Sliding Injury Protective Base Design

A Major Qualify Project Report:

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the

Degree of Bachelor of Science in Mechanical Engineering

By

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Date: September 5, 2019

Approved:

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Abstract

The goal of this project is to reduce the occurence of sliding injuries in baseball and softball. Through the literature review, it was discovered that effective countermeasures do exist, but are underused due to a variety of factors, including impracticality, cost, and effect on gameplay. Axiomatic design principles were used to generate the best solution for this problem. Through this approach, a base for softball and baseball was developed which will absorb injurious loads before they reach the player while remaining suitable for gameplay, thereby reducing sliding injuries.

1. Introduction

1.1 Objective

The objective of this project is to design an injury reducing base for use in baseball and softball.

1.2 Rationale

It has been estimated by the National Electronic Injury Surveillance system of the United States Consumer Product Safety Commission that softball and baseball combined are the number-one sports leading to emergency room visits in the United States. Additionally, it has been found that 35% to 71% of all softball-related injuries were due to sliding (Janda et al. 1986). Baseball and softball combined for 25 million participants in 2016 which make it the largest team sport in the United States (Major League Baseball, 2017). Nearly 5 million of these participants are youths playing in over a dozen baseball and softball organizations (American Academy of Pediatrics, 2012).

Sliding injuries are not unavoidable and effective countermeasures do exist. It was found that the use of breakaway bases reduce sliding injuries by a staggering 98% (Janda et al. 1992). Using these numbers, the Centers for Disease Control performed an analysis which determined that implementation of breakaway bases across the United States could prevent 1.7 million injuries per year and save $2 billion in health care costs annually (Centers for Disease Control, 1986). Furthermore, this analysis was done in 1986 using a cost per injury figure of $1,223. Average injury costs have almost certainly increased since this time due to inflation and increasing healthcare costs. For example, average charges nowadays for an adult range from $2,294 for a sprain to $7,666 for an arm fracture (Misra, 2014).

Despite their effectiveness in reducing injuries, breakaway bases are underused. In highly competitive and especially pro-level play, this is likely due to concerns that the breakaway bases will interfere with the game itself. Then presiding MLB Deputy Commissioner Steve Greenberg illustrated this sentiment well in 1992: "The last thing you need is in the seventh game of the World Series to have the deciding run slide into third base with one out and have a controversial call because the base pops out... absent some really compelling reason to change, it's not going to happen"(Steve Wulf, 2014).

Breakaway bases are only one potential sports engineering use for non-linear springs. Past MQP's have used them to design improved shoulder pads, baseball helmets, and acl injury reducing shoes.

1.3 State-of-the-Art

Baseball is played on a baseball diamond where four bases, first, second, third, and home, are laid out in a square. Home plate is placed such that it is flush with the playing surface while the other three bases are typically raised 3-5 inches off the ground (Major League Baseball, 2018). These three bases are 15 inches square and made out of canvas or soft rubber. The bases are typically anchored to the ground through a square metal stake attached to the base set into concrete. The bases are easily removable but rigid while in place.

There currently exists some injury reducing base designs. The most popular of these is the Rogers Break-Away. All of the bases work by releasing from the ground or otherwise moving out of the way of the player once a certain injury threshold has been reached.

1.3.1 Mechanism and Definition of Injury

Sliding in baseball and softball can result in a wide array of injuries. This is because sliding can be done with a head-first or feet-first technique, essentially opening up the entire body to injury. The majority of slides are of the feet-first variety. Another technique is the Dive Back where a base runner dives back to the base head first to avoid being thrown out. This is much less dangerous as the base runner does not have a running start.

Sport	Number of games	Head-first slides		Feet-first slides		Dive-back slides		Total slides	Per-game average
		Total	Per-game average	Total	Per-game average	Total	Per-game average		
Baseball	215	283	1.32	684	3.18	696	3.24	1663	7.73
Softball	422	565	1.34	1394	3.30	267	0.64	2226	5.27
Total	637	848	1.33	2078	3.26	963	1.50	3889	6.11

Figure 1.1: Sliding Rates Per Game for Baseball and Softball (Hosey and Puffer, 2000)

A field investigation by Hosey and Puffer found that 70% of slides in baseball and 71% in softball were feet first. The remainder were head first. They also found a surprisingly low proportion of lower extremity injuries compared to the distribution of slides. Only 16% of injuries were ankle sprains. The most common injuries were contusions at 30%, followed by ankle sprains, and lacerations next at 14% (Fig. 1.2). Overall, they found that 54% of injuries were to the upper extremities and head region, while the remaining 46% were to the lower extremities. This is similar to the results found in another study, which found that 58% of sliding injuries were to the foot, ankle, and tibia/fibula (Janda et al. 2001). However, Hosey and Puffer also found that the average participation time lost due to feet-first injuries was 3.16 days compared with 0.67 days for head-first injuries which would suggest that feet-first slides could result in worse injuries. So, generally speaking, head first slides appear to result in more injuries but feet first slides are more common, can result in more severe injuries, and can be considered the more costly technique to teams and players.

Base	Slide type			Total	Injuries
	Head-first	Diveback	Feet-first		
					Baseball
First	0 (0)	3 (622)	0 (6)	3 (628)	Hand laceration, shoulder subluxation, forearm contusion
Second	1 (197)	0 (61)	3 (476)	4 (734)	Finger laceration, triangular fibrocartilage complex sprain, thigh contusion, Achilles tendon strain
Third	0 (58)	1 (13)	0 (114)	1 (185)	Finger laceration
Home plate	0 (28)	0 (0)	2 (88)	2 (116)	Ankle sprain, shoulder dislocation
					Softball
First	0 (23)	2 (170)	1 (13)	3 (206)	Metacarpal fracture, elbow contusion, ankle sprain
Second	7 (319)	0 (64)	7 (831)	14 (1214)	Contusion (5), laceration (2), ankle sprain (2), concussion, shoulder subluxation, metacarpal phalangeal dislocation, proximal interphalangeal joint sprain, quadriceps strain
Third	3 (150)	0 (33)	3 (293)	6 (476)	Ulnar collateral ligament of the thumb sprain (2), pectoralis strain, ankle sprain, patellar contusion, shoulder dislocation
Home plate	1 (73)	0 (0)	3 (257)	4 (330)	Contusion (2), neck sprain, ankle sprain

Figure 1.2: Number of Injuries Categorized by Base, Slide Type, and Sport (Hosey and Puffer, 2000)

1.3.2 Breakaway Base Mechanisms of Action

There are a number of different breakaway base designs. These bases use a variety of different mechanisms to accomplish one similar goal; for the base to dislodge from the ground once a certain force threshold deemed dangerous has been reached during a slide. This will free the base for lateral movement and should reduce forces on the player in dangerous situations. All common breakaway bases work on this principle.

Three popular designs are the Rogers Break-Away Base, the Stay Down base, and the Magnetic Base. Each uses a unique mechanism to achieve the breakaway action. The Rogers base is the most popular and its composition is shown below.

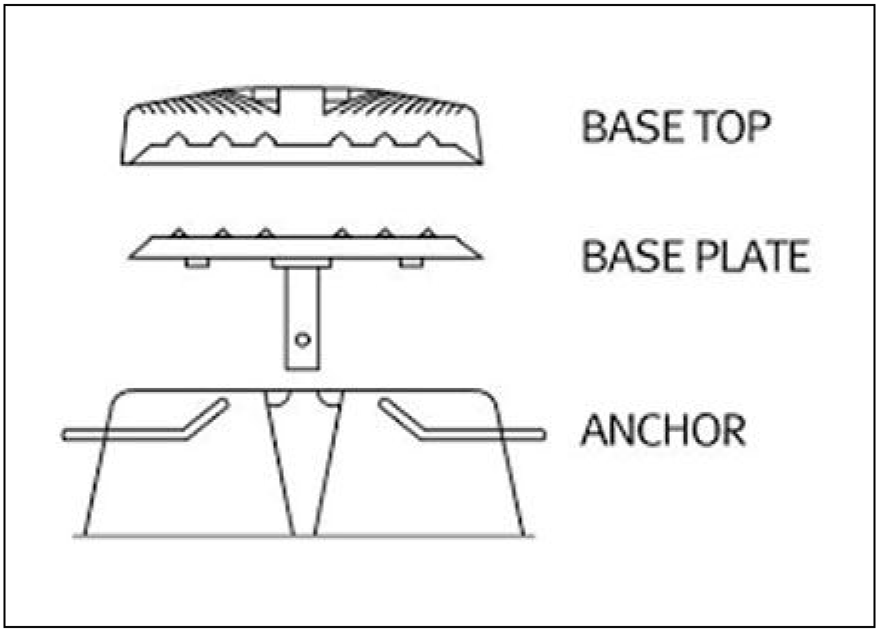


Figure 1.3: Rogers Break-Away Base composition

This base is made of three main components; the base top, the base plate, and the anchor. The base top is anchored by receiving holes fitting into grommets on the base plate which is flush with the infield surface. If sufficient force is applied to the base from the runner, the base top will totally disconnect from the base plate and anchor. The base then has to be manually reset after the play. The whole assembly is anchored to the ground through a metal stake sunk into the same receiving hole as a typical baseball base, meaning that the base is easily interchangeable with others.

Each level of play necessitates a different activation force as the players size and strength varies greatly. This is achieved by altering the number of grommets on the base plate and the stiffness of the base top. This strategy results in four different models of the Rogers base; Youth, Teen, Adult, and Pro.

Another popular design is the Stay Down base show below (Fig 1.4). This base uses a similar design principle to the Rogers base except that it can partially flex before breakaway as well. Once a particular activation force is reached, the base completely unhinges from the T shaped anchor. The anchor is aligned such that the top part of the T is perpendicular to the base path and that the bottom part is aligned with the base path.

The activation force of the base is not adjustable and there is only one model commercially available meant for youth play. The base can also be placed in any field as it does not require the concrete moorings of normal baseball bases.

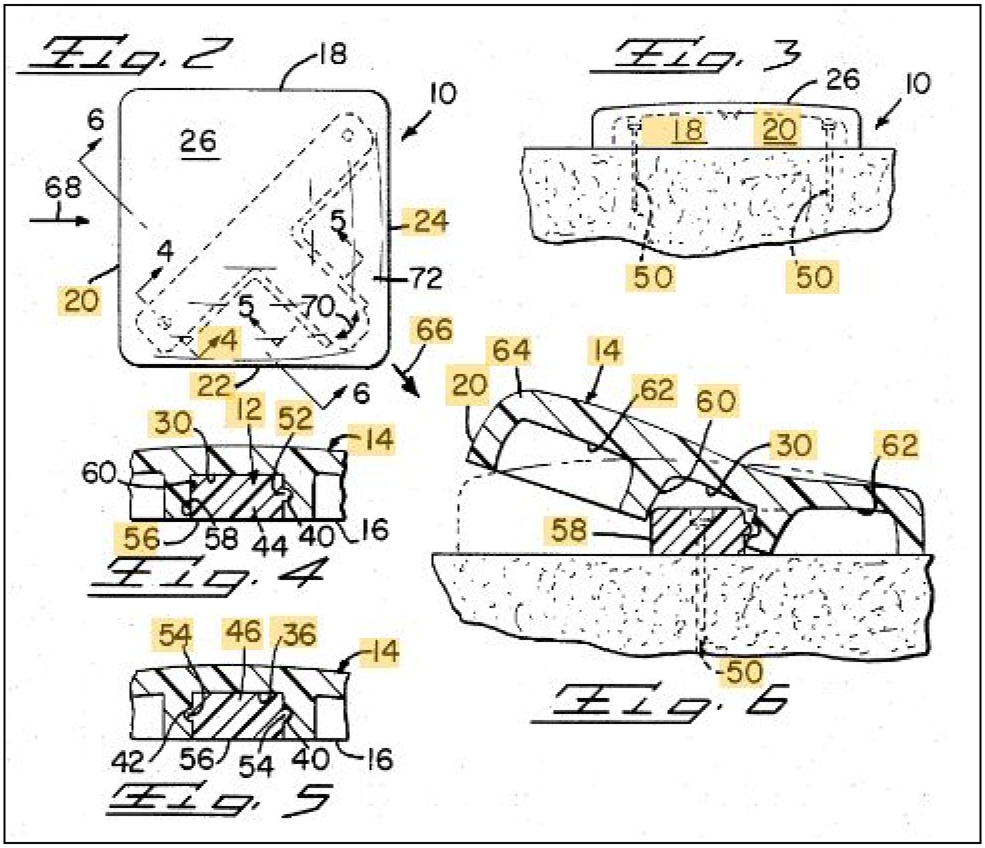


Figure 1.4: Stay Down Base Patent Diagram

1.3.3 Effectiveness of Existing Breakaway Bases

A 1986 study by Janda et al. explored preventative measures with regards to sliding injuries. The researchers found multiple measures to be ineffective, including instructional courses, a no-sliding rule, and recessed bases. Finally, all bases at a number of baseball fields were replaced with breakaway bases. During 1,035 recreational softball games played with the breakaway bases, 2 ankle sprains were the only injuries resulting from sliding. The researchers determined this to be an impressive 98% reduction in sliding based injuries.

In a follow-up 1992 study, the researchers experimented with breakaway bases in high-level play. 19 baseball teams in the National Collegiate Athletic Association (NCAA) and professional minor league baseball agreed to use the bases. 492 games were played with standard bases and 486 games were played with the Rogers Break-Away Base. In the games played with breakaway bases, 2,028 slides were recorded and the base released 54 times, which constitutes 3% of slides. Only 2 injuries, a shoulder contusion and an ankle fracture, were recorded in these games compared to 10 in the static base games. This represents an 80% reduction in injuries in the high-performance population (Janda et al, 1993).

Table 1. *Sliding related injuries*

Types of injury	Number of injuries involving stat. bases	Number of injuries involving B-A bases
Ankle sprains	7	
Ankle fracture		1*
Knee MCL sprain	1	
Knee meniscal tear	2	
Shoulder contusion		1
TOTAL	10	2

* Player never reached base.

Figure 1.5: Sliding Related Injuries in a 1992 Study

A later study in 2001 by Janda et al. investigated seven breakaway bases and compared them to the standard bases. These bases were the four models of the Rogers Breakaway (Youth, Teen, Adult, and Pro), a large and a small MegNet (magnetic) base, and the Stay Down base. The researchers used a horizontal impact machine in conjunction with the bases and a crash test dummy used in the automotive industry. The crash test dummy could be shot down the 16 foot track of the horizontal impact machine into the bases. Additionally, the velocity could be regulated to closely match those experienced in professional baseball play. Finally, the leg was instrumented with load cells, accelerometers, and linear transducers. The forces in the foot (Fx), in the ankle (Fy), and in the tibia/fibula (Fz) could all be measured. The amount of inversion or eversion (Mx), plantarflexion or dorsiflexion (My), and the moments involved could also be found.

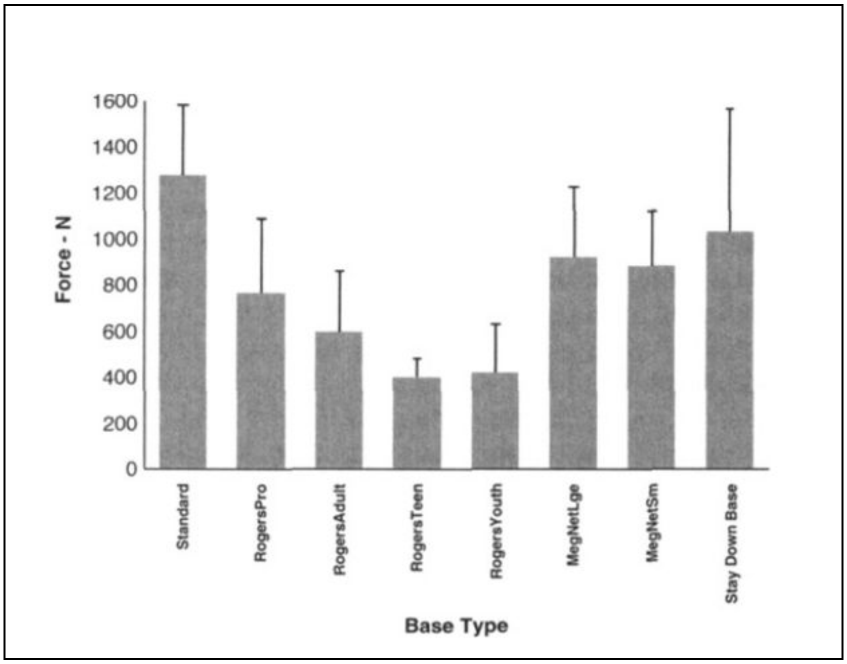


Figure 1.6: Average Forces Generated in the Fx (force in foot) Direction with Given Impacts

It was found that each model of the Rogers Break-Away Base was the most effective by almost every measurement. In the force in foot measurement, the Rogers base was the only one which reduced forces by a statistically significant amount (Fig 1.6). In fact, the forces experienced by the tibia/fibula actually increased in the large MegNet base and the Stay Down Base. On the other hand however, all bases reduced the Fy, Mx, and My.

These results can be interpreted to support the claim that the reduction of loads present in the foot, ankle, and tibia/fibula are the primary mechanism of action in breakaway bases. That is to say that injuries are primarily reduced by reducing the loads on the player. These loads are dissipated into the base, the ground, and lost to friction.

1.4 Approach

Current breakaway baseball base designs are effective. Field studies have shown injury reduction numbers ranging from 80% to 98% and the CDC has determined an annual healthcare cost savings of $2 billion if the bases were implemented across the United States. Despite these promising numbers, breakaway bases are still rarely used in recreational or professional baseball and softball. This is most likely due to two factors; cost and the potential impacts to the game. A Rogers Break-Away Base Set costs $465 while typical pro bases cost $180. The difference is even more pronounced in Little League where a $30 set of Throw-Down bases would commonly be used. All current popular breakaway bases fully dislocate from the ground in an injury situation. This has lead to concerns about the effect of the bases on gameplay and the rule changes which may be required to compensate for the new base design.

To solve these problems and increase breakaway base implementation, a base should be developed which can reduce sliding injuries without completely dislocating from the ground. This base would instead displace laterally and then automatically return after impact. The base also should not displace during normal play, only during a high risk injury situation. In this way, the base functions practically without being noticed by the players or umpires. It is important that the base design has as little impact on the game as possible to maximize its utilization. The base should also be as economical as possible and interchangeable with typical base moorings.

For this solution, a specific load-absorbing device must be developed and implemented into the base. One possibility is a spring with a specific force-displacement curve which can absorb the loads in an injury situation. In this example, the spring must not displace until an injurious threshold is reached so as to ensure that the base will not move during normal play. The specifics of this threshold must also be determined based on the loads that cause injury. Then, the spring has to displace with near-constant force to a large enough distance to effectively reduce the probability of injury. Finally, the spring must undergo only elastic deformation during this process to ensure a suitable return.

This load-absorbing device will be designed based on two principle equations which can be applied to impact force reduction.

$$(1)\ v^2 = 2as$$

$$(2)\ F\Delta t = m\Delta v$$

v	Velocity of the player sliding into base
a	Acceleration the player will undergo during impact
s	Displacement distance of the base
F	Maximum force experienced by the player during impact
t	Elapsed time during the impact
m	Mass of the player

The velocity and mass of the player is fixed while the acceleration and maximum force are dependant variables. This leaves two independent variables, distance and time, which can be tweaked to minimize the magnitude of the impact.

2. Methods

2.1 Axiomatic Design

Axiomatic Design is a design methodology used in this project which was developed by Nam Suh during his work at MIT in the 1970's. The goal of any design method is to provide a set of procedures which will result in a desirable end product. Axiomatic Design is one of these design methods and gets its name from the two design axioms which guide the decision making process. The two axioms are:

1. The Independence Axiom: Maximize Independence of the Functional Elements.
2. The Information Axiom: Minimize the Information Content of the Design.

These axioms sequentially result in Customer Needs (CN's), Functional Requirements (FR's), Design Parameters (DP's), Constraints (CON's) and finally Process Variables (PV's). Axiomatic Design ultimately reduces complexity, removes non-productive iterations, provides metrics for progress and quality, results in better, faster, and cheaper solutions, and can be used to look at the design solutions in the conceptual stage.

2.1.1 Axiom One: Maximize Independence of the Functional Elements

The first axiom states that the design should maximize the independence of the functional elements. The goal of this axiom is to decouple each aspect of the design so that they can be individually manipulated. In this way, a specific DP, which is a physical property of the design, can be manipulated to satisfy the corresponding functional requirements without affecting other functions. By reducing the dependence of the functional elements, the number of prototype iterations and steps to a final product are minimized.

2.1.2 Axiom Two: Minimize the Information Content

The second axiom states that the design should have minimum information content. The information content describes the complexity of the design and should be kept at a minimum to maximize the probability of a products success. If multiple designs satisfy axiom one, then axiom two is used to determine the best one.

2.1.3 Functional Matrix: Decomposition and Constraints

The overall design will eventually be decomposed into FRs and DPs in a functional decomposition. This is the bread and butter of the design. Functional requirements are the functions of the design which exist in abstraction. The design parameters are the real and physical means which achieve the functions. The FRs and DPs are developed within a set of rules and together they define nearly the entire design. The development process begins with the customer needs.

The primary CN for this project is to reduce injuries to the lower extremities during sliding in baseball and softball. Of course, this comes with some important caveats. Sliding injuries could easily be avoided by foregoing sliding altogether. This would not be a suitable solution however, due to the fact that the CN is secondary to the need to play baseball. Therefore, another CN can be added.

The secondary CN is for a base which is acceptable to use under the rules of high level play. This CN has obviously been achieved many times by typical bases, but never in conjunction with the first CN. Pairing these CNs into one design is the primary objective of this project. The functional requirements will eventually come from the CNs and from research.

Other CNs exist as well which help to characterize what exactly makes a good base. Given that base designs have not drastically changed in the last 100 years (source?), it can be assumed that current base designs are satisfactory. These are characterized by a rigid connection to the ground, durability, interchangeability, ease of installation, grippy surface which is suitable to stand on, and more.

Next, the constraints were developed. The constraints act as a set of boundaries constraining the design. Each constraint represents a hard barrier which the design cannot breach if it is to be deemed successful. They help to eliminate non-productive designs. Eventually, the design decomposition will have to fit within the constraints. They were chosen based off of MLB rules and to maximize practicality. Successful breakaway base designs already exist, although they see little use in high level play due to disruptions to gameplay.

Constraints	**Justification**
Must satisfy proper baseball base dimensions and rules: 15 in x 15 in x 3-5 in	The base has to be acceptable to use at all levels of play. MLB rule 2.03 states that: "*First, second and third bases shall be marked by white canvas or rubber-covered bags, securely attached to the ground... The bags shall be 15 inches square, not less than three nor more than five inches thick, and filled with*

	soft material." (MLB, 2018) The base will be designed to match these requirements although it is likely that other rule changes will have to take place for any base which moves to be acceptable to use.
Must be easily interchangeable with normal baseball bases.	The base must be similar enough to other base designs that it has the same anchoring system. Most baseball and softball bases are anchored to the ground through a 2'' x 2''x 5'' metal spike sunk into the infield dirt. This way, the bases can be easily replaced and gameplay will not be substantially different than with other designs.
All components of the base must not undergo plastic deformation to ensure a long lifetime.	The load-absorbing component of the base must be reusable. The base would be unacceptable under the rules if any components had to be replaced or reset after a slide. Plastic deformation in any of the load-absorbing components would likely necessitate frequent replacement. Elimination of plastic deformation will also help increase the lifetime of the base.
The injury reducing mechanism must not alter normal gameplay.	Current breakaway base designs have a severe impact on gameplay; the majority of designs require the base to be manually reset on the field after release. This factor has severely limited the use of injury reducing bases, especially in high level play.
Must be affordable, not significantly more expensive than typical baseball bases	A typical set of anchored baseball bases costs ~$250. It would be unacceptable if an expensive, nonetheless effective, load-absorbing system is implemented into the base. The solution must be simple and practical enough that the base does not see a drastic price increase.

Table 2.1: Constraints and Justifications

Now that the constraints are defined, the FR's and DP's can be developed in a design decomposition. They are developed in a zigzagging fashion beginning with FR0. FR0 defines the direction of the entire design. It is accomplished with DP0. Additional FRs are developed by level with all of the children summing up to the parent. The children describe the function in increasing complexity according to CEME min until the parent is completely exhausted. The children of an FR must be collectively exhaustive (CE), mutually exclusive (ME), and be minimal in number (min). CE means that the children must totally describe the function. ME means that the children must remain independent from one another. Finally, this all must be done with the fewest number of FRs.

The creation of the decomposition was a highly iterative process which helped to explore which designs were possible. FR0 changed many times throughout this process. Eventually it was decided that the design will be directed towards controlling the loads to as high a degree as possible while remaining within the constraints.

The decomposition development took 7 iterations to result in the preliminary design decomposition (Fig. 2.1). The functions of the base can now be explored in more depth. Note that the DP's are still relatively abstract in this phase, as no specific design has been chosen.

#	[FR] Functional Requirements	[DP] Design Parameters
0	Control loads transferred to player during sliding impact	Load-controlling system
1	Function as a typical base under injury threshold	Champion Hollywood Pro Anchored Base housing
2	Absorb loads above Injury threshold while being acceptable to use	Load-absorption device
2.1	Displace laterally with the players motion and provide constant force	Load-absorption device provides constant force
2.2	Self-return to initial position after movement	Return system

Figure 2.1: Preliminary Axiomatic Design Decomposition

2.1.4 Preliminary FRs and DPs

Here, the preliminary FRs and DPs will be discussed along with their justifications and some other considerations in their development.

FR 0: Control loads transferred to the player during impact

FR0 is the highest level FR which the rest of the decomposition will be trying to achieve. Ultimately, the bases goal is to control the loads transferred to the player throughout the game. It is not desirable to reduce all loads as a baseball base is typically expected to be immobile and rigid. Ideally, loads would never exceed normal playing levels and the base would function just like a typical base all of the time. However, this is not the case. Once loads exceed a certain injurious threshold, they should be absorbed by the base which will consequently reduce injury risk and satisfy the CNs. Of course, this all must be done within the constraints.

DP 0: Load-controlling system

DP0 is the physical component which satisfies FR0. There must be a physical system in place in the base to achieve the FR of controlling the loads transferred to the player.

FR 1: Function as a typical base under the injury threshold

The base has to accomplish its job as a baseball base first and foremost to fit within the constraints. The need for injury reduction comes secondary to the need for a functioning baseball base. A typical baseball base is 15 inches square and between 3-5 inches in height off the playing surface. It is covered in white rubber and rigidly connected to the ground. The typical base has no active load-absorption system so most loads are transferred directly to the player. There is a small amount of load-mitigation provided by the soft rubber exterior layer of the base. These are the characteristics which describe how the base will function in ordinary playing conditions.

DP 1: Champion Hollywood Pro Anchored Base housing

The load-absorption system will be housed inside of a Champion M500 Hollywood style base. The base will provide most of the functions required of a typical baseball base, including the dimensions, the anchor to the ground, and the rubber surface for collisions and to stand on.

FR 2: Absorb loads above injury threshold while being acceptable to use

Ideally, the only loads which the base will absorb are those which would otherwise cause injury to the player sliding. In theory, this would eliminate all injuries. Of course, this is unrealistic due to the unpredictable nature of sports injuries. It would be nearly impossible to determine whether a given load on the base will result in an injury to the player or not.

There are many factors which play into whether or not a particular load will cause injury. First of all, there is a wide variety of injury types and locations. In feet-first sliding, the most frequent injuries are to the ankle (23.8%), knee (17.1%), upper/lower legs (13.9%), and wrist (12.3%) (Table 2.2). Each of these areas have different thresholds and mechanisms for injury. Ankle sprains alone, the most common injury, have staggering complexity. The talocrural joint in the ankle has several main ligaments, namely the anterior talofibular ligament (ATFL), the calcaneofibular ligament (CFL) and the posterior talofibular ligament (PTFL). The ATFL is the most commonly injured ligament in an ankle sprain. It is the weakest of the ligaments with an ultimate load of 138.9N and is most often injured when the foot is in plantarflexion (Fong et al. 2009). Meanwhile, the CFL is most often injured when the foot is in dorsiflexion and exhibits three times the ultimate load of the ATFL at 345.7N. These ligaments control complicated foot movement and respond to forces on the foot in different ways. The load present in the base will not be equivalent to the loads present in ankle ligaments and other areas. The load on the base relates to the load in a players joints through a complex biomechanical relationship depending on the players orientation. The difficulties involved in preventing specific injuries make it an unreasonable prospect.

Ranking of the Most Common Body Regions Injured and Diagnoses Rendered

	Injuries		Days Missed		Head-First Slide		Feet-First Slide	
	No. (%)	Rank	Mean	Median	No. (%)	Rank	No. (%)	Rank
Body region								
Hand, finger, thumb	413 (25.3)	1	15.6	4	324 (45.4)	1	89 (9.7)	4
Ankle	223 (13.7)	2	16.3	5	4 (0.6)	15	219 (23.8)	1
Shoulder, clavicle	200 (12.2)	3	19.8	9	161 (22.5)	2	39 (4.2)	8.5
Knee	194 (11.9)	4	15.2	4	37 (5.2)	5	157 (17.1)	2
Wrist	156 (9.6)	5	13.8	6	43 (6.0)	4	113 (12.3)	3
Head, face	94 (5.8)	6	8.5	5	49 (6.9)	3	45 (4.9)	7
Upper leg (thigh)	86 (5.3)	7	10.1	6	19 (2.7)	6	67 (7.3)	5
Lower leg, Achilles tendon	65 (4.0)	8	12.5	2	4 (0.6)	15	61 (6.6)	6
Hip, groin	46 (2.8)	9	7.4	4	11 (1.5)	8.5	35 (3.8)	10
Foot, toes	41 (2.5)	10	16.2	5	2 (0.3)	17	39 (4.2)	8.5
Lower back, sacrum, pelvis	39 (2.4)	11	7.8	4	18 (2.5)	7	21 (2.3)	11
Chest, sternum, ribs, upper back	21 (1.3)	12	9.7	3	9 (1.3)	10	12 (1.3)	12
Neck, cervical spine	20 (1.2)	13	8.2	4	11 (1.5)	8.5	9 (1.0)	13
Elbow	12 (0.7)	14	4.7	2.5	5 (0.7)	13	7 (0.8)	14
Abdomen	9 (0.6)	15.5	15.7	10	7 (1.0)	11	2 (0.2)	16
Forearm	9 (0.6)	15.5	20.2	2	6 (0.8)	12	3 (0.3)	15
Upper arm	5 (0.3)	17	3.6	3	4 (0.6)	15	1 (0.1)	17
Total	1633 (100)							
Diagnosis								
Sprain, ligament injury	550 (33.7)	1	16.8	5	202 (28.6)	1	346 (37.6)	1
Contusion, hematoma	297 (18.2)	2	5.7	2	124 (17.4)	2	173 (18.8)	2
Muscle strain, tear, rupture, cramps	205 (12.6)	3	9.9	5	79 (11.1)	5	126 (13.7)	3
Other injuries	184 (11.3)	4	10.5	4	96 (13.4)	3	88 (9.6)	4
Dislocation, subluxation	119 (7.3)	5	24.9	13.5	90 (12.6)	4	29 (3.2)	6
Fracture	98 (6.0)	6	48.2	46	43 (6.0)	6	55 (6.0)	5
Laceration	45 (2.8)	7	8.3	7	28 (3.9)	7	17 (1.8)	10.5
Concussion, brain injury	40 (2.4)	8	14.8	11	21 (2.9)	8	19 (2.1)	9
Tendinopathy, bursitis	39 (2.4)	9	10.0	4.5	14 (2.1)	9	24 (2.6)	7
Lesion of meniscus, cartilage, disc	27 (1.7)	10	26.2	16.5	4 (0.6)	11	23 (2.5)	8
Abrasion	22 (1.3)	11	2.8	1	5 (0.7)	10	17 (1.8)	10.5
Not presented[a]	7 (0.4)							
Total	1633 (100)							

[a]Diagnoses with <5 events are not presented in this analysis.

Table 2.2: Sliding Injuries Categorized by Type, Region, Quantity, Days Missed, and Technique (Camp et al, 2017)

A more reasonable approach is reducing the maximum load which will be transferred to the player as a whole. If specific injuries are unreasonable to solve for, then it makes sense to absorb as much sliding energy as possible while remaining within the constraints, i.e. reasonable for play. This involves determining an injury threshold above which loads are absorbed and below which loads are transferred to the player. Unfortunately, this method neglects many injuries which occur at lower loads, such as hand, finger, and thumb injuries. If the loads from these injuries were absorbed, then the base would move far too often for acceptable use. Additionally, many of these injuries are due to improper form or awkward landings (lacerations, contusions, etc.) irrespective of the bases immobile nature.

This injurious load threshold can be chosen based on the level of play the bases will be used for. It will change with the mass and speed of the player, technique, field conditions, shoes, and the biomechanical orientation of the player at impact.

DP 2: Load-absorption device

There will be an encompassing load-absorption system which will not allow loads above the injury threshold to be transferred to the player. The loads and physical properties present in the load-absorption system will relate to the loads transferred to the player in some way. The relation between these two will be solved for in design equations.

FR 2.1: Displace laterally with the players movement and provide constant force

Once an excessive load has been encountered, the base will displace laterally with the player. Now that the base is in movement, it should absorb as much energy as possible. The energy absorbed can be described by the work-energy equation $\Delta KE=Fd$. To absorb as much energy as possible, both F, the force exerted on the player by the base, and d, displacement, should be maximized. F is at a maximum at the injury threshold and d will be maximized based on the dimensions of the base and the specific load-absorption device. Therefore, the base should provide a constant return force during displacement which is at or just below the injury threshold. This provides the ideal stress-strain response of the base.

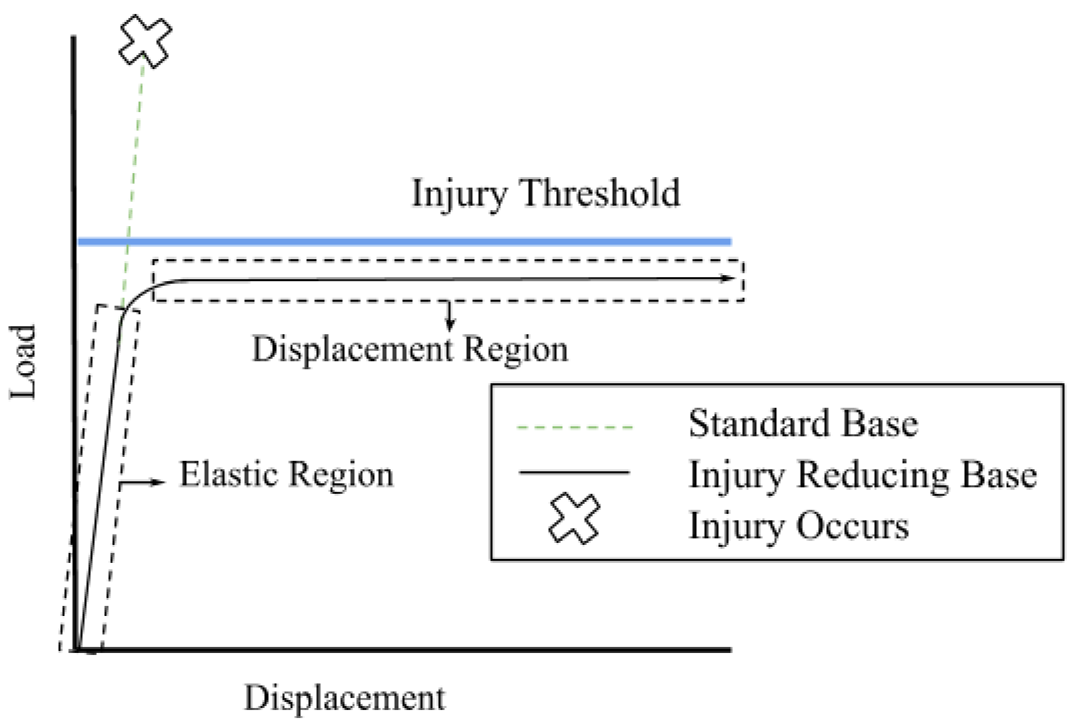


Figure 2.2: Stress-Strain Response Comparison Between the Injury Reducing Base and a Standard Base

DP 2.1: Load-absorption device provides constant force

The movement of the base top will depend on the load-absorption system. The load-absorption system will have to provide constant force during displacement.

FR 2.2: Self-return to initial position after movement

Part of ensuring acceptable usability is making sure the base requires as little upkeep as possible. If the base did not return after movement, it would have to be manually reset which would be excessively disruptive to gameplay. A typical base rarely has to be adjusted.

Additionally, the return force should be significantly lower than the force required to displace. This is because the player should not be pushed back by the base, instead the base should return once pressure has been relieved.

DP 2.2: Return system

A return system will be present in the final design. This will achieve the FR of self-returning to the initial position, and may take many different forms. For example, some designs include an inherent return system, while others require a return system separate from the load-absorption.

3. Iteration

In this section, the iteration of the design is discussed. This included further axiomatic design, measurements, optimization constraints, and design exploration.

3.1 Functional Measurements

Once the preliminary FR's were complete, a system was needed to evaluate and compare potential design. Each function can be measured by criteria named functional measurements. These measurements can be used to determine whether or not each function has been fulfilled. The measurements can then be compared between designs to determine the best possible design. The measurements also help to further clarify the design. Additional gauges are the constraints, developed earlier, and optimization criteria. Optimization criteria are the aspects of the design which should be improved to create a good design, but are not essential. The functional measurements and optimization criteria are listed below, along with justifications:

FR	Measurement	Justification
FR 0 - Control loads transferred to player during sliding impact	FR 0 will be collectively measured by each one of its children, i.e. the rest of the decomposition. The Axiomatic design rules require that the children of an FR are collectively exhaustive and mutually exclusive. Collectively exhaustive means that the functions of the children entirely sum up to the function of the FR. Mutually exclusive means that the function of each child is independent from each other.	
FR 1- Functional as a typical base under injury threshold	Must maintain MLB base dimensions	*15'' x 15'' x 3-5'' dimensions: These are the dimensions for a base set forth by the MLB (MLB, 2018)*
	Allow minimal displacement before injury threshold	*The base is expected to be static in ordinary situations by the players so it must be fixed to the ground under the injury threshold. Somewhere around 1/4-1/2 inch would be acceptable*

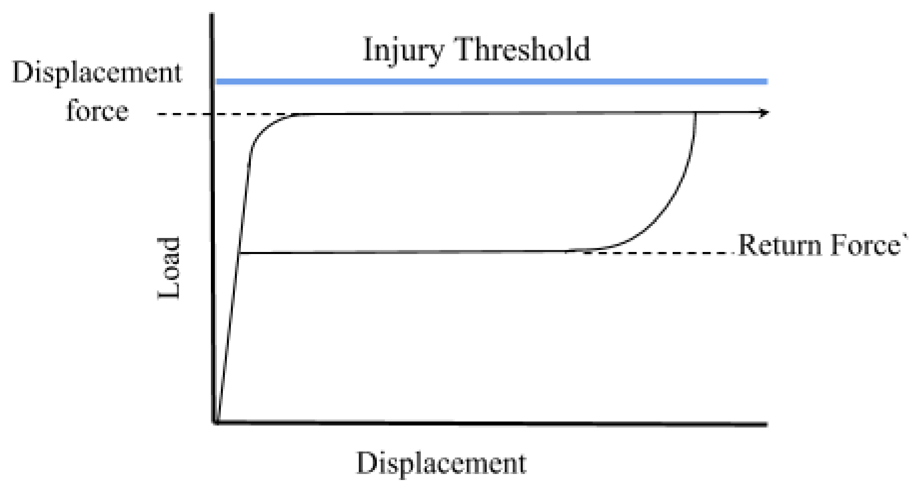
<table>
<tr>
<td rowspan="2"></td>
<td>Allow small initial strain</td>
<td>The outer layer of the base should provide a small amount of strain as typical bases do. This is to provide the player with a soft material to slide into.</td>
</tr>
<tr>
<td colspan="2">Note: Measurements 2 and 3 of FR 1 can be easily confused. The displacement of the base refers to the movement of the entire base top assembly. The strain refers to the deformation of the rubber and foam outer layers of the base top where the foot will impact during a slide.</td>
</tr>
<tr>
<td>FR 2 -
Absorb loads above injury threshold while being acceptable to use</td>
<td colspan="2">FR 2 can be measured collectively by FR 2.1 and 2.2.</td>
</tr>
<tr>
<td>FR 2.1 -
Displace laterally with the players motion and provide constant force</td>
<td colspan="2">


Figure 3.1: Graph showing the ideal stress-strain response of the base. There is a section of steep elastic loading until the displacement force is reached where the base will begin to displace at constant force (the upper line). When the slide has been arrested, the base will begin to return at a certain load (return force).
</td>
</tr>
</table>

	Must provide displacement force at or below the injury threshold	*The displacement force is the level at which the base will begin to displace. The base must exert this force on the player in order to absorb energy from the player. There is a finite amount of room in the base so the slide must be stopped as evenly as possible.*
	Must provide constant force	*In order to maximize total energy absorbed, the force should be as high as possible, but also below the injury threshold. Therefore, it should be a constant force just below the injury threshold.*
FR 2.2 - Self-return to initial position after movement	Return must be consistent	*The base should successfully return often enough to avoid negatively impacting gameplay. If the base does not successfully return, it will have to be manually reset in the middle of a game.*
	The base must fully return to the initial position	*The return system must successfully return the base all the way to the initial position. Some tolerance (~1/2 inch) is acceptable.*
	Return force must be ≤ 1/2 injury threshold	*The return force provided by the base must be significantly less than the injury threshold. If the base were to push back too forcefully, it could cause additional injury.*
Optimization Criteria	Displacement distance	*Ultimately, the energy absorbed by the base is critical to reducing injury. This is found through the work-energy equation $\Delta KE=Fd$. Because each design should have constant force, only distance can be*

		maximized to maximize energy absorption.
Optimization Criteria	Ease of adjustment for different levels of play	*Graded Minimal→Moderate →High The ease of adjustment for each design is graded empirically. A base which can be easily adjusted on site for different levels of play will see more widespread use. A typical base is suitable for all levels of play.*
Optimization Criteria	Effect on gameplay	*Graded Low→Moderate →Severe The effect on gameplay for each design was graded empirically.*

Table 3.1: Measurements, Optimization Criteria, and their Justifications

3.2 Expanded Decomposition

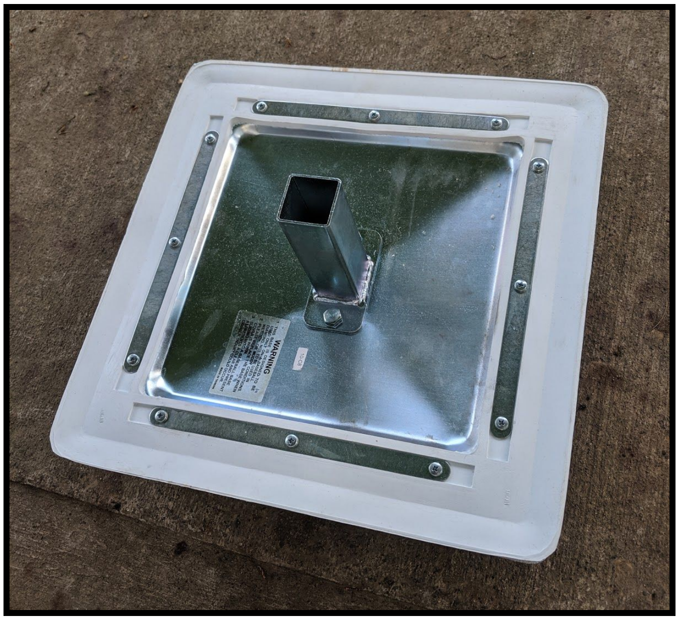
With the measurements completed, the decomposition could be expanded. Some FR's required multiple measurements to satisfy, which highlighted the need for additional children in the decomposition. The new FR's were used to outline the design in greater clarity and choose a design. DPs will be chosen based on whether or not they satisfy the measurements and a final design can be chosen by applying the axioms. The expanded decomposition is shown below:

#	[FR] Functional Requirements	[DP] Design Parameters
0	Control loads transferred to player during sliding impact	Load-controlling system
1	Function as a typical base under injury threshold	Champion Hollywood Pro Anchored Base housing
1.1	Connect to the ground statically	Metal anchor system
1.2	Allow small initial strain	Outer rubber layer + inner foam layer
2	Absorb loads above Injury threshold while being acceptable to use	Load-absorption system
2.1	Displace laterally with the players motion and provide constant force	
2.2	Self-return to initial position after movement	Return system
2.2.1	Return consistently	
2.2.2	Return completely to the initial position	
2.2.3	Provide return force which is lower than injury threshold	

Figure 3.2: Expanded Design Decomposition, Design Parameters are not Defined

3.3 Design Selection

Various potential designs were conceived and considered. They all involved the modification of a Champion Hollywood Pro Anchored Base. The fundamental design was consistent across all considerations; the rigid connection between the base and its anchor previously secured by a pair of bolts will be replaced with a connection through a load-limiting device. This configuration will allow the base to move while maintaining the connection to the ground through the metal anchor. Maintaining the same anchor system was necessary to make the base interchangeable with other designs, which was a major constraint.



Decomposition of the Champion base. The metal stake is sunk into the ground which secures the base. The stake is easily removable with 2 bolts. These bolts will be undone and the connection from the base plate (top right) and the anchor (the stake) will go through the load-absorption system. Note the significant concavity of the base plate. Also note the foam within the base which provides some small load-mitigation (bottom left).

The design will be chosen using the constraints, measurements, and OCs. Using the Champion base as a foundation immediately fulfills a number of the criteria. First of all, the base already has the structure and dimensions necessary for gameplay as clarified by the MLB. There is also an outer layer of rubber and an inner layer of foam which provide initial impact absorption and strain without moving the base.

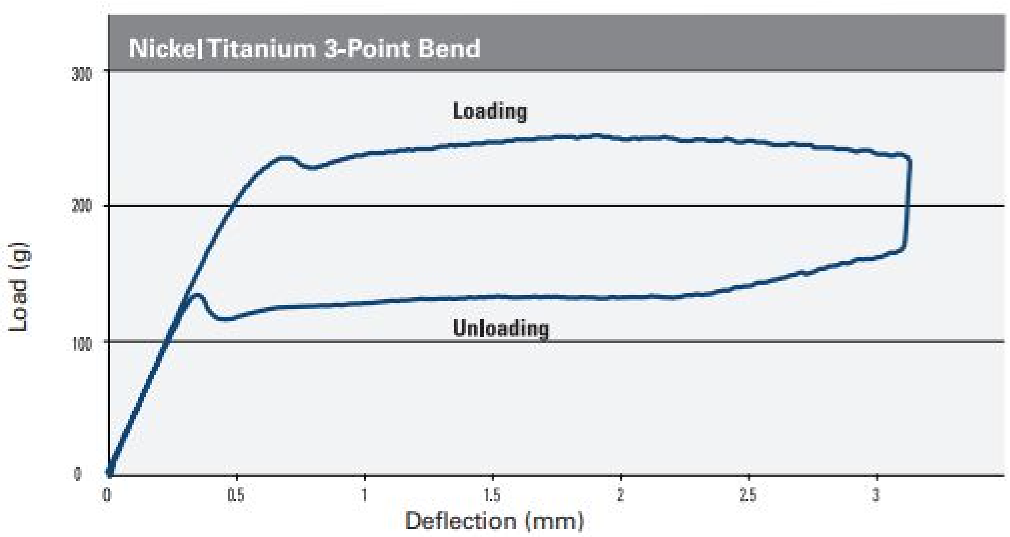
The essential differences from design to design involve the load-limiting system itself. The load-limiting system includes the displacement and load-absorption capabilities, the return system, and the connection of the base top to the anchor.

3.3.1 Nitinol Wire Three-Point Bending

The most immediately promising design was using superelastic Nitinol as the spring mechanism. Nitinol is a Nickel-Titanium alloy developed by the Naval Ordnance Laboratory (NOL) which exhibits superelastic as well as shape memory properties, although the shape memory properties are not important for the base. Nitinol can sustain unusually high amounts of strain, depending on the brand and composition, without suffering plastic deformation. One example of 10mm length, tested by ultimatewireforms.com, underwent 3.1mm deflection under three point bending, which is a 31% strain (Figures 3.3-3.4). Additionally, the stress strain curve of the wire is particularly unique and potentially useful for the project. After ~0.5mm strain, the load on the testing equipment was constant at ~250g until ~3.1mm strain, where it was unloaded. Furthermore, the unloading was also constant force, although at a lower load of ~125g. Finally, the wire returned completely elastically back to its initial position.

Figure 3.3 (Left): Three-Point Bend test on a Nickel-Titanium Wire nearing maximum deflection

Figure 3.4 (Below): Three-Point Bend Test graph of loading and unloading for 10mm length Nickel-Titanium wire. The upper line representing the loading forces and the lower line representing the unloading forces (Ultimate Wire Forms) .



A design utilizing Nitinol three point bending has some potential benefits. The first is the simplicity of the design. The stress-strain curve of the material almost perfectly matches the ideal stress-strain curve of the base (Fig. 3.1). The loading curve provides constant force and the unloading curve provides for a full return of the material back to its initial position at a lower load. If the connection of the base to the ground goes through a Nitinol 3-point bending system, the stress-strain response of the base could closely match that of Nitinol itself. However, the stress-strain curve of Nitinol is not entirely desirable. There is a significant non-constant force loading region (~0-0.75mm deflection) which would be unacceptable as the base would move too easily in this region.

Another important factor in the design is the displacement distance achievable. The superelastic properties are what allow the large displacement distance of Nitinol, especially when compared with other metals. Aluminum 1100 alloy, for example, can reach only 2.5% strain before fracture. In the test by Ultimate Wireforms, Nitinol wire reached 31% strain without plastic deformation.

$$\varepsilon = \frac{\Delta L}{L} = \frac{3.1mm}{10mm} = 0.31$$

This figure would allow for 3.1in of displacement if the wire were mounted in the 10in space inside the base. In this configuration, however, the base would displace 0.6in in each direction across the ground before the injury threshold force, which would be unacceptable.

$$0.6mm * \frac{10\ in}{10\ mm} = 0.6\ in$$

Another benefit of this design is that the displacement force could be easily adjustable for different levels of play. First, an understanding of Nitinol wire and 3-point bending is needed so that the force can be solved for. In a normal 3-point bending test, the force is given by the flexural strength σ_f and dimensions of the material, and the length of the support span *L*. The dimensions of the test beam are either the radius *R* or the width *b* and depth *d*.

$$F = \frac{\sigma f * \pi * R^3}{L} \text{ for a circular cross-section}$$

$$F = \frac{\sigma f * 2bd^2}{3L} \text{ for a rectangular cross-section}$$

However, this is slightly different for Nitinol due to its non-linear elastic properties. It does not have a typical flexural strength or modulus. One group of researchers found an elastic limit of 0.84-1.27 GPa (1.10 GPa avg.) for Nitinol wires of varying diameters under 3-point bending (Table 3.2). These will be used for the flexural strength figure.

Overall Wire Diameter (mil)	d_i (mil)	σ_{YS} (GPa)	σ_{EL} * (GPa)	σ_{UTS} (GPa)	σ_{EL}/σ_{UTS}
12‡	11.75	0.51	0.84	1.82	0.46
14‡	13.80	0.97	1.27	1.81	0.70
16‡	15.82	0.66	1.19	1.79	0.67
18‡	17.74	0.66	0.98	1.86	0.53
20‡	19.76	0.85	1.23	1.77	0.70

* Highest stress at which plastic behavior was not evident under cyclic loading (see Figure 4).
† d_i indicates inner strand diameter; σ_{YS}, 0.1% yield strength; σ_{EL}, clastic limit; σ_{UTS}, ultimate tensile strength; and GPa, gigapascal.
‡ 3M/Unitek, Monrovia, Calif.

Table 3.2: The yield strength, elastic limit, and ultimate tensile strength of varying diameters of Nitinol wire, as tested by one group of researchers (Rucker et al, 2002)

So, the displacement force can be adjusted by tweaking the length and radius of the wire. The length of the wire could be easily adjusted inside the base by changing the position of the fixtures at each end of the wire thereby changing the length of the bending beam.

One additional concern is the lack of research done on larger nitinol wires. The primary use case for Nitinol today is in orthodontics. They are used in braces to provide a constant, but very small, force on the teeth over many months to shape them into position. Thus, most research done on Nitinol involves small (~0.3mm diameter) wires. The most commonly used wire is rectangular at 0.016 x 0.022 in (0.405 x 0.558 mm). A small wire like this results in a loading force of only ~250g (Fig. 3.4). It is unknown whether or not much thicker wire will exhibit similar properties. For example, to achieve a displacement force of ~5000 N with a 10 in span (0.254m), the wire would have to be about 45 times larger in diameter at 14mm.

$$F = \frac{\sigma f * \pi * R^3}{L}$$

$$R = \sqrt[3]{\frac{F * L}{\sigma f * \pi}}$$

$$R = \sqrt[3]{\frac{5000N * 0.254m}{1.10GPa * \pi}} = 0.0713m$$

Measurement	Pass/Fail	Constraint/OC	-
Allow only minimal displacement before injury threshold	F	Easily interchangeable with normal base [CON]	P
Must provide displacement force at or below the injury threshold	P	All components must not undergo plastic deformation [CON]	P
Must provide constant force	P	Displacement distance [OC]	3.1 *in*
Must fully return to the initial position	P	Ease of adjustment for different levels of play [OC]	High
Return force must be ≤ 1/2 injury threshold	P	Effect on gameplay [OC]	Moderate

Table 3.3: Nitinol Wire Comparison Table

3.3.2 Non-Newtonian Fluid

A design utilizing non-Newtonian fluids was also considered. Non-Newtonian fluids are those which exhibit a change in viscosity with duration or magnitude of stress applied. Shear thinning and shear thickening non-Newtonian fluids change in viscosity with magnitude of stress, while Rheopecty and thixotropic fluids show a time-dependant change in viscosity proportional to the duration of stress. Shear thinning and thickening thickening fluids are more suitable for this project.

The most popular example of a shear thickening fluid is cornstarch dissolved in water. If you punch a bucket full of cornstarch, the stress applied by your fist causes the atoms to rearrange in such a way that the fluid acts as a solid. Your hand will not go through. If you slowly lower your hand into the bucket, however, you will penetrate it easily because the applied stress is much lower. The alternative scenario exists in shear thinning fluids, such as ketchup. You may be familiar with violently shaking the bottle to get the ketchup out. In this case, applied stress causes the viscosity of the fluid to decrease and behave more like a liquid. Before and after pouring, however, the ketchup behaves more like a solid.

These principles could be applied to make a suitable design for a load-limiting system as the base would theoretically only move when the stress applied is high enough to lower the viscosity of the liquid. The human body already uses shear-thickening fluid for shock absorption. Synovial fluid, found in the cavities of synovial joints, the most common type of joint in the body, becomes more viscous the moment shear is applied in order to protect the joint and thins to normal viscosity afterwards to resume its lubricating function (Zhang et al, 2014).

A liquid spring employing a Non-Newtonian fluid could be suitable for the design. One possible liquid spring was envisioned in a Solidworks model (Figure 1.6). Here, the fluid is kept within a channel with actuators attached to the base. When the player contacts the base with sufficient force, the actuators would move through the fluid, providing a resisting force against the movement of the base. The resisting force would be proportional to the viscosity of the liquid. If the viscosity of the liquid is high enough under ordinary playing conditions, the resisting force would arrest the movement of the base. Then, once the injury threshold is reached and a consequently high enough stress is applied to the liquid, the viscosity will decrease and the base will displace through the liquid, which produces a constant resisting force.

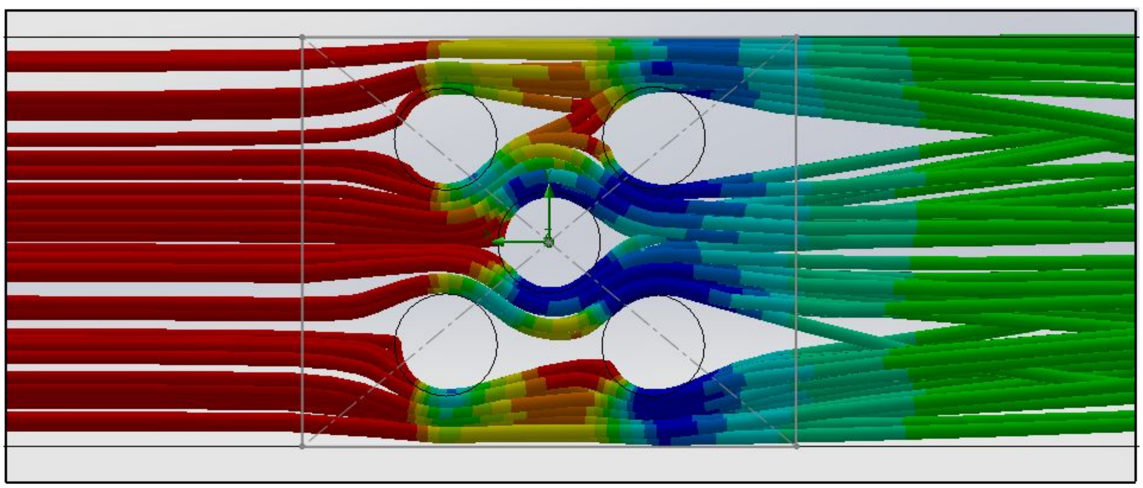
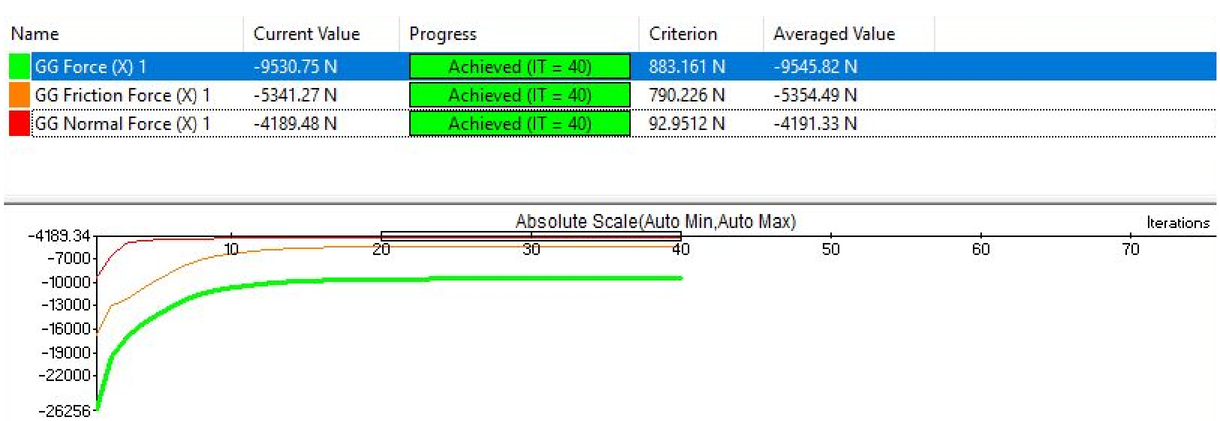


Figure 3.5: Five cylindrical actuators under lateral stress within a Non-Newtonian Fluid. Solidworks Simulation.



Name	Current Value	Progress	Criterion	Averaged Value
GG Force (X) 1	-9530.75 N	Achieved (IT = 40)	883.161 N	-9545.82 N
GG Friction Force (X) 1	-5341.27 N	Achieved (IT = 40)	790.226 N	-5354.49 N
GG Normal Force (X) 1	-4189.48 N	Achieved (IT = 40)	92.9512 N	-4191.33 N

Figure 3.6: Frictional and Normal Force profile of a Non-Newtonian Fluid design using Eastman 9921 PET 0.8 IV. Solidworks Simulation.

Figure 3.6 shows the potential of the design through a Solidworks simulation. The actuators were set to move through the fluid at 5 m/s, or about 11 mph, to simulate a player sliding into the base. The graph shows the resisting force against the movement of the base on one axis, and iterations, on the other axis. The initial force is quite high but eventually drops to a constant resisting force. In this way, the base would not move until the force is sufficiently high.

Although the simulation shows some potential, the feasibility of a real design is questionable. The fluid used was a molten polymer solution provided by Solidworks 2018 Edition which would be entirely unusable in a real design due to its high melting point. In fact, many molten polymers exhibit non-Newtonian properties. The simulation was done purely to demonstrate the potential of a non-Newtonian fluid but it is unclear whether or not a more suitable fluid exists. Solidworks includes a thin selection of non-Newtonian fluids and most are molten polymers so further testing is required.

If a suitable fluid was identified, there would still be notable drawbacks to this design. First of all, production and maintenance would be more difficult than other designs. The tube housing the fluid would have to be watertight over a long period of time and during movement. Any leaking fluid would have to be replaced manually. Additionally, there is no inherent return mechanism in this design, like there is in a Nitinol based design. Therefore more design would have to be done on a return system, further complicating the base. Finally, the temperature of non-Newtonian fluids significantly alters their properties, including viscosity (Samantaray, 2009). This would restrict use to a window of suitable playing temperatures.

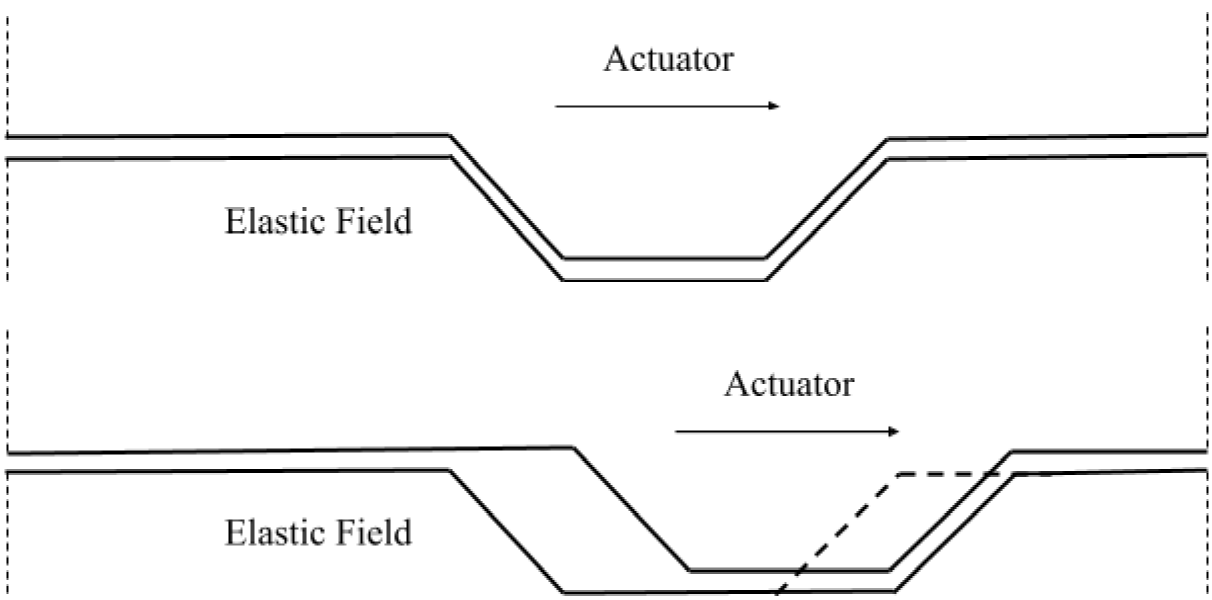
Measurement	Pass/Fail	Constraint/OC	-
Allow only minimal displacement before injury threshold	F	Easily interchangeable with normal base [CON]	P
Must provide displacement force at or below the injury threshold	P	All components must not undergo plastic deformation [CON]	P
Must provide constant force	P	Displacement distance [OC]	Up to ~8-9in
Must fully return to the initial position	F	Ease of adjustment for different levels of	Minimal

		play [OC]	
Return force must be ≤ 1/2 injury threshold	F	Effect on gameplay [OC]	Moderate

Table 3.4: Non-Newtonian fluid comparison table

3.3.3 Actuators in Elastic Field (AEF)

The Actuators in Elastic Field (AEF) design is one currently under development in the Sports Engineering Lab at WPI. This design involves solid actuators inside of a compressible elastic field. The actuators compress the field by moving laterally through it. In theory, the field provides a return force on the actuator towards its initial position which results in a desirable stress-strain curve. The force on the actuator increases as it slides into the field (Fig. **???)**. Once it is fully surrounded by the field, the actuator will be in equilibrium and require a constant force to move in any direction. This force can be adjusted to be equivalent with the injury threshold.



Figures 3.7-3.8: Mechanism of Action in the AEF

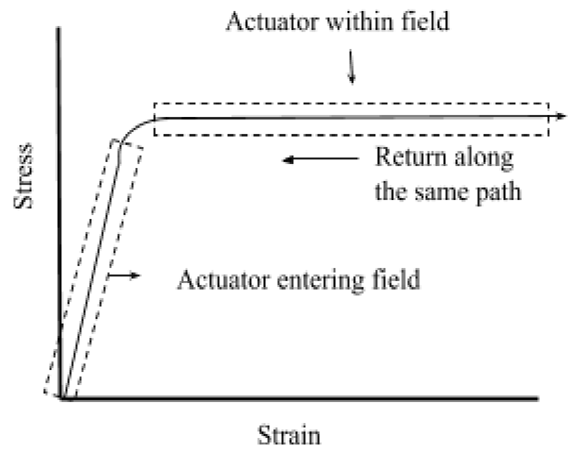


Figure 3.9: Theoretical Stress-Strain Curve of the AEF

The specifics of the stress strain curve can be adjusted. Once the actuator is within the field, the force required to move it should be equivalent to the injury threshold. This can be adjusted by changing the properties of the field and geometry of the actuator. The elastic modulus of the field material, the depth of the actuator, the friction in the interface between the two, and perhaps more unknown factors all have an impact. Fortunately, all parts of the design are 3D printable and thus easily tweaked. Students in the WPI Sports Engineering lab are working towards optimizing the stress-strain curve.

Unfortunately, the concept has encountered some obstacles in development and testing. The AEF is tested using an Instron 3300 series mechanical testing machine which can measure the stress-strain response as the actuator is pulled through the field. A suitable stress-strain curve has not yet been demonstrated through testing. Additionally, the field often tears during testing. Furthermore, the forces experienced during these tests are considerably less than those experienced during sliding collisions. Another drawback is the lack of inherent return system.

Measurement	Pass/Fail	Constraint/OC	-
Allow only minimal displacement before injury threshold	F	Easily interchangeable with normal base [CON]	P
Must provide displacement force at or below the injury threshold	P	All components must not undergo plastic deformation [CON]	P
Must provide constant force	P	Displacement distance [OC]	Up to ~8-9in

Must fully return to the initial position	F	Ease of adjustment for different levels of play [OC]	Minimal
Return force must be ≤ 1/2 injury threshold	F	Effect on gameplay [OC]	Low

Table 3.5: AEF Comparison Table

3.3.4 Preloaded Spring/Cam-Follower Designs

The mechanics of a preloaded spring are in the name, the spring is preloaded to an intended deflection with an associated spring force. Until that spring force is reached, the spring will not displace. They have a variety of uses, including in injury prevention. A preloaded spring can be used in conjunction with a cam-follower system to provide a particular stress-strain response. This mechanism is used in the hell of modern ski bindings. A preloaded spring inside of the heel of the binding will give way once a certain injurious load is reached, releasing the skier from the ski immediately.

The preloaded cam-follower mechanism could also be beneficial for this project. It provides an ideal breakaway mechanism where the breakaway force, which would be the injury threshold for the base, is easily set by adjusting the spring preload. The mechanism allows minimal displacement of the follower until the breakaway force is reached. This is a crucial characteristic of a successful base design.

The preloaded cam-follower could be used in conjunction with another design to provide the initial static connection to the ground. For example, the base top could be connected to the follower such that it will displace only after the spring preload is reached. The load-absorption itself can then be achieved through another design such as the AEF or a liquid spring.

There are some potential drawbacks as well. A preloaded cam-follower may be difficult to self-reset after actuation. The spring will have to be re-loaded after every actuation. This could possible be circumvented using a specific cam-follower design.

Measurement	Pass/Fail	Constraint/OC	-
Allow only minimal displacement before injury threshold	P	Easily interchangeable with normal base [CON]	N/A
Must provide displacement force at	P	All components must not undergo plastic	P

or below the injury threshold		deformation [CON]	
Must provide constant force	N/A	Displacement distance [OC]	N/A
Must fully return to the initial position	F	Ease of adjustment for different levels of play [OC]	High
Return force must be ≤ 1/2 injury threshold	N/A	Effect on gameplay [OC]	Low

Table 3.6: Preloaded Cam-Follower Comparison table

4. Final Design

The final design will use two preloaded Nitinol beams mounted within the base housing as the primary load-absorption mechanisms. This was determined using the measurements, constraints, and OC's. By preloading the Nitinol beams, the initial movement was eliminated. This was one of the primary concerns highlighted by the measurements. Additionally, the Nitinol has the lowest impact on gameplay and a high ease of adjustment.

The beams will be 10.2mm in diameter and 0.254m (10in) in span each giving an injury threshold of 3500N. This injury threshold figure is a ballpark estimation. It was calculated using a number of assumptions:

Average Major League Baseball player mass: 93 kg

Speed of player at impact: 5 mph

The mass was found from a baseball statistics website (We Are Fanatics, 2018). The speed figure is the same used by researchers testing various breakaway bases (Janda et al, 2001). It was determined using speed-gun analysis by the manufacturers. The injury threshold itself was found as follows:

$$KE = 0.5mv^2$$
$$KE = 0.5(93kg)(2.2m/s)^2 = 225\ J$$
Maximum displacement is 2.5 in , by design
$$\Delta KE = Fd$$
$$225\ J / 0.063\ m = 3571\ N$$

To absorb all of the sliding energy in this situation, the two beams would have to provide 3571N over 2.5in or 0.063m. This is ~1750N per beam. Consequently, this base design can absorb a maximum of 3500N. The beam dimensions were found as follows, for more clarification refer to section 3.1.1:

$$R = \sqrt[3]{\frac{F*L}{\sigma f*\pi}}$$

$$R = \sqrt[3]{\frac{1750N*0.254m}{1.10GPa*\pi}} = 0.005m$$

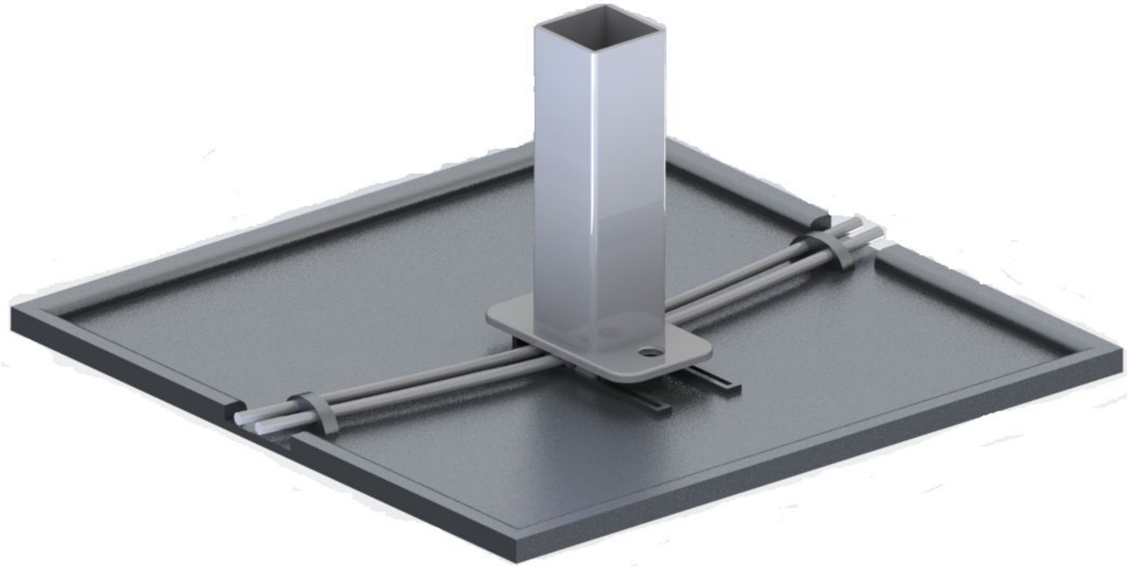


Figure 4.1: Base Plate and Anchor at Minimum Extension, Solidworks Rendering

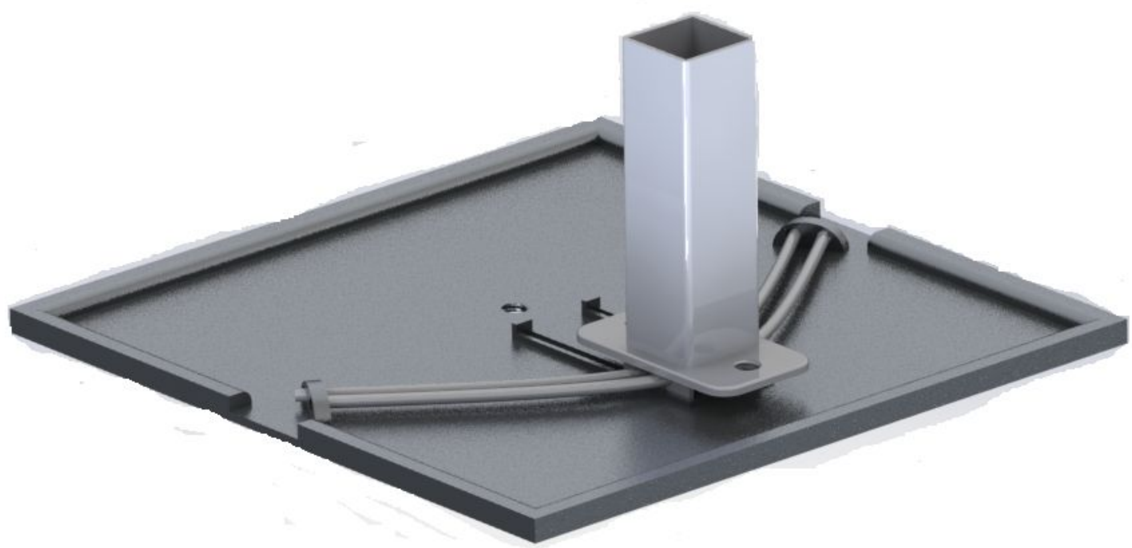


Figure 4.2: Base Plate and Anchor at Maximum Extension, Solidworks Rendering

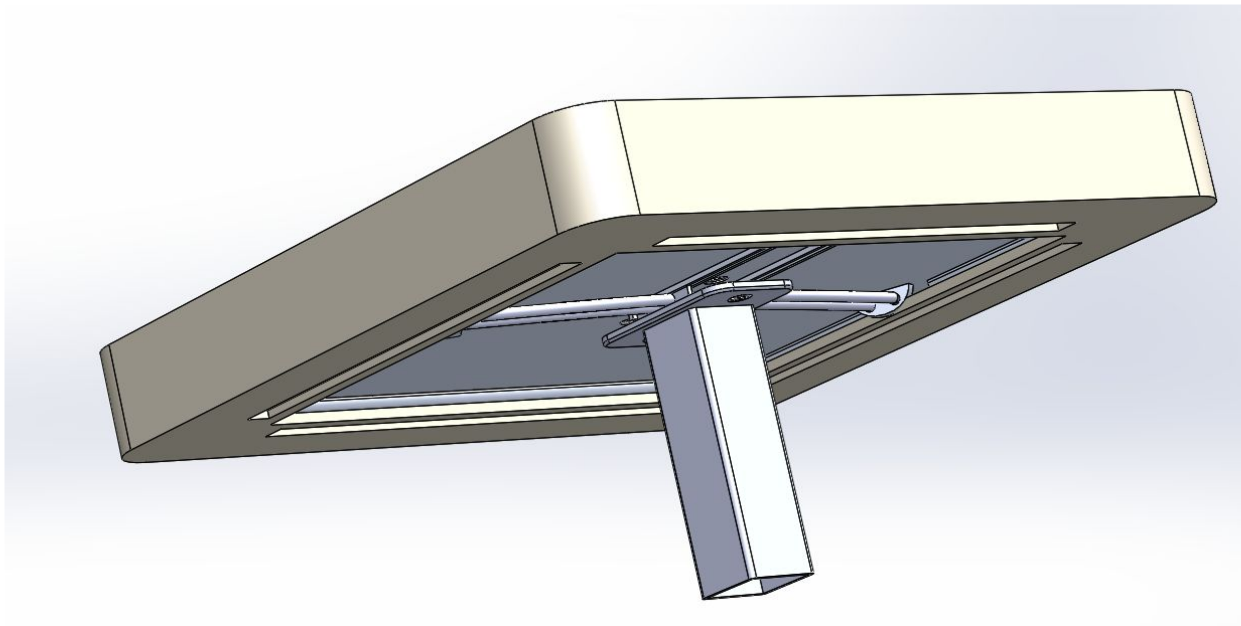


Figure 4.3: Entire Base Assembly in Solidworks

The design involves fixtures welded to the base plate which the Nitinol beams run through. The beams then run through the anchor (the large metal stake) and then to the fixture on the other side of the base plate. In the Solidworks renderings above, the base is inverted as the anchor would normally be fixed into the ground. The base top displaces across the ground as the stake remains immobile in the ground.

There are a few design elements which were not included in any decomposition. There are a set of metal rails guiding the beam-anchor system. These will have to be welded to the base plate itself, along with the fixtures for the beams. The rails also serve the function of fixing the base in the other directions. The base plate will also have to be flattened. The base plate is normally concave and fits into the foam layer within the base, which will also have to be reshaped. A section of the base plate must also be cut out. The beams are 10.4in from fixture to fixture at minimum extension and 12.2in at maximum extension. The extra length (figure 4.1) creates the need for cutouts in the base plate.

There are a few shortcomings of the design. First of all is the small displacement distance. Due to limitations in the elasticity of Nitinol, only ~3.1in of displacement were possible even though the base theoretically has room for ~8-9in which other designs can reach. This limits the total energy absorption potential. Fortunately though, a smaller displacement distance also has a lighter impact on gameplay.

The base also may have improper fixturings. The anchor was previously bolted into the base plate while it now rest freely within two rails, in addition to the Nitinol beam connection.

This may be insufficient to secure the base in other lateral directions although no analysis was done on this.

#	[FR] Functional Requirements	[DP] Design Parameters
0	Control loads transferred to player during sliding impact	Load-controlling system
1	Function as a typical base under injury threshold	Champion Hollywood Pro Anchored Base housing
2	Absorb loads above Injury threshold while being acceptable to use	Preloaded Nitinol beams
2.1	Displace laterally with the players motion and provide constant force	Connection to anchor through load-absorption system
2.2	Self-return to initial position after movement	Nitinol superelastic properties
2.2.1	Return consistently	Metal sliding rails for the anchor
2.2.2	Return completely to the initial position	Nitinol fully returns after elastic deformation
2.2.3	Provide return force which is lower than injury threshold	Nitinol unloading curve

Figure 4.4: Final Axiomatic Design Decomposition

5. Discussion

This section discusses in detail portions of the project that were not previously discussed in the paper and future considerations.

5.1 Unidirectionality

` The final design is unidirectional. Loads are only absorbed in one lateral direction and the base may as well be a standard base from the perspective of the other three lateral directions. On the surface, this may seem to highly limit the designs potential by eschewing 3/4ths of injury. However, it is suitable given the nature of the sports. In baseball and softball, baserunners run clockwise around a square of four bases in a sequential fashion. In this way, there are only two sliding situations for each base; players will either slide into a base coming from the preceding one with either feet-first or head-first technique, or perform a dive back into the base they are on during a pickoff. For simplicity's sake these situations will be referred to as ‘into’ and ‘back to’. Slides into and back to a base have important differences.

Feet-first and head-first slides into a base occur at a much higher speed than dives back into the base. This is simply due to the nature of the game. High speed slides are due to balls in play (BIP) or stolen bases (SB). Low speed givebacks are due to pickoffs (PO). Slides into the base are what cause the majority of lower extremity injuries and would benefit from load absorption due to the high speeds. Slides back into the base generally result in contusions, lacerations, dislocations, and other injuries unrelated to the bags immobility. For these reasons, load-absorption is generally beneficial in only one direction. For example, at second base, 99.4% of feet-first slides are into the bag due to BIP or SB. Meanwhile, at first base, 92.5% of head-first slides are back to the bag due to PO (Table 5.1).

	Head-First Slides				Feet-First Slides				
Base	No. (%)	BIP	SB	PO	No. (%)	BIP	SB	PO	Total, No. (%)
First base	1570 (53)	117	N/A	1453	32 (1)	30	N/A	2	1602 (22)
Second base	944 (32)	297	554	93	3078 (72)	2447	613	18	4022 (55)
Third base	313 (11)	218	84	11	588 (14)	490	95	3	901 (12)
Home plate	136 (5)	127	9	N/A	596 (14)	575	21	N/A	732 (10)
Totals	2963 (41)	759	647	1557	4294 (59)	3542	23	729	7257

[a]Slides categorized by base, head first vs feet first, and type of play. BIP, ball in play; N/A, not applicable; PO, pickoff; SB, stolen base attempt.

Table 5.1: Video Analysis of Accumulated Sliding Events for June, July and August of the 2015 Major League Season (Camp et al, 2017)

Location	Injuries, No. (%)	Rank	Days Missed		Direction, No. (%)		Requiring Surgery, No. (%)
			Mean	Median	Head First	Feet First	
First base	201 (12.3)	4	13.1	5	180 (89.6)	21 (10.4)	15 (7.5)
Second base	924 (56.6)	1	14.9	5	338 (36.6)	586 (63.4)	75 (8.1)
Third base	243 (14.9)	3	15.0	5	114 (46.9)	129 (53.1)	21 (8.6)
Home plate	246 (15.1)	2	13.1	5	74 (30.1)	172 (69.9)	21 (8.5)
Other	19 (1.2)	5	11.4	5	8 (42.1)	11 (57.9)	2 (10.5)
Totals	1633 (100)		14.0[a]	5	714 (43.7)	919 (56.3)	134 (8.2)
P value			.628[b]				

[a]Total mean days missed for all locations, excluding "other."
[b]Owing to low prevalence of injuries occurring in "other" locations, these were excluded from statistical comparisons.

Table 5.2: Sliding Injuries Based on the Location on the Field in Which the Slide Occurred (Camp et al, 2017)

Part of the challenge of designing an injury reducing base is that each base has many different functions and use cases. For example, one runner might dive back to second base while another will use the same contact area to push off towards the next base. One situation calls for a rigid base, while the other requires a soft base. There could also be a baseman standing on the base, or a runner rounding the base who contacts the corner facing towards home. All of these use cases have different functions which were not entirely explored in this project.

5.2 Challenges

A number of challenges were encountered which lead to complications or could not be entirely overcome. The most important of these was the difficulty in determining a proper injury threshold. The science of injury prevention involves complex biomechanical problems beyond the scope of this project. A sliding injury depends on factors such as the players mass, speed, and contact area with the base all the way down to the individual ligaments, tendons, and muscles connecting ankle, knee, and hip joints. Such a wide variety of injuries (Section 2.1.4, Table 2.2) makes it virtually impossible to design a base with each one in consideration. Furthermore, it was difficult to find any figures concerning injury level forces, leaving most of it up to guesswork.

It makes the most sense to design a base which absorbs as much overall energy as possible. However, even this proved challenging, as there was no basis for what would be acceptable in Major League Baseball and what wouldn't be. Ultimately, this is a decision that can only be made by Major League Baseball and the players.

6. Conclusion

To conclude, the project accomplished several goals; successfully designing a base which could reduce the occurrence of sliding injuries in baseball and softball, maintaining proper playing conditions, and gaining an understanding of Axiomatic design principles. A great deal was learned about engineering design and the steps that can be taken to streamline the process.

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Appendix: Axiomatic Design Decompositions

A large portion of the project was spent learning Axiomatic design principles. In the process, many different iterations of design decompositions were created. While they are not important to the end result of the project, they may help to clarify the engineering design process.

FR's - DP's	Load-limit	Maximize	Disconnec	Base is co	Load-limit	Load-limit	High mod	-	Load-limit	Low impac
Limit loads transferred to the player	x	o	o	o	o	o	o	o	x	o
Minimize acceleration of the player during collision	o	x	o	o	o	o	o	o	o	o
Maximize displacement by allowing base to move	o	o	x	o	o	o	o	o	o	o
Secure base when movement is not necessary	o	o	o	x	x	o	o	o	o	o
Base only moves above ordinary playing load	o	o	o	x	x	o	o	o	o	o
Base self-returns after movement	o	o	o	x	o	x	o	o	o	o
No plastic deformation in the load-limiting device	o	o	o	o	o	o	x	o	o	o
Reduce friction between the base and the ground	o	o	o	o	o	o	o	x	o	o
Stop the slide over the impact distance	o	o	o	o	o	o	o	o	x	o
Base deforms before player injury	o	o	o	o	o	o	o	o	o	x

Figure A.1: The First Axiomatic Design Decomposition and Functional Matrix, in Microsoft Excel

#	FR	DP
0	Limit loads transferred to the player	Load-limiting system
1	Minimize acceleration of the player during collision	Maximize displacement of the load-limiting system
1.1	Allow the base to move	Disconnect the base from its anchor
1.1.1	Secure base when movement is not necessary	Base is connected to the ground through load-limiting device
1.1.2	Base only moves above ordinary playing load	Load-limiting system actuates only above playing loads
1.1.3	Base self-returns after movement	Load-limiting device returns completely after deformation
1.1.4	No plastic deformation in the load-limiting device	High modulus of elasticity or low strain
1.1.5	Reduce friction between the base and the ground	Roller system
1.2	Stop the slide over the impact distance	Load-limiting device provides constant return force
2	Base deforms before player injury	Low impact stregth of materials in the impact zone

Figure A.2: The Second Axiomatic Design Decomposition, done in Acclaro

#	[FR] Functional Requirements	[DP] Design Parameters
0	Limit forces transferred to the player	Injury reduction mechanism
1	Limit maximum acceleration of the player during collision	Load-limiting system within the base
1.1	Allow the base to displace and return under certain condition	Base is connected to the ground through the load-limiting system
1.1.1	Allow movement exclusively above ordinary playing loads	Load-limiting system actuates above ordinary playing loads
1.1.2	Base self-returns after movement	Load-limiting device returns completely after deformation
1.1.3	Limit friction in the interface between the base and ground	Roller system
1.2	Stop the slide within the range of movement	Load-limiting device provides sufficient total impulse
1.3	Slow the slide evenly over the collision distance	Constant force during displacement
2	Base deforms before player injury	Low impact stregth of materials comprising the base top

Figure A.3: The Third Axiomatic Design Decomposition

#	[FR] Functional Requirements	[DP] Design Parameters
0	Limit maximum loads transferred to player during impact witl	Load-limiting system
1	Rigidly connect to ground in normal playing loads	Pre-loaded spring + cam-roller system
2	Increase distance of impact above normal playing loads	Base displacement system
2.1	Flexibily connect to ground above normal playing loads	Connection to ground through flexible load-limiting device
2.2	Self-return to initial position after mvoement	Load-limiting device self-returns after strain

Figure A.4: The Fourth Axiomatic Design Decomposition

#	[FR] Functional Requirements	[DP] Design Parameters
0	Control loads transferred to player during sliding impact	Load-controlling system
1	Transmit loads to player in ordinary playing levels	Pre-loaded spring + cam-roller system
2	Limit loads transferred to player above ordinary playing levels	Non-linear stress-strain curve of load-limiting device
2.1	Displace from the ground and provide constant force	Connection to ground through load-limiting device
2.2	Self-return to initial position after movement	Load-limiting device self-returns after strain

Figure A.5: The Fifth Axiomatic Design Decomposition

	[FR] Functional Requirements	[DP] Design Parameters
0	Control loads transferred to player during sliding impact	Load-controlling system
1	Function as a typical base under injury threshold	Pre-loaded spring + cam-follower design
2	Absorb loads above Injury threshold while being acceptable to use	Load-absorption device
2.1	Displace laterally with the players motion and provide constant force	Friction system provides constant force
2.2	Self-return to initial position after movement	High strength spring return system

Figure A.6: The Sixth Axiomatic Design Decomposition