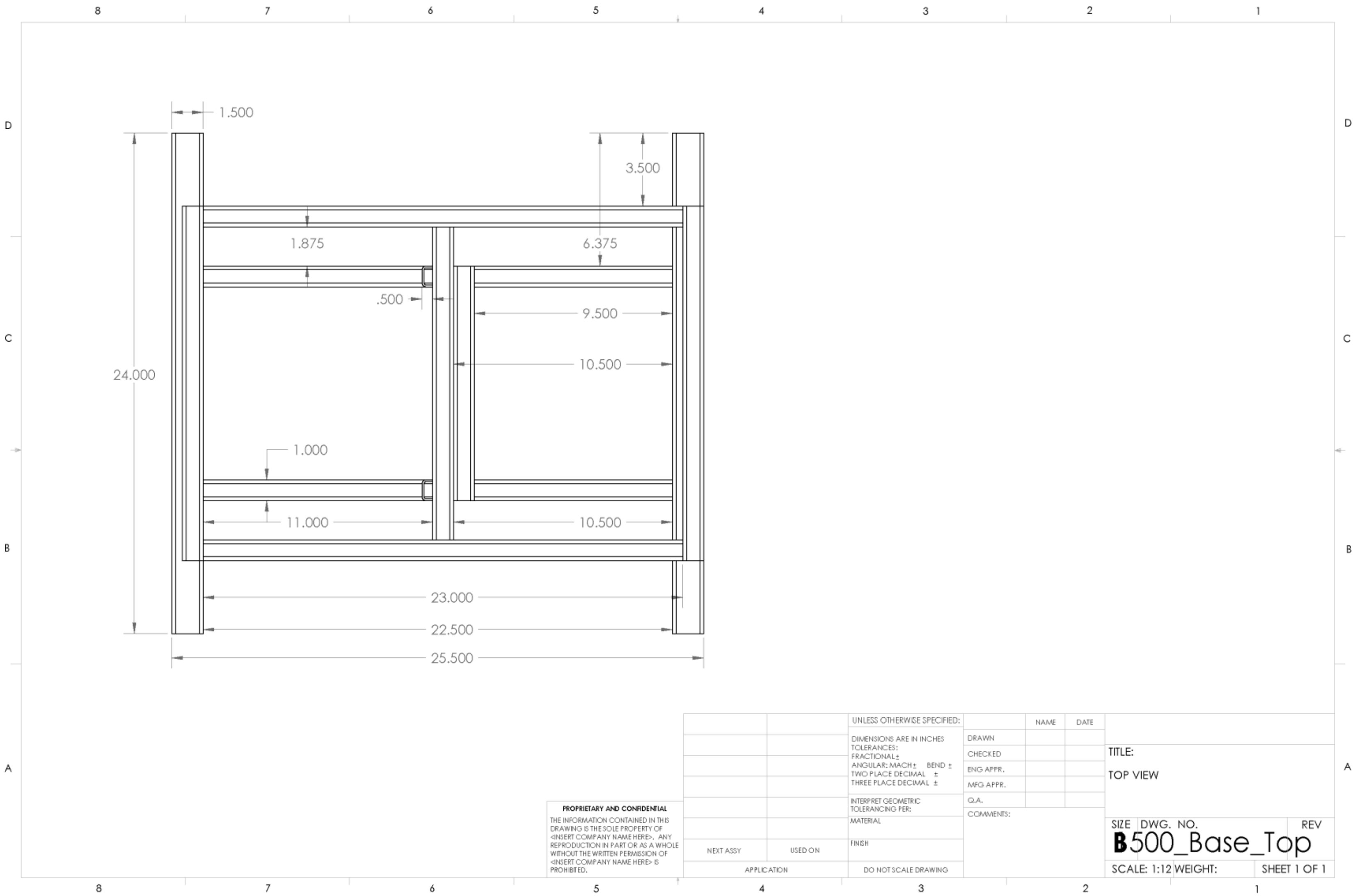



Figure A.6: Base Top View

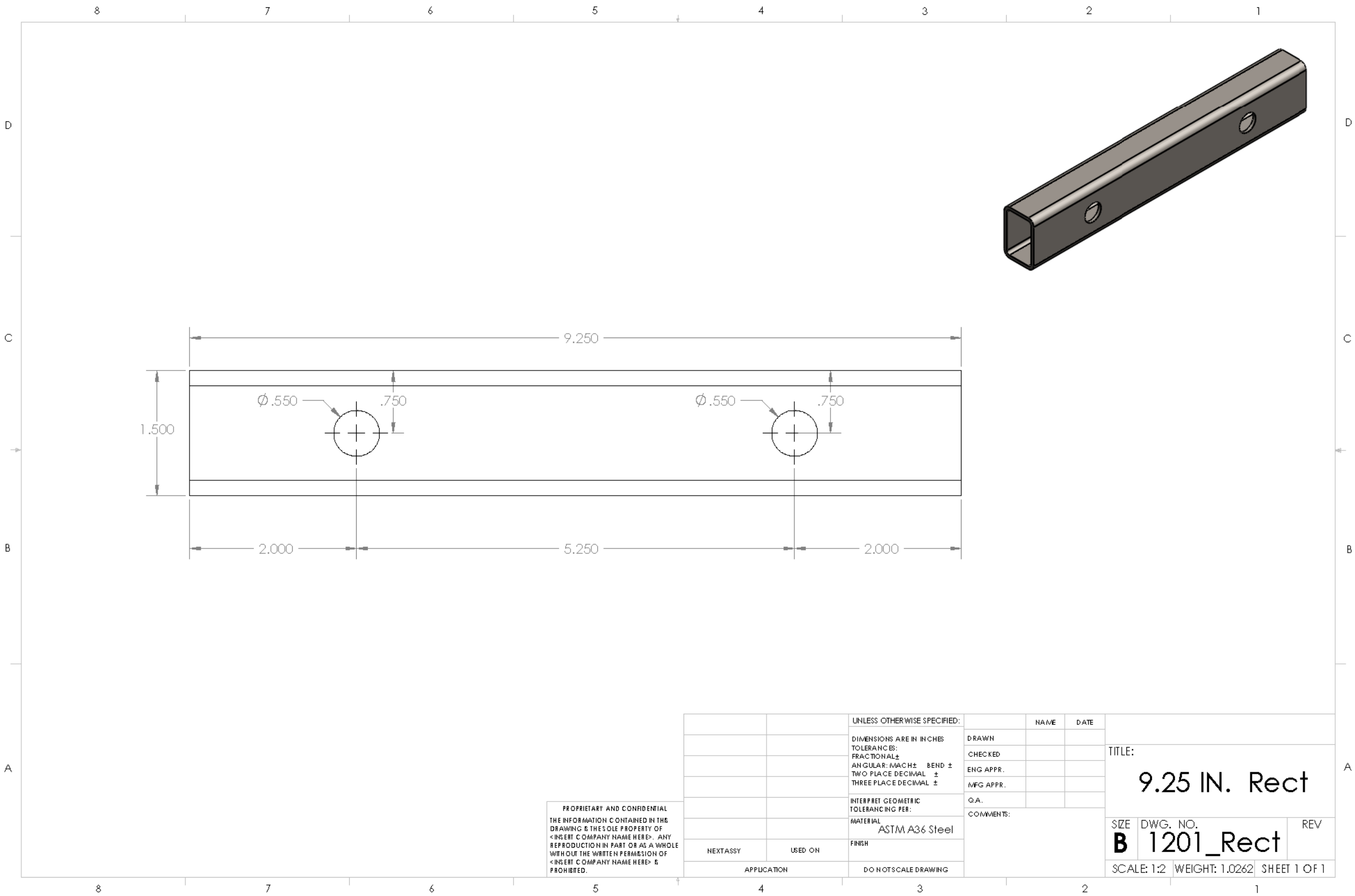



Figure A.7: Drawing of Part 1201

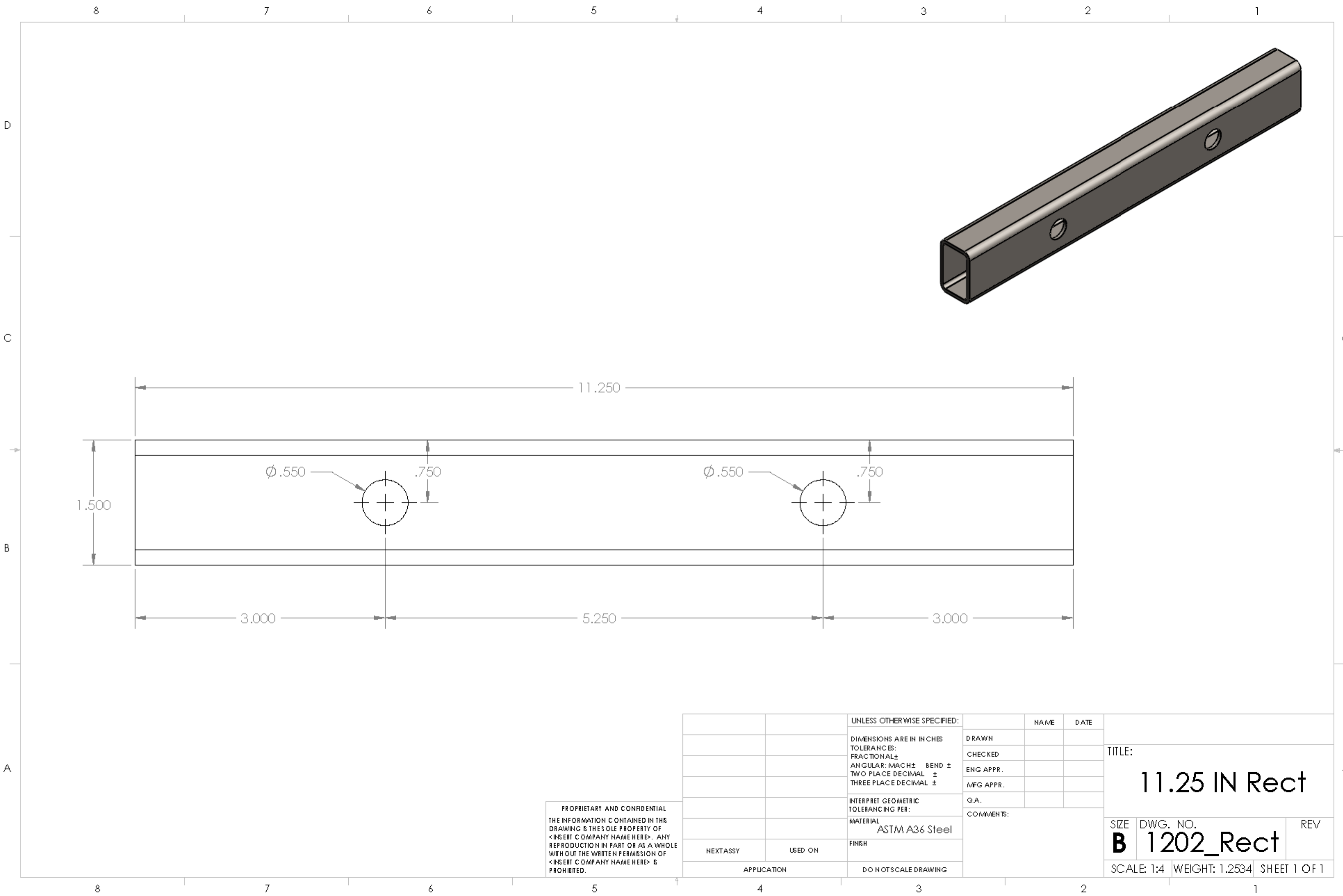



Figure A.8: Drawing of Part 1202

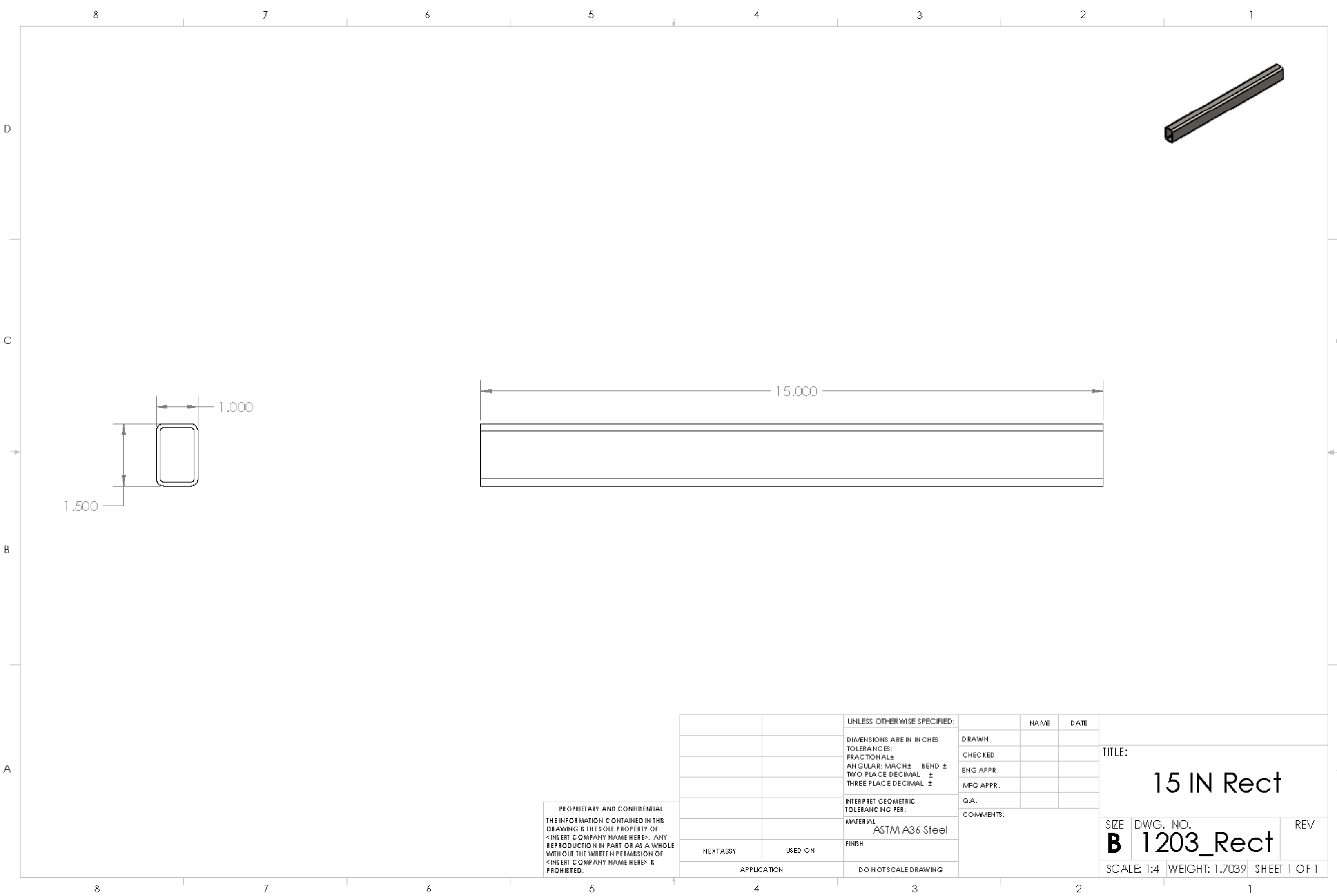



Figure A.9: Drawing of Part 1203

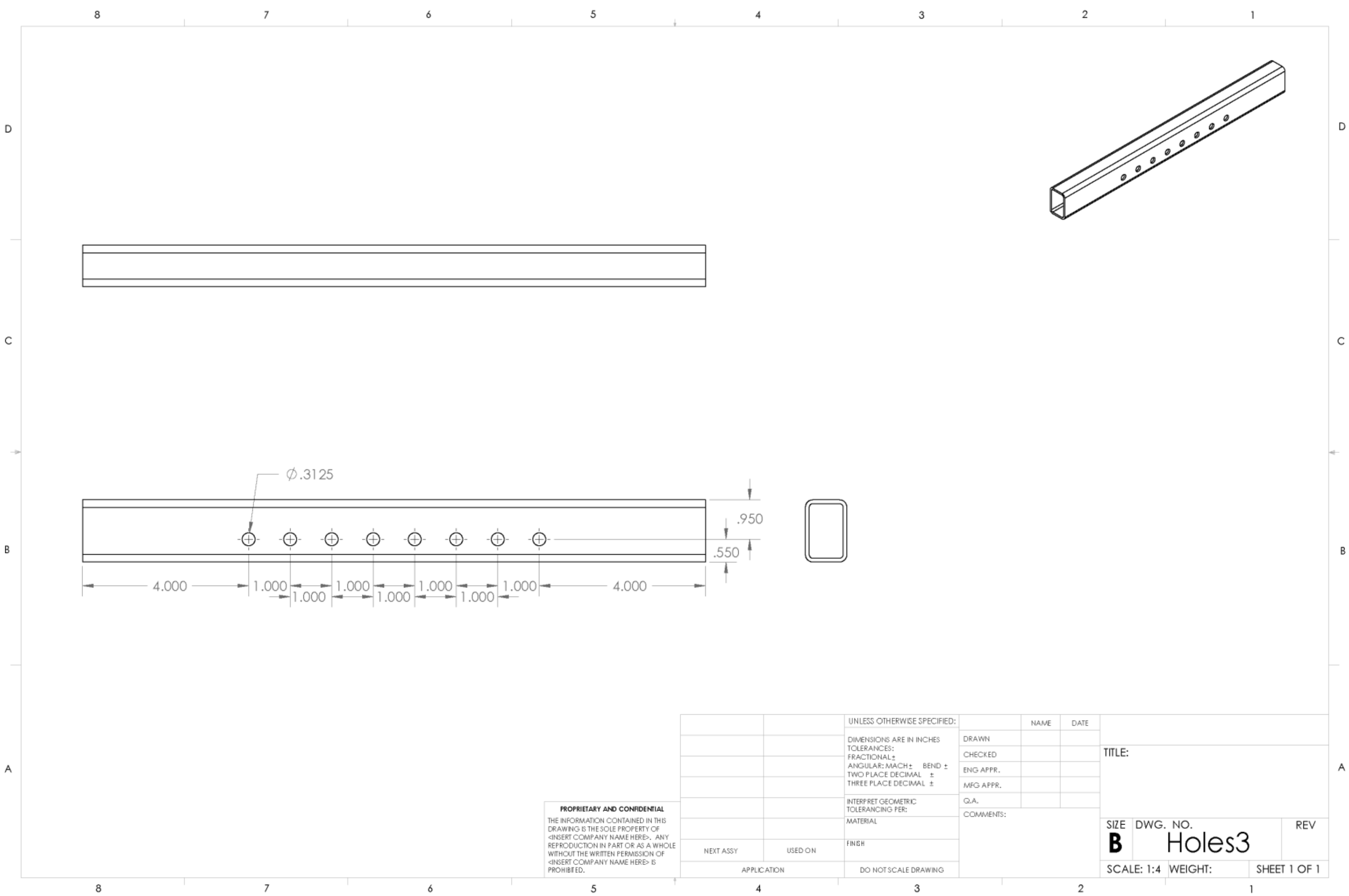



Figure A.10: Drawing of Part 1203 with Holes for Pulley Mounting

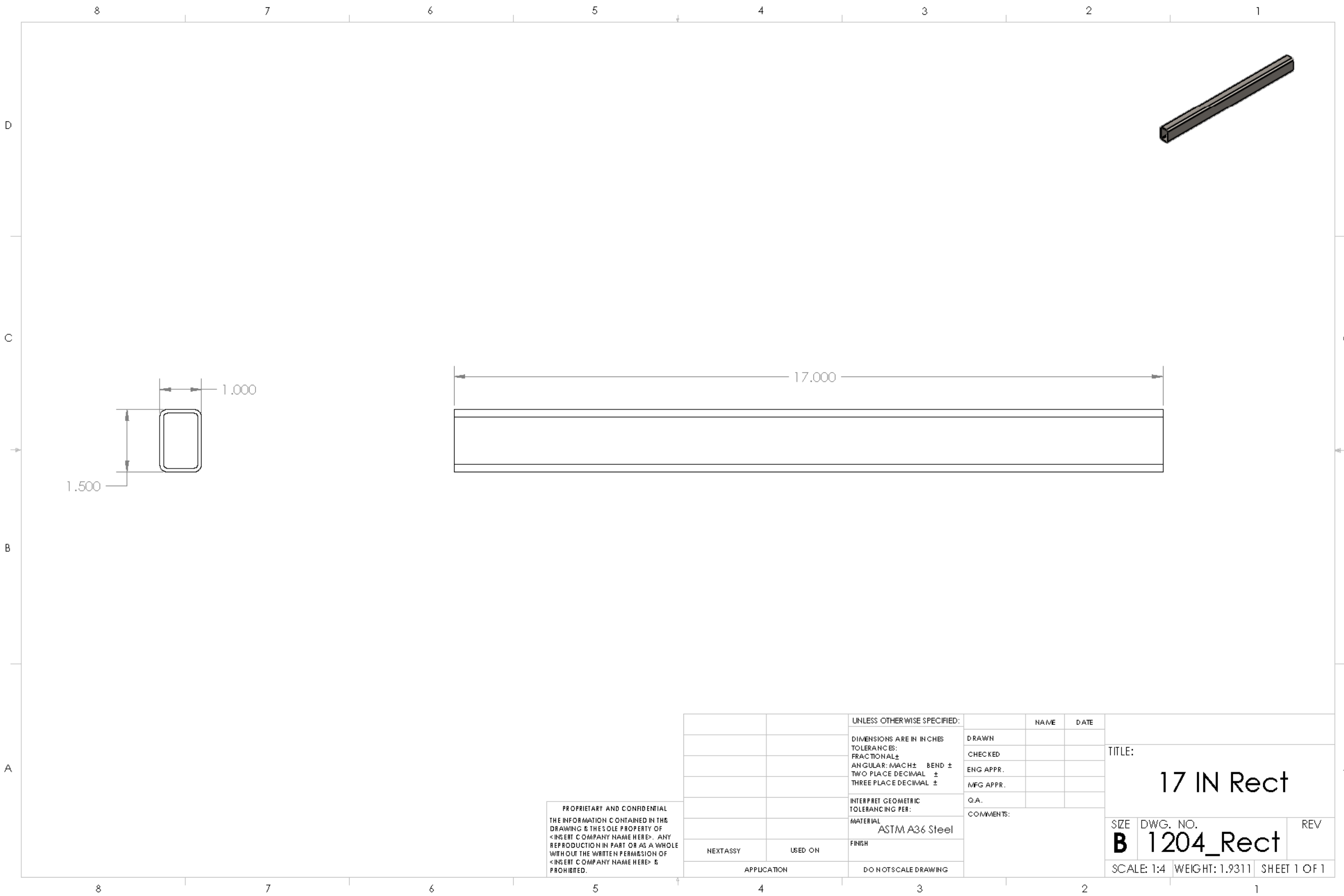



Figure A.11: Drawing of Part 1204

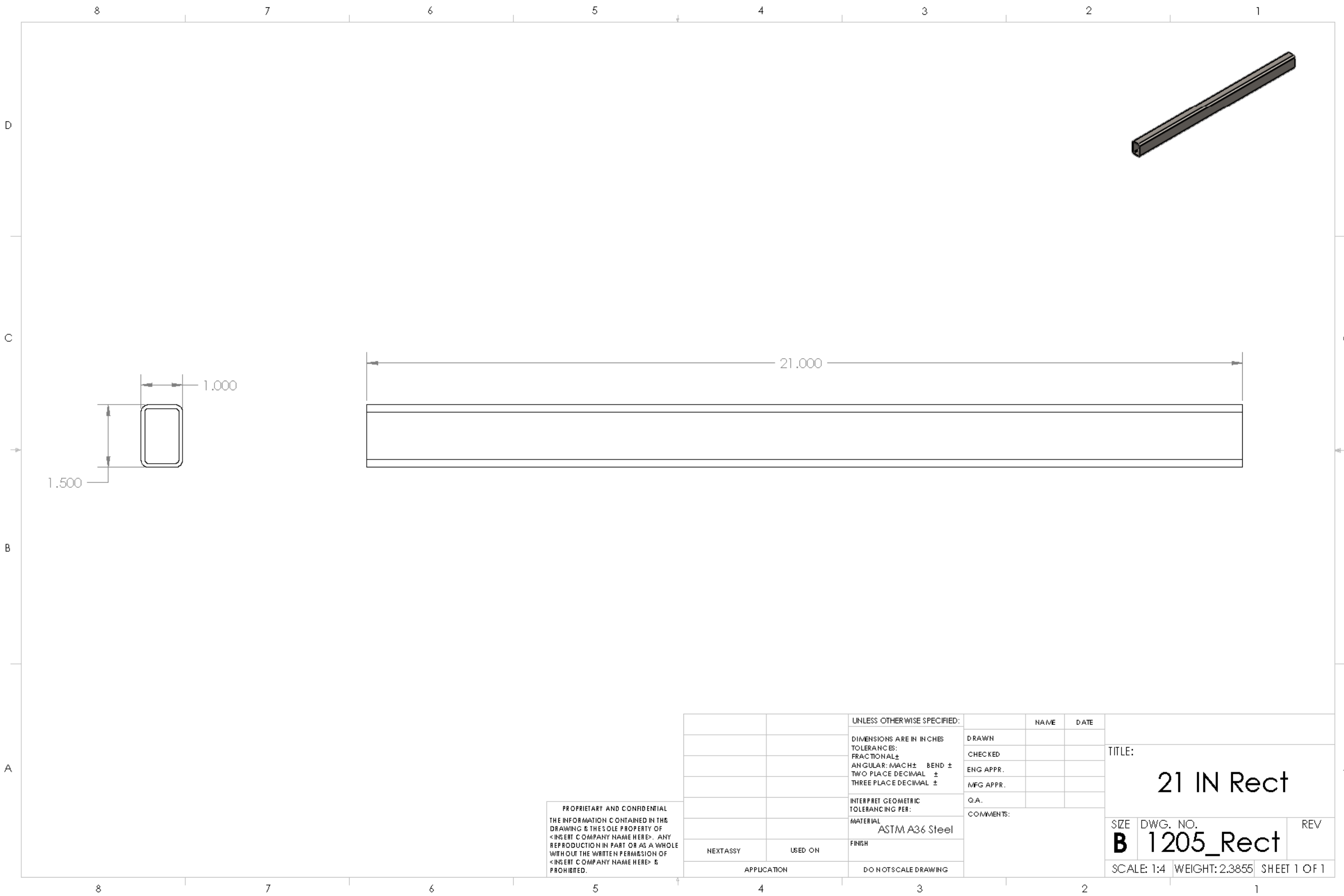



Figure A.12: Drawing of Part 1205

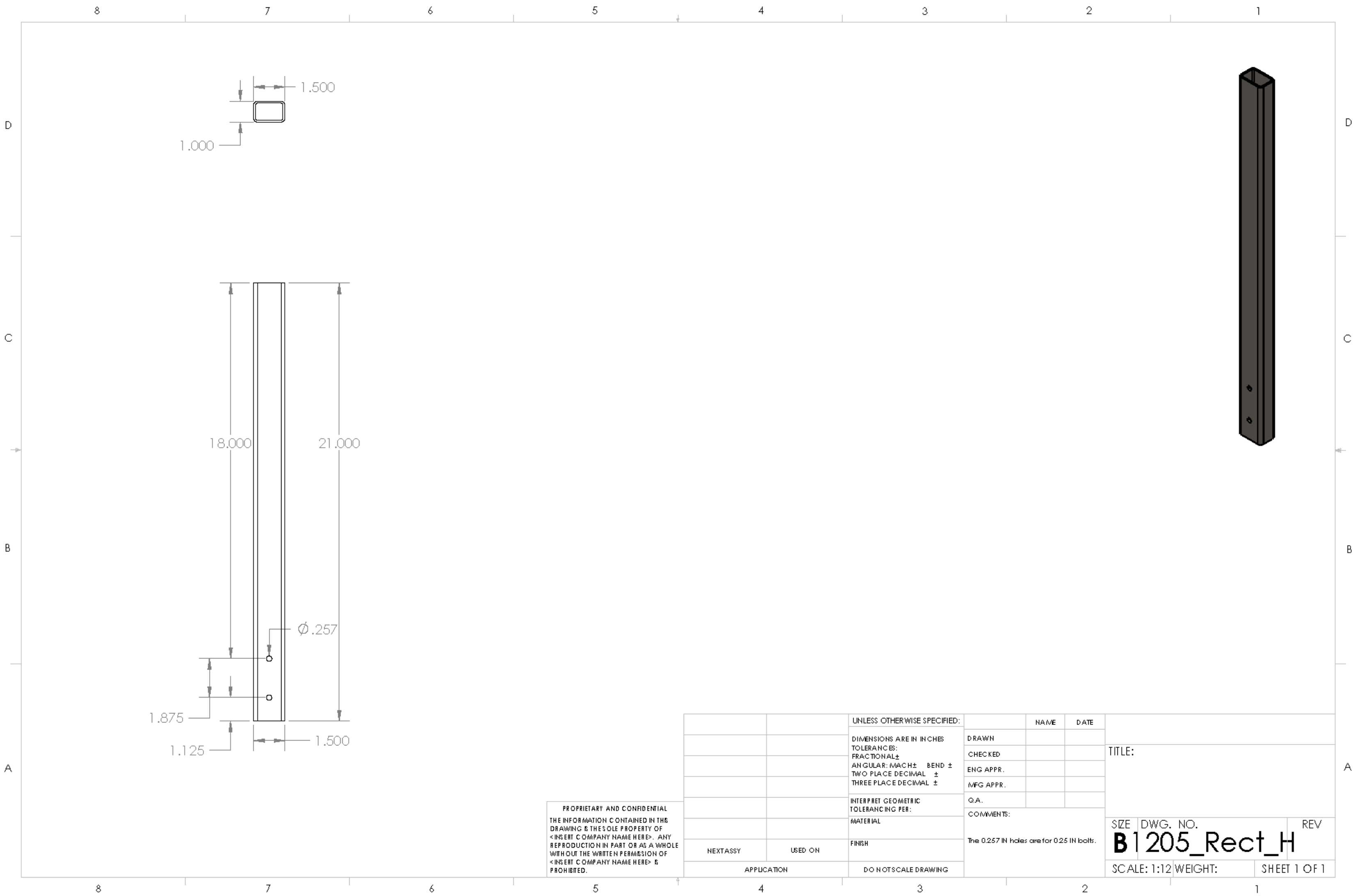



Figure A.13: Drawing of Part 1205 with Holes for Mounting Plates

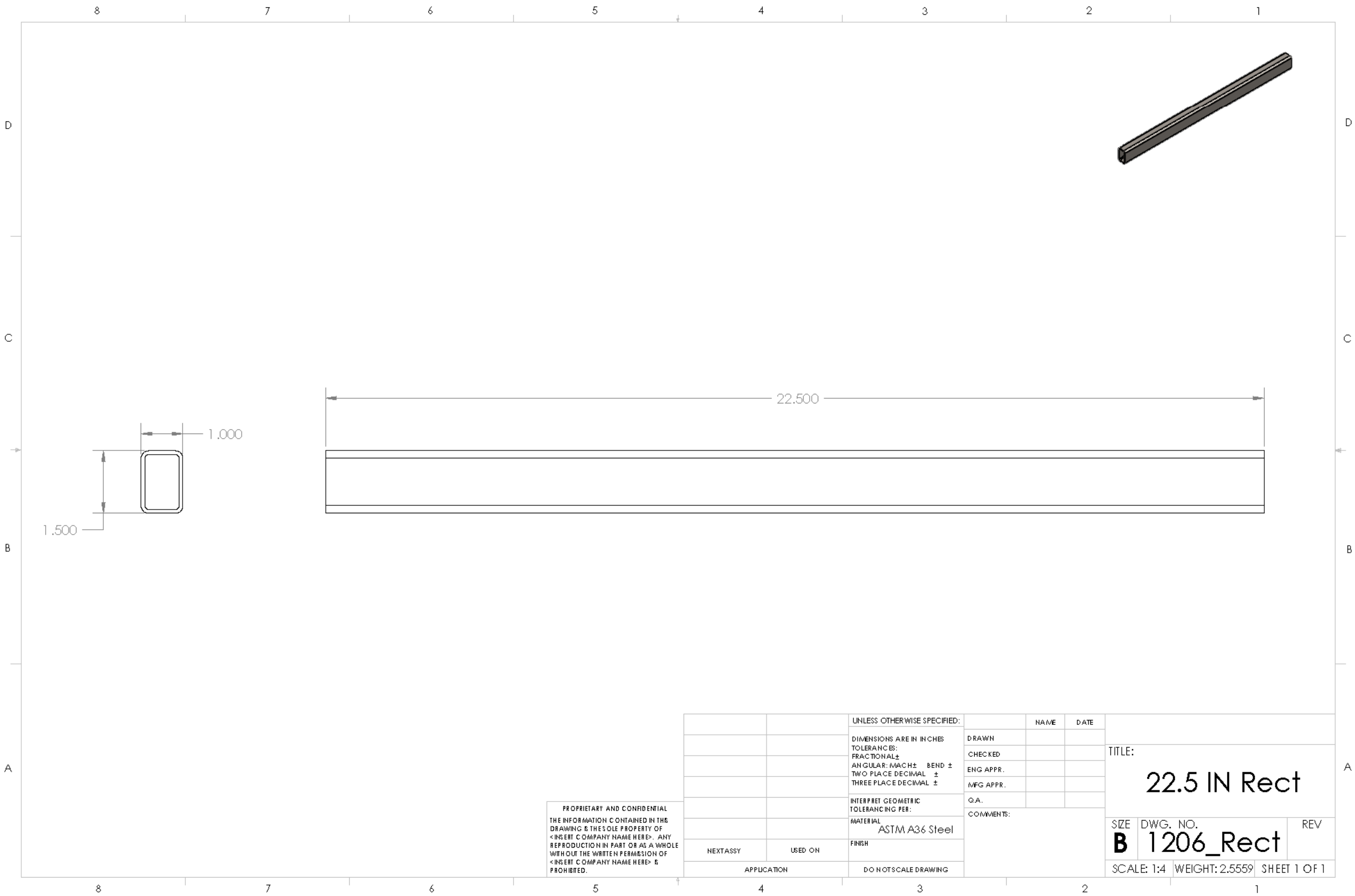



Figure A.14: Drawing of Part 1206

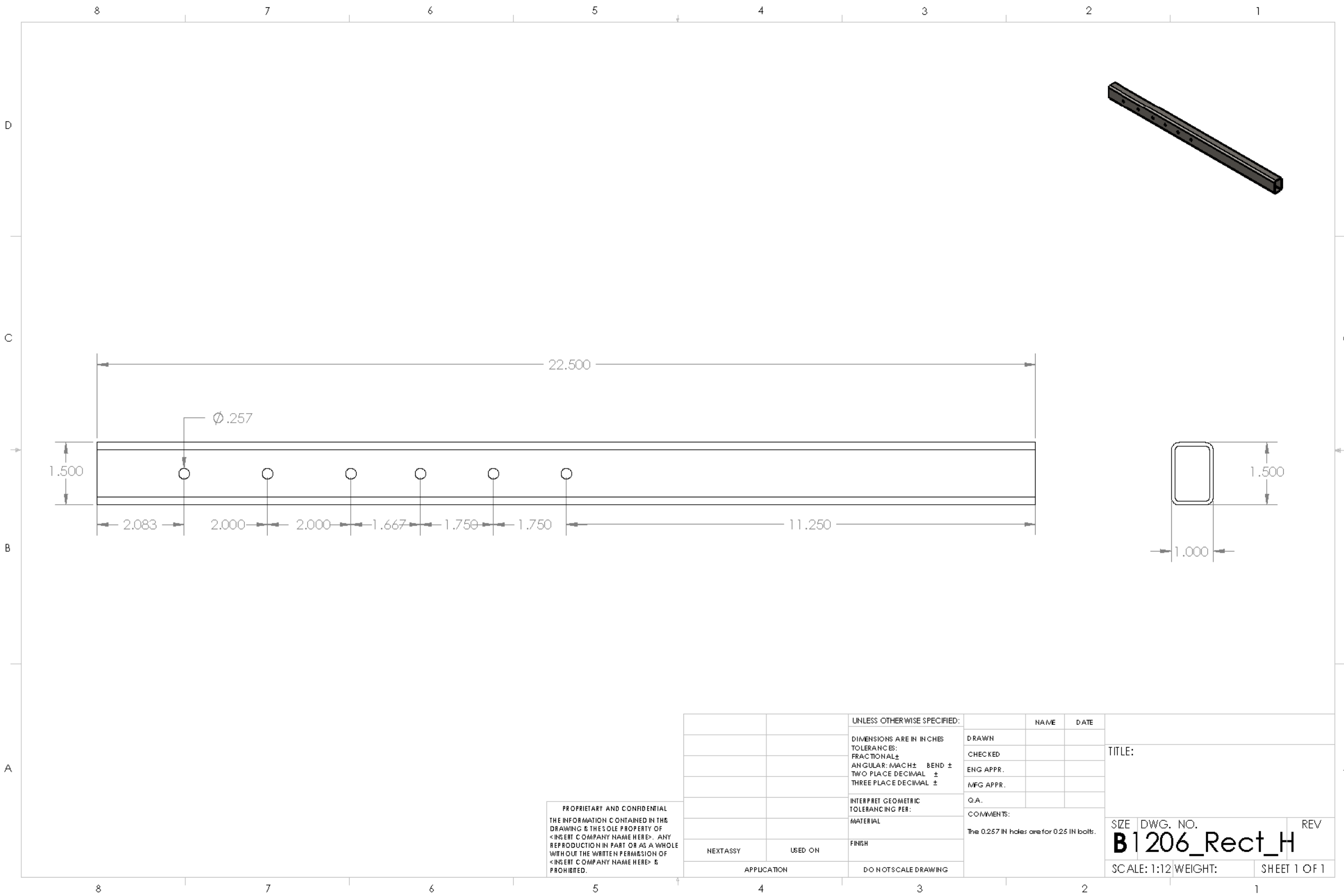



Figure A.15: Drawing of Part 1206 with Holes for Mounting Plates

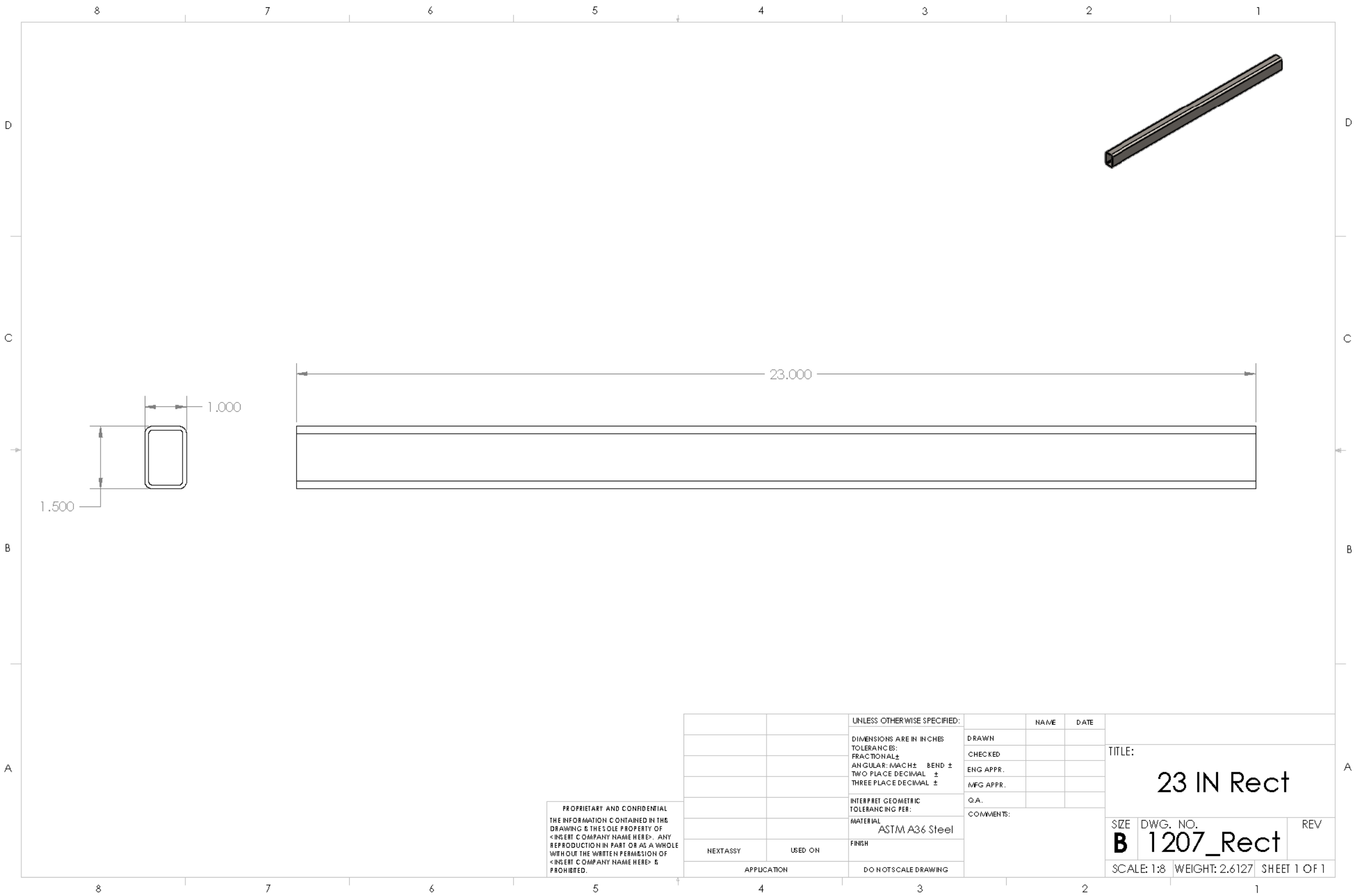



Figure A.16: Drawing of Part 1207

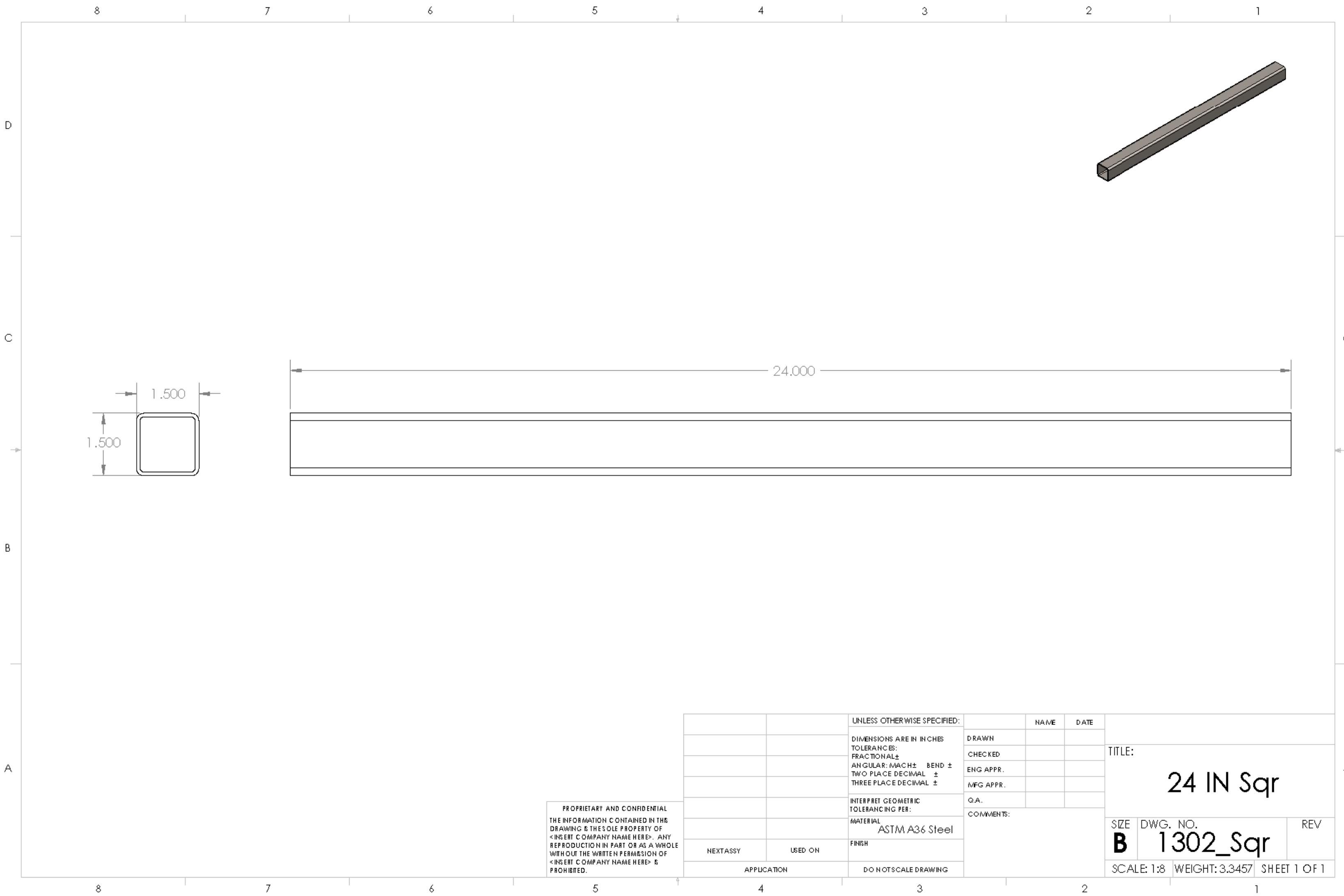



Figure A.17: Drawing of Part 1302

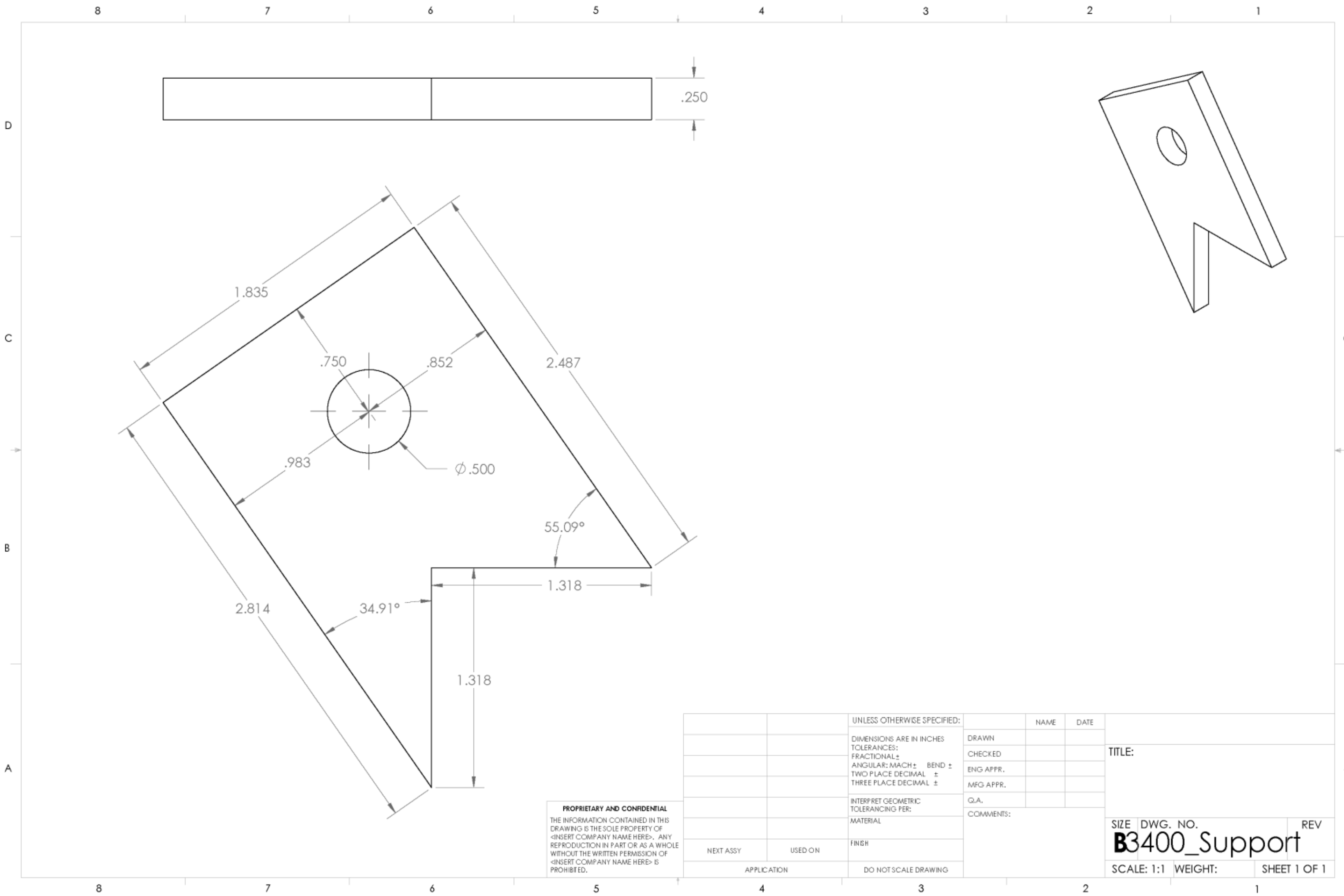



Figure A.18: Drawing of Part 3400

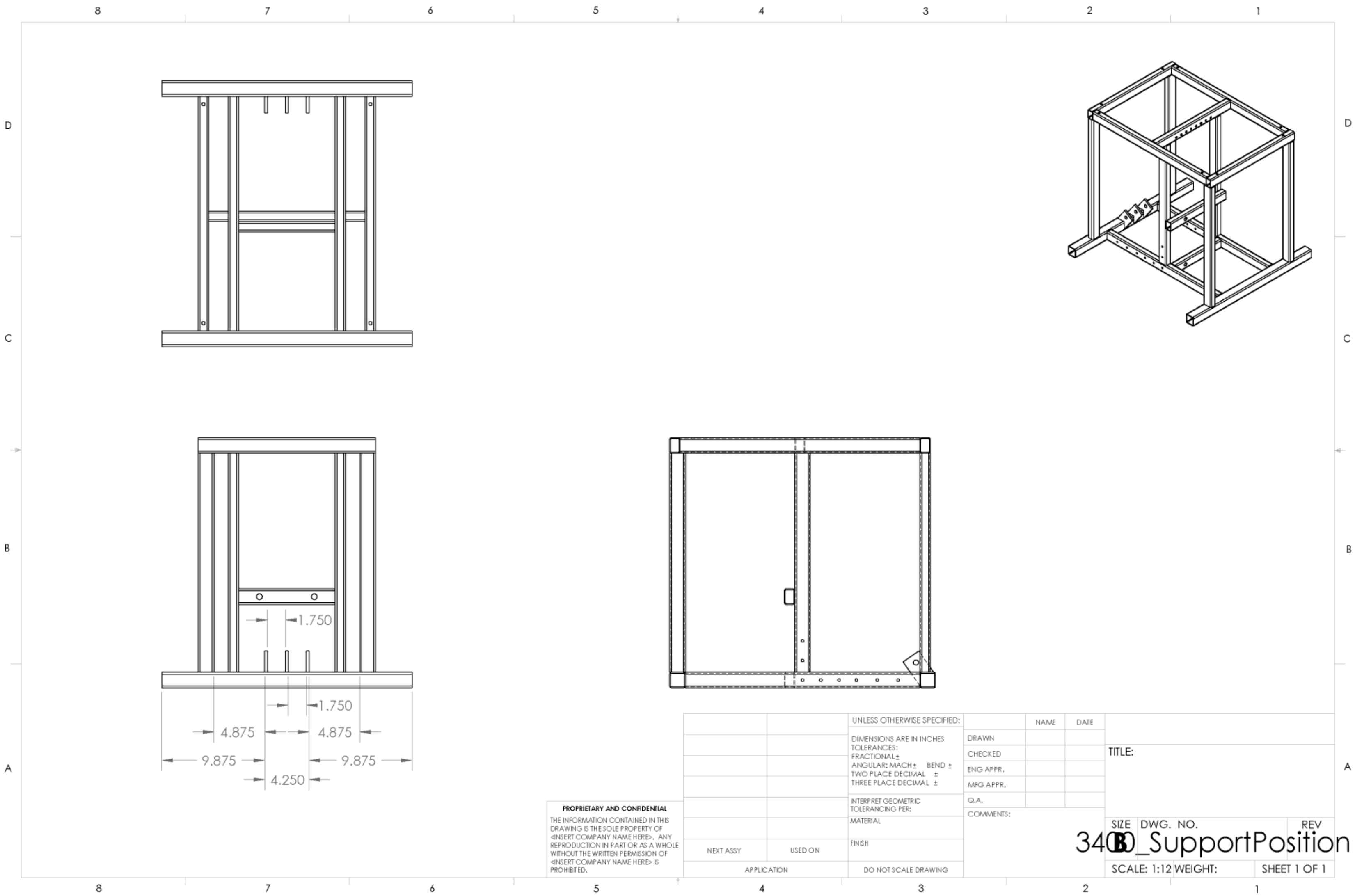



Figure A.19: Drawing of Placement of Part 3400

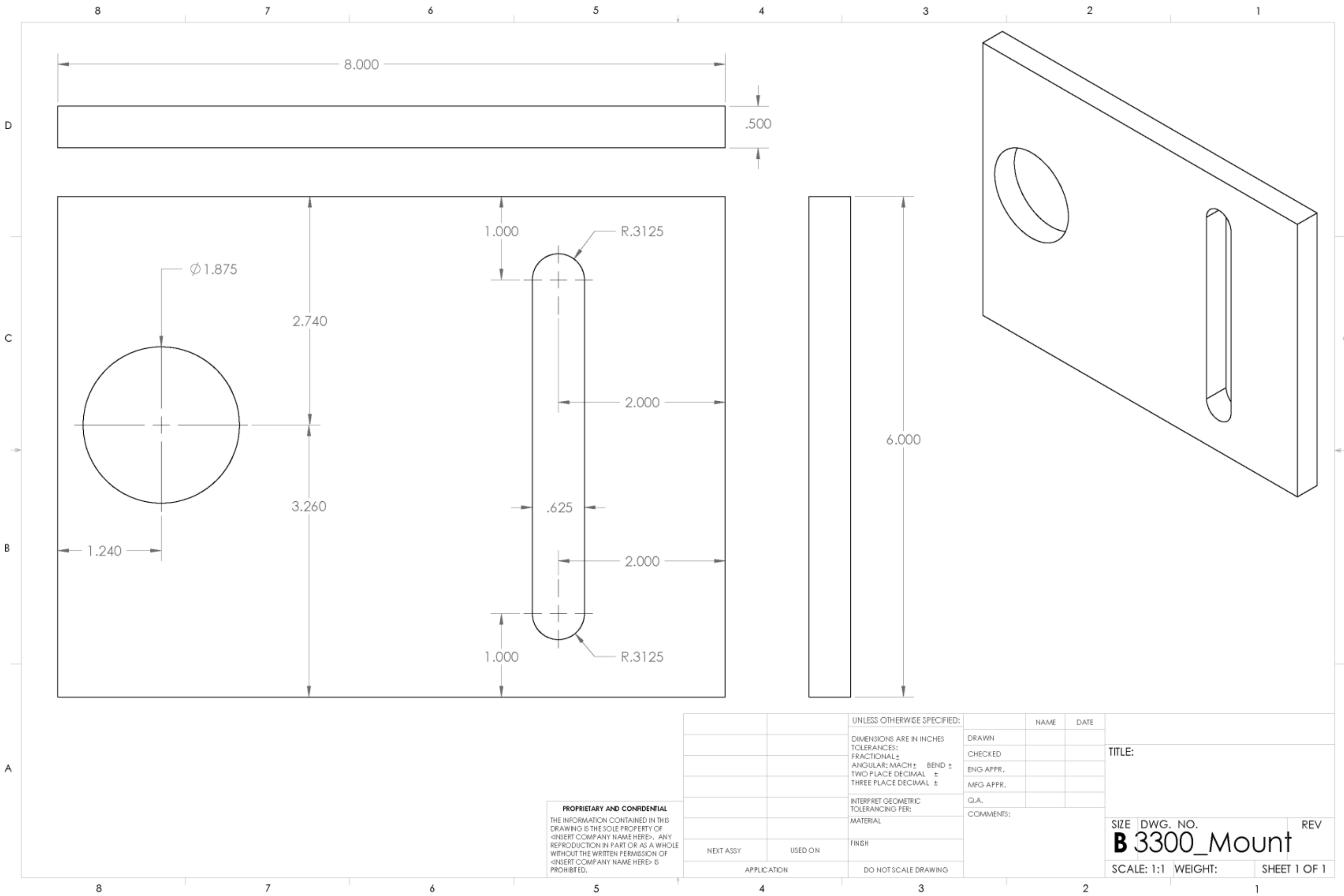



Figure A.20: Drawing of Part 3300

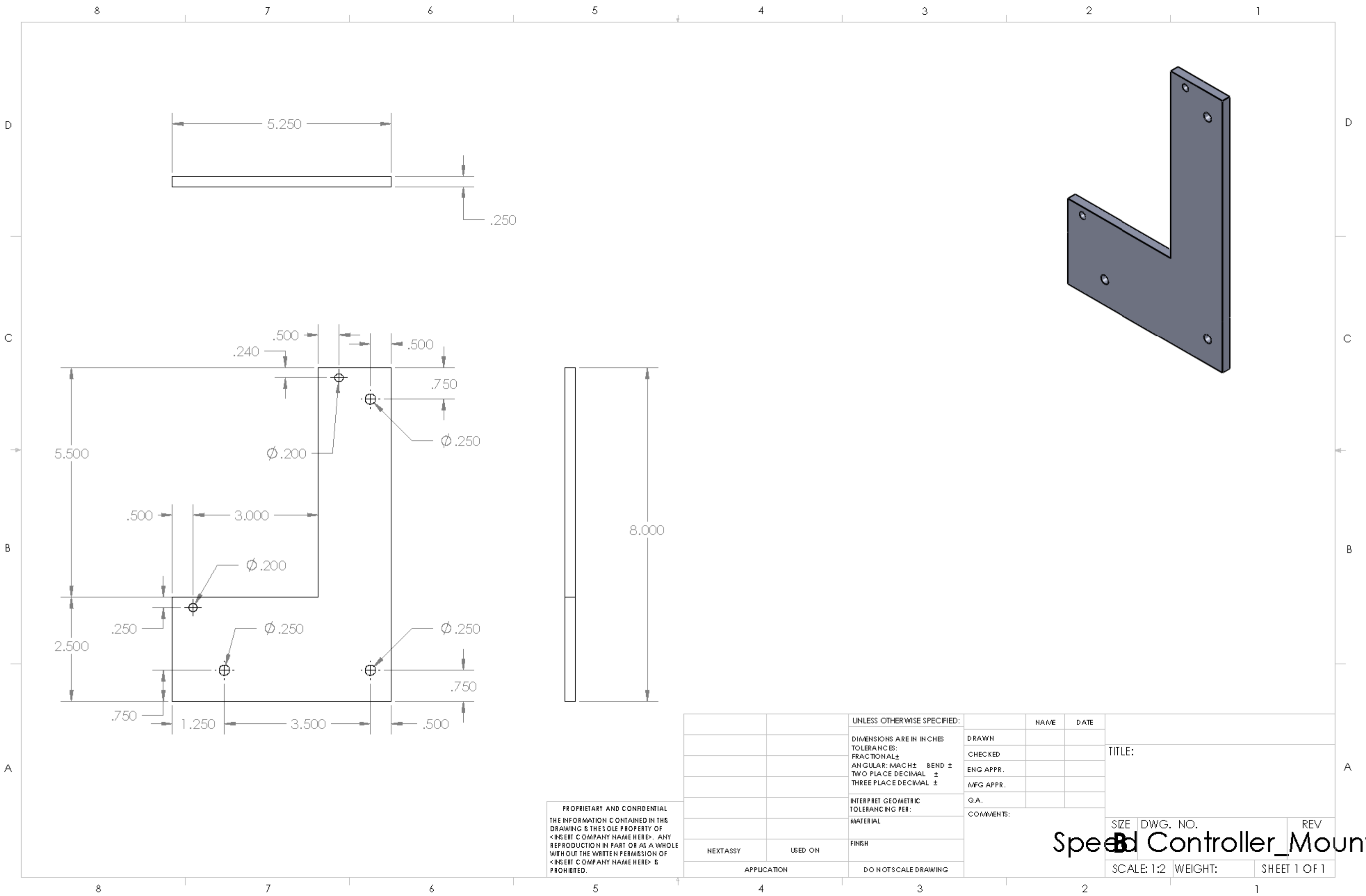



Figure A.21: Drawing of Speed-controller Mount

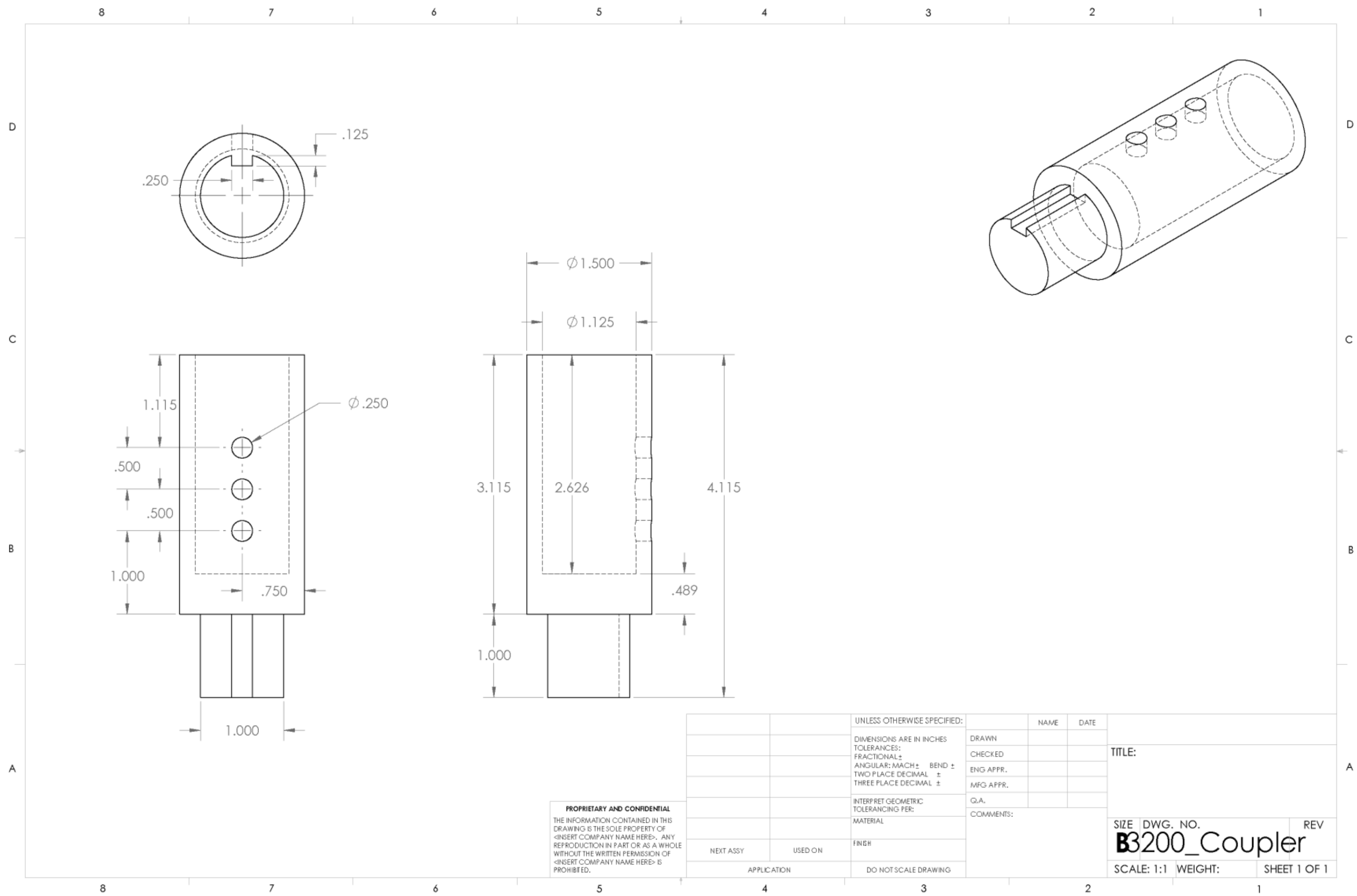



Figure A.22: Drawing of Part 3200

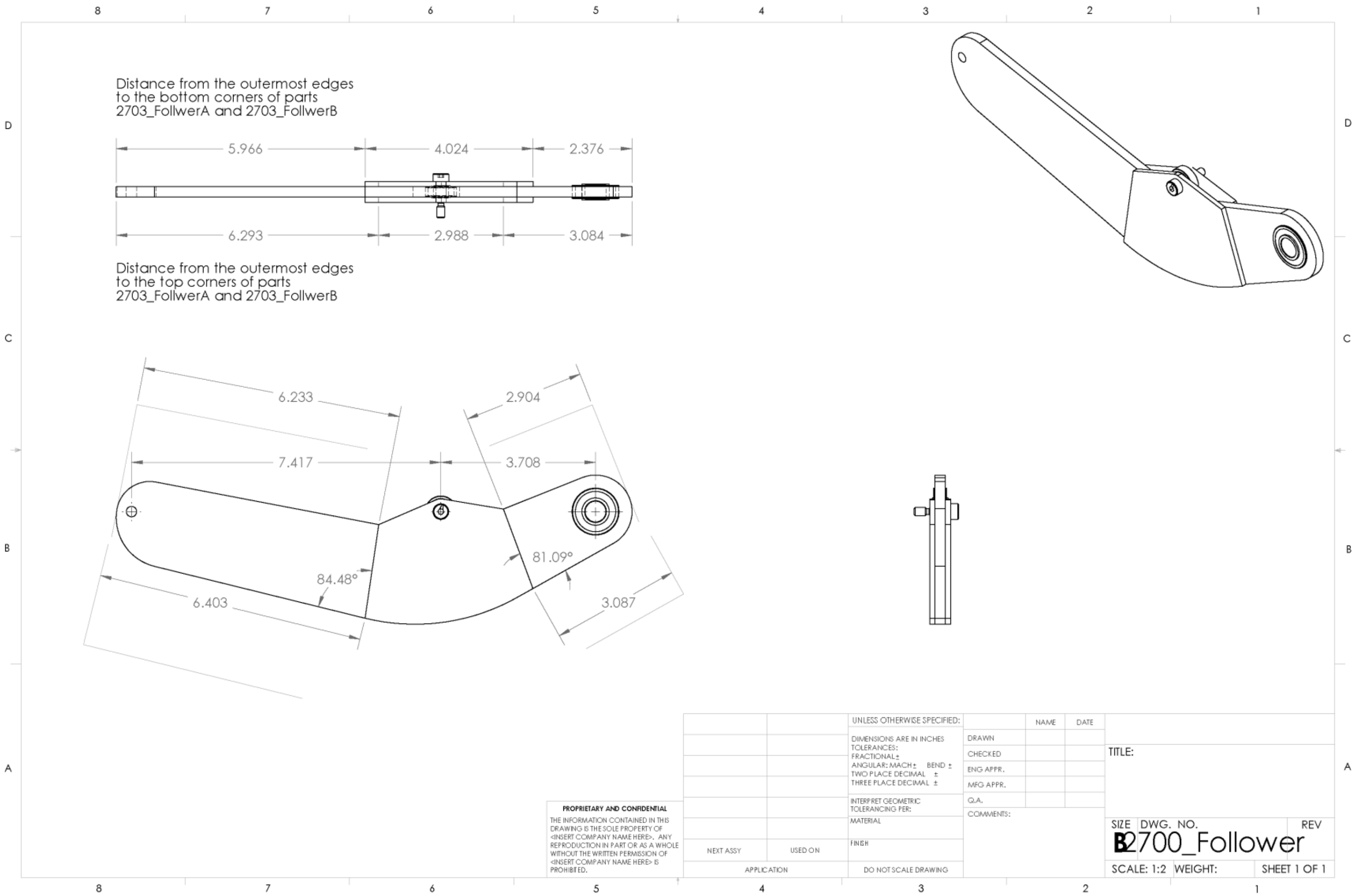
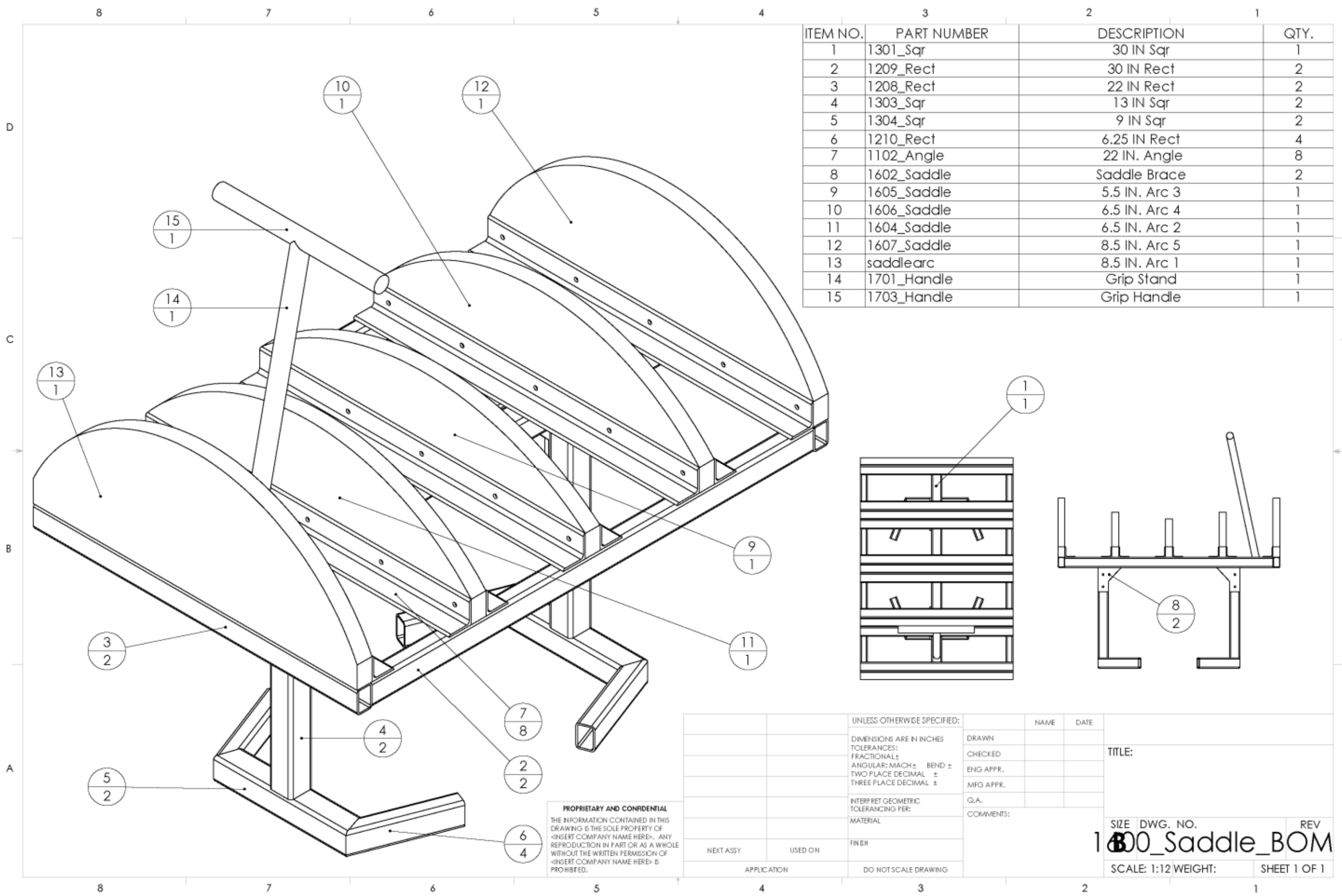



Figure A.23: Drawing of Part 2700

*Saddle Subsystem*




| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | 1301_Sqr | 30 IN Sqr | 1 |
| 2 | 1209_Rect | 30 IN Rect | 2 |
| 3 | 1208_Rect | 22 IN Rect | 2 |
| 4 | 1303_Sqr | 13 IN Sqr | 2 |
| 5 | 1304_Sqr | 9 IN Sqr | 2 |
| 6 | 1210_Rect | 6.25 IN Rect | 4 |
| 7 | 1102_Angle | 22 IN. Angle | 8 |
| 8 | 1602_Saddle | Saddle Brace | 2 |
| 9 | 1605_Saddle | 5.5 IN. Arc 3 | 1 |
| 10 | 1606_Saddle | 6.5 IN. Arc 4 | 1 |
| 11 | 1604_Saddle | 6.5 IN. Arc 2 | 1 |
| 12 | 1607_Saddle | 8.5 IN. Arc 5 | 1 |
| 13 | saddlearc | 8.5 IN. Arc 1 | 1 |
| 14 | 1701_Handle | Grip Stand | 1 |
| 15 | 1703_Handle | Grip Handle | 1 |

Figure A.24: Bill of Materials for Saddle Subsystem

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | 1301_Sqr | 30 IN Sqr | 1 |
| 2 | 1209_Rect | 30 IN Rect | 2 |
| 3 | 1208_Rect | 22 IN Rect | 2 |
| 4 | 1303_Sqr | 13 IN Sqr | 2 |
| 5 | 1304_Sqr | 9 IN Sqr | 2 |
| 6 | 1210_Rect | 6.25 IN Rect | 4 |
| 7 | 1102_Angle | 22 IN. Angle | 8 |
| 8 | 1602_Saddle | Saddle Brace | 2 |
| 14 | 1701_Handle | Grip Stand | 1 |
| 15 | 1703_Handle | Grip Handle | 1 |

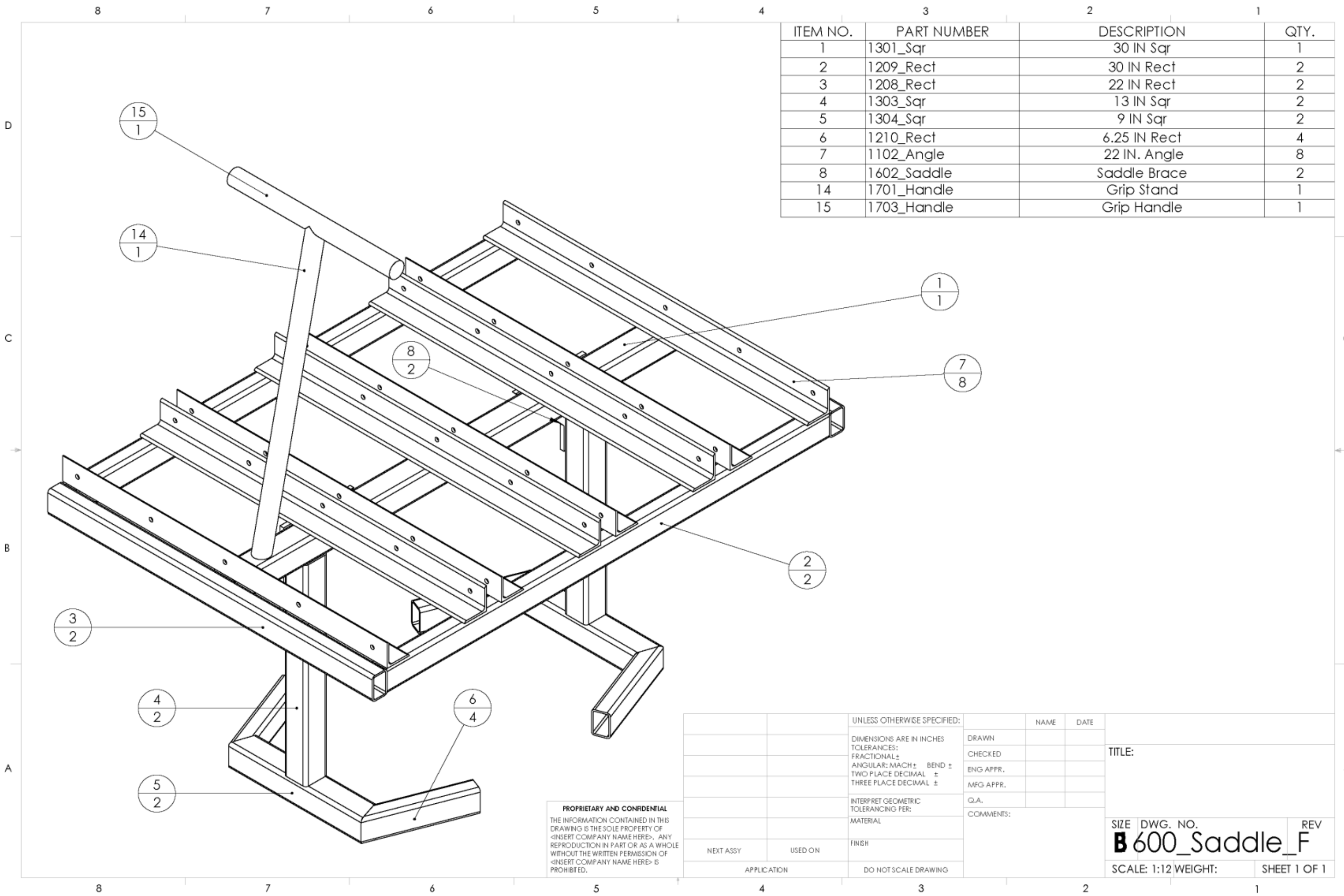



Figure A.25: Bill of Materials of Saddle Subsystems Including Part 1602

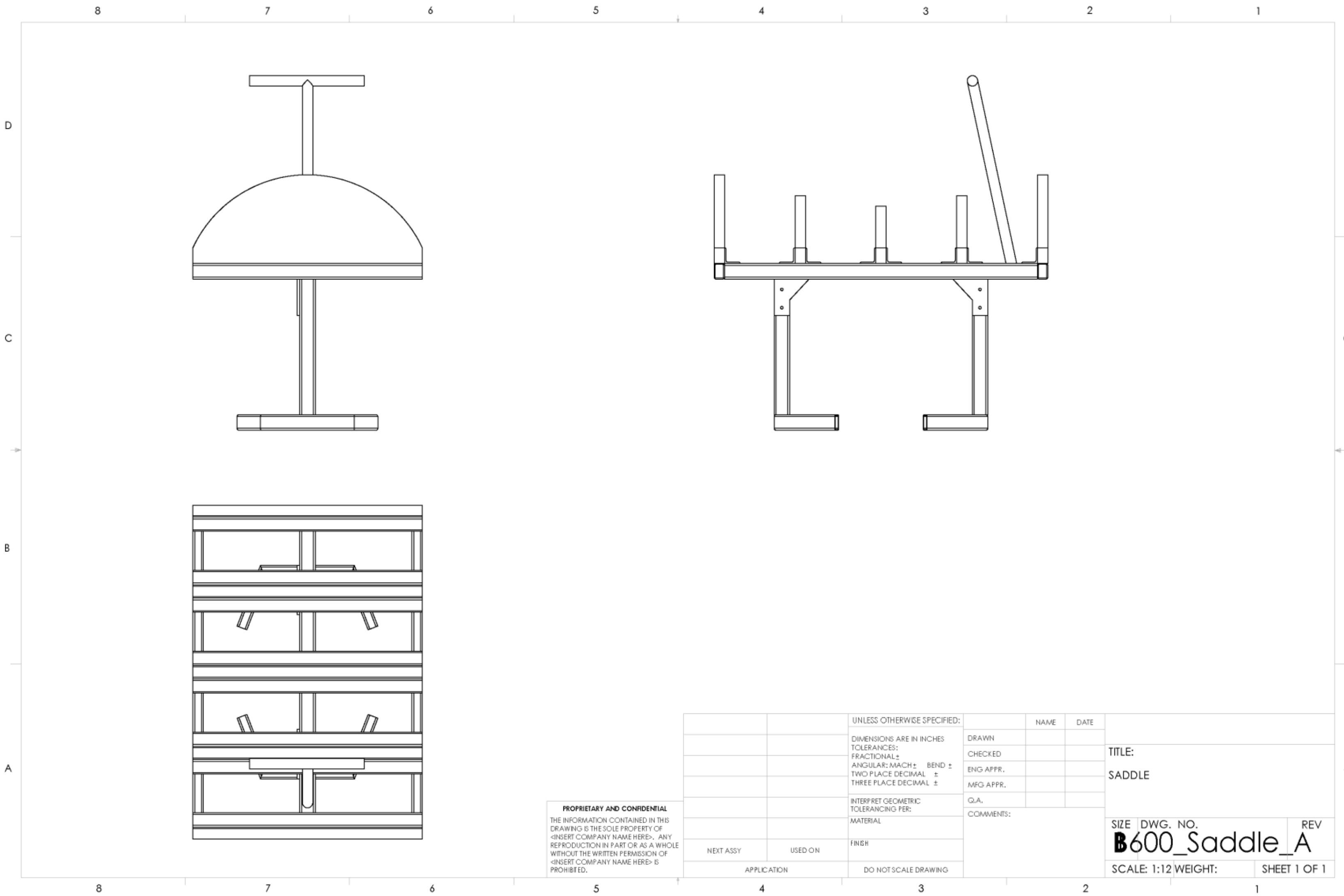



Figure A.26: Two-Dimensional Views of Saddle

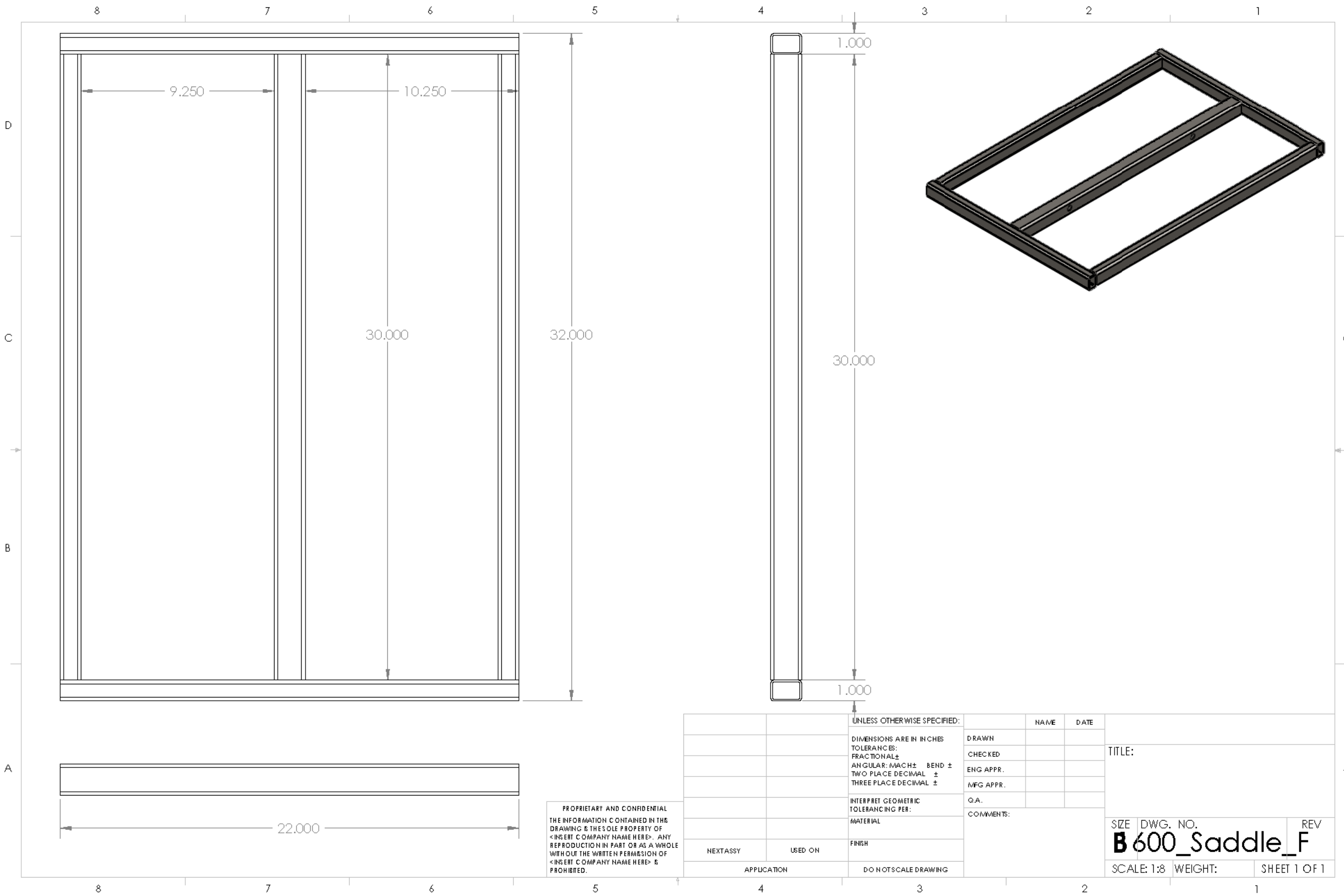



Figure A.27: Drawing of Saddle Frame

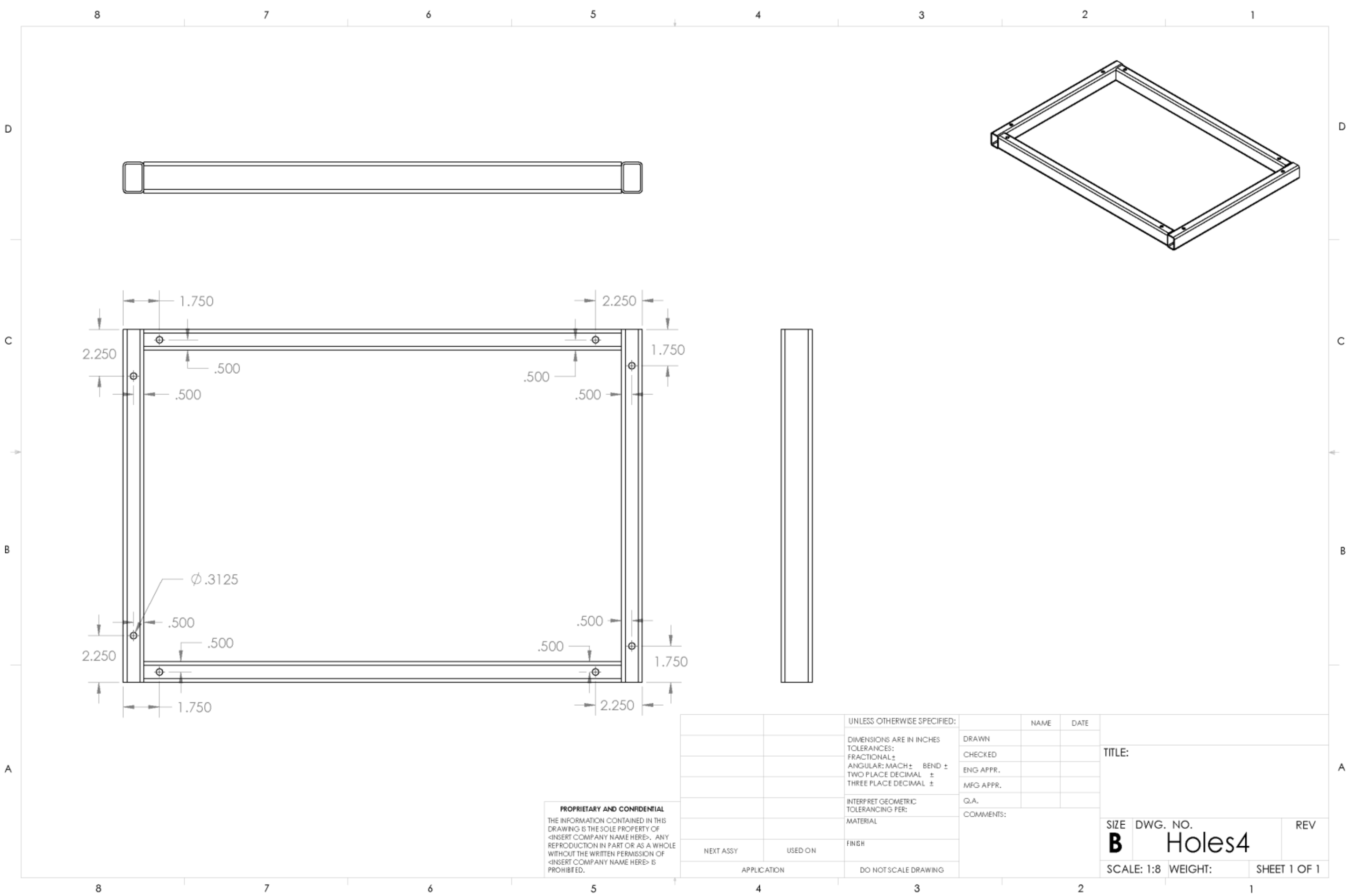



Figure A.28: Drawing of Location of Holes for Mounting Pulleys

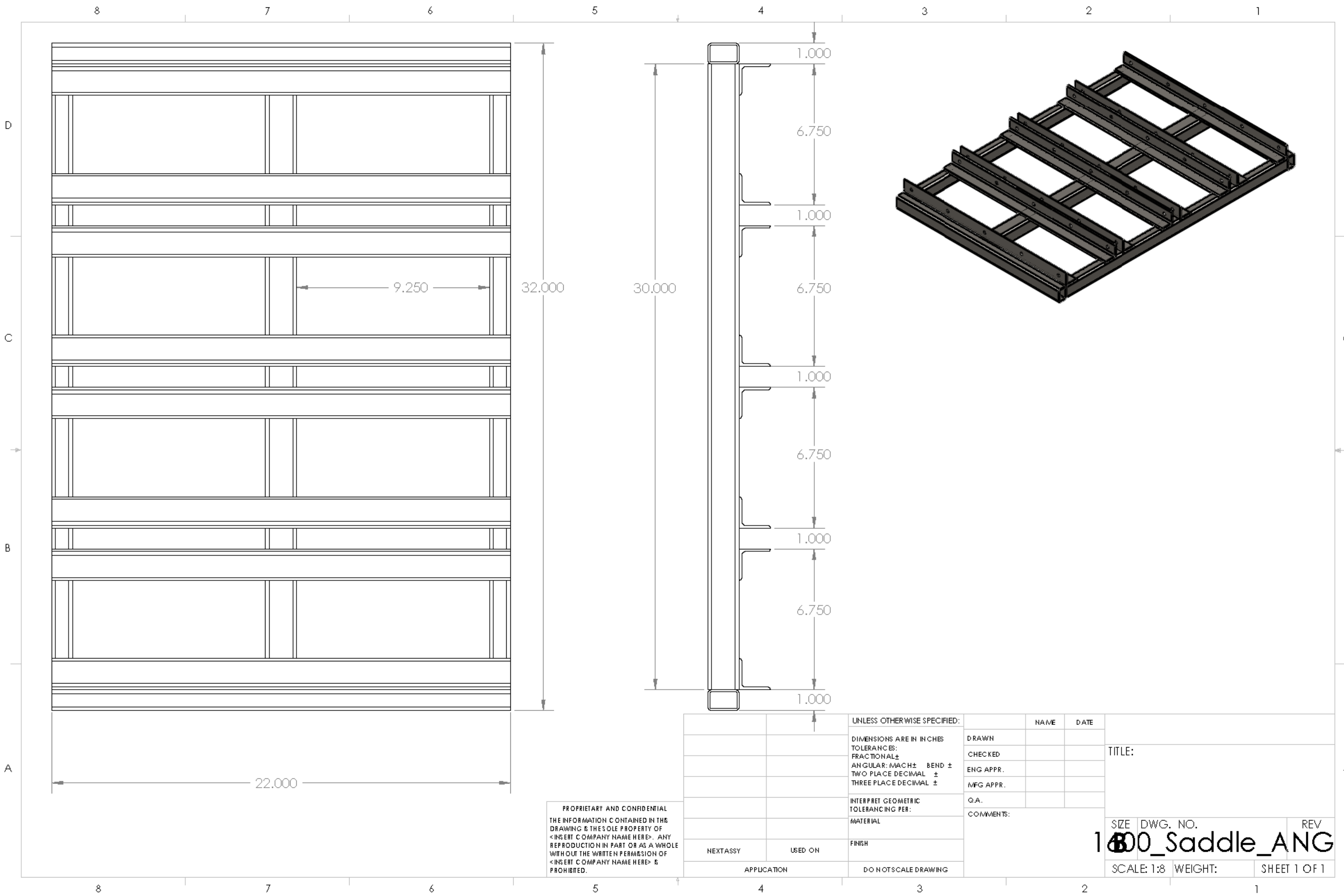



Figure A.29: Drawing of Saddle Braces

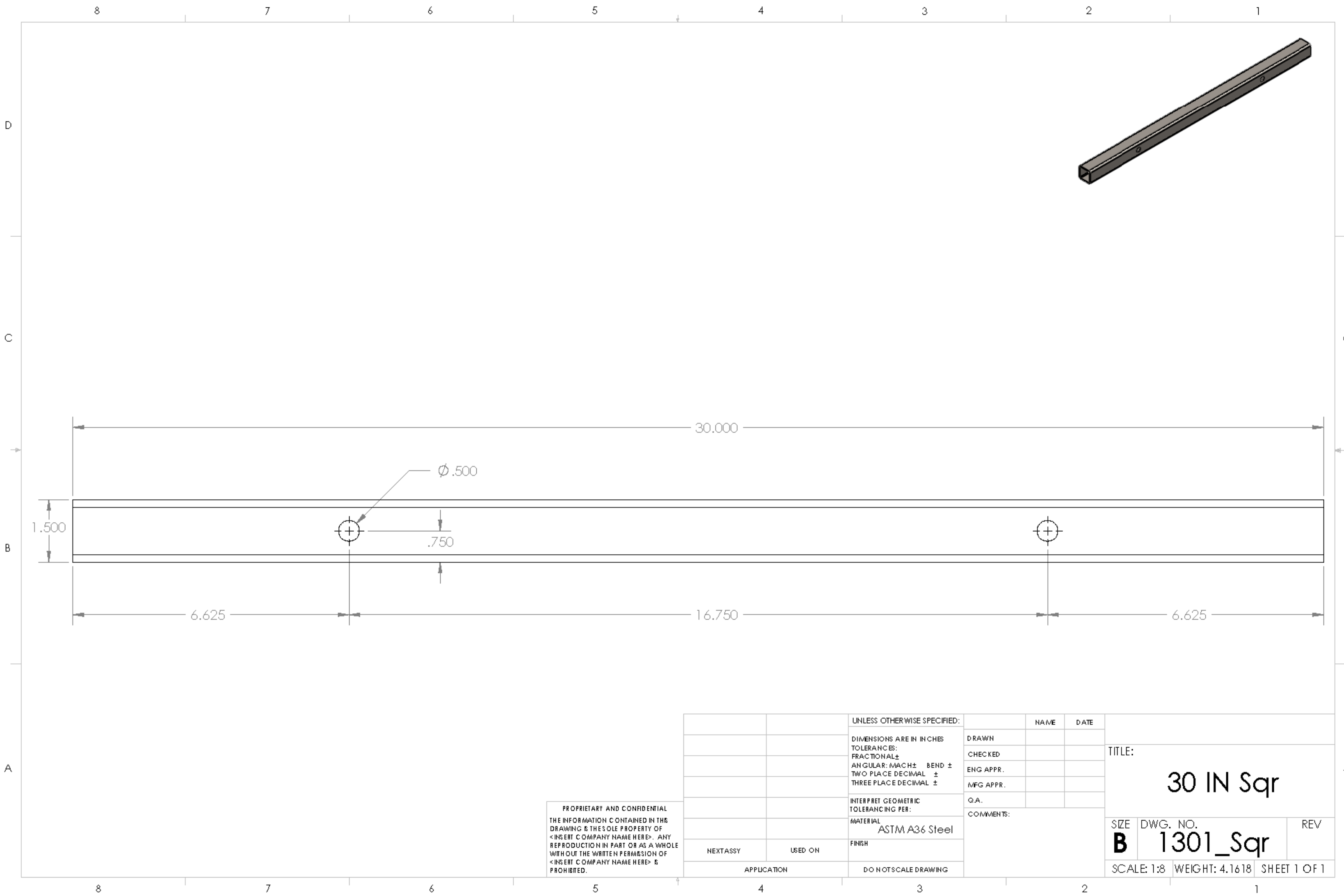



Figure A.30: Drawing of Part 1301

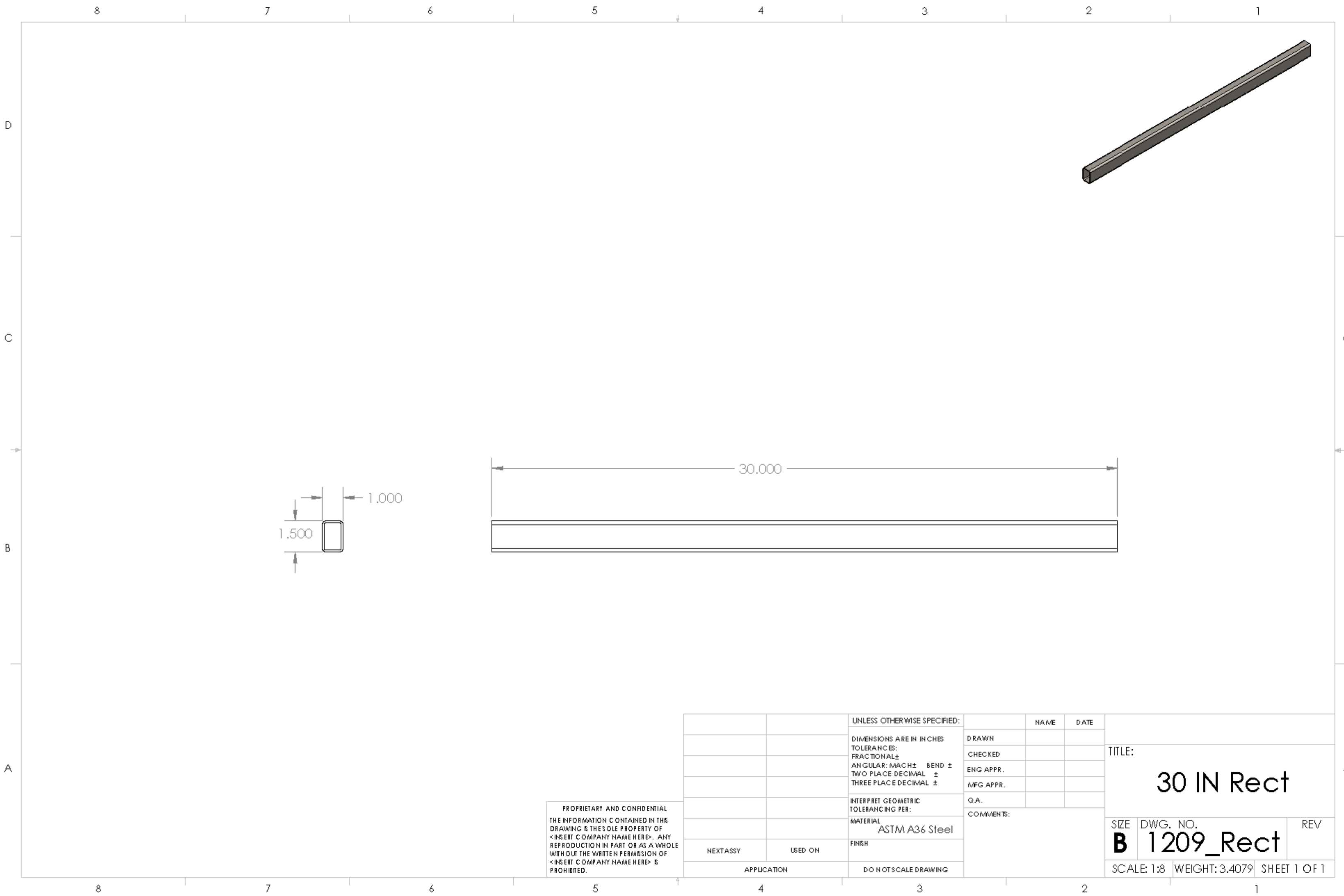



Figure A.31: Drawing of Part 1209

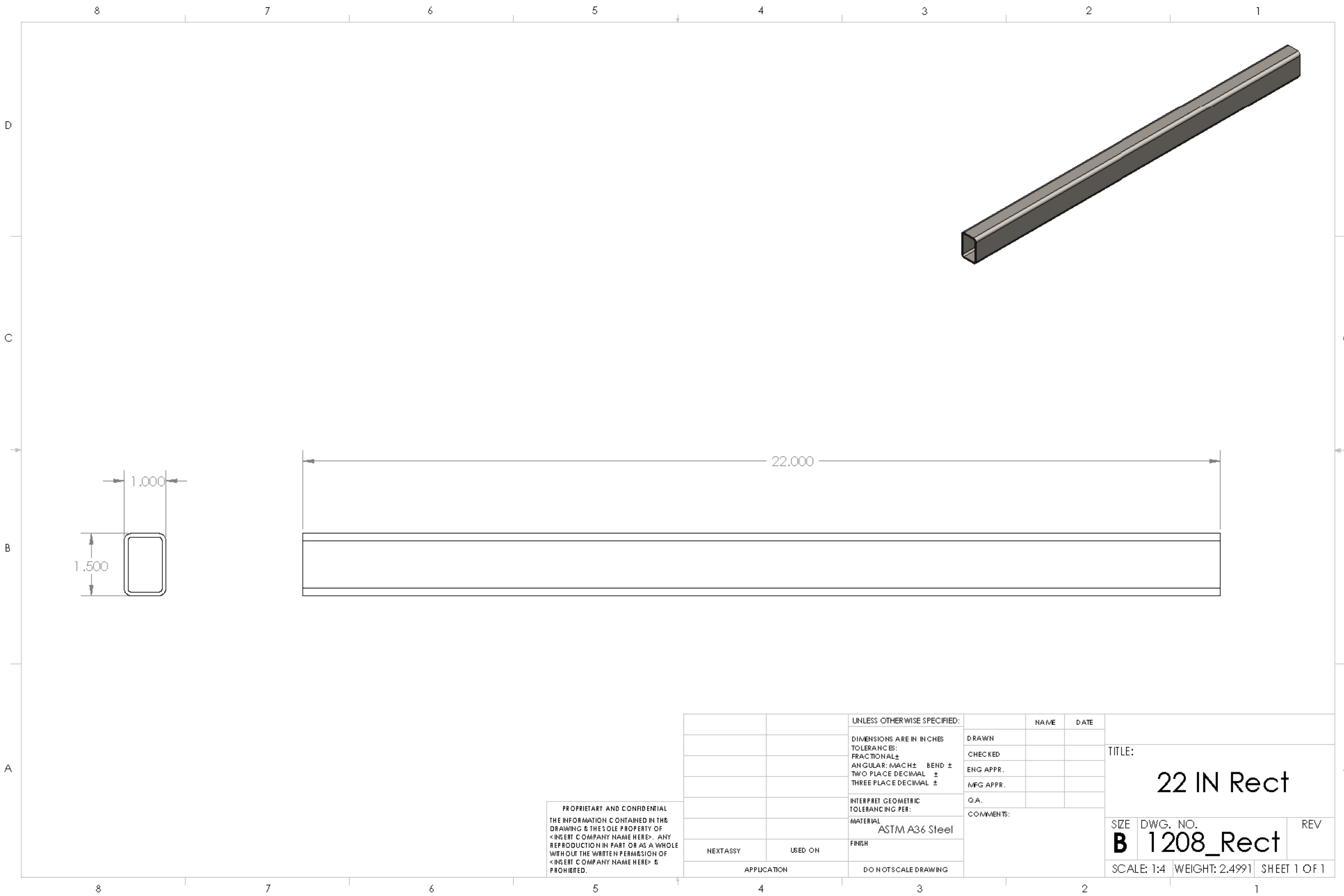



Figure A.32: Drawing of Part 1208

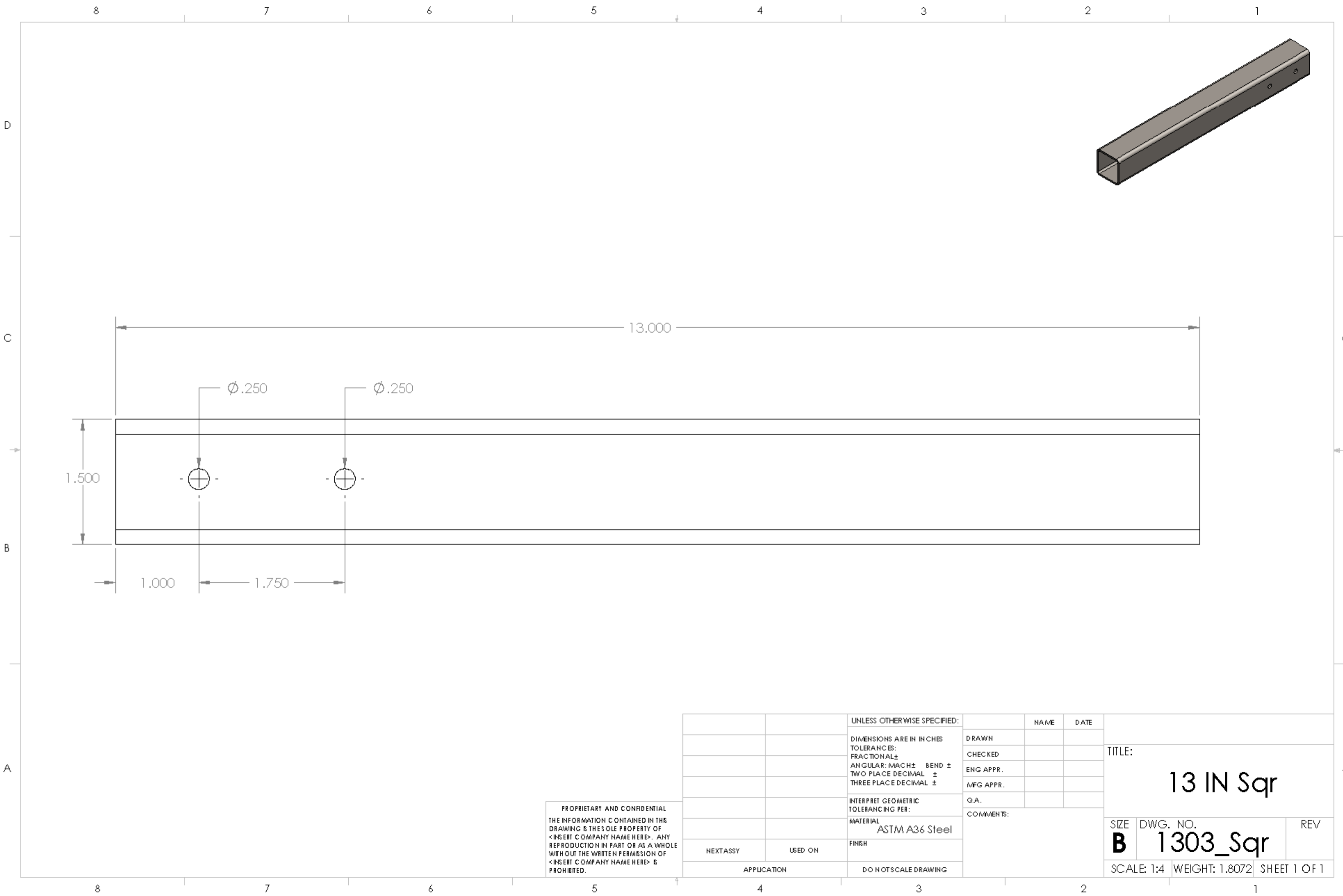



Figure A.33: Drawing of Part 1303

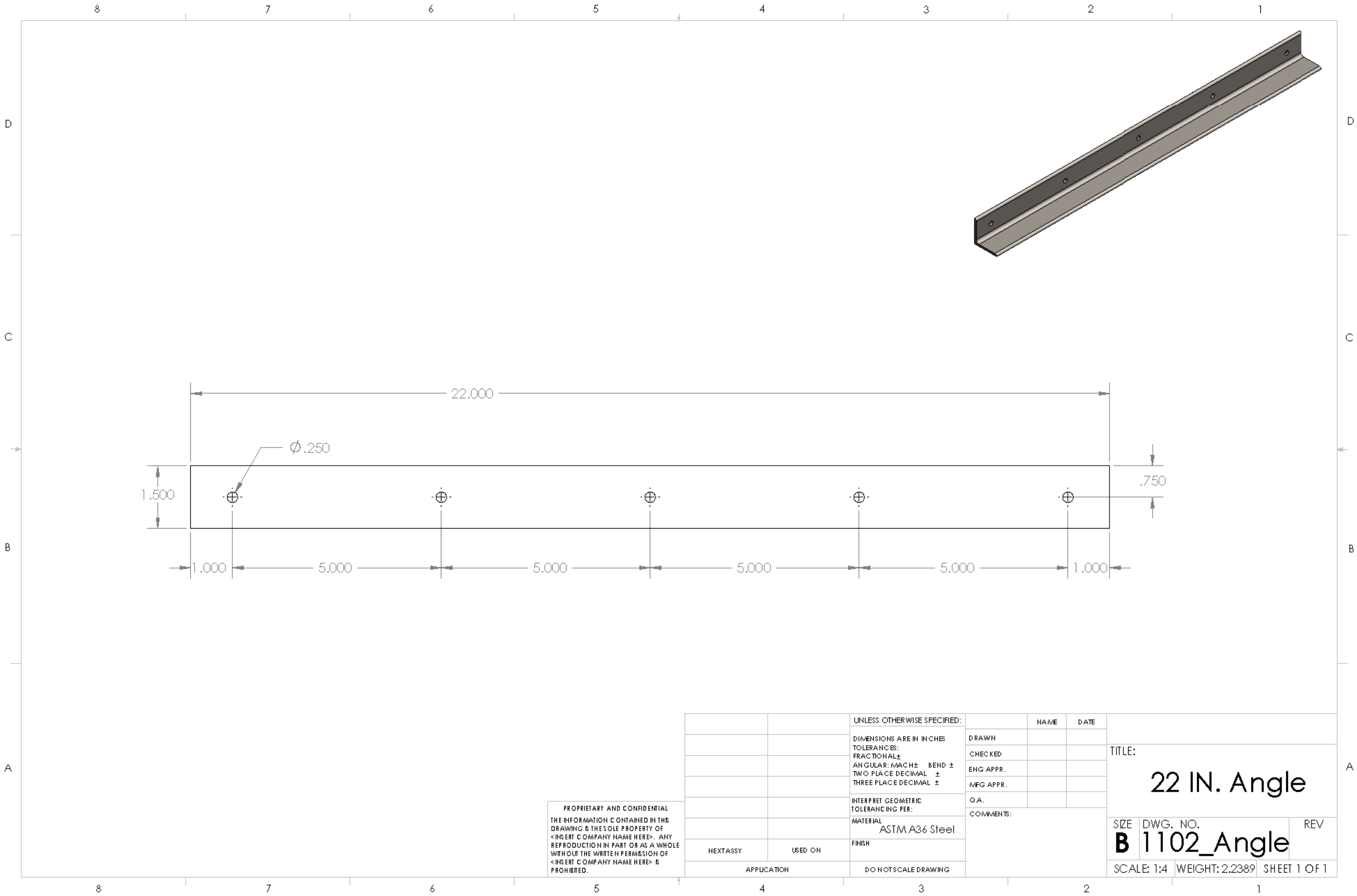



Figure A.34: Drawing of Part 1102

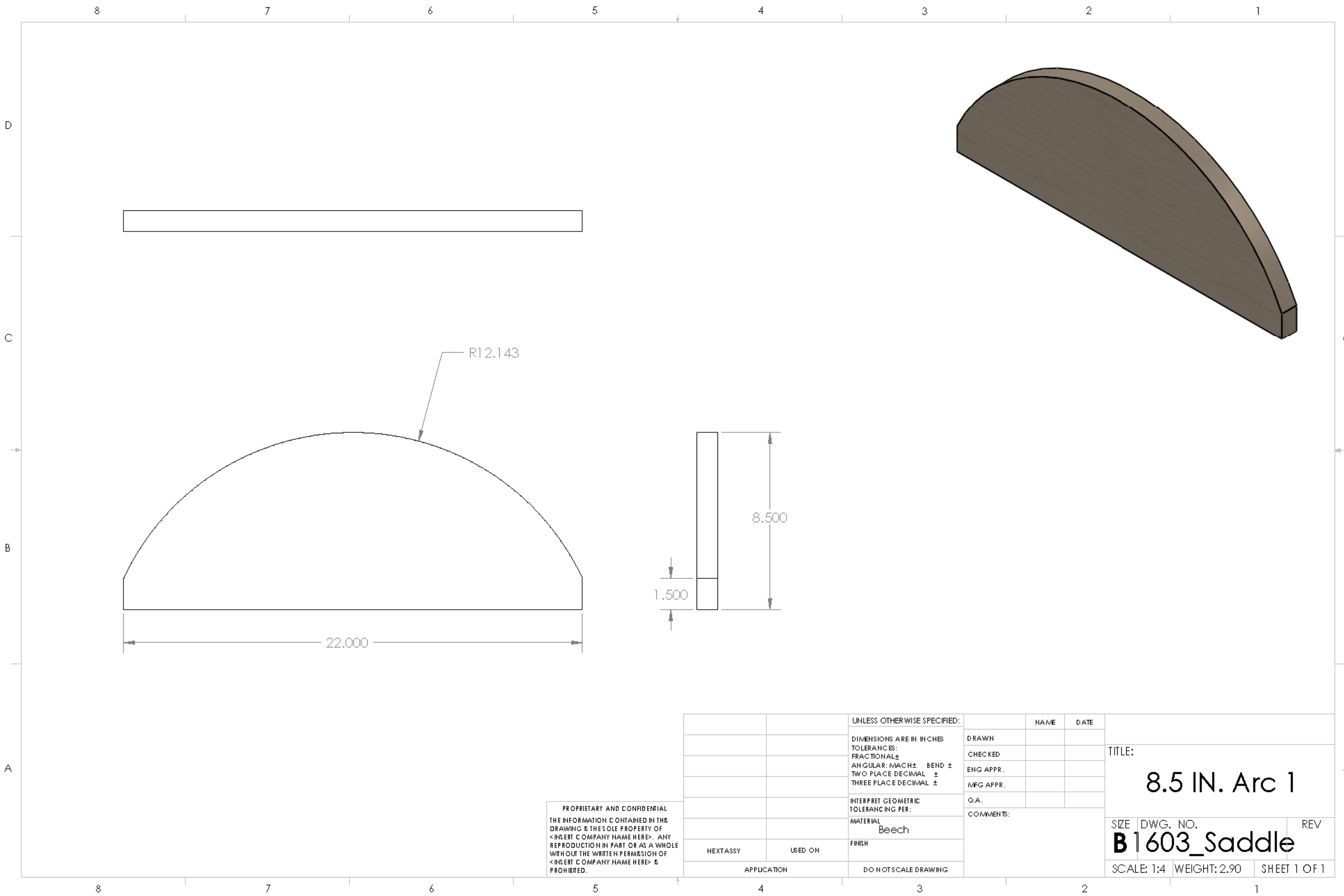



Figure A.35: Drawing of Part 1603

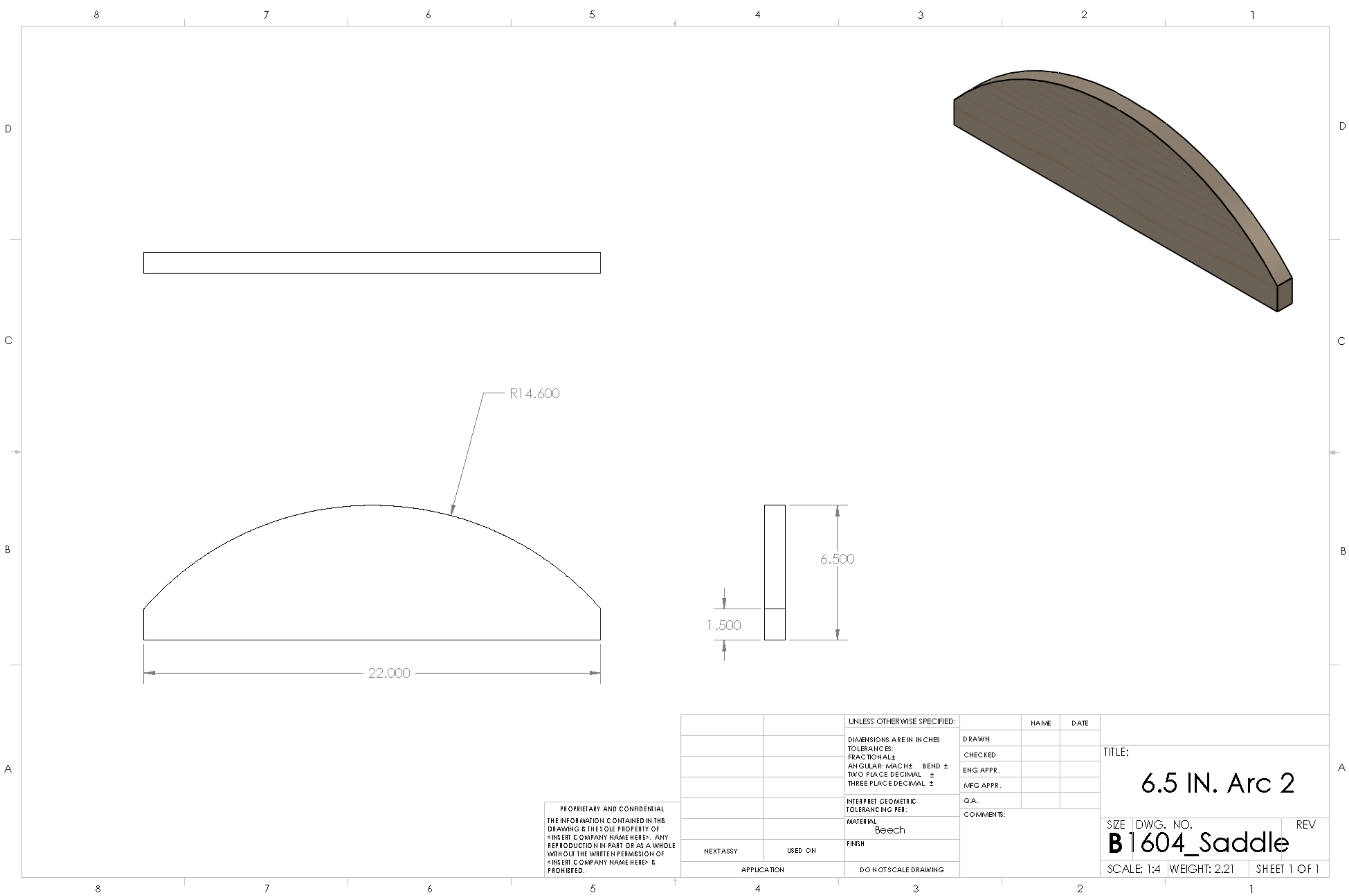



Figure A.36: Drawing of Part 1604

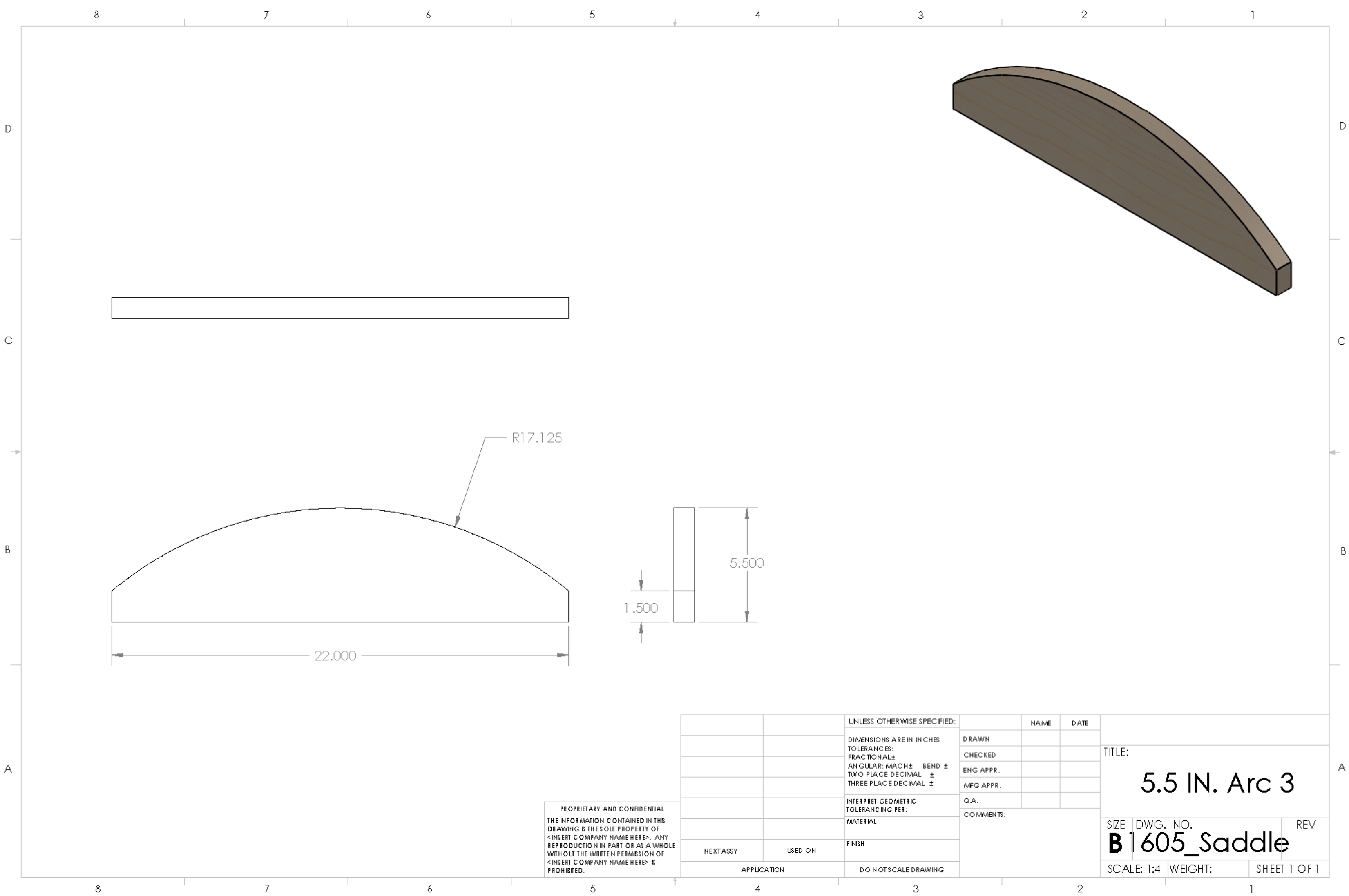



Figure A.37: Drawing of Part 1605

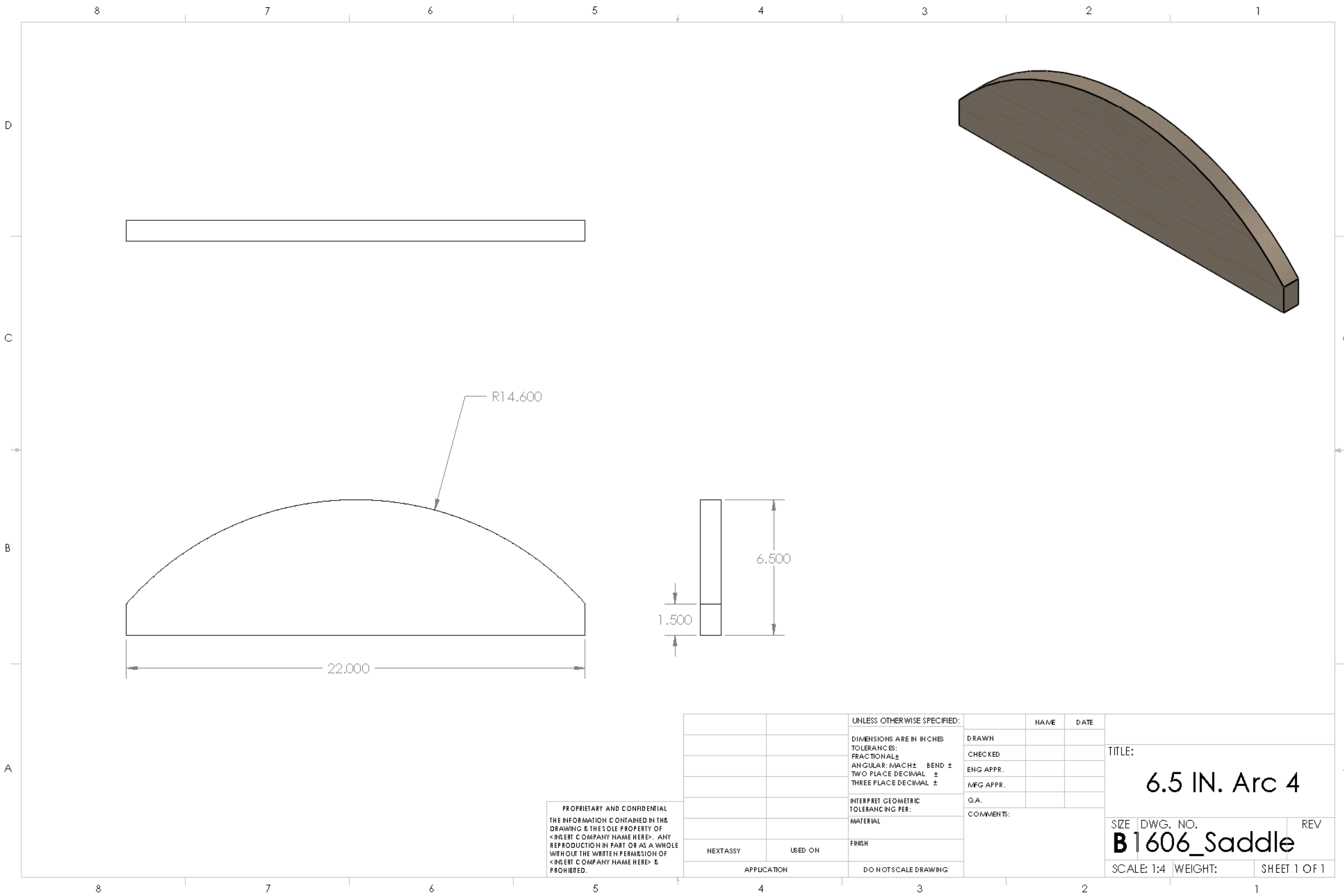



Figure A.38: Drawing of Part 1606

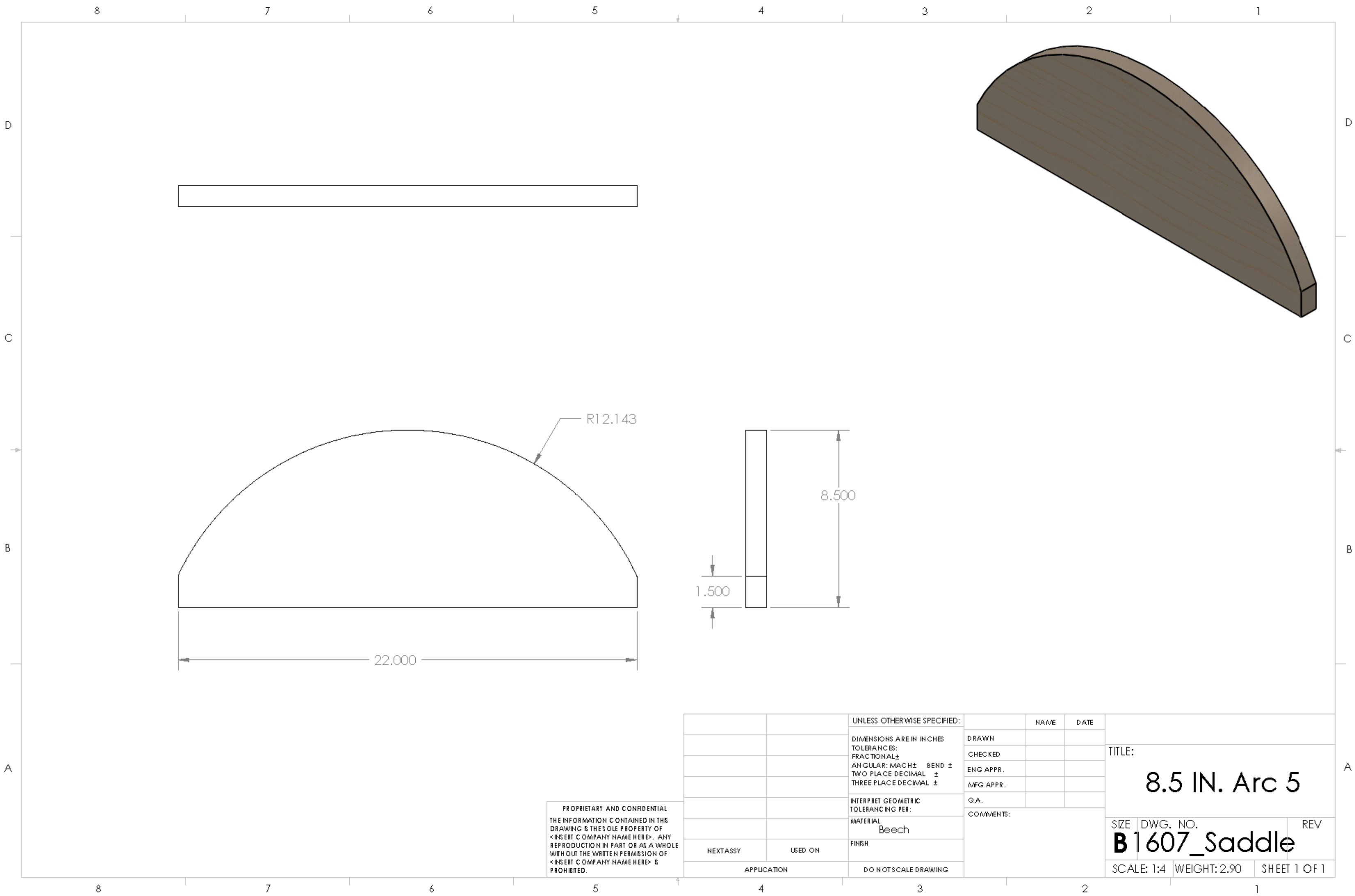



Figure A.39: Drawing of Part 1607

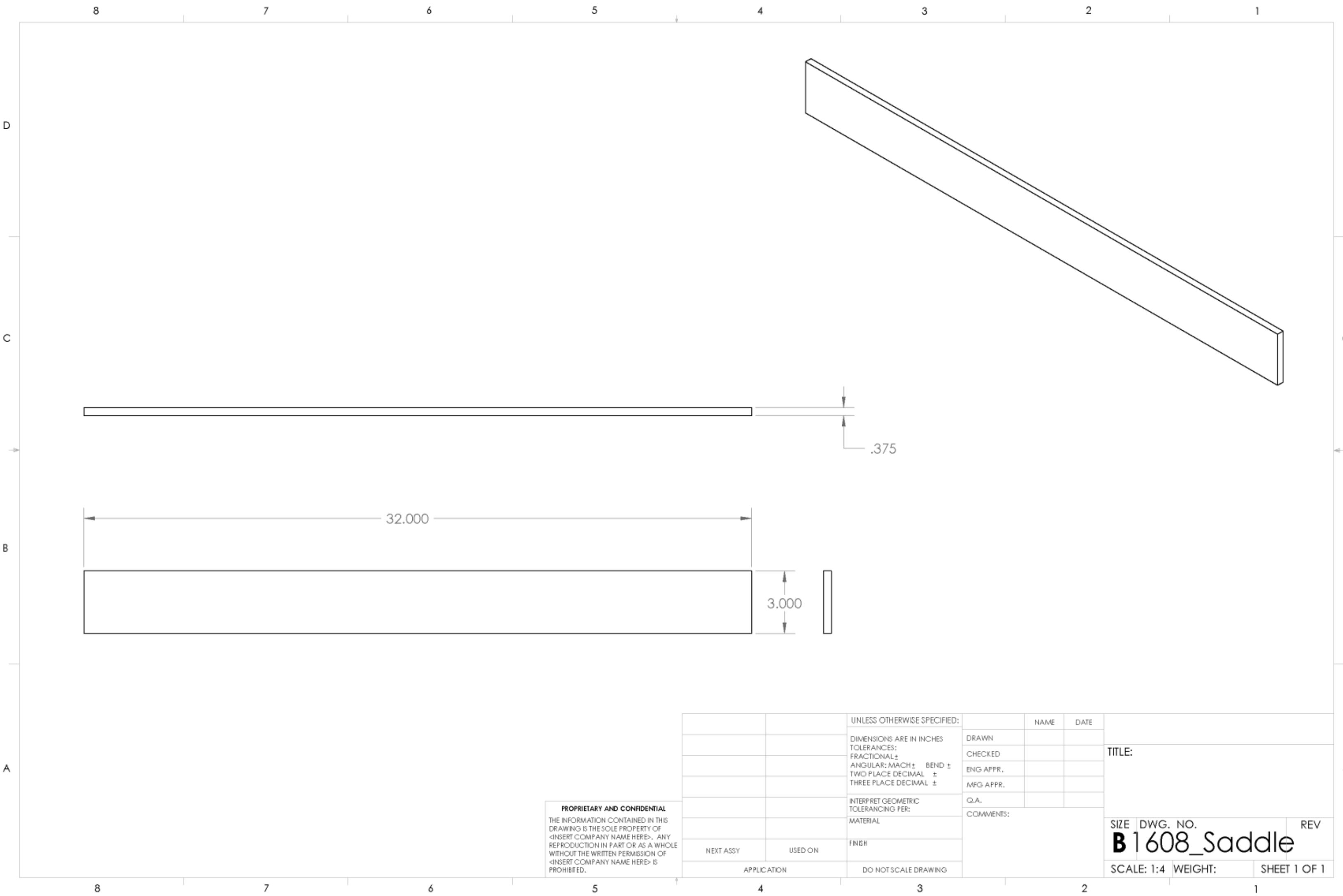



Figure A.40: Drawing of Part 1608

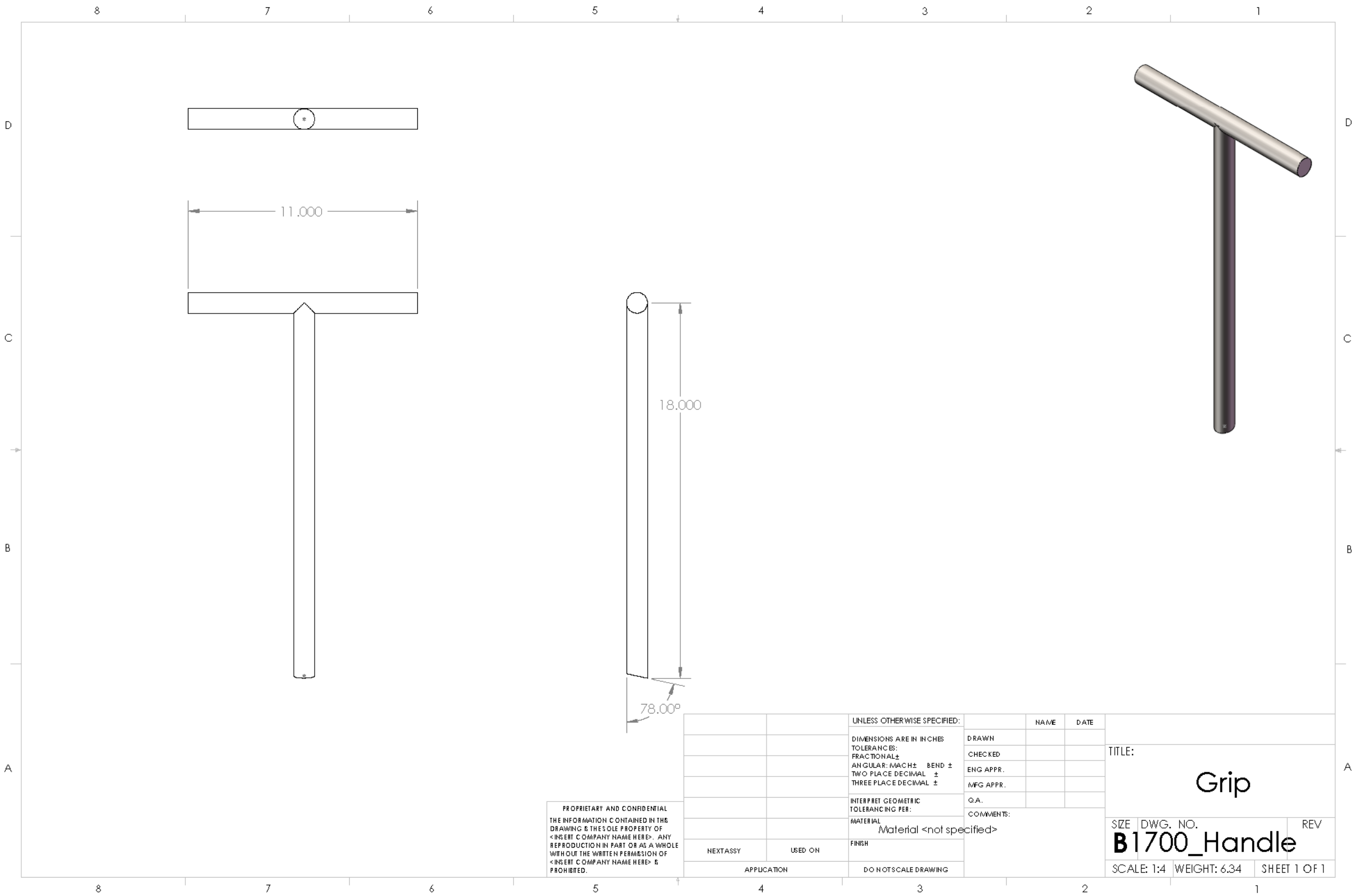



Figure A.41: Drawing of Part 1700

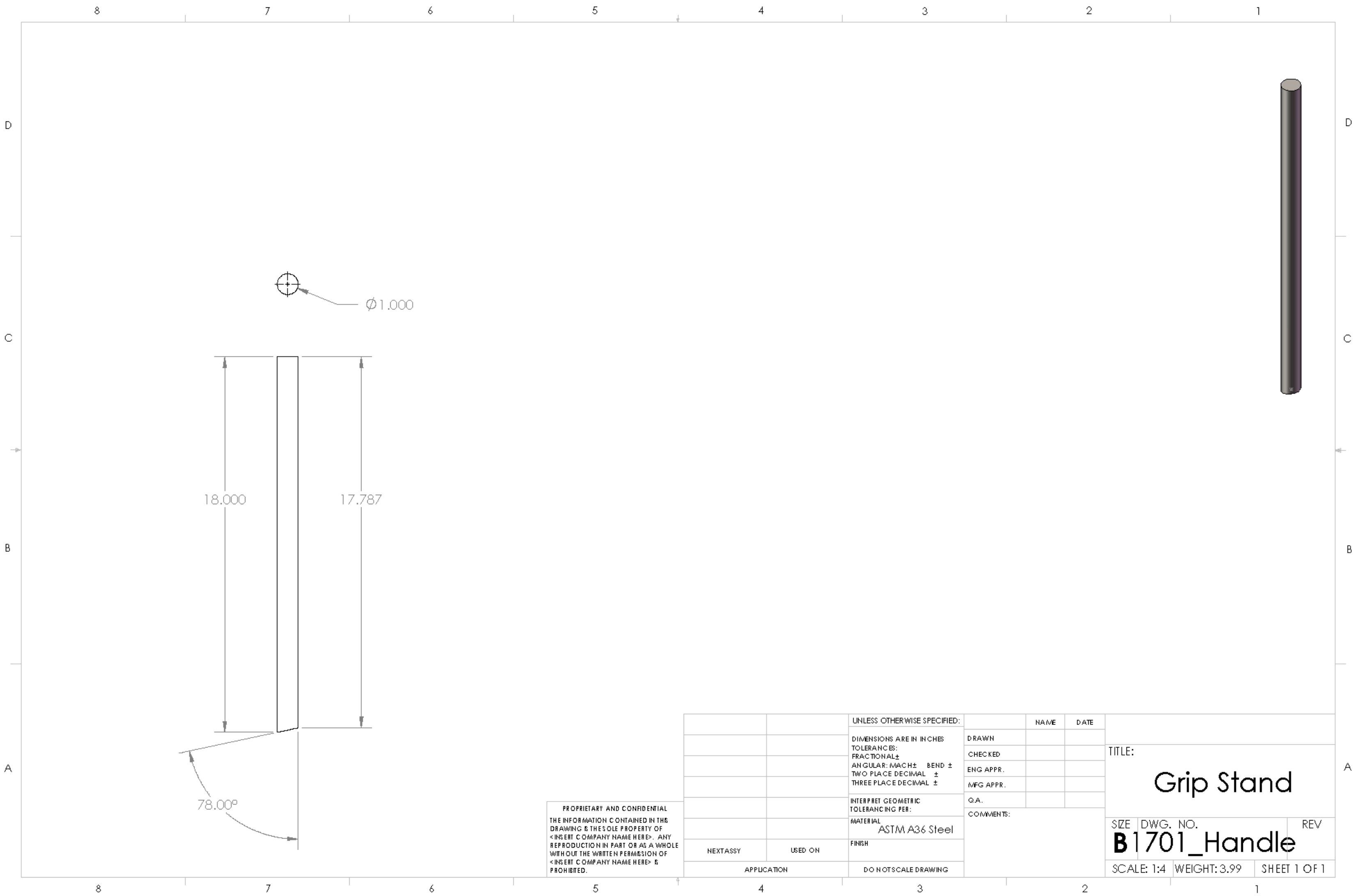



Figure A.42: Drawing of Part 1701

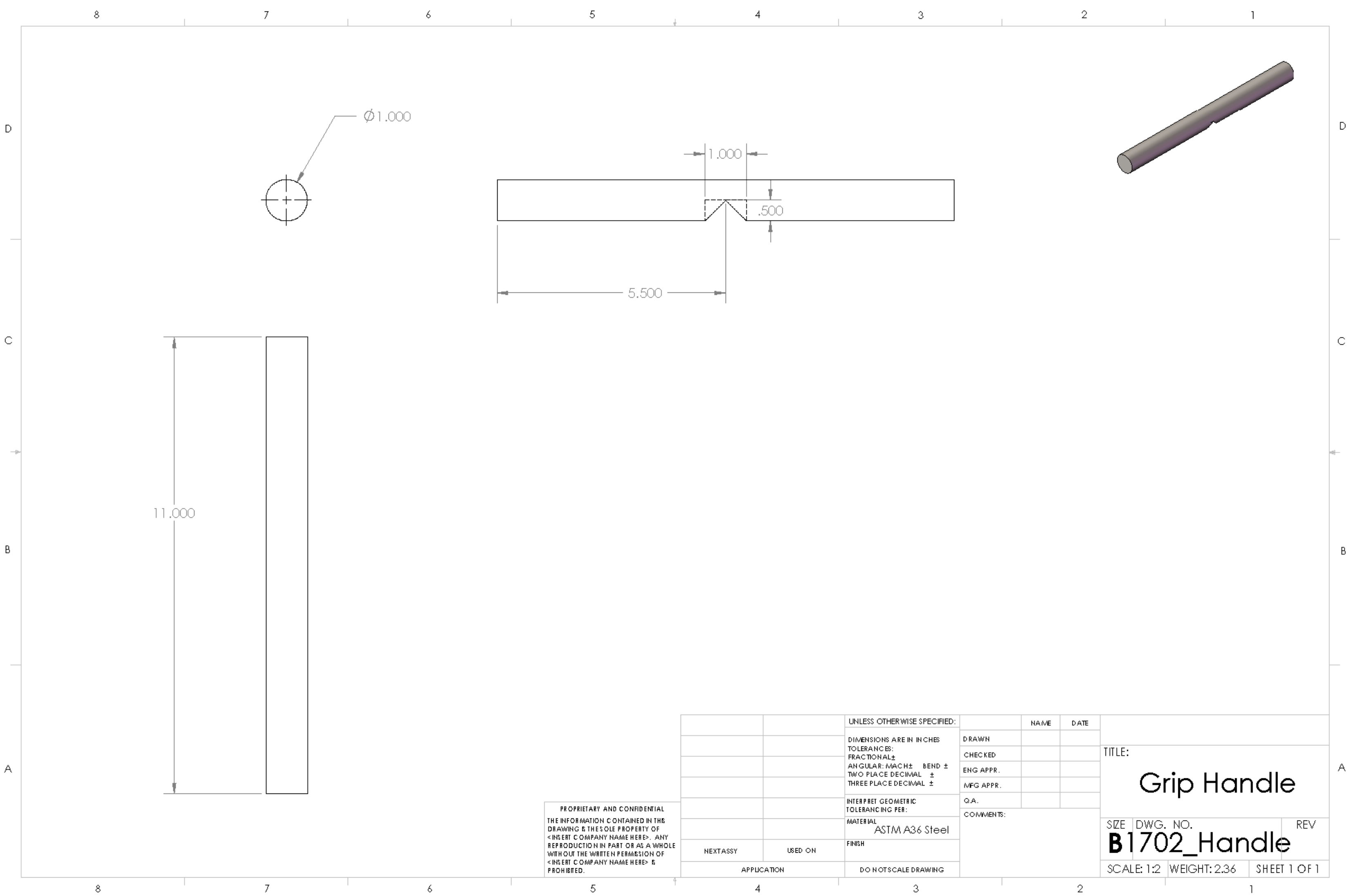



Figure A.43: Drawing of Part 1702

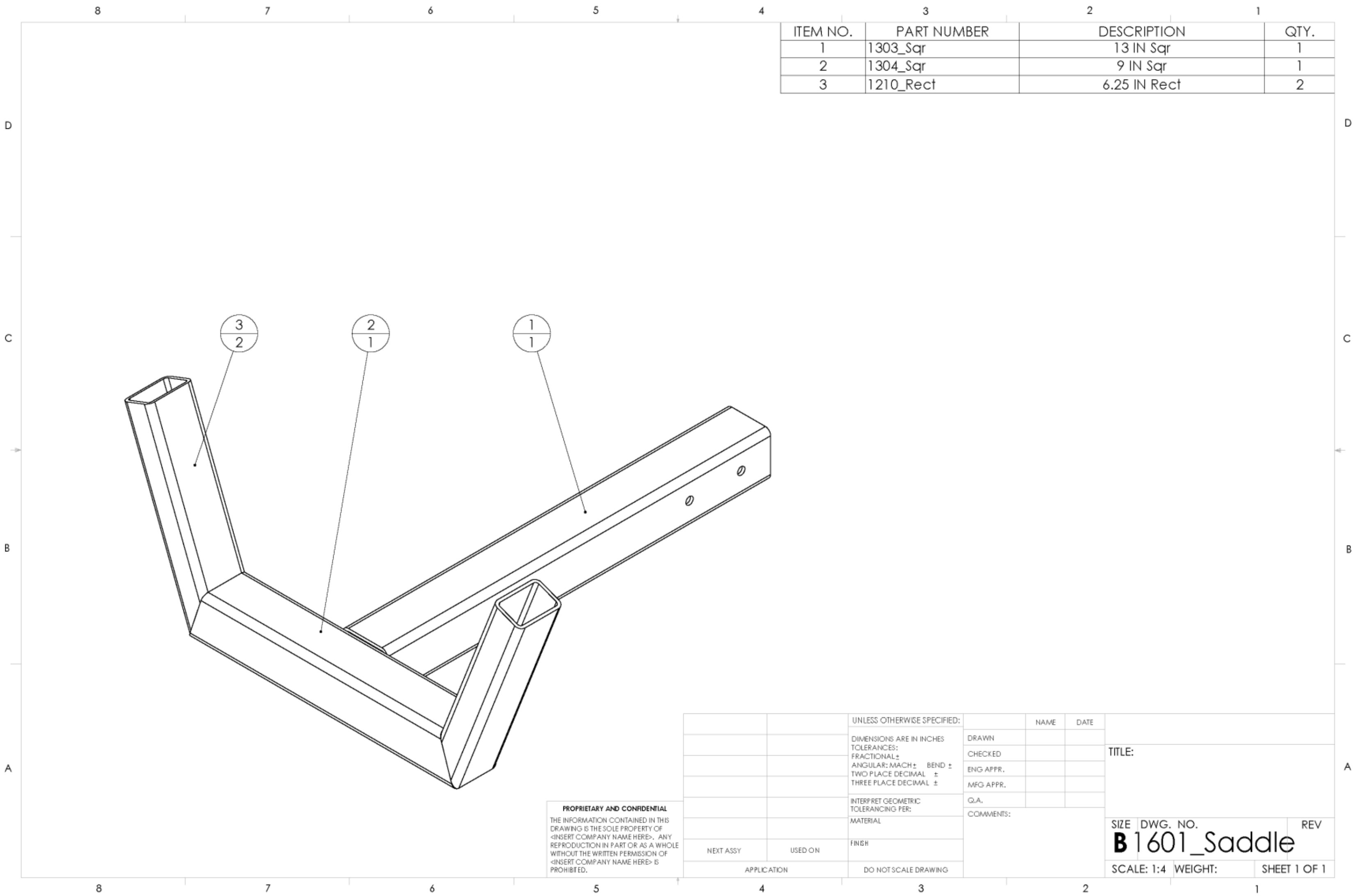



Figure A.44: Drawing of Part 1601

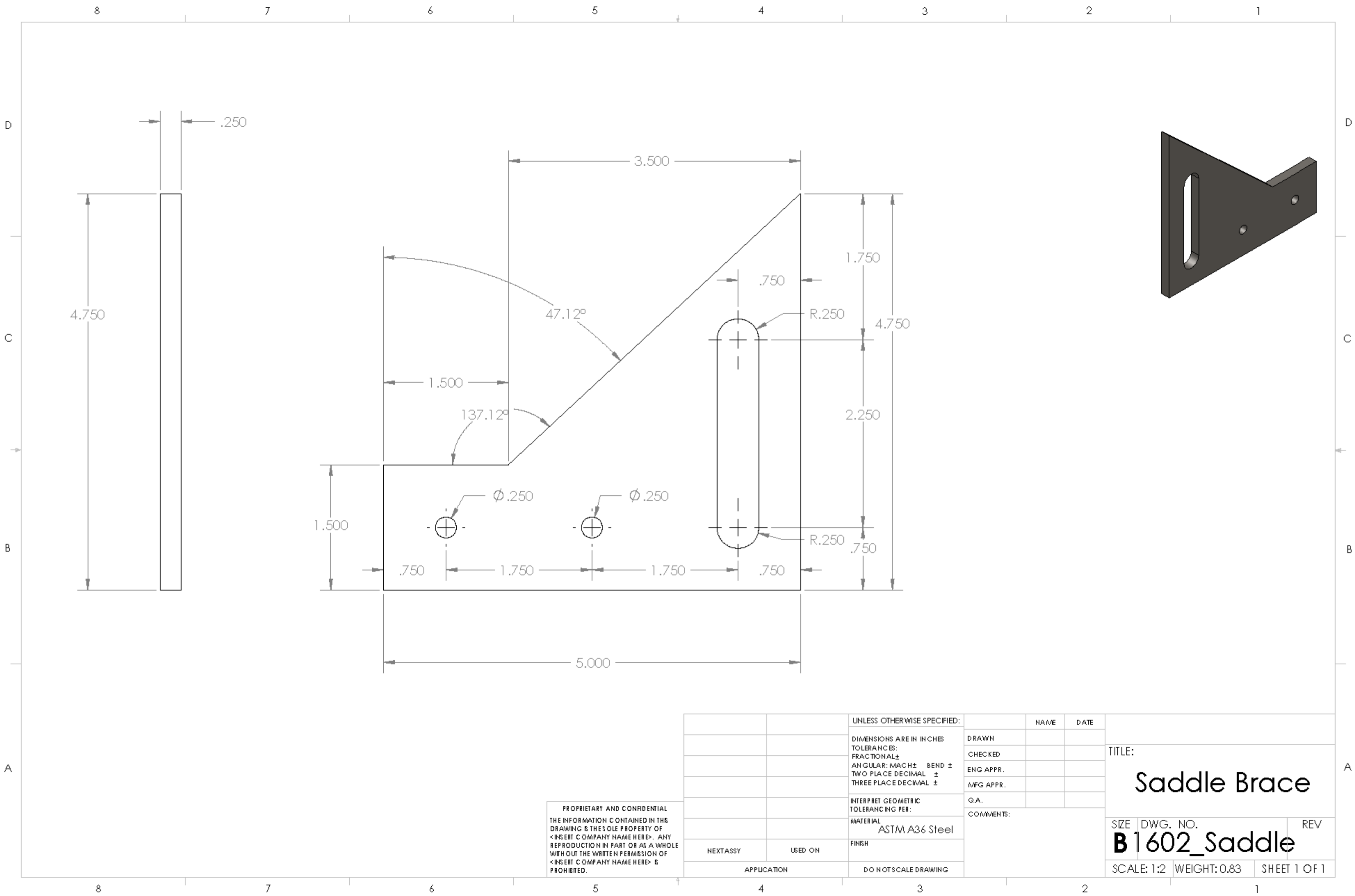



Figure A.45: Drawing of Part 1602

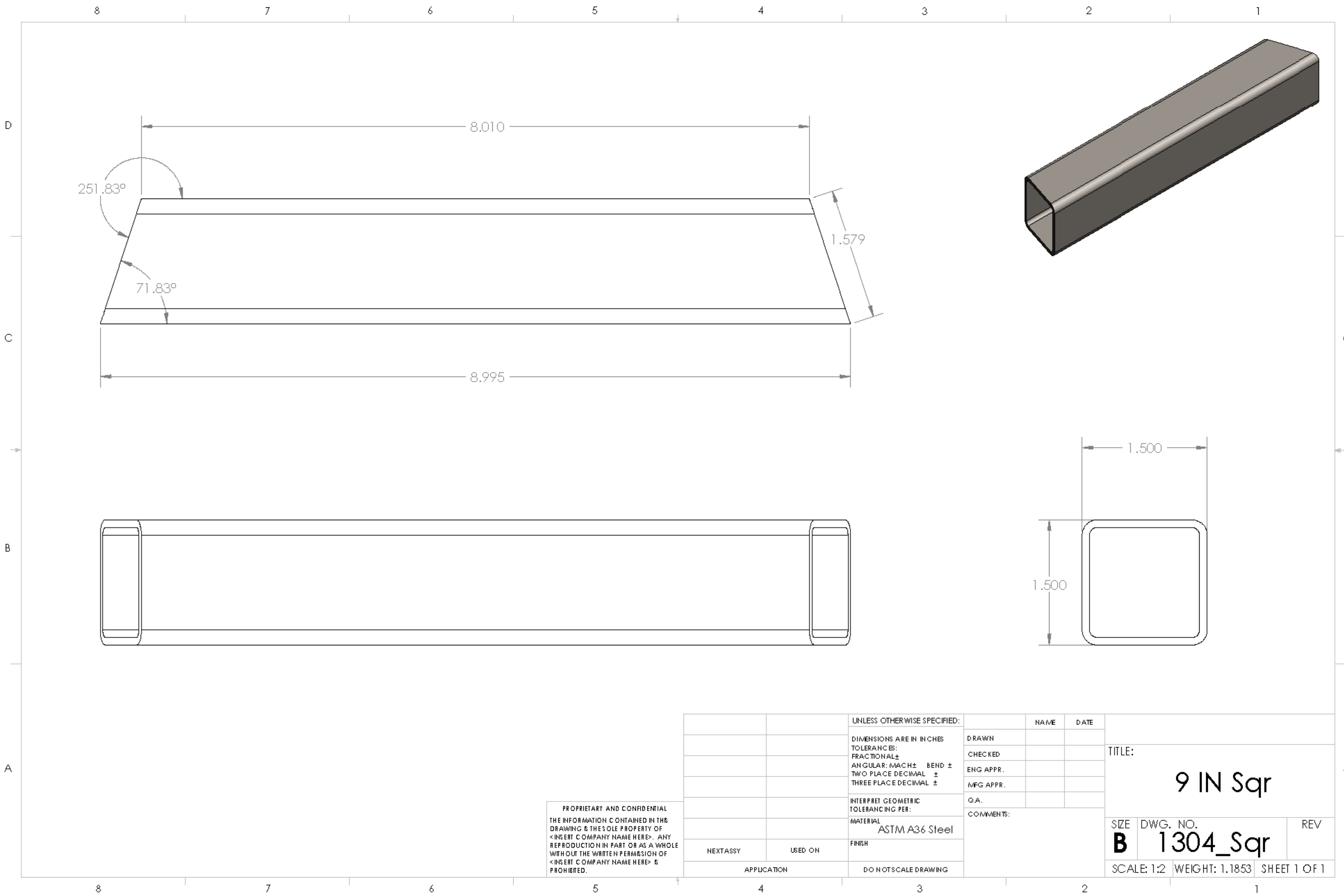



Figure A.46: Drawing of Part 1304

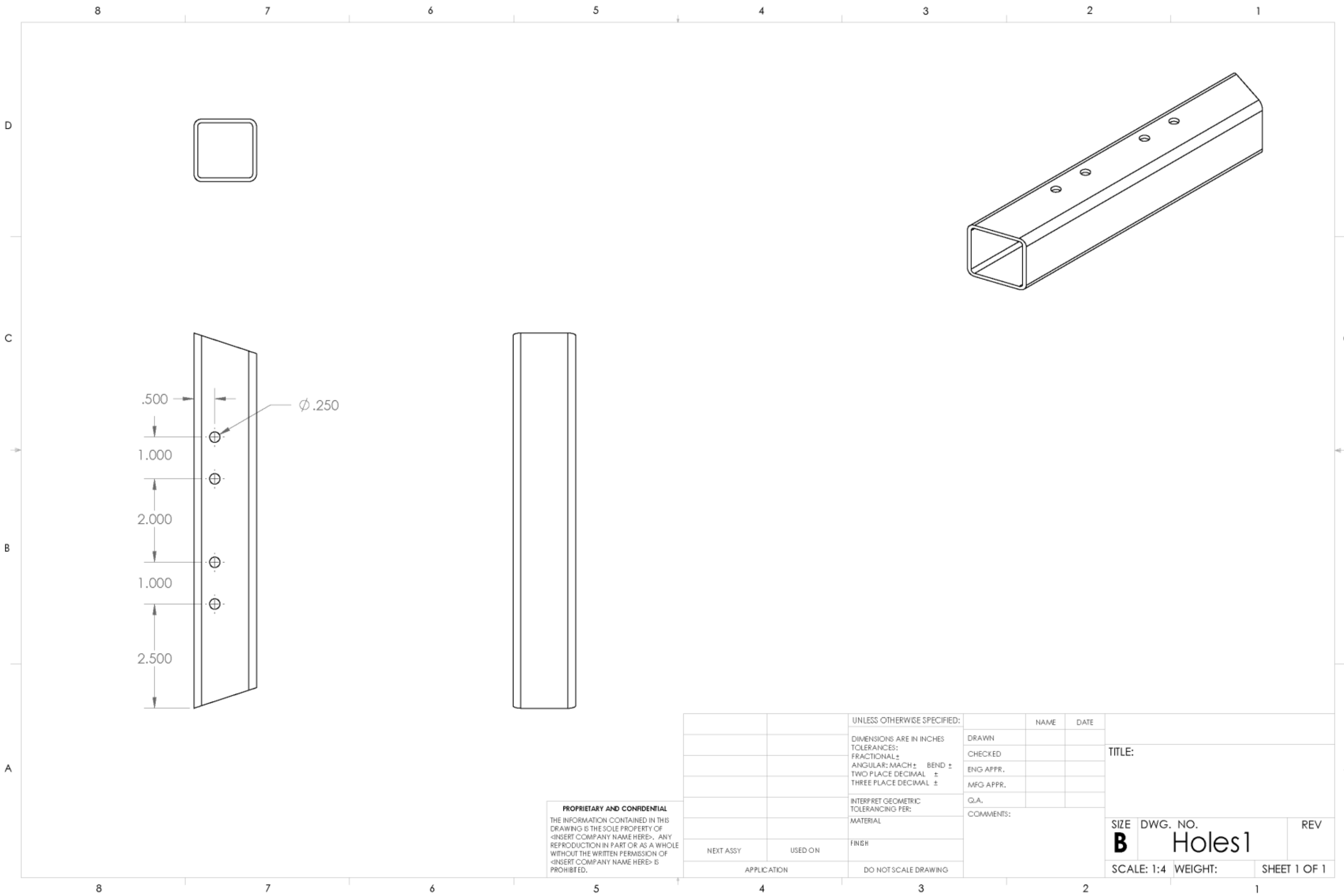



Figure A.47: Drawing of Part 1304 with Holes for Mounting U-Bolts

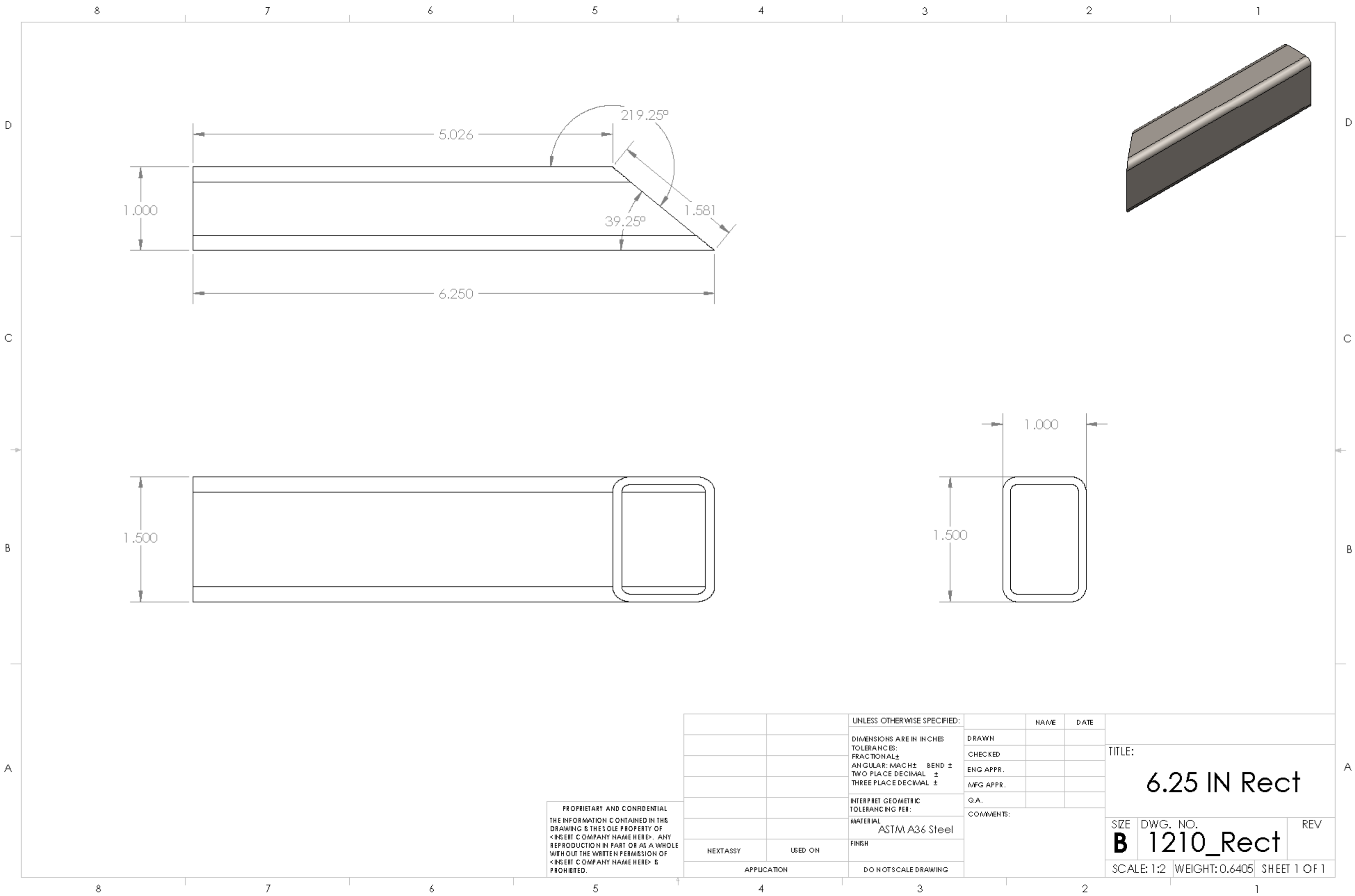



Figure A.48: Drawing of Part 1210

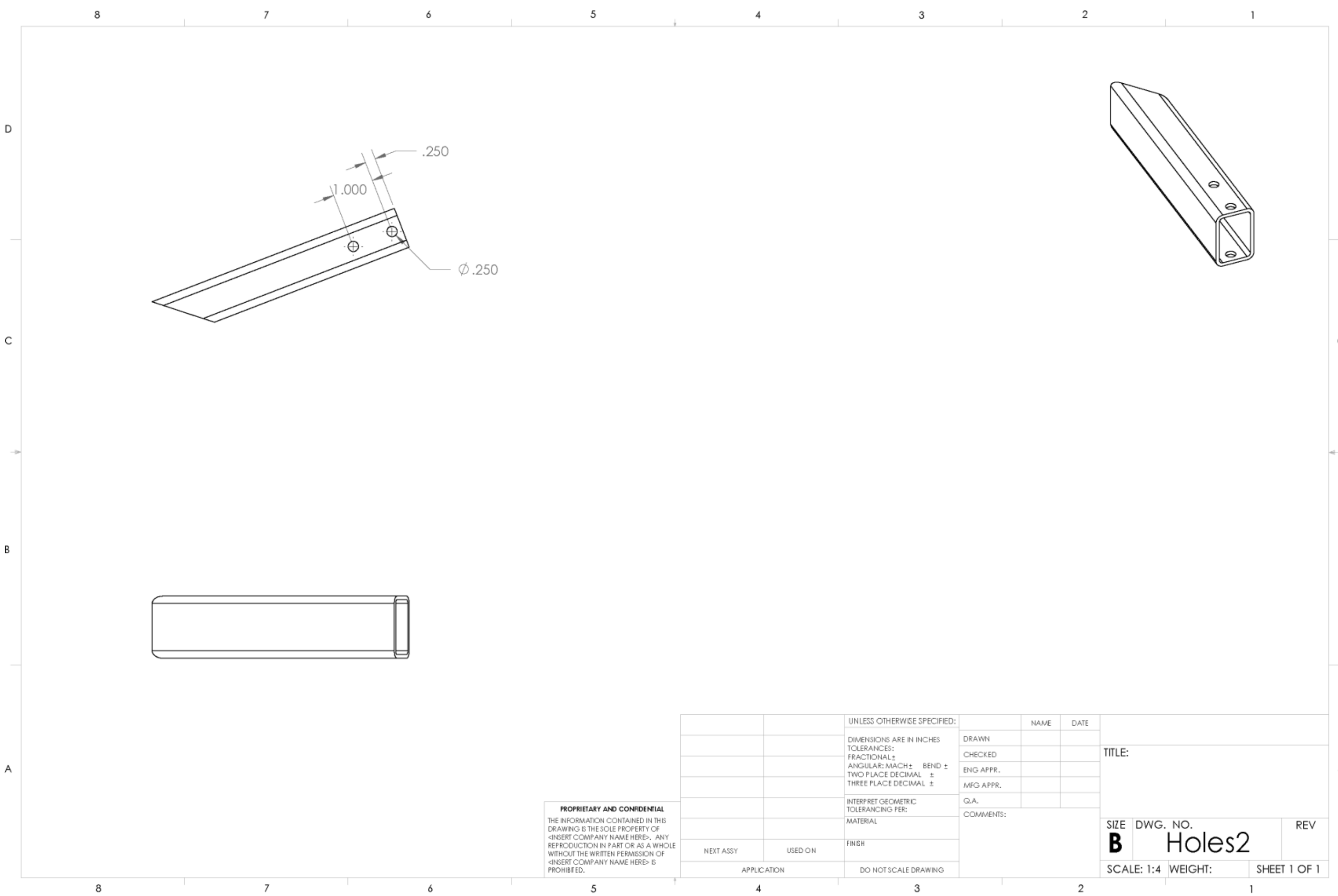



Figure A.49: Drawing of Part 1210 with Holes for Mounting U-Bolts

# APPENDIX B

# MATLAB Functions

*Data Repopulation Function*

```
function WildBill_repop()

% Retrieve the motion data from excel
inputData=xlsread('ExcelFile.xlsx','ExcelWorksheet');

% Create the time vectors & input the normalized time column
normTime=inputData(:,2);

% Create the motion vectors for each measure
xHorn=inputData(:,3);
yHorn=inputData(:,4);
zHorn=inputData(:,5);
xBackLeft=inputData(:,6);
yBackLeft=inputData(:,7);
zBackLeft=inputData(:,8);
xBackRight=inputData(:,9);
yBackRight=inputData(:,10);
zBackRight=inputData(:,11);
xAngle=inputData(:,12);
yAngle=inputData(:,13);
zAngle=inputData(:,14);
xAvgSaddle=inputData(:,15);
yAvgSaddle=inputData(:,16);
zAvgSaddle=inputData(:,17);

% Fit polynomial curve to data for each measure
pOrder = 16;
p_xHorn=polyfit(normTime,xHorn,pOrder);
p_yHorn=polyfit(normTime,yHorn,pOrder);
p_zHorn=polyfit(normTime,zHorn,pOrder);
p_xBackLeft=polyfit(normTime,xBackLeft,pOrder);
p_yBackLeft=polyfit(normTime,yBackLeft,pOrder);
p_zBackLeft=polyfit(normTime,zBackLeft,pOrder);
p_xBackRight=polyfit(normTime,xBackRight,pOrder);
p_yBackRight=polyfit(normTime,yBackRight,pOrder);
p_zBackRight=polyfit(normTime,zBackRight,pOrder);
p_xAngle=polyfit(normTime,xAngle,pOrder);
p_yAngle=polyfit(normTime,yAngle,pOrder);
p_zAngle=polyfit(normTime,zAngle,pOrder);
p_xAvgSaddle=polyfit(normTime,xAvgSaddle,pOrder);
p_yAvgSaddle=polyfit(normTime,yAvgSaddle,pOrder);
p_zAvgSaddle=polyfit(normTime,zAvgSaddle,pOrder);

% Generate new normalized time vector of 250 data points
time=0:1/250:1;

% Fit motion data to new normalized time vector using polynomial curve
r_xHorn=polyval(p_xHorn,time);
r_yHorn=polyval(p_yHorn,time);
r_zHorn=polyval(p_zHorn,time);
r_xBackLeft=polyval(p_xBackLeft,time);
```

```
r_yBackLeft=polyval(p_yBackLeft,time);
r_zBackLeft=polyval(p_zBackLeft,time);
r_xBackRight=polyval(p_xBackRight,time);
r_yBackRight=polyval(p_yBackRight,time);
r_zBackRight=polyval(p_zBackRight,time);
r_xAngle=polyval(p_xAngle,time);
r_yAngle=polyval(p_yAngle,time);
r_zAngle=polyval(p_zAngle,time);
r_xAvgSaddle=polyval(p_xAvgSaddle,time);
r_yAvgSaddle=polyval(p_yAvgSaddle,time);
r_zAvgSaddle=polyval(p_zAvgSaddle,time);

results=[time', r_xHorn', r_yHorn', r_zHorn', r_xBackLeft', r_yBackLeft', r_zBackLeft', r_xBackRight',
r_yBackRight', r_zBackRight', r_xAngle', r_yAngle', r_zAngle', r_xAvgSaddle', r_yAvgSaddle',
r_zAvgSaddle'];

% Optional Plotting Commands (check that polyfit is accurate)
subplot(211)
hold on
plot3(xAvgSaddle,yAvgSaddle,zAvgSaddle,'.')
plot3(r_xAvgSaddle,r_yAvgSaddle,r_zAvgSaddle,'.r')
hold off
subplot(212)
hold on
plot(normTime,xAvgSaddle)
plot(time, r_xAvgSaddle,'r')
hold off

% Store results files in results matrix to export
xlswrite('ExcelFile.xlsx',results,'ExcelWorksheetError');
```

*Range of Data Function*

```
function resultRange = WildBill_range()

% Retrieve the motion data from excel
inputData=xlsread('ExcelFile.xlsx','ExcelWorksheet');

% Create the motion vectors for each measure
%xHorn=inputData(:,3);
%yHorn=inputData(:,4);
%zHorn=inputData(:,5);
%xBackLeft=inputData(:,6);
%yBackLeft=inputData(:,7);
%zBackLeft=inputData(:,8);
%xBackRight=inputData(:,9);
%yBackRight=inputData(:,10);
%zBackRight=inputData(:,11);
xAngle=inputData(:,12);
yAngle=inputData(:,13);
zAngle=inputData(:,14);
xAvgSaddle=inputData(:,15);
yAvgSaddle=inputData(:,16);
zAvgSaddle=inputData(:,17);

% Find data range (max and min)
max_xAngle=max(xAngle);
min_xAngle=min(xAngle);
max_yAngle=max(yAngle);
min_yAngle=min(yAngle);
max_zAngle=max(zAngle);
min_zAngle=min(zAngle);
max_xAvgSaddle=max(xAvgSaddle);
min_xAvgSaddle=min(xAvgSaddle);
max_yAvgSaddle=max(yAvgSaddle);
min_yAvgSaddle=min(yAvgSaddle);
max_zAvgSaddle=max(zAvgSaddle);
min_zAvgSaddle=min(zAvgSaddle);

% Store range results in a matrix with measures as columns, max as row 1, and min as row 2
resultRange=[max_xAngle, max_yAngle, max_zAngle, max_xAvgSaddle, max_yAvgSaddle,
max_zAvgSaddle; min_xAngle, min_yAngle, min_zAngle, min_xAvgSaddle, min_yAvgSaddle,
min_zAvgSaddle];
```

# APPENDIX C

Motion Graphs of Prototype #2

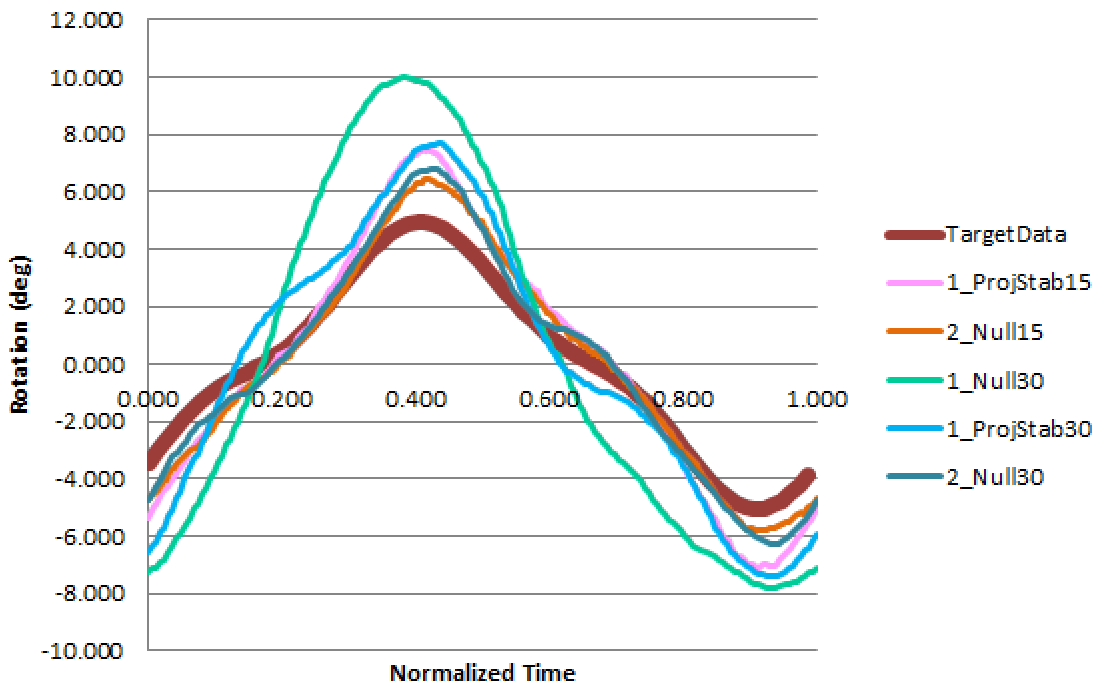



Figure C.1: Effect of Stabilization Conditions at Speeds of 15 and 30 Hz (X-Rotation)

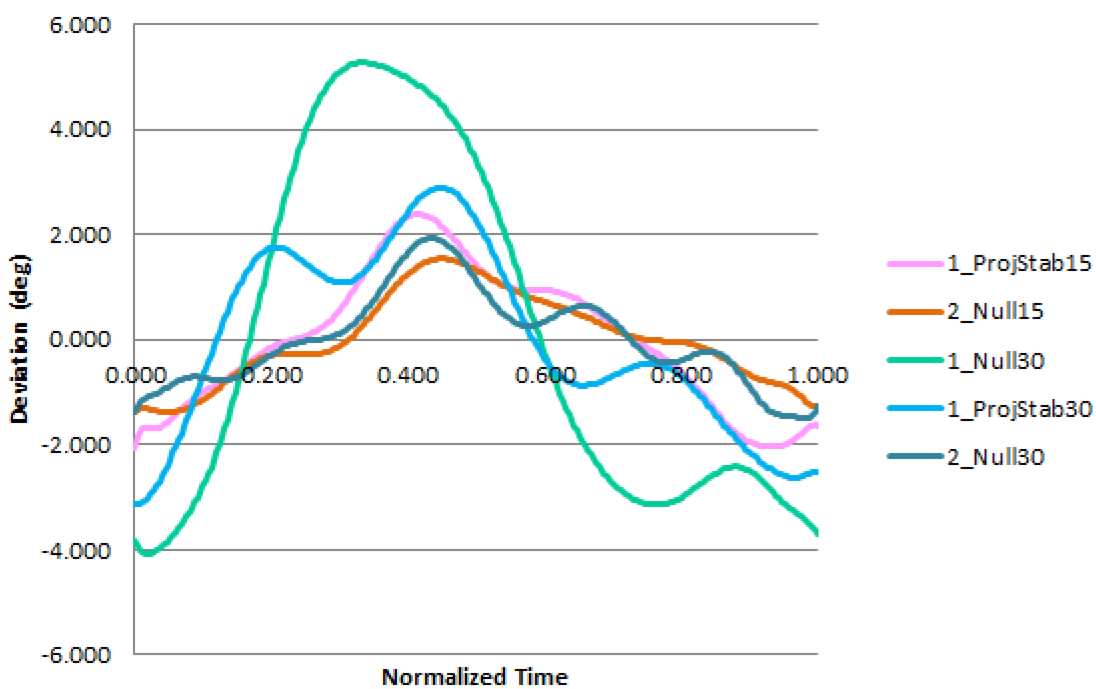



Figure C.2: Deviation from Target Data (X-Rotation)

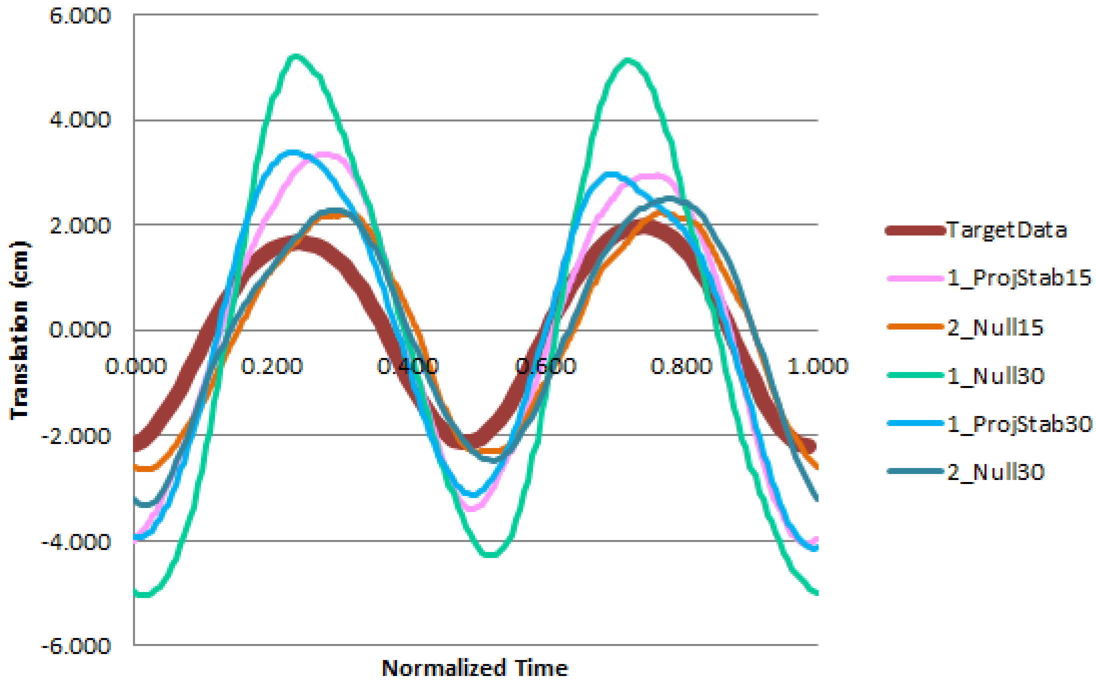



Figure C.3: Effect of Stabilization Conditions at Speeds of 15 and 30 Hz (X-Translation)

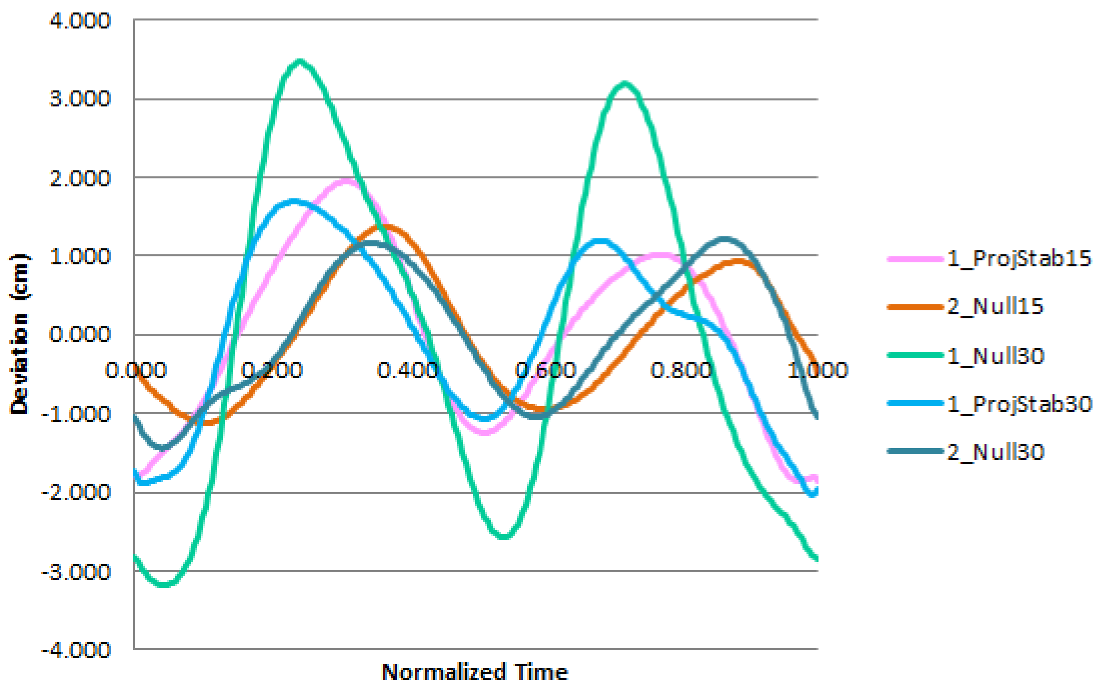



Figure C.4: Deviation from Target Data (X-Translation)

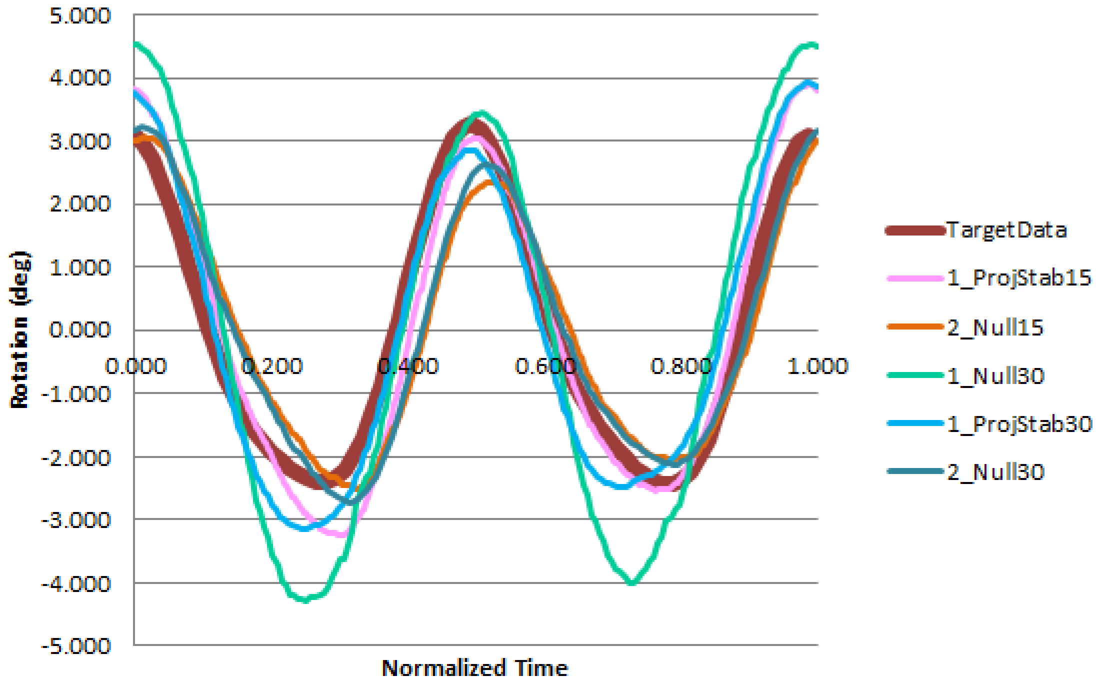



Figure C.5: Effect of Stabilization Conditions at Speeds of 15 and 30 Hz (Z-Rotation)

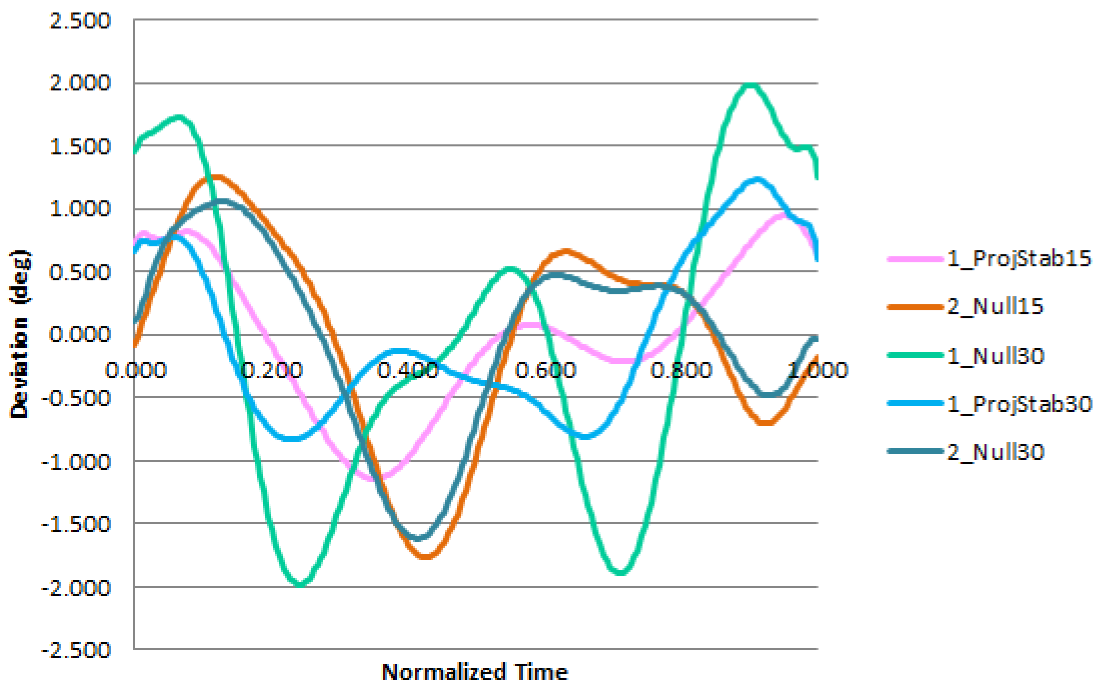



Figure C.6: Deviation from Target Data (Z-Rotation)

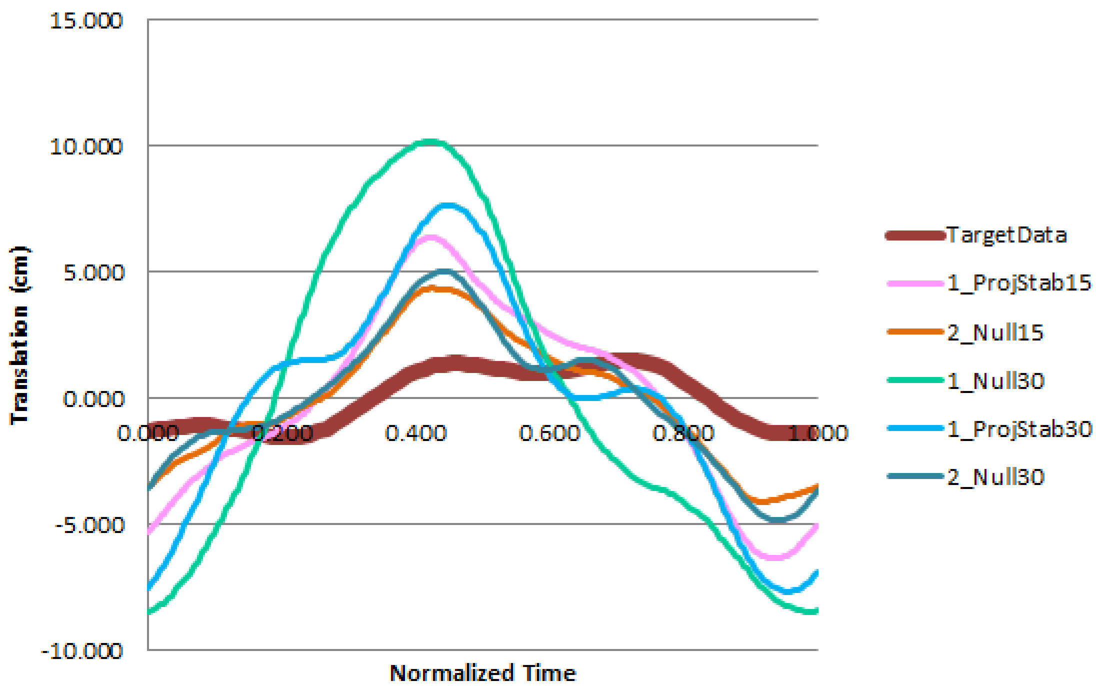



Figure C.7: Effect of Stabilization Conditions at Speeds of 15 and 30 Hz (Z-Translation)

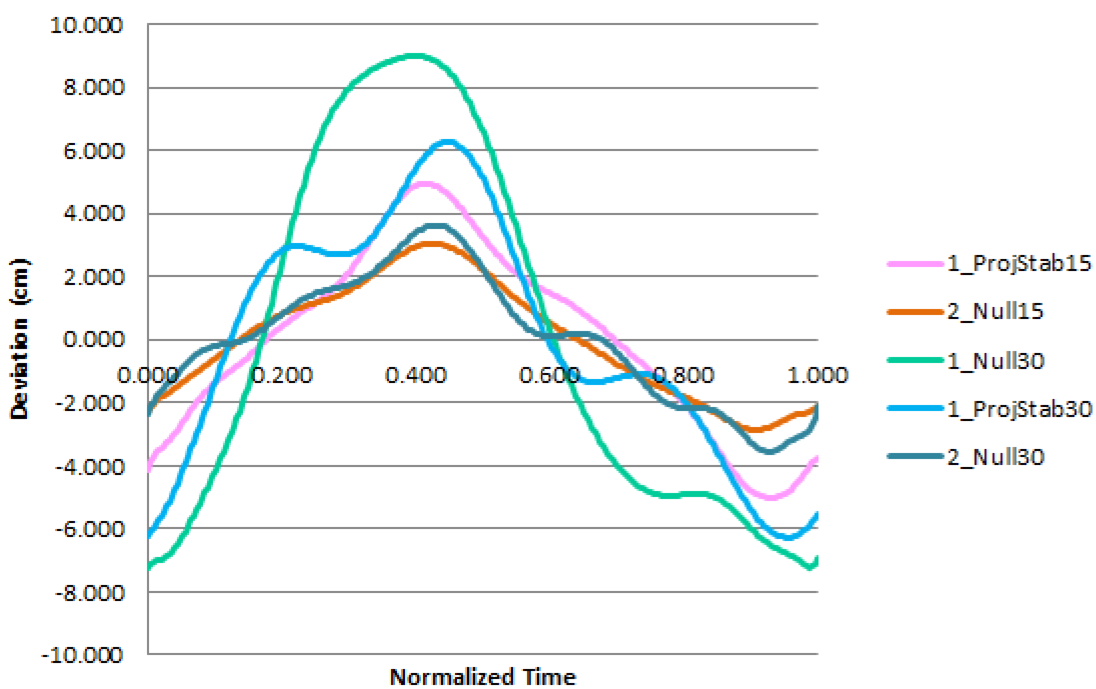



Figure C.8: Deviation from Target Data (Z-Translation)

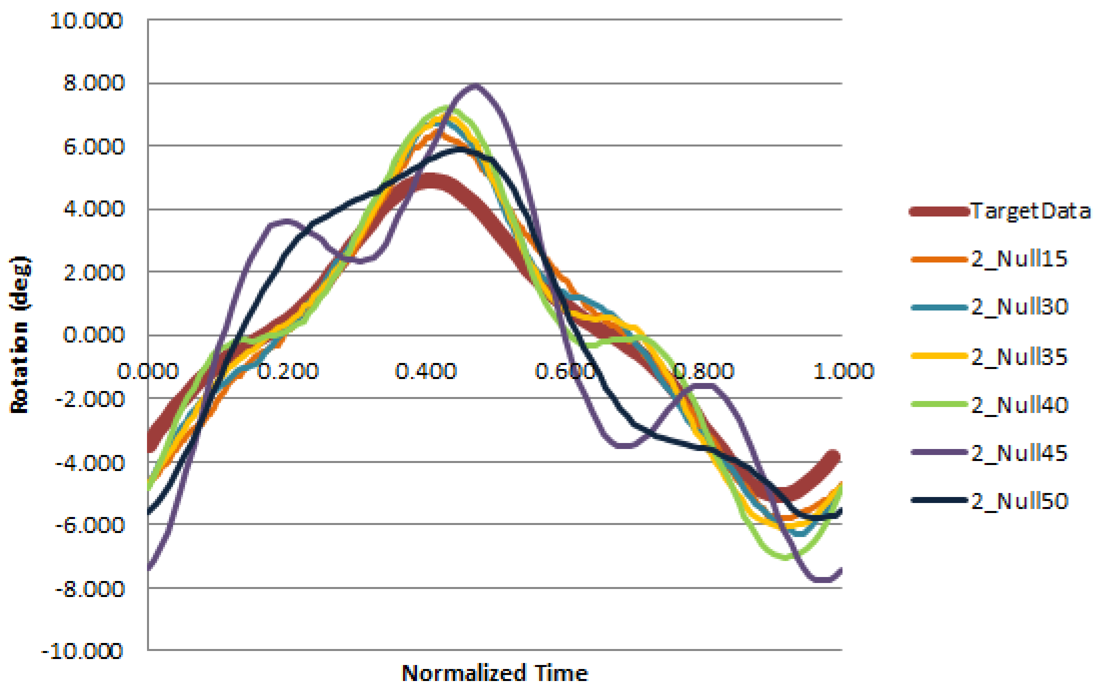



Figure C.9: Effect of Speed Conditions with Spring Stabilization (X-Rotation)

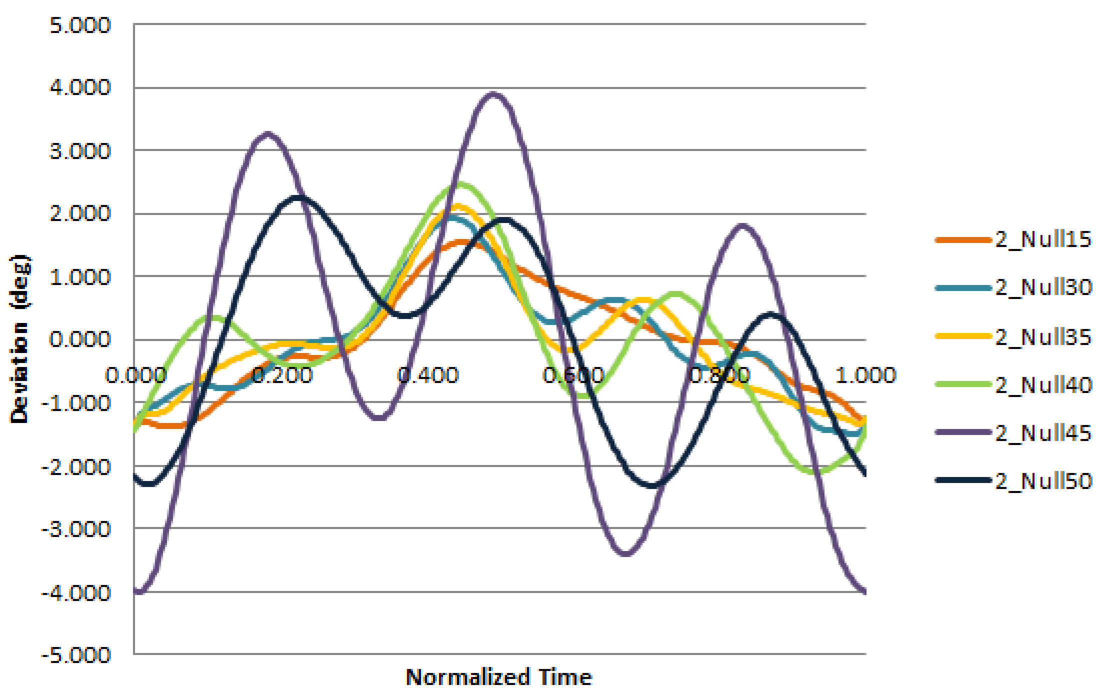



Figure C.10: Deviation from Target Data (X-Rotation)

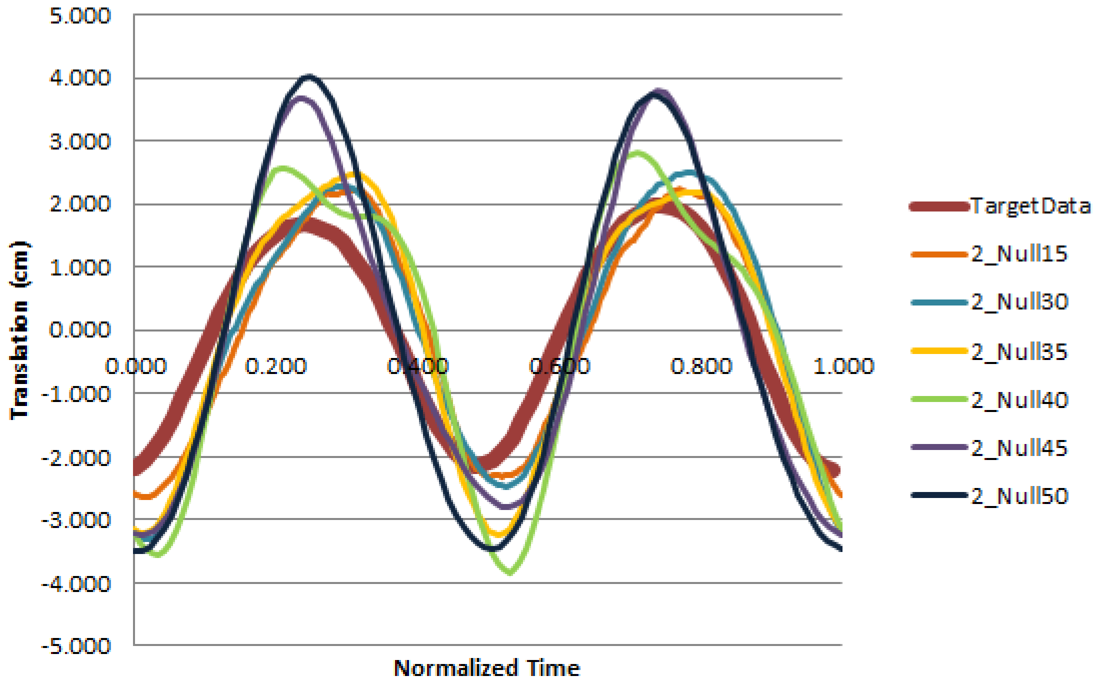



Figure C.11: Effect of Speed Conditions with Spring Stabilization (X-Translation)

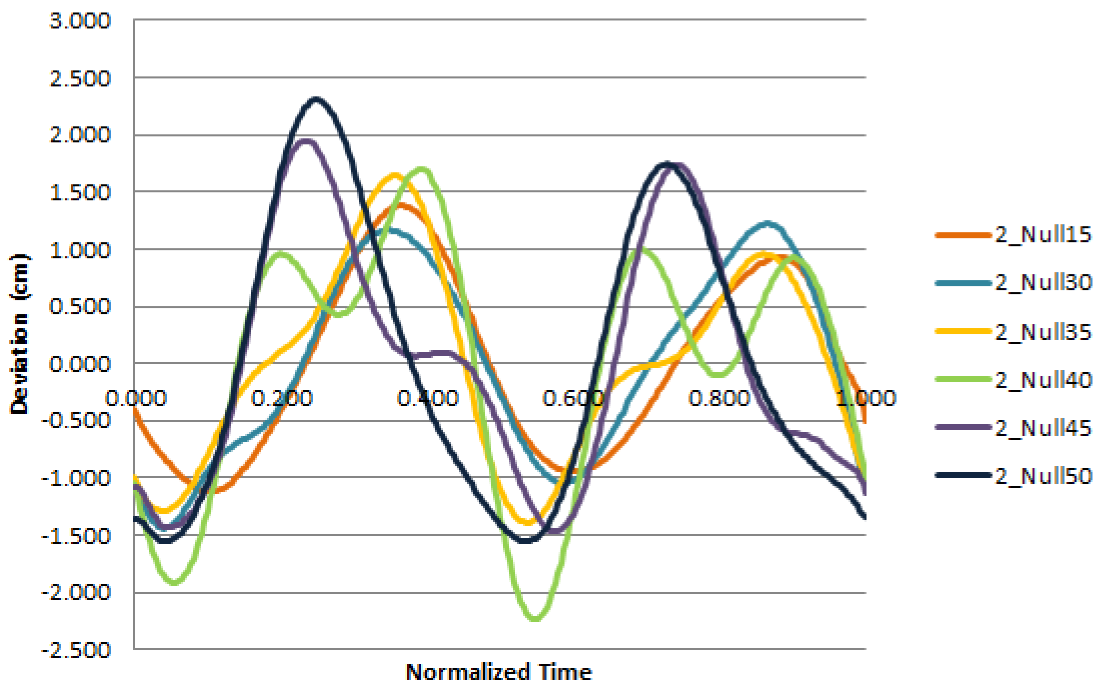



Figure C.12: Deviation from Target Data (X-Translation)

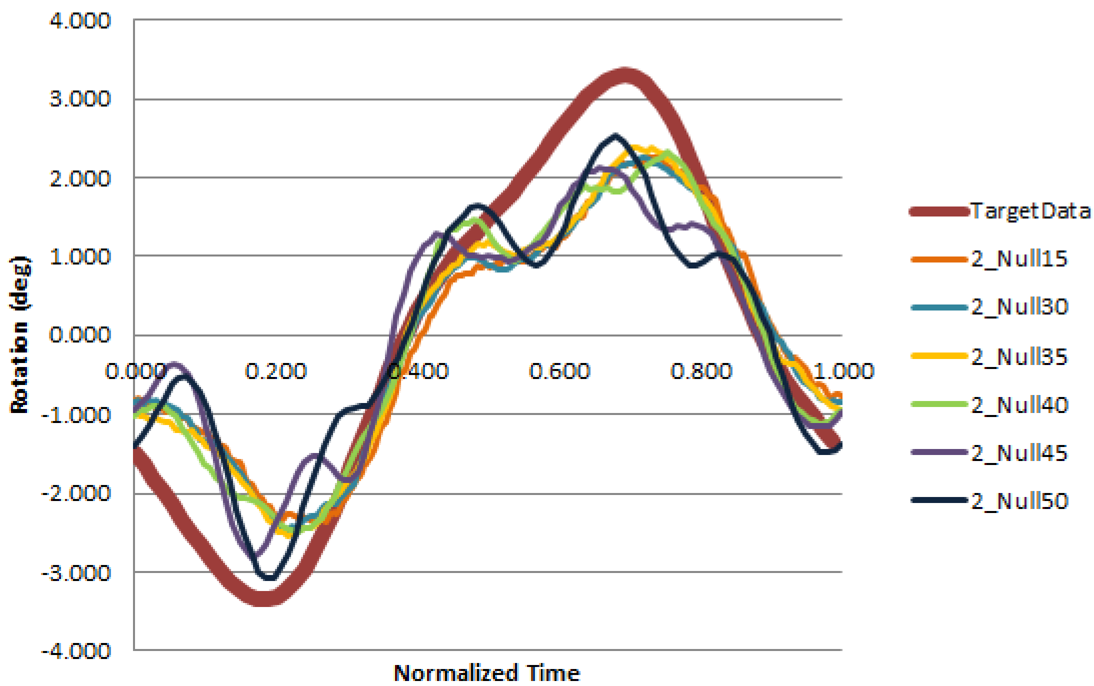



Figure C.13: Effect of Speed Conditions with Spring Stabilization (Y-Rotation)

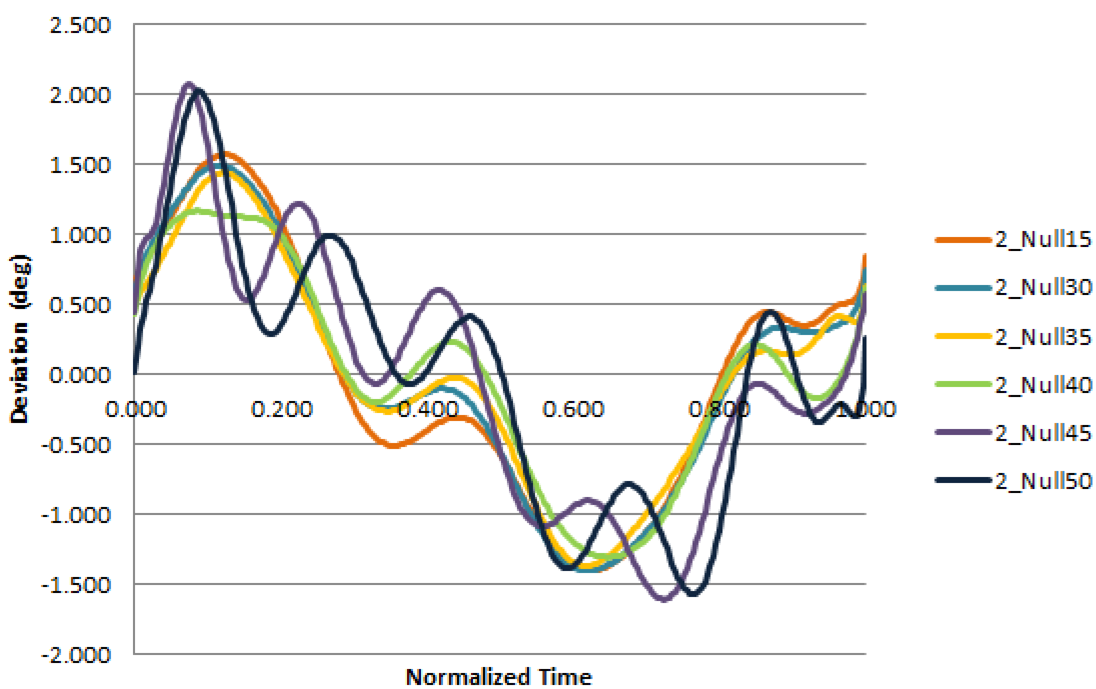



Figure C.14: Deviation from Target Data (Y-Rotation)

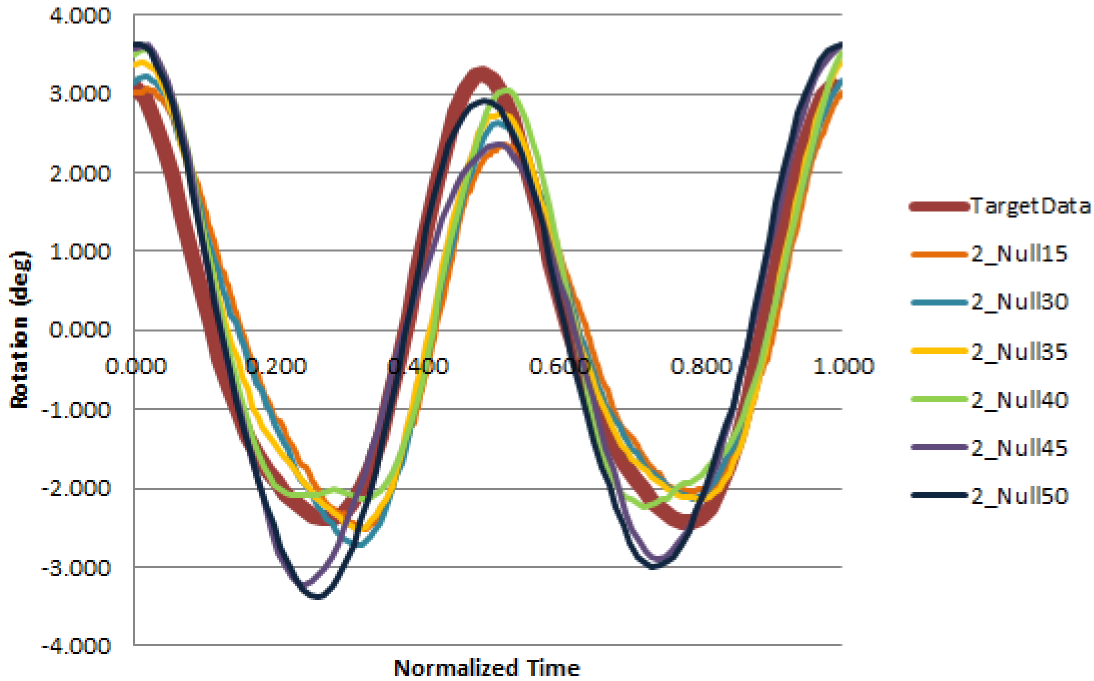



Figure C.15: Effect of Speed Conditions with Spring Stabilization (Z-Rotation)

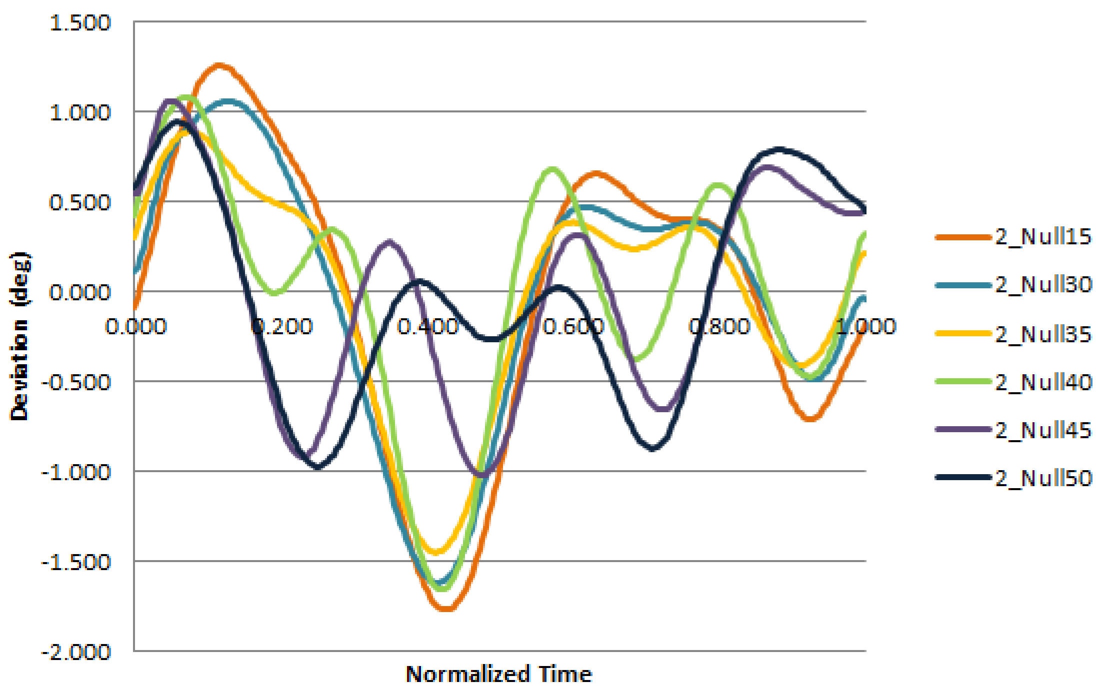



Figure C.16: Deviation from Target Data (Z-Rotation)

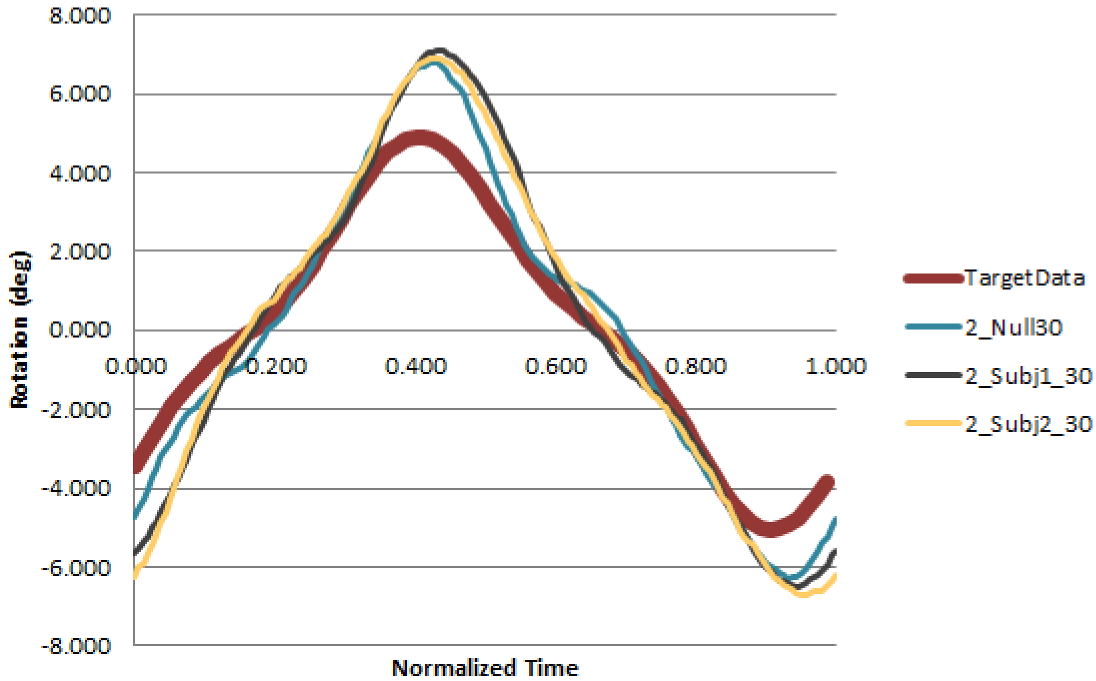



Figure C.17: Effect of Loading Conditions at Speed of 30Hz with Spring Stabilization (X-Rotation)

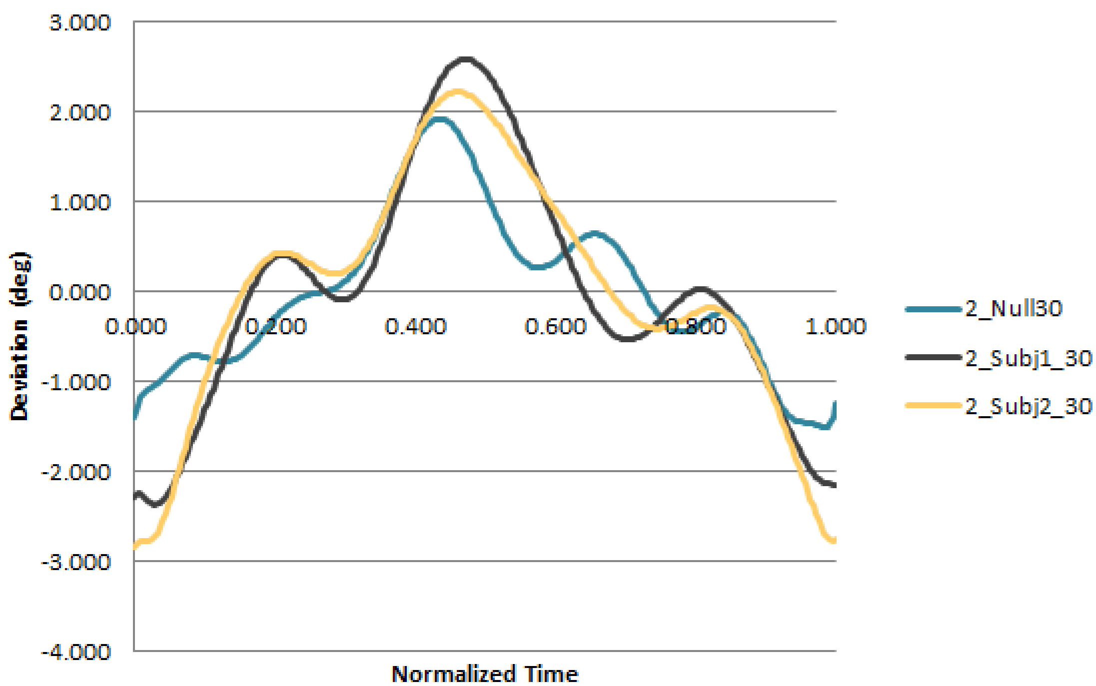



Figure C.18: Deviation from Target Data (X-Rotation)

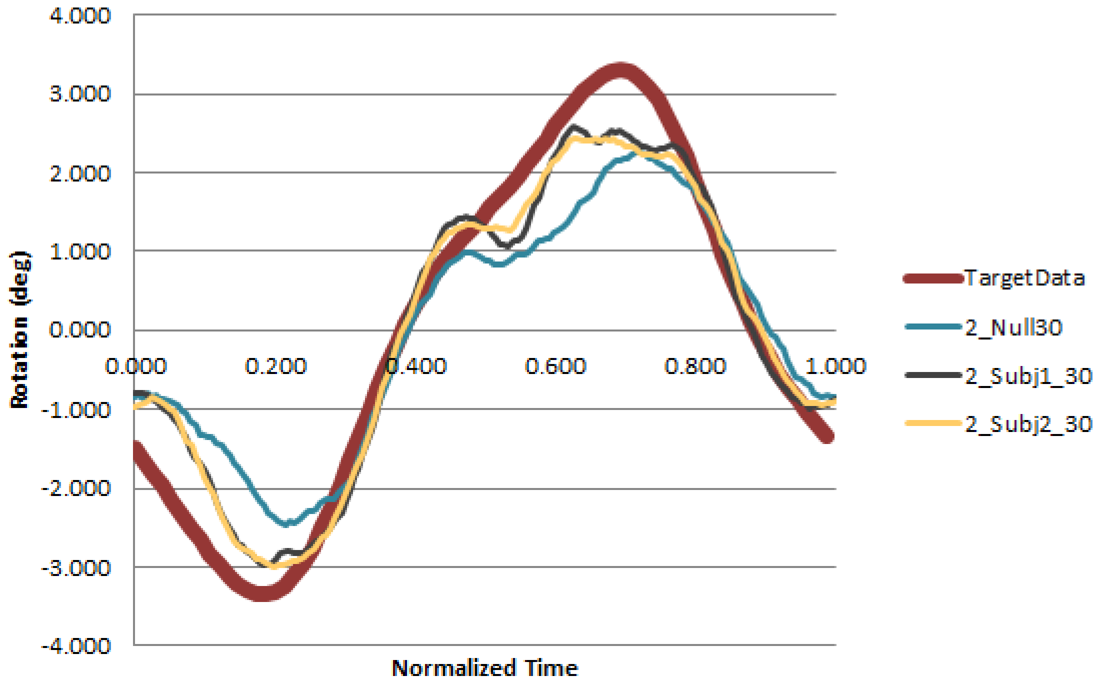



Figure C.19: Effect of Loading Conditions at Speed of 30Hz with Spring Stabilization (Y-Rotation)

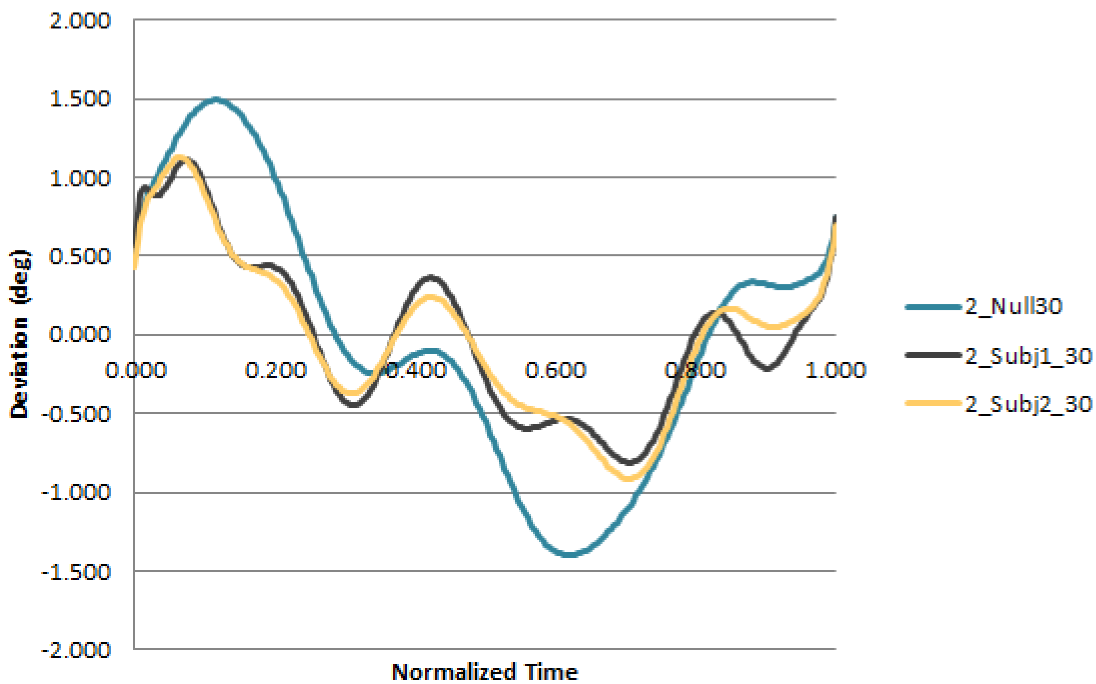



Figure C.20: Deviation from Target Data (Y-Rotation)

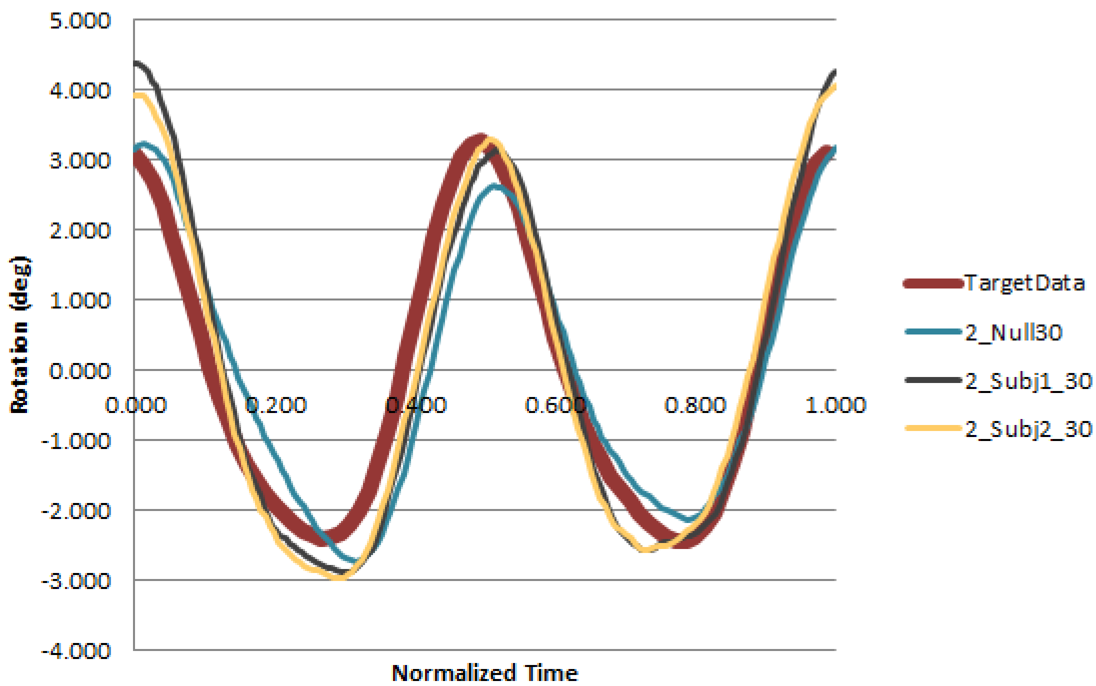



Figure C.21: Effect of Loading Conditions at Speed of 30Hz with Spring Stabilization (Z-Rotation)

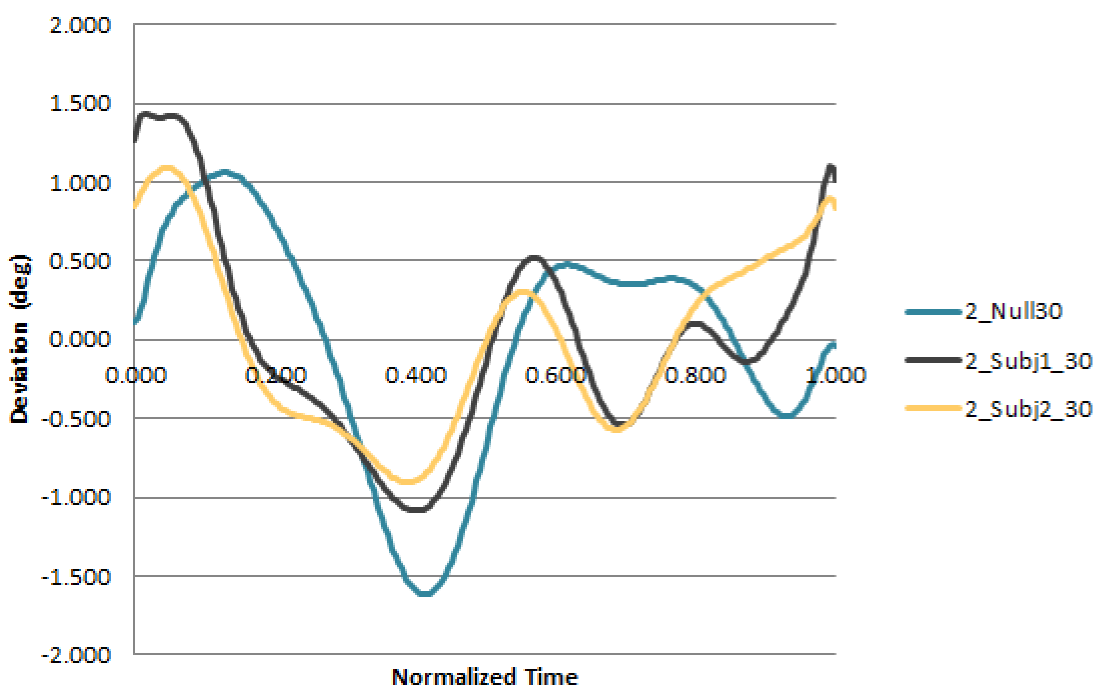



Figure C.22: Deviation from Target Data (Z-Rotation)

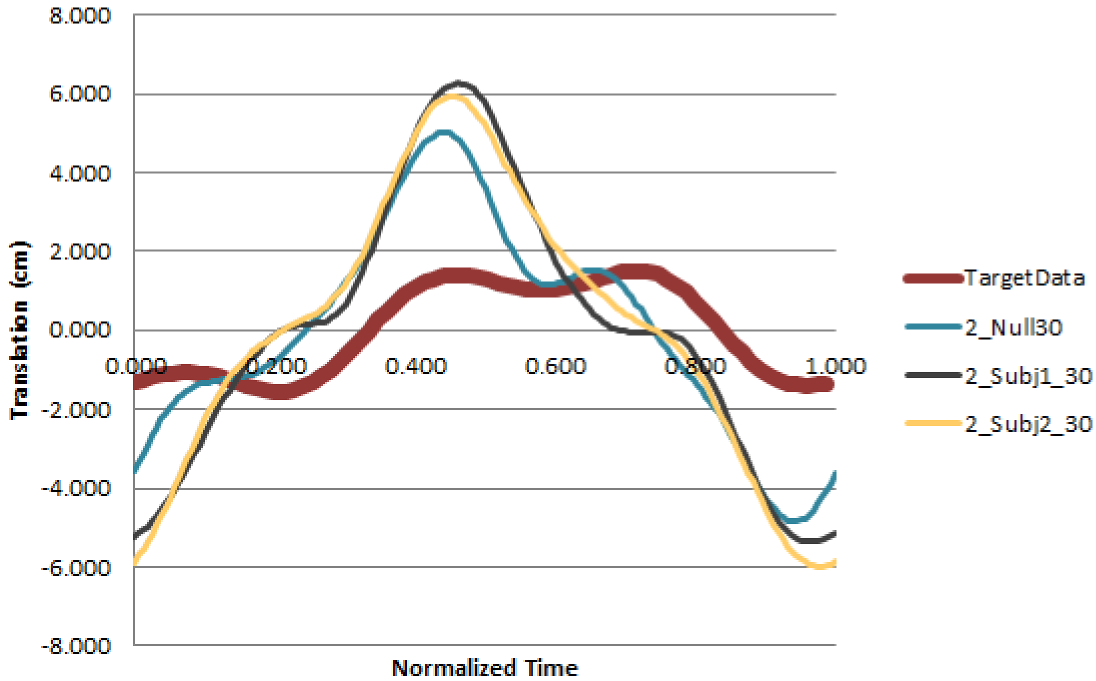



Figure C.23: Effect of Loading Conditions at Speed of 30Hz with Spring Stabilization (Z-Translation)

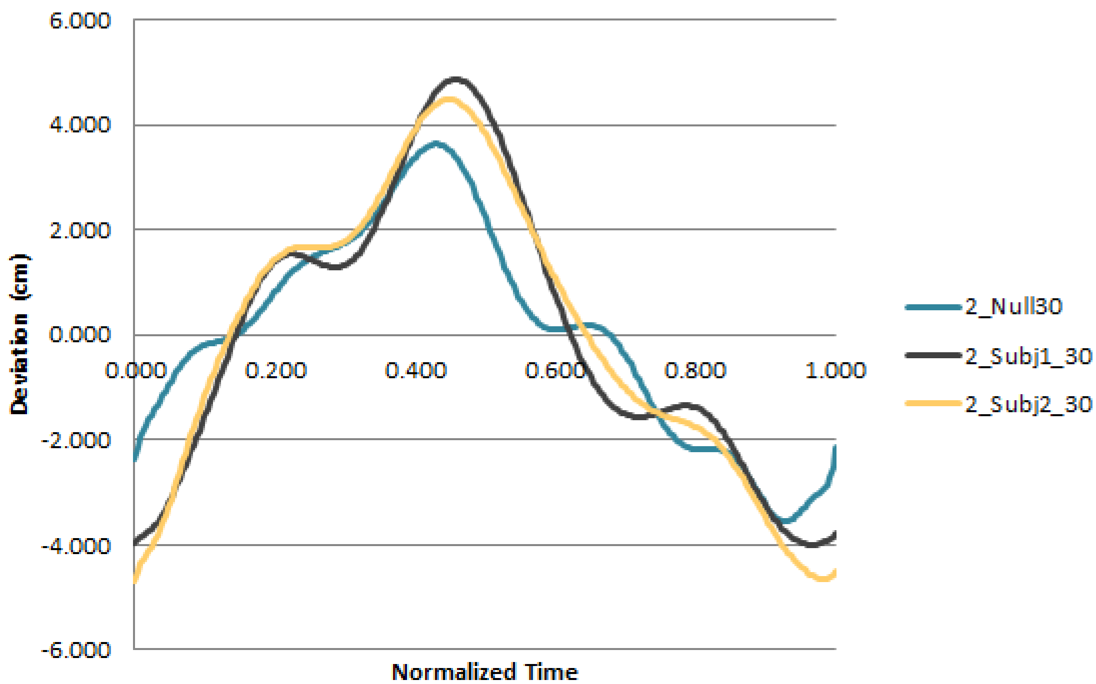



Figure C.24: Deviation from Target Data (Z-Translation)

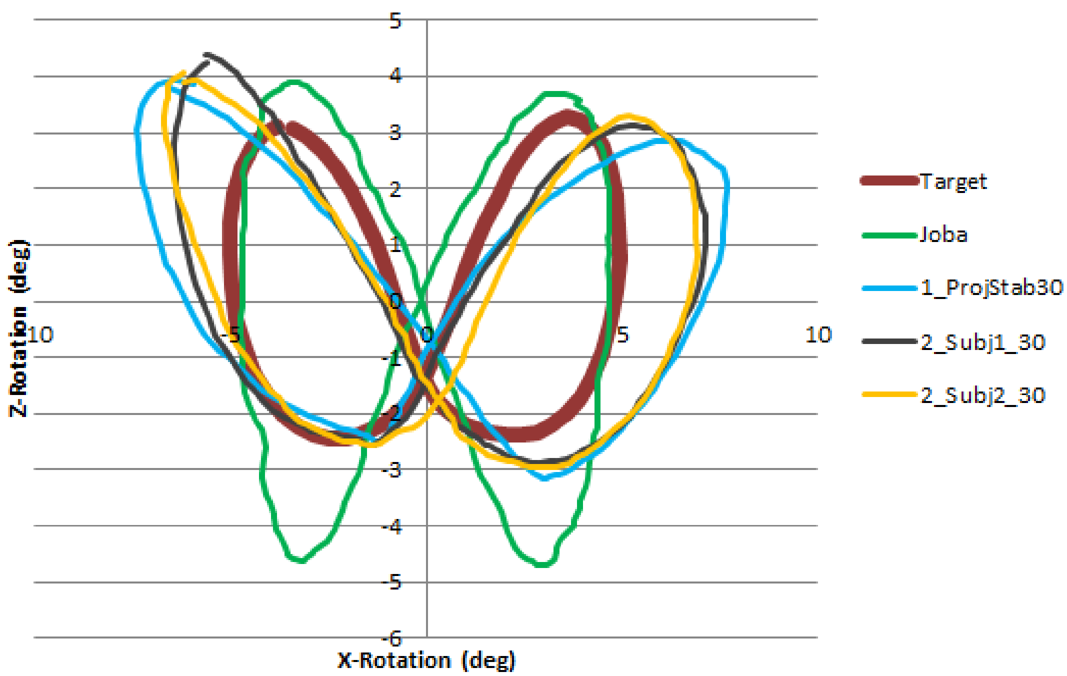



Figure C.25: Comparison of X-Z Rotation with Joba at Speed of 30 Hz with Various Spring Stabilization and Loading Conditions (Top View)

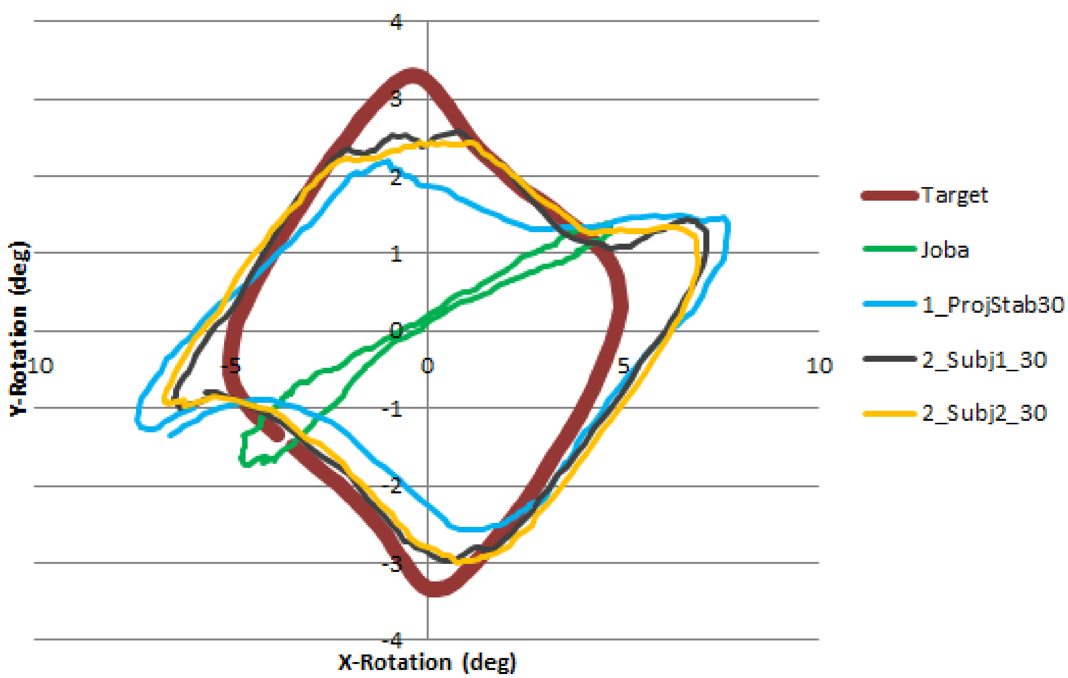



Figure C.26: Comparison of X-Y Rotation with Joba at Speed of 30 Hz with Various Spring Stabilization and Loading Conditions (Side View)

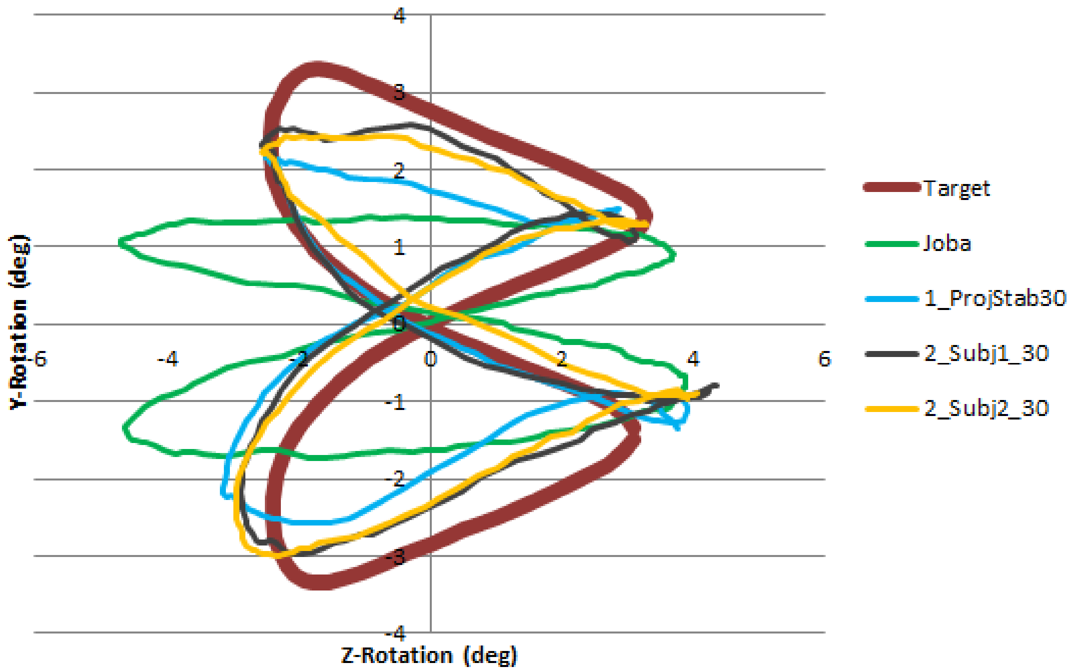



Figure C.27: Comparison of Z-Y Rotation with Joba at Speed of 30 Hz with Various Spring Stabilization and Loading Conditions (Back View)

# APPENDIX D

## Motion Graphs of Prototype #1

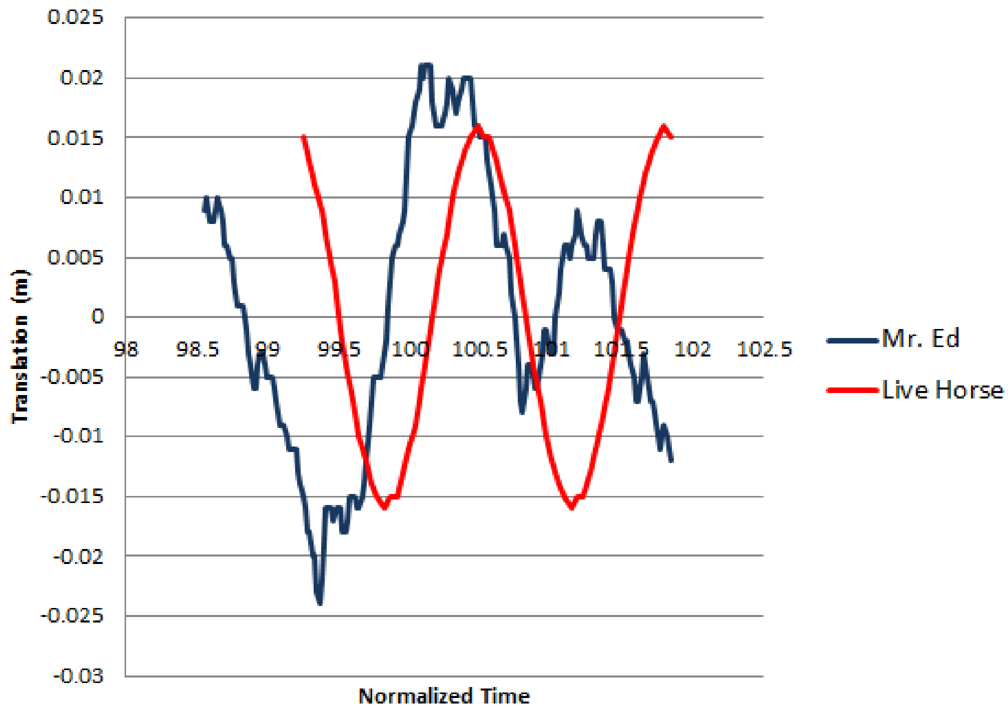



Figure D.1: Mr. Ed Prototype X-Translation

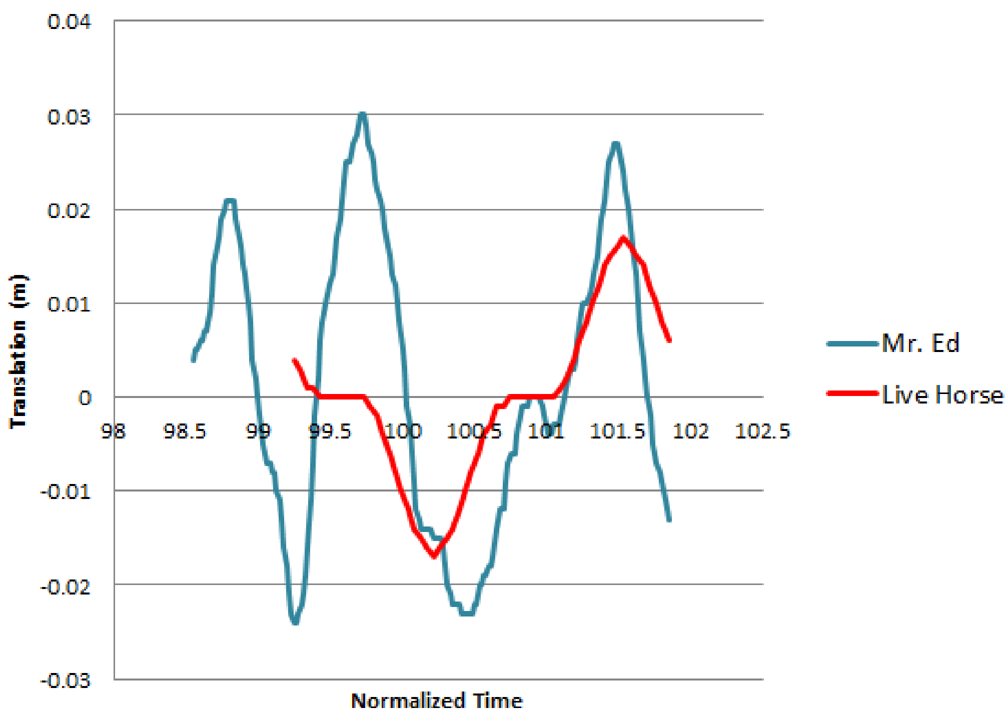



Figure D.2: Mr. Ed Prototype Z-Translation

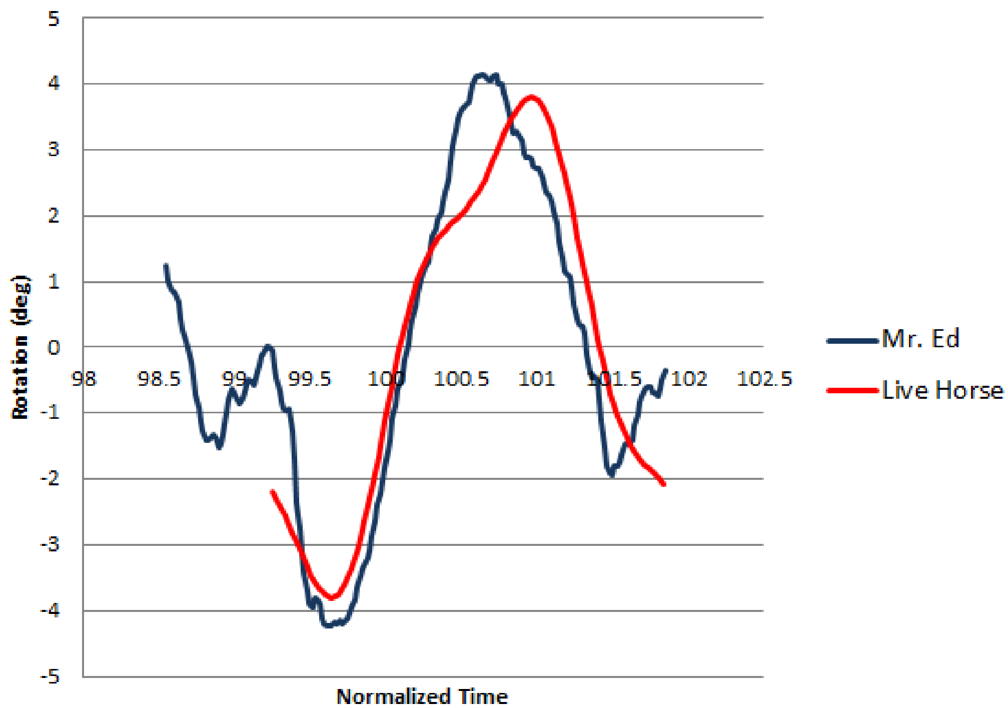



Figure D.3: Mr. Ed Prototype X-Rotation (Roll)

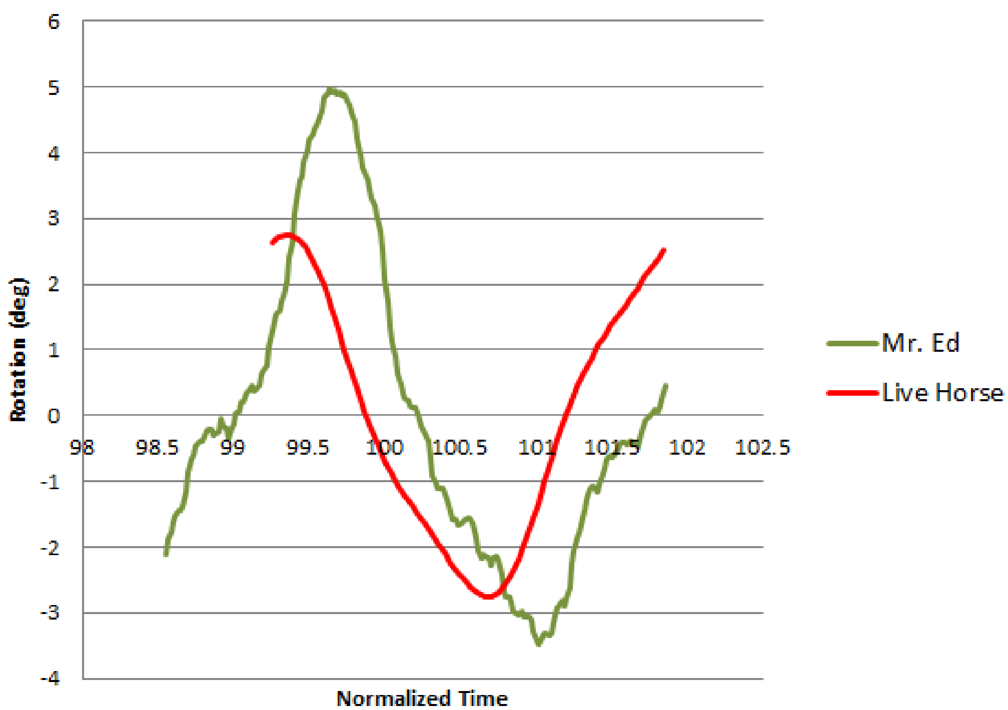



Figure D.4: Mr. Ed Prototype Y-Rotation (Yaw)

# GLOSSARY

***Calibration Object*** – a three-dimensional object of a known geometry with markers indicating the location of specific locations on the object which is used to measure a three-dimensional space, *i.e.* a three-dimensional ruler.

***Hippotherapy*** – a type of physical or occupations therapy in which a licensed therapist conducts therapy sessions on the back of a horse and during which the movement of the horse is used to benefit the patient.

***Four-Bar Mechanism*** - a type of mechanical linkage comprised of four distinct links (the crank, coupler, rocker, and base), in which the base is stationary and houses all other links, the crank is driven 360 degrees by some external perturbator, the coupler connects the crank to the rocker, and the rocker swings as far as its physical geometrical constraints will allow.

***Observation Space*** – a three-dimensional space that has been calibrated and in which motion capture studies are conducted.

***Motion Capture*** – a type of study wherein multiple cameras are arranged in such a way that they are capable of capturing video of markers used to indicate specific landmarks on the body or an object of interest that are moving through an observation space and that can be used to generate three-dimensional data for each marker, such as the coordinates of the marker in the x, y, and, z directions.

***Stewart Platform*** – a platform, commonly used in the robotics field, on which six linear actuators are mounted in a specific orientation that allows full control of all six degrees-of-freedom.

***Therapeutic Riding*** – a type of physical or occupational therapy conducted on horseback with a focus on horsemanship and riding skills.

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