ASHESI UNIVERSITY COLLEGE

AFFORDABLE EXOSKELETON BRACE FOR PEOPLE WITH LIMITED LOWER LIMB MOBILITY

CAPSTONE PROJECT

B.Sc. Mechanical Engineering

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CAPSTONE PROJECT

Capstone Project submitted to the Department of Engineering, Ashesi University College in partial fulfilment of the requirements for the award of Bachelor of Science degree in Mechanical Engineering.

Julianne Djan-Sampson

2020

DECLARATION

I hereby declare that this capstone is the result of my own original work and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature:

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I hereby declare that preparation and presentation of this capstone were supervised in accordance with the guidelines on supervision of capstone laid down by Ashesi University College.

Supervisor's Signature:

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Date:

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To my parents and my brother whose support carried me through.

To all my friends and colleagues who helped me in one way or another.

Abstract

This report determines the feasibility of designing an affordable Knee Ankle Foot Orthosis or Exoskeleton Brace that can provide support to a user with lower limb mobility.

This report reviews existing designs of braces and scrutinizes that which makes them expensive but efficient. It looks into alternatives for materials, locations of supports and sizing of the parts of the braces.

The report also includes an analysis of the forces at play in the supporting frame of the exoskeleton brace.

The report details a meticulous selection process for the subsystems that make an exoskeleton brace work.

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Chapter 1: Introduction

1.1 Background

There are a vast majority of people who for one reason or another have difficulties with lower limb mobility. These difficulties could be due to several factors such as the arthritis, sports injuries, strokes, and multiple sclerosis, to name a few. Orthosis treatment is one of the most common treatments used to control biomechanical alignment, correct deformities, support injuries, assist rehabilitation, reduce pain, and increase mobility [1]. It involves the use of braces, splints, or artificial external devices to assist in ambulation. International Organization for Standardization defines an orthosis as a “device used to modify the structural and functional characteristics of the neuromuscular and skeletal systems” [1]. There are a variety of orthoses for different parts of the body, some of which are, the Ankle Foot Orthosis (AFO), Fracture and Spinal Orthoses and many others.

1.2 Problem Definition

It is important to note that knee injuries account for 41% of all sports injuries [1], the knee can be significantly weakened by stroke and multiple sclerosis and arthritis can lead to severe pain in the knees. All the above have an adverse effect on the walking pattern of the affected person because the knees play a major role in the process of ambulation.

For years, orthosis treatment has been used to provide support for users who have weak knees due to one reason or another, however, these assistive devices tend to have high costs, with the lowest costing thousands of dollars. The Indego ®, the Rewalk ®, and the HAL-5 ® are mechanical exoskeleton braces which range in prices from $65,000 to $150,000 [2].

1.3 Objectives of the Project

The objective of this project is to design an affordable Knee Ankle Foot Orthoses (KAFO). Its task would be to adequately provide support for users suffering from knee instability. This project seeks to determine whether natural alternative can be used to replace the current materials used on the market, whether the passive mechanical KAFO can provide as much support as the motorized KAFO and whether there is opportunity to improve upon the existing designs of knee orthoses.

1.4 Proposed Solution

One of the factors that escalate the prices of these braces are the materials used in their manufacture. Carbon fibre, fibre-reinforced prepreg, and duralumin are a few of the costly materials that are used. These materials are used because of their superb qualities such as their energy storing properties, reduced deformation over time, amongst others. This project would entail the selection of an alternative low-cost material that would be able to carry out most, if not all the functions of the costly materials. This selection would be based on the design requirements of the brace as well as the properties of the material. Some properties which would be taken into consideration are the yield strength, weight, toughness and more.

A material that is a viable option is bamboo, which has notable strength and levity. Use of the Cambridge Engineering Selector (CES) application would be employed in the process of determining whether the various properties of bamboo are suited for the brace. Since, the brace is being designed for everyday use, fatigue tests would have to be carried out to determine the product's life cycle.

In a bid to reduce the price of the exoskeleton without compromising on its ability to provide support to the user, the following question would be taken into consideration: 'Should the brace be powered or passive?'. If it is powered, it would employ the use of motors and actuators to aid in the movement of the lower limbs. However, with the passive device, springs, locking mechanisms, pulleys, and dampers would be used to divert the weight of the user towards the ground. Via comparison of the disadvantages and advantages, a suitable option would be selected.

The forces at play on the lower limb in the various stages of motion would also be analysed using moment diagrams to determine the best placements of the supports within the structure. Simulations would also be carried out with the use of Solidworks ® software as well as Finite Element Analysis (FEA). The product would provide support from the knee to the ankle to the foot. They all have different degrees of freedom which would be considered when modelling begins. Depending on the feasibility, a low-fidelity prototype would be created for demonstration purposes.

1.5 Foreword

Throughout this report, words and phrases such as gait, gait analysis, swing and stance phase as well as energy expenditure will be referred to and as such this foreword will shed light on them. Gait is a skill, defined here as the cyclic motion of lower and upper limbs that aims to move the body forward. A set of coordinated movements are used to locomote with the goal of moving from one point to another while supporting and transferring the weight of the body [3].

The typical gait pattern consists of the following:

The body moves forward, one limb provides support.

The other limb simultaneously moves to the next support position.

The limbs alternate their roles until the subject's destination is reached.

The gait cycle can be defined as the time interval between two successive occurrences of one of the repetitive events of walking [intro to gait analysis]. It begins when one foot contacts the ground and ends when that same foot contacts the ground again.

Figure x shows the positioning of the legs throughout the gait cycle.

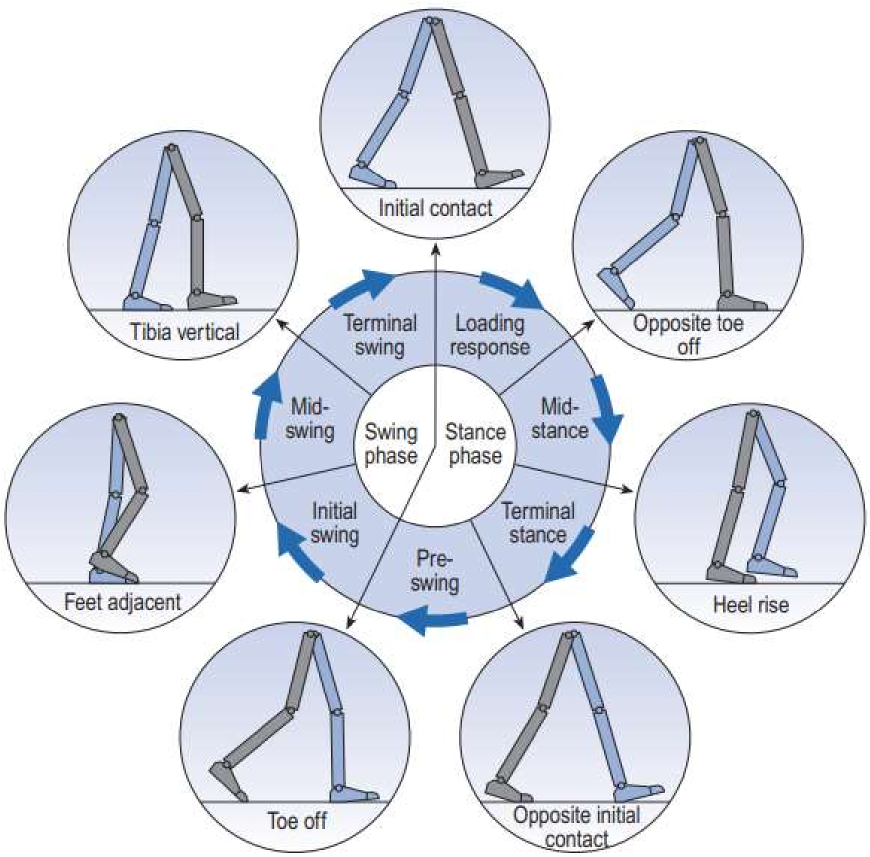


Figure 1 Leg positions during a single gait cycle

Source: Adapted from [An intro to Gait Analysis]

Each circle depicts a specific motion that corresponds to a particular section of the gait cycle.

The gait cycle comprises two main phases, the swing and stance phase. The stance phase comprises 60% of the gait cycle and the stance represents the latter 40%. The cycle begins with the stance which involves the heel strike as displayed by the bubble labelled ‘initial contact’.

Chapter 2: Literature Review

It is undisputed that knee instability as a result of injury or muscle weakness is often treated with the use of orthoses. The goal of the lower limb orthoses is to improve upon the ability and quality of walking, protect, and provide stability for the user. There exist several kinds of orthoses used in the treatment of knee instability.

As the common name suggests the Knee-Ankle Foot Orthoses (KAFO) spans the knee, ankle and foot in order to stabilise the joints for safe ambulation. There are several types of KAFO designs, some of which have been used for centuries. The conventional KAFOs were made of metal and leather and the modern ones are made from carbon fibre composites which are lighter and fit the users more closely and subsequently enable better control of the limb [10]. KAFOs typically consist of shells or padding that enclose the thigh and calf area, frames or uprights that go on the sides, locking mechanisms, joints and/or actuation systems.

Figure 2 Conventional KAFO comprising leather and metals.

A leg brace that was used half a century ago in the treatment of poliomyelitis. It is a rigid structure that does not allow for bending of the knee

Source: Adapted from [11]

Figure 2 showcases the form KAFOs took in the 1950's. Poliomyelitis was rampant in the U.S, during that period. It was a contagious virus that led to several deaths and the few that managed to survive it were paralysed and braces such as the ones shown in Figure 2 e were used to aid the patients in maintaining stability. These designs were bulky, stiff and heavy. As the image showcases, the joint that the design comprises is entirely locked at the knee. Using a KAFO with a locked knee requires the individual to alter their gait to allow their foot to clear the ground in the swing phase of walking [10]. This results in the formation of compensatory gait patterns such as raising the pelvis on the side of the swinging leg to allow the leg to clear the floor or rather singing the leg forward around the side of the body [13]. These gait patterns bear no semblance to the typical gait patterns and end up causing pain and reduction in the range of motion of the users.

It can also be observed that the metal uprights are bolted to the shoe. To offset the weight of the upper part of the brace, the shoes are quite heavy. This design does not allow for the user to change footwear.

Over recent years, the stance control KAFO (SCKAFO) has gained popularity, and this is because it allows a more natural knee motion. The mechanically or actuator-controlled knee joints enable the knee to flex during the swing phase of walking but lock when the knee is extended during stance phase of walking and when weight is borne through the leg to provide stability to the knee [10]. The SCKAFO improves gait kinematics, increases knee flexion during the swing phase, provides a more symmetrical gait, and requires less compensatory movement than the conventional, passive KAFO [12]. There are different types of SCKAFOs, but they all have the same general mode of operating which is for the knee joint to allow flexion in swing phase and lock in stance phase. The mechanisms involved in the control of the knee joins are the eccentric cam locking system, inner pendulum mechanism, ratchet and pawl, belt clamping dual stiffness mechanism and hydraulic system [14].

In the journal of pain and relief, a design evaluation was carried out on the existing SCKAFO designs. Even though all the SCKAFOs perform better than the conventional KAFO it can be observed that a major drawback that runs through the above designs was the fact that these devices tend to be bulky, not aesthetically pleasing, and noisy [14].

Figure 3 showcases the SCO with the knee joint belt clamping mechanisms. It consists of a disk, belt, hammer, anvil, compression spring, sensors, and a control system.

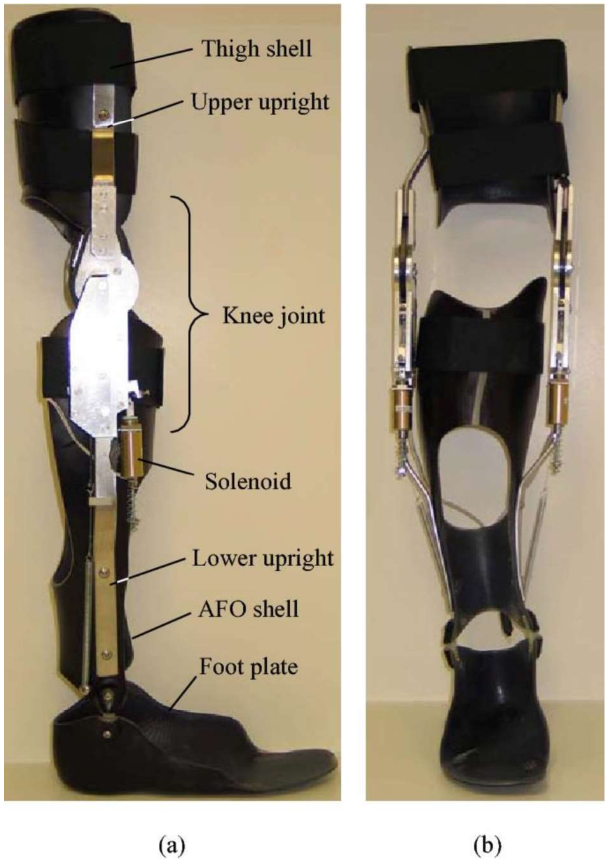


Figure 2 SCKAFO with belt clamping mechanism. This is a modern design which uses a control system for operation. It is comprised of a disk, belt, hammer, anvil compression spring and sensors.

Source: Adapted from [15]

Chapter 3: Design

The design of the prototype considered these four subsystems with:

- The knee joint locking mechanism
- The Shell supports
- The Uprights or framework
- The foot supports

More emphasis was placed on the uprights due to the fact that majority of the correction from the KAFO is dependent on the uprights.

2.1 Review of Existing Designs

The existing designs that were found to be the most significant pertaining to the project were the traditional/passive KAFO, Scott-Craig KAFO, the Ottobock Free Walk, Swing Phase Lock by Fillauer LLC and the Dual Stiffness KAFO.

The passive KAFO provides knee stability however it prevents knee motion in swing phase. It is uncomfortable and can lead to long term hip damage. It can reduce gait efficiency by 23% which means that users can be better off without them [14]. It is no surprise that these passive KAFO's tend to have a very high rejection rate [14]. The passive KAFOs [Figure 1] are normally paired with crutches otherwise ambulation would be a very slow process for the user. The only advantage this design presents is the fact that is very affordable.

The Otto Bock Free Walk is a stance control orthosis manufactured by Otto Bock ®, a German prosthetics company. The free body diagram of the design's working mechanism is shown in Figure 4.

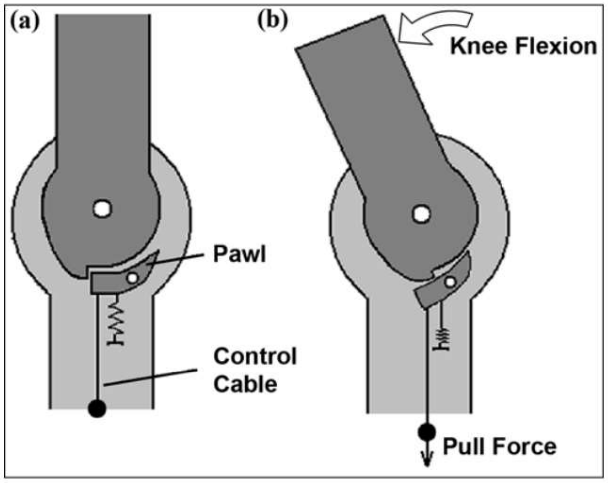


Figure 3 Otto Bock Free Walk Working Mechanism which consists of a pawl, control cable and a compression spring.

Source: Adapted from [14]

It consists of a spring-loaded pawl as shown above. The control cable is connected to the foot support of the KAFO. The spring-loaded pawl locks the knee automatically when the user is in a standing position as in part (a) and when the user dorsiflexes or raises their ankle at an angle above 10 degrees, the pawl disengages and allows the user to swing and bend their leg freely. This is advantageous over the passive KAFO as it resembles the natural gait more. The Otto Bock free walk has several other upsides ranging from the fact that it is relatively lightweight, aesthetically pleasing, easy to use and easier to maintain [14]. Since, it requires an ankle dorsiflexion of 10 degrees to engage the locking mechanism users with biomechanical problems that limit use of the ankles cannot use this product.

Figure 5 comprises an image of the Becker UTX which uses the same pawl-spring mechanism.

Figure 4 Becker UTX Orthopaedic Stride which uses the same working mechanism as the Otto Bock Free Walk.

Source: Adapted from [19]

The supporting pads that are normally located behind the thigh and the calf area are typically made up of carbon fiber, duralumin, or thermoplastics for most of the existing designs.

Fillauer LLC. (an American center for orthotic design) developed a gravity-actuated knee joint locking mechanism for the Swing Phase lock orthoses [4]. It consists of a simple inner pendulum mechanism which governs the locking and unlocking of the knee with respect to the joint angle at sagittal plane [4]. This design also comprises a weighted pawl that moves in and out of locking position based on the angle of the user's thigh. Consider Figure 5, when the thigh is anterior to the user's body and the knee is in full extension, the weighted pawl falls into position as shown in (a) and when the thigh is posterior to the user's body the pawl falls out of engagement as shown in (b) [4]. For the locking mechanism to properly engage the knee must fully extend. Since the locking mechanism depends on limb-segment orientation, the Fillauer Swing Phase Lock is not effective for users to securely climb stairs or walk on uneven ground [9].

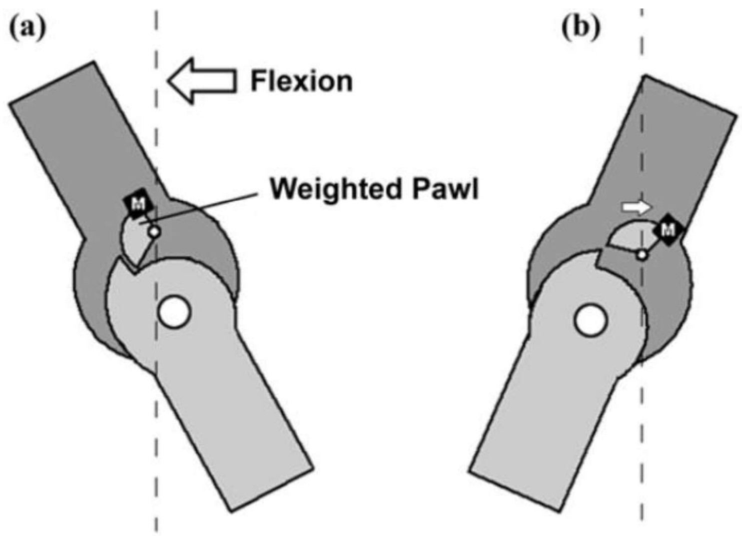


Figure 5 Working Mechanism of the Fillauer Swing Phase Lock Orthosis

Source: Adapted from [9]

A dual stiffness KAFO is referred to as a dynamic KAFO as it employs the use of compression spring actuators to replicate the normal knee stiffness throughout the entire gait cycle. Figure 7 displays the compression spring actuators and their moments of loading and unloading. During the stance phase, the knee joint actuator absorbs shock and enables the knee to extend fully whereas in the swing phase it helps free knee motion [14]. It is very bulky and not cosmetic enough for patient usage. It is also not commercially available. [14]

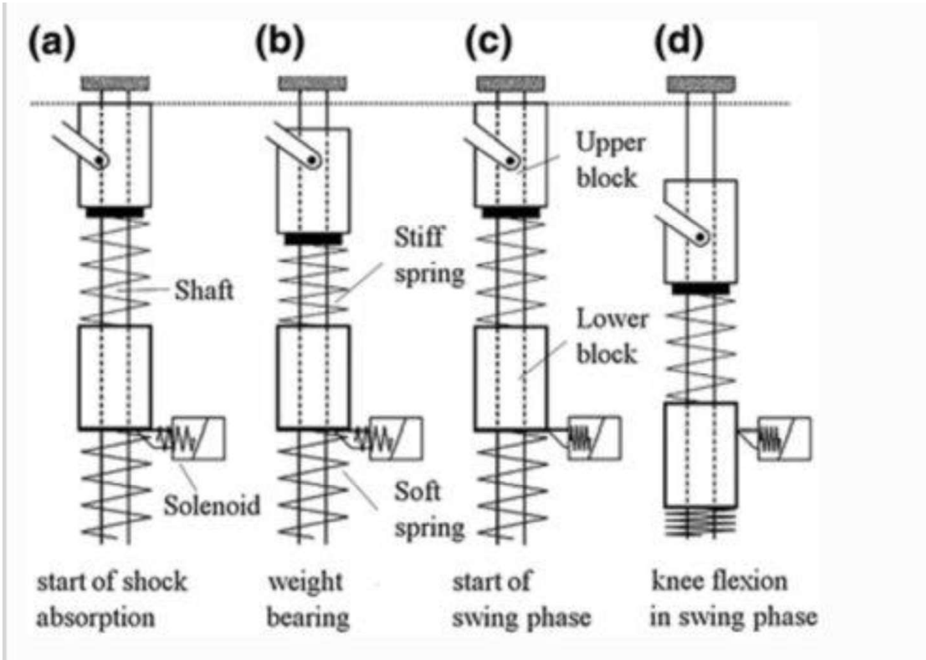


Figure 6 Loading and unloading of the spring in the Dynamic KAFO. A and B represent the spring positioning during the stance phase and C and D represent the springs in the swing phase.

Source: Adapted from [9]

2.1.1 System Requirements

- The exoskeleton brace must be durable
- The device should be lightweight
- The device should enable the user to effectively switch between swing and stance phase.
- The device should be able to support at least mass of 68 kg.
- The device should be environmentally friendly.

2.1.2 User Requirements

- The device must be more affordable than existing devices on the market.

- The device should be easy to put on and take off.
- The device should be aesthetically pleasing
- The device should be quiet
- The device should be able to be worn under clothes

Affordable and easy to wear vibes lightweight

2.2 Pugh Chart Matrices

This section contains the Pugh charts that aid in the evaluating of the various systems involved in the design of the exoskeleton brace. The Pugh chart is a framework or tool used for evaluating multiple options against each other [20]. It gives a holistic overview of the requirements set versus the available alternatives [20]. In the case of the frameworks below each criterion is given a weighting which showcases the ranking of importance, with 5 being the most important and 1 being the least. In the case of the overall KAFO design, cost-effectiveness is ranked higher than manufacturability.

The weighting is the product of the weight and the rating of the objects being compared. The variable with the largest sum of weightings has the most pros according to the selected criteria.

2.2.1 Determining the most suitable KAFO

Criteria		Passive KAFO		Stance Control KAFO		Dynamic KAFO	
	Weight	Rating	Weighting	Rating	Weighting	Rating	Weighting
Cost effective	5	5	25	3	15	2	10
Comfort	4	3	12	4	16	3	12
Close to normal gait	5	0	0	3	15	2	10
Ease of use (minimal energy expended by user)	5	2	10	3	15	4	20
Flexion in swing phase	5	0	0	5	25	5	25
Flexion in both swing and stance phase	3	0	0	0	0	5	15
Aesthetic	4	3	12	4	16	4	16
Levity	4	4	16	3	12	1	4
Quietness	3	5	15	4	12	2	6
Manufacturability	3	4	12	3	9	2	6
TOTAL			102		135		124

Based on the objectives of the project, the best type of design is the Stance Control KAFO. The individual criterion weightings were determined using pros and cons discussed in Section 3.2. The criteria of utmost importance were cost-effectiveness, the device producing a gait that's close to normal, ease of use and flexion in the swing phase. For a KAFO to provide flexion in both the swing and stance phase, it must be able to fully automate the walking process without any aid from the user. It can be seen above that the only type of device that does this is the dynamic KAFO. The SCKAFO allows flexion in the swing phase, the user dorsiflexes their ankles in order to enable this flexion.

2.2.2 Determining the most suitable knee-locking mechanism

Criteria		**Weighted Pawl-Lock**		**Pawl-Spring**	
	Weight	Rating	Weighting	Rating	Weighting
Ease-of-use	5	3	15	4	20
Can be used to climb stairs	4	0	0	5	20
Quietness	3	3	9	3	9
Levity	5	2	10	4	20
Closer to normal gait	5	3	15	4	20
TOTAL			49		89

The SCKAFO design can incorporate many different types of lock mechanisms but the two being compared are the most cost-effective as they have fewer moving parts.

The Pawl-Spring locking mechanism is the better design of the two as it gives the user a higher semblance of normal gait, it does not inhibit a user from climbing the stairs and it is relatively easy to use. The pawl spring mechanism unlocks during the swing phase when the user dorsiflexes allowing the user to swing the leg freely and locks when the stands providing stability for the knee of the user.

2.2.3 Determining the most suitable material for the support shells:

Below is a table with values compiled from Ashby's [28] Material Selection in Mechanical Design:

	Bamboo	Carbon Fiber	Leather
Young's Modulus, E /GPa	20	150	0.5
Density/ Mg/m^3	0.8	1.6	1.05
Yield Strength, σ_y / MPa	44	1050	10
Tensile Strength, σ_{ts} /MPa	45	1050	26
Cost / $ per kg	2.1	44	21
CO_2 Footprint/ kg per kg	0.33	18.3	4.5

The table of values above informed the weighting values in the Pugh Chart Matrix:

Criteria		**Bamboo**		**Carbon Fiber**		**Leather**	
	Weight	Rating	Weighting	Rating	Weighting	Weighting	Rating
Density	4	5	20	4	16	4	16
Toughness	4	3	12	5	20	2	8
Cost	5	5	25	2	15	1	5
TOTAL			57		51		29

For the material selection of the support, it is imperative that the material be lightweight, tough and cost effective. The most lightweight and cost-effective material turned out to be bamboo however, the toughest material was carbon fiber. The material selected does not need to have the highest toughness but must be tough enough that it supports the weight of the user. Carbon fiber came in as a good alternative with only 6 points behind bamboo, but the cost of carbon fiber is a deterring factor.

Bamboo also leaves behind the lowest carbon dioxide footprint which would go a long way into protecting the environment from the effects of greenhouse gas emissions.

2.2.4 Determining the most suitable material for the uprights:

The uprights play a major role in the provision of support to the user while ambulating. aluminium and stainless steel have been used in the past for the fabrication of the uprights however, recent studies have shown that carbon fiber or titanium uprights can reduce the weight of the KAFO without compromising on the strength of the brace.

Consider the following properties of bamboo, titanium and stainless steel adapted from [28]:

	Stainless Steel	Bamboo	Titanium	Carbon Fiber
Young's Modulus, E /GPa	210	20	120	150
Density/ Mg/m^3	8.1	0.8	4.8	1.6
Yield Strength, σ_y / MPa	170	44	250	1050
Tensile Strength, σ_{ts} /MPa	480	45	300	1050
Cost / $ per kg	7.2	2.1	74	44
CO_2 Footprint/ kg per kg	5.4	0.33	11	18.3
Thermal Expansion, 10^{-6}/C	20	10	11	4

Fracture Toughness/ (MPa √m)	280	7	120	88

The specific strength or strength-to-weight ratio is a material's strength divided by its density. The equation below is used to fill the specific strength table:

$$Specific\ Strength = \frac{Yield\ Strength}{Density}$$

	Stainless Steel	Bamboo	Titanium	Carbon Fiber
Specific Strength / MPa m^3/mg	21	55	52.1	656.3

2.2.5 Material Fabrication Processes for Uprights

This section contrasts the fabrication processes for the selected materials.

For stainless steel, the fabrication process is as follows [21]:

i. Raw materials are melted in a furnace.
ii. Excess Carbon is removed using a vacuum oxygen decarburization system.

iii. Molten steel is stirred to ensure uniform quality.

iv. Stainless steel is cooled and hot-rolled into billets or slabs.

v. Stainless steel is heat treated or annealed to relieve internal stresses.

vi. Stainless steel is cut into desired shapes using laser cutting machines, metal shears etc.

vii. Surface finishes are applied.

For bamboo, the fabrication process is as follows [22]:

i. Bamboo (*Phyllostachys edulis*) is selected and harvested.

ii. The bamboo poles are split up into slats using a 'star shaped splitter' which is made of metal.

iii. The bamboo slats are planed to remove the green outer layer.

iv. The bamboo slats are boiled in hydrogen peroxide to protect them from fungi or insect attacks.

v. The bamboo slats are carbonized in a high-pressure tank to release bamboo's natural starch.

vi. The bamboo is dried in a kiln and sanded to desired dimensions

For titanium, the process of fabrication is as follows [23]:

i. The titanium ore is extracted from mines.

ii. It is purified by means of fractional distillation and precipitation.

iii. The purified titanium tetrachloride is poured in a s steel reactor vessel with argon and magnesium to produce pure titanium.

iv. Titanium is converted into a usable alloy using a consumable electrode arc furnace.

v. It is melted using a vacuum arc and an ingot is formed.

vi. The ingot is remelted three times to produce a commercially acceptable ingot with no defects.

For carbon fiber, the process of fabrication is as follows [24]:

i. The raw material (polyacrylonitrile) is drawn into long fibers.
ii. The fibers are heated in air which rearranges their atomic bonding pattern.
iii. The fibers are taken through a series of complex stabilizing chemical reactions which involve several steps.
iv. After the fibers are stabilized, they are heated in a furnace at very high temperatures with no oxygen to prevent the fibers from burning. This process is called carbonization as the non-carbon atoms are expelled and the carbon atoms from tightly bonded carbon crystals.
v. The surface is treated to give it better bonding properties. They are either coated electrolytically or oxidized by immersion in air.
vi. The fibers are then coated with materials such as epoxy, nylon and others.
vii. The coated fibers are wrapped around bobbins and twisted into yarns with varying sizes.

It can be observed from the fabrication processes outlined above; carbon fiber has the most complex procedure. It involves complex reactions with several steps. Titanium fabrication is also relatively complex and almost every step outlined requires heating. The fabrication procedures for both stainless steel and bamboo are fairly simple. Out of the four materials, stainless steel and bamboo are more likely to be able to be fabricated in a standard workshop.

Consider the Pugh Chart for material selection for the uprights:

Criteria		Stainless Steel		Bamboo		Carbon Fiber		Titanium	
	Weight	Rating	Weighting	Rating	Weighting	Rating	Weighting	Rating	Weighting
Cost Effectiveness	5	5	25	5	25	2	10	1	5
Levity	5	4	20	5	25	5	25	4	15
Specific Strength	5	3	10	4	20	5	25	3	15
Ease of Fabrication	4	5	20	4	20	3	12	3	12
TOTAL			75		90		72		47

Bamboo best satisfies the criteria given and would therefore be used for the metal uprights.

2.3 Design Iterations

First Design Sketch

Figure 8 showcases the initial rough sketch of a generic KAFO which consists of the ankle foot orthoses, shell supports, uprights and a pawl and spring locking mechanism. This sketch (Figure 8) depicts the positioning of the exoskeleton brace when the user is in the stance phase.

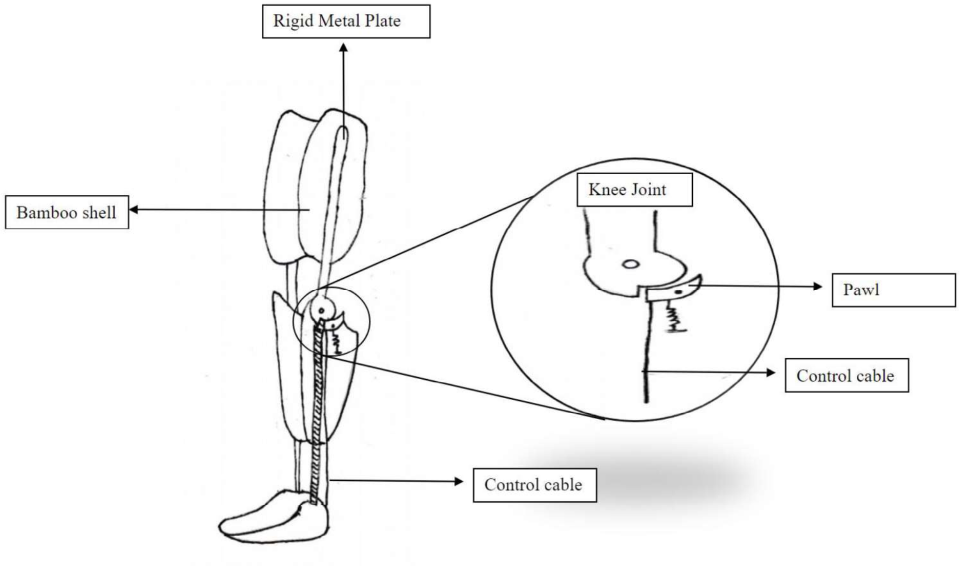


Figure 7 The first rough sketch of the general design with the chosen locking mechanism which consists of a pawl and spring to control the knee joint. It showcases the user in the stance phase.

Figure 9 depicts the positioning of the exoskeleton brace when the user is in the swing phase. It is evident that the control cable is in tension, the spring is compressed, and the pawl is released. At this point, the user can swing or bend their knee freely.

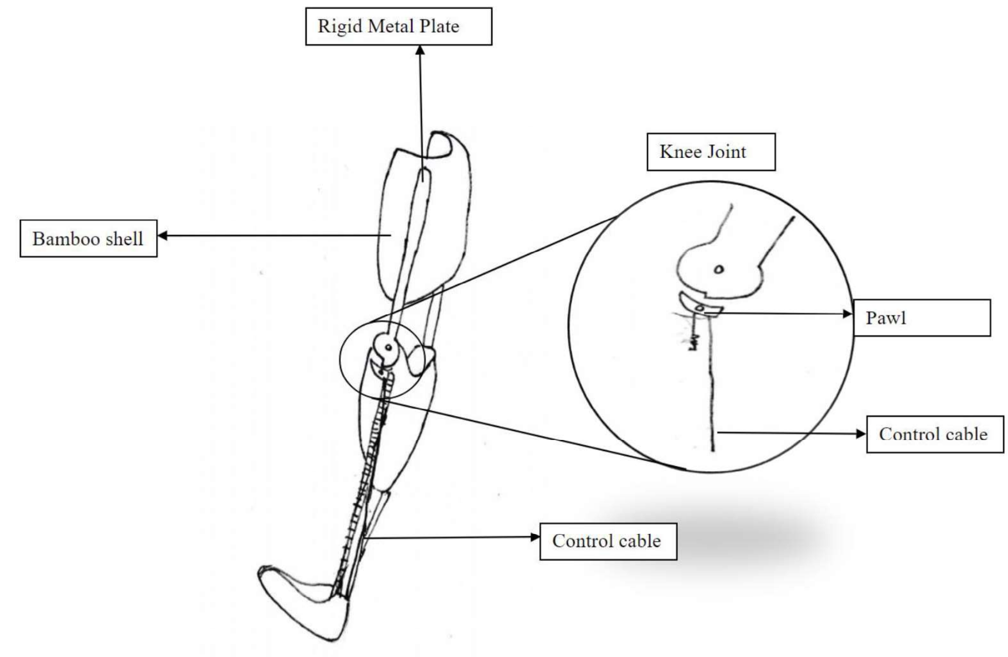


Figure 8 The initial rough sketch of the general design with the chosen locking mechanism which consists of a pawl and spring to control the knee joint. It showcases the user in the swing phase.

2.4 Low-Fidelity Prototype of Design

2.5 Design Iterations

The main aim of this project is to reduce the cost of the KAFO without compromising upon on its ability to provide support to users with knee instability.

The support that encompasses the thigh and calf as shown in the designs in chapter 2 [Figure 2,3, and 5] can be reduced in order to save on cost.

Research carried out by Edelstein [27], complete with survey data from orthosis users has proven that they prefer bands to support shells, and this is because the latter tend to be cumbersome to don on and retain body heat.

Lehmann et al. [17] showed that most of the support variations on KAFOs, including the posterior calf, and suprapatellar band, are often unnecessary [16].

Based on these findings, the design iteration involves replacing the thigh and calf supports with a rigid posterior thigh band and an anterior tibial band.

Figure 9 Solidworks model of a thigh support modelled for a user with a mass of 68 kg.

Figure 10 displays a model of a bamboo thigh support designed with parameters to encompass the thigh of a female user with a mass of 68 kg. Using the Solidworks ® Mass Property Evaluation Tool, the mass of the support was determined to 93.54g.

According to [28], the cost per kg of bamboo is $2.1. It can therefore be inferred that this support costs $1.96.

Figure 11 displays the rigid posterior thigh band which is also designed with parameters to encompass the thigh of a female user with a mass of 68 kg. The black inner material is polyurethane foam to cushion the thigh of the user. Using the Solidworks ® Mass Property Evaluation Tool, the mass of the band was determined to 58.07g which costs $1.22.

The replacement of the thigh support with the thigh band leads to a 37.8% reduction in cost due to material being conserved.

With this iteration, the calf support would also be replaced by a tibial band as shown in the next section.

Figure 10 Solidworks model of a posterior thigh band with a polyurethane foam cushioning interior.

2.6 Final Design

The final design incorporates different features of various designs that reduce the overall cost of the exoskeleton brace without compromising on its function.

The design comprises a rigid posterior thigh band as well as an anterior tibial band. It also comprises the spring-pawl knee locking mechanism.

The ankle foot support can be enclosed in a shoe which gives the user more options unlike the conventional KAFOs. Figure 12 showcases a rough sketch of the design.

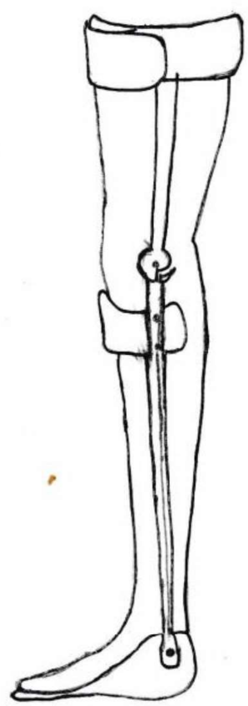


Figure 11 Final Exoskeleton Brace Design

2.7 Design Analysis

2.7.1 Analysis for Uprights

Considering the forces acting at the joints:

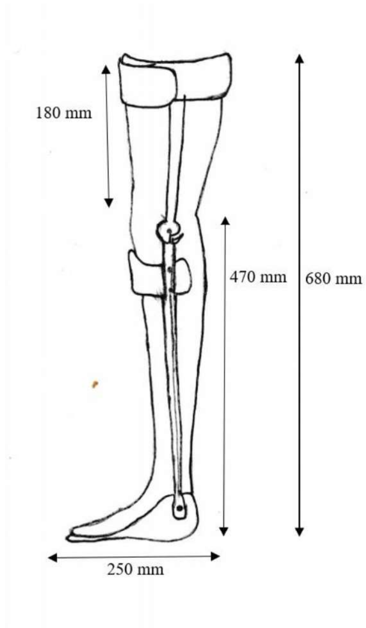


Figure 12 Labelled exoskeleton brace design

The orthosis is supposed to provide stability to the knee of the user. The diagram below shows one of the possible torques responsible for an unstable knee (T_{unst}). T_{unst} is the product of the ground reaction force (F_{fr}) and the floor reaction lever at the knee joint L_{fr}

The F_{corr} force acts as a restraint to provide stability. This force and its lever (L_{corr})must produce at least as much torque as T_{unst}.

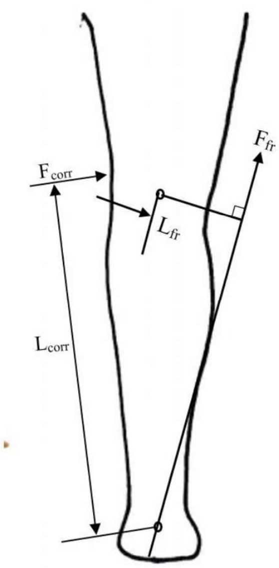


Figure 13 Moments and Torque around a weak knee

$$F_{corr} \times L_{corr} \geq F_{fr} \times L_{fr}$$

$$F_{corr} \geq \frac{F_{fr} \times L_{fr}}{L_{corr}}$$

$$F_{corr} \geq \frac{F_{fr} \times L_{fr}}{L_{corr}}$$

The ground reaction force, F_{fr}, is equal to the body weight of the user, i.e., 68g N and L_{fr} spans the length of the knee joint, which is 80 mm. L_{corr} spans the length of the frame from the knee to the foot which is 470 mm.

We can determine F_{corr}:

$$F_{corr} \geq \frac{68 \times 9.81 \times 80}{470}$$

$$F_{corr} \geq 113.55\ N$$

The knee instability is corrected by the F_{corr} produced by the uprights as displayed in Figure 11.

This arrangement can be considered as a freely supported beam and the following equations can therefore be used to calculate the stress and the maximum deflection acting on the bars.

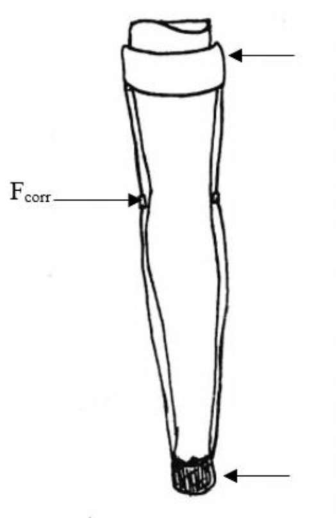
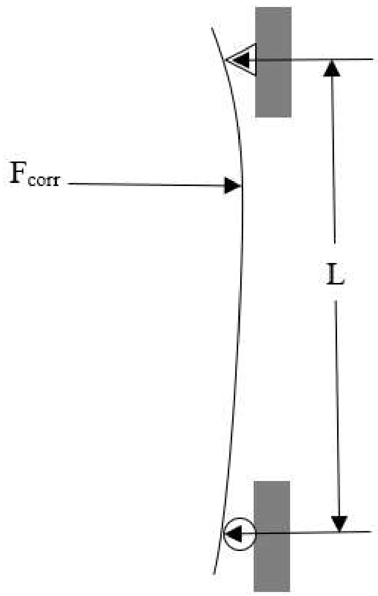


Figure 14 Forces on leg in KAFO



Stress in a freely supported beam is given by:

$$\sigma = \frac{3FL}{2bh^2}$$

$$where\ F = F_{corr}$$

$$L = distance\ from\ between\ the\ two\ supports$$

$$b = width\ of\ the\ bar$$

$$h = thickness\ of\ the\ bar$$

$$\sigma = \frac{3 \times 113.55 \times 680}{2 \times 3 \times 20^2}$$

$$\sigma = \frac{231642}{2400}$$

$$\sigma = 96.52\ MPa$$

The maximum deflection in a free supported bamboo beam is given by:

$$y_{max} = \frac{FL^3}{-48EI}$$

$$where\ E = Young's\ Modulus\ of\ Bamboo \quad = 20\ 000\ MPa$$

$$I = \frac{bh^3}{12} = \frac{(20)(3)^3}{12} = 44\ mm^4$$

$$y_{max} = \frac{FL^3}{-48EI}$$

$$y_{max} = \frac{113.55 \times 68^3}{-48 \times 20000 \times 44}$$

$$y_{max} = \frac{35703753.6}{-42240000}$$

$$y_{max} = -0.581\ mm$$

The stress in the leg frames is > 96.52 MPa and the maximum deflection is -0.581 mm. The negative shows that the deflection is in an inward direction.

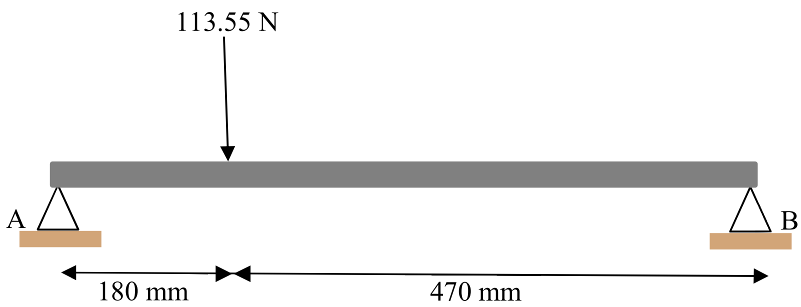
A rule of thumb in the Codes of Practice in Beam Design is the fact that maximum deflection is limited to the beam's span length divided by 250, for example a 5m span beam can deflect as much as 0.02 m without adverse effect [25].

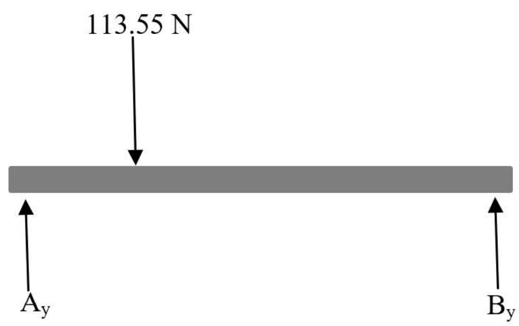
The span of the upright is 0.68 m and can deflect as much 0.00272 m without adverse effect. This means the deflection must not go beyond 2.7 mm or there would be structural damage.

This maximum deflection calculated is less than 2.7mm.

In order to draw the shear force diagrams and bending moment diagram, the reaction forces must be calculated:

Based on Figure X and Y, the free body diagram is as follows:



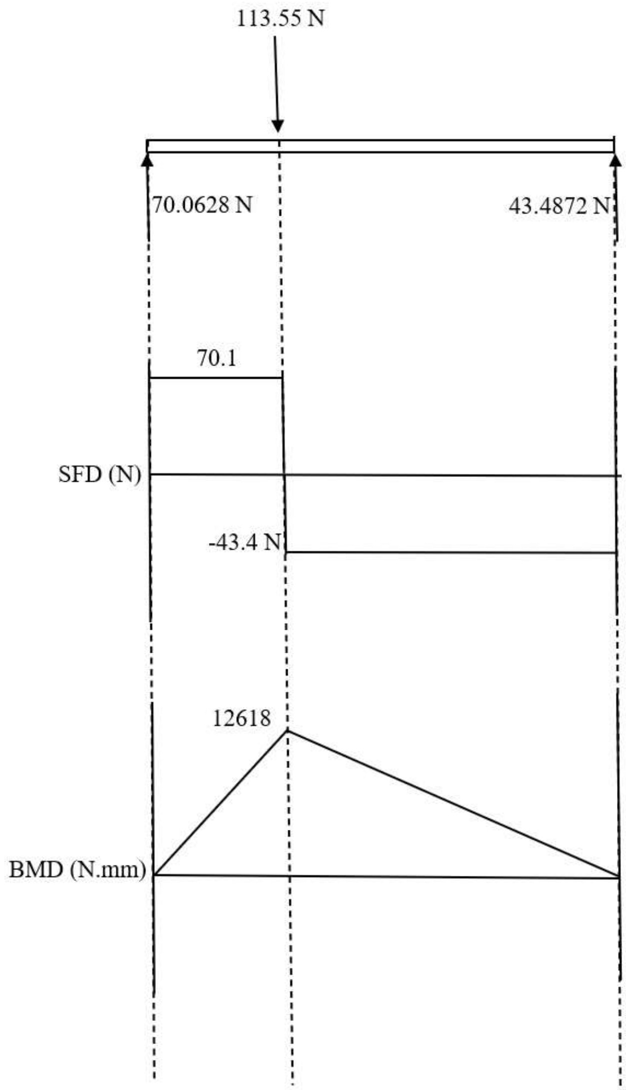


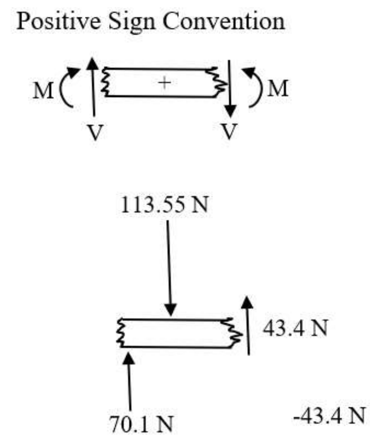
$$\sum F_y = A_y + B_y = 113.55N$$

$$\sum M_A = 113.55(180) = B_y(470)$$

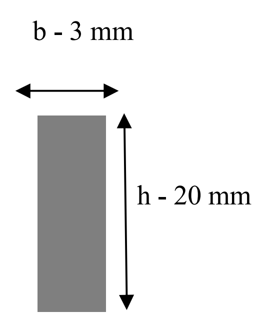
$$A_y = 70.0628\ N$$

$$B_y = 43.4872\ N$$





Consider the applied stresses:



Normal Stresses:

Maximum Moment is given by 12618 N.mm.

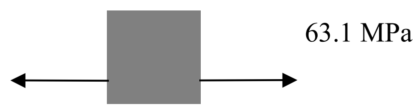
For normal bending stress applied on a solid rectangular section:

$$\sigma_x = \frac{6M}{bh^2}$$

$$\sigma_x = \frac{6(12618)}{(3)(20)^2}$$

$$\sigma_x = \frac{75708}{1200} = 63.1\ MPa$$

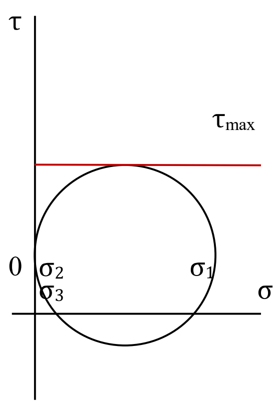
There is no torsional stress and transverse shear stresses can be ignored. Consider the stress element below:



$\sigma_1 = 63.1$ MPa

$\sigma_2 = \sigma_3 = 0$

Mohr's Circle to determine c:



$$\tau_{max} = \frac{\sigma_1}{2} = \frac{63.1}{2} = 31.55 MPa$$

This bamboo beam is expected to experience ductile failure.

Using the Maximum Distortion Energy Theory (MDET):

Design equation is given by:

$$n = \frac{S_y}{\sigma_e}$$

$$where\ \sigma_e = (\sigma_1^2 - \sigma, \sigma_2 + \sigma_2^2)^{\frac{1}{2}}$$

$$\sigma_e = (31.55^2 - 0 + 0)^{\frac{1}{2}} = 31.55\ MPa$$

The design is safe when $\sigma_e < S_y$ and distortion occurs when $\sigma_e \geq S_y$

According to [28], S_y for bamboo is given by 44MPa

$$n = \frac{S_y}{\sigma_e} = \frac{44}{31.55} = 1.39$$

The design is safe.

A safety factor between 1.3 and 1.5 is recommended for use with a highly reliable material where loading and environmental conditions are not severe and where weight is an important consideration [26].

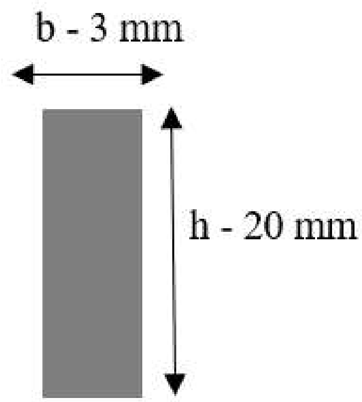
Fatigue Analysis

Cyclic Loading Type – Repeated

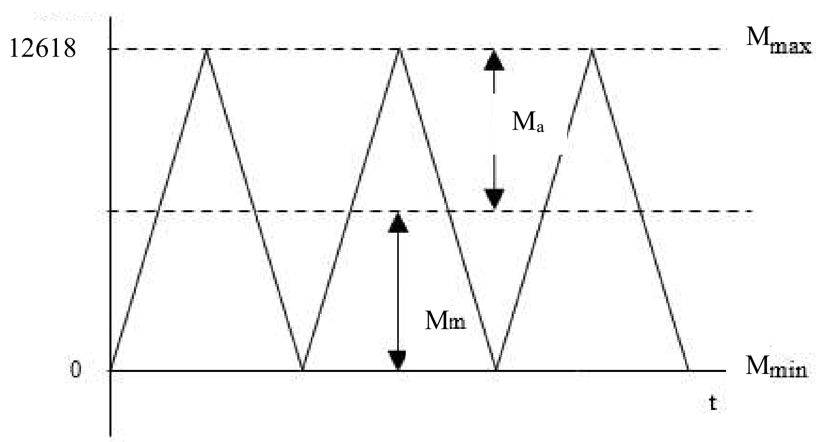
Force - 113.55 N

Bending Moment – 12618 N.mm

Cross Section:



Repeated Loading – M ~ (0, 12618) N.mm



Stress analysis

Stress type – Bending

$M_m = M + 0$

$M_a = M - 0$

$M_a = M_m = 12618$ N.mm

$$\sigma_a = \frac{6M_a}{bh^2} = \frac{6(12618)}{3(20)^2} = 63.1\ MPa$$

$$\sigma_m = \frac{6M_m}{bh^2} = \frac{6(12618)}{3(20)^2} = 63.1\ MPa$$

Von Mises Normal Stresses

$$\sigma'_m = (\sigma_m^2 + 3\tau_m^2)^{\frac{1}{2}} = (63.1^2 + 0)^{\frac{1}{2}} = 63.1\ MPa$$

$$\sigma'_a = (\sigma_a^2 + 3\tau_a^2)^{\frac{1}{2}} = (63.1^2 + 0)^{\frac{1}{2}} = 63.1\ MPa$$

Material Properties

Material: Bamboo

S_y – 44 MPa

S_{ut} – 45 MPa

Specimen Endurance Limit, s'_e= 30 MPa [27]

Marin Correction Factors	k_a	1.811 (Machined)
	k_b	1.019
	k_c	1 (bending)
	K_d	1
	K_e	1
	k_f	1 (No miscellaneous effects)

Endurance Strength, $S_e = k_a k_b k_c k_d k_e k_f S'_e$

$$S_e = 1.811 \times 1.010 \times 1 \times 1 \times 1 \times 1 \times 40$$

$S_e = 73.1644\ MPa$

Failure Criterion – Modified Goodman

$$s_m = \frac{(s_y - s_e)s_{ut}}{Su_t - S_e} = \frac{(44 - 73.1644)(45)}{45 - 73.1644} = 46.5978\ MPa$$

$$s_a = s_y - s_m = 44 - 46.5978 = -2.598 MPa$$

Slope of reference line = $r_c = s_a/s_m$ = -2.598/46.5978= -0.0557

Slope of load line = $r_L = \sigma_a/\sigma_m = 1$

Since $r_L > r_c$, failure will be by fatigue.

$$\frac{1}{n} = \frac{\sigma_m}{s_{ut}} + \frac{\sigma_a}{S_e} = \frac{63.1}{45} + \frac{63.1}{73.1644}$$

$$\frac{1}{n} = 2.265$$

$$n = 0.44$$

This low fatigue factor of safety indicates that the structure fails well before its design life is achieved. Increasing the thickness of the uprights would increase the factor of safety and increase the life cycle of this product.

Chapter 4: Manufacturing Process

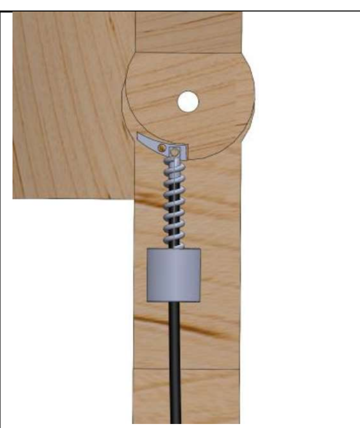
This chapter outlines how the exoskeleton brace can be manufactured in a workshop. The starting material for the uprights would be processed bamboo, that is bamboo that has undergone the fabrication steps outlined in the section 3.2.4 of chapter 3.

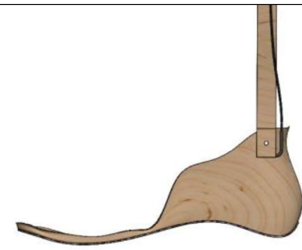
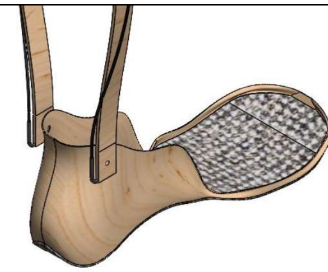
Chapter 5: Simulation and Results

Solidworks ® does not contain the bamboo material and therefore in order to complete the analysis with this software, a custom material had to be created and the various parameters for bamboo were entered into the application and the appearance that best resembled bamboo was selected.

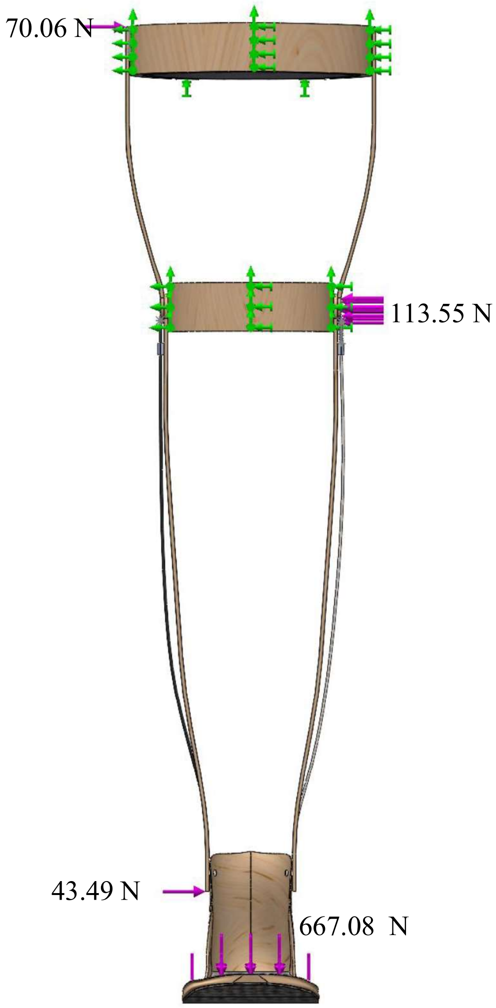
Solidworks Model:

Components of the 3D Model

Knee Locking Mechanism	

<table>
<tr><td rowspan="2">Ankle Foot Orthoses</td><td></td></tr>
<tr><td></td></tr>
<tr><td>Rigid thigh posterior band and tibial knee band</td><td></td></tr>
</table>

Static Analysis in SolidWorks

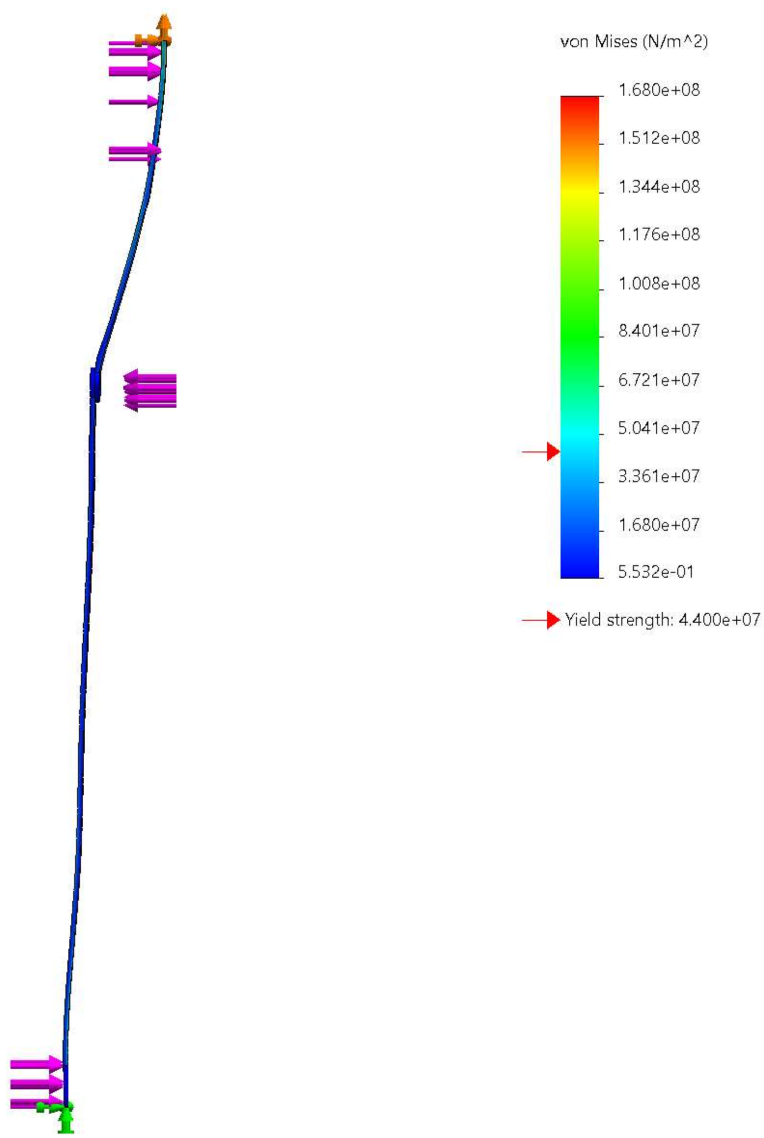


In order to carry out the static analysis on the structure, the thigh and knee bands were constrained using the SolidWorks fixtures advisor, denoted by the green arrows. The forces that were determined in chapter 3 were applied in this study. They are showcased in figure x. The force acting directly on the foot is the weight of the individual who would be using the KAFO.

When the study was run, the meshing tool run into errors when attempting to mesh the smaller components such as the spring and the swept model of the cable.

To avoid meshing errors, the static study was run on critical locations of the individual parts of the model.

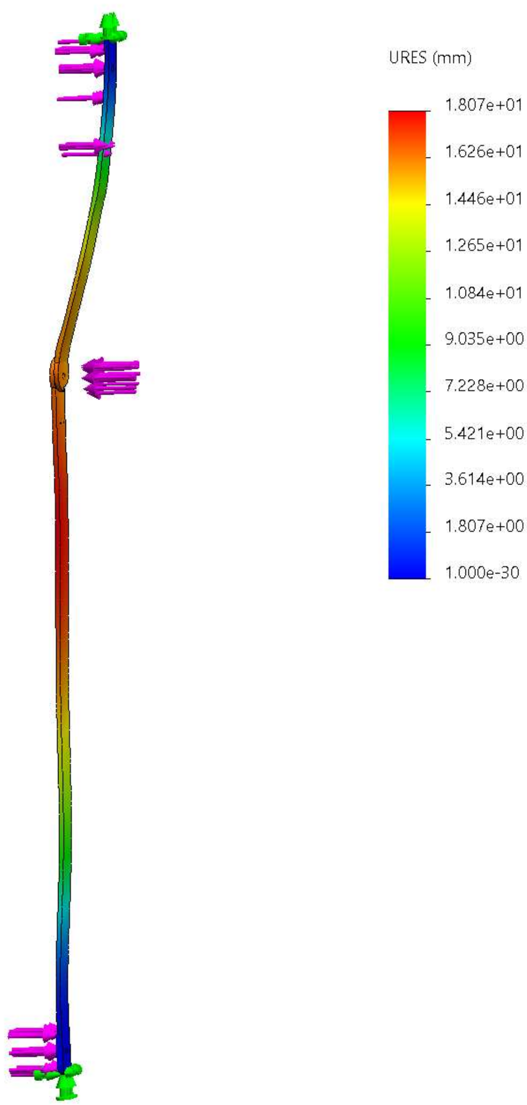
Stresses acting on the Uprights



The yield strength as calculated by Solidworks is 4.400e+07 N/m^2 which is 44 MPa. The von Mises stress calculated in the analytical section came up to a value of 63.1 Mpa which differs from the Solidworks ® value by only 19.1.

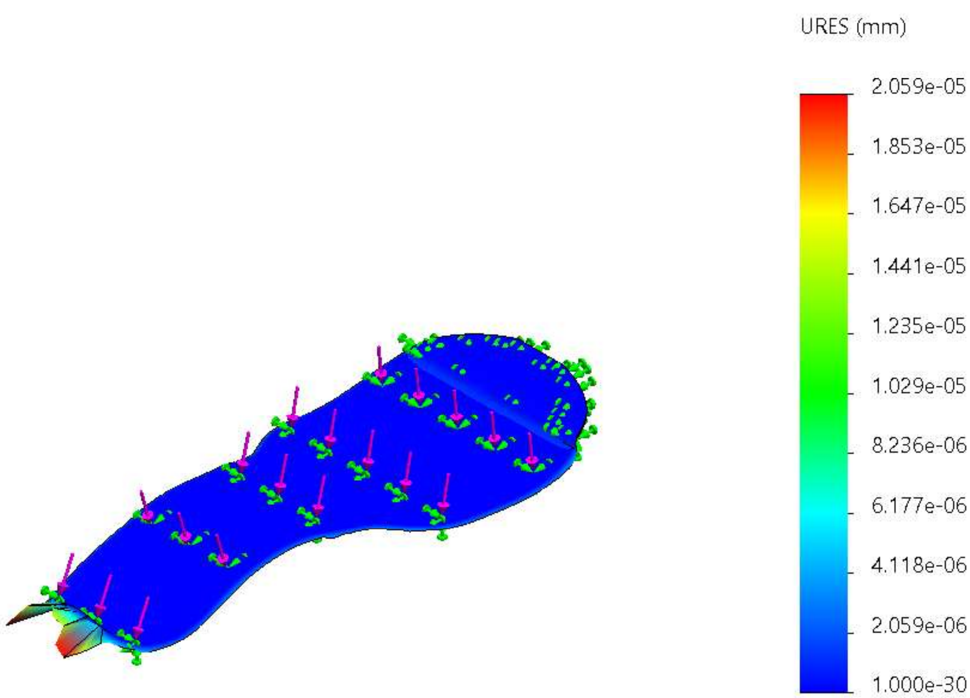
It can be concluded that it corresponds with the hand-calculated values.

Deformation



The above graph showcases the areas that are prone to deformation with forces acting on the uprights. The knee joint and the part that directly touches the calf has the highest deformation and this is most likely due to the holes and non-uniform shape around the knee joint. The highest deformation is 1.8mm which is still below the cut-off mark of 2.7mm as calculated analytically and is therefore acceptable.

Deformation of AFO Support



It can be observed that there is very little deformation on the sole of the foot support with the static analysis. The highest deformation occurs where the sole meets the back of the ankle support and this is because they are not continuous but rather are joined.

Chapter 6: Conclusion and Future Recommendations

It is evident that bamboo can be used to replace carbon fibre due to its properties, low cost, availablity, its harmful effect on the environment and more. Although stainless steel is a good alternative for the uprights, it cannot surpass bamboo's strength to weight ratio and neither can it surpass bamboo's low cost and malleability. Bamboo can be used for both the supports and the uprights however stainless steel cannot be used for the supports due to its hardness and its lack of pores to emcourage breathability.

Bamboo also leaves behind the smallest carbon footprint and replacing all existing KAFO's materials with bamboo would contriubute towards reducing the effects of global warming and the emission of greenhouse gases. This project involved a careful procedure of combing through research and selecting the better features of several existing KAFO designs and combining the top features in order to settle with this design which is both aesthetically pleasing and lightweight.

A future recommendation for this design would be to include a way to make the design extensible such that a user who buys this as a teenager can continue to use it and extend the height as it grows. It would save the user a lot of cost to be able to keep the KAFO for a long time without having to replace it.

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Appendix

Solidworks Drawing of the Upright