DESIGN AND DEVELOPMENT OF ADJUSTABLE RANGE OF MOTION KNEE AND ELBOW BRACES

A Final Year Project Progress Report

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Bachelors of Mechanical Engineering

by

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ABSTRACT

Our project is focused on the design and development of wearable post-operative Knee and Elbow brace with adjustable range of motion for upper and lower limb rehabilitation. In order to in cooperate adjustable range of motion, a unique design was developed that includes two locking pins which makes sure the motion of the limbs stays in between those pins with the increment of 10°. Since the two joints (knee and elbow) are different from each other, the design was slightly modified accordingly. Stress analysis was carried out on locking pins and central pin for both designs on ANSYS. It also has a slider mechanism which makes sure that it can be worn by people of different heights. It also contains an angle sensor which records motion of the patient over the time which could be used by therapists to see the patient's progress.

PREFACE

Elbow and knee joint of human body are frequently involved while carrying out daily activities and also knee joint is involved in carrying the weight of the body making them more vulnerable to injury. Thus, in that case, they can be treated in number of ways.

In Pakistan traditional bone settling methods are used. In backward areas, the condition is much worse where a bone is set with mere instincts and then set with the help of sticks but this practice leads to severe complications and different form of deformities which may lead to amputation. Other bone setting methods such as external cooptation or orthopedic casts are very common because this method is rather cheap and effective in some of the cases but these methods lead to mal-union, delayed union or non-union, fracture disease and soft tissue injury.

Hence, the solution was to develop a multi-purpose brace that is easy to use and tackles all the complications related to external cooptation. Thus, our project was focused around this and was to develop locking mechanism of knee and elbow brace which will allow certain degree of motion with 10°increments allowing speedy recovery of patient and avoid other complexities. It also keeps a data base of angles of the motion of limbs with the help of angle measuring sensor which could be used by the therapists.

ACKNOWLEDGEMENTS

While working on this project, everyone we came across were encouraging and helpful. In particular, we would really like to thank Sir Ahmed Raza, for his exceptional support and cooperation. He helped us in every single step of the project whether it was research work or fabrication of the prototype. Without him, it would not have been possible to complete the project.

We also want to thank all the staff of DMRC for their time and effort during the manufacturing of the device.

In the end a very special gratitude to our supervisor Dr. Nabeel Anwar who has guided us at every single step. We have not only learnt the technical and theoretical aspects of the project under the supervision but also the way of handling pressure situation.

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ABBREVIATIONS

ROM	Range of Motion
ACL	Anterior cruciate ligament
UCL	Ulnar collateral ligament
MCL	Medial collateral ligament
PCL	Posterior cruciate ligament
LCL	Lateral collateral ligament

NOMENCLATURE

M	Moment
r	Moment arm
F	Force applied
m_t	Total mass that needs to be supported by the brace
g	Gravitational acceleration
l_a	Length of forearm
l_h	Length of hand
COM	Center of mass of lower arm
σ_{max}	Maximum tensile stress
τ_{max}	Maximum shear stress
J	polar moment of inertia

MOTIVATION

Being in good shape is one of the most important aspects of human life and it depends on how flexible and healthy are your joints and bones. In human body, the joints like hip joint, knee joint bear the most of the weight of the body. Moreover, joints like elbow joint are frequently used in common day chores. Due to these reasons, these joints are likely to get fractured more. In case of fracture, they need to be treated as quickly as possible. In Pakistan, a number of methods are used. In rural areas, traditional bone setting methods are generally used where a bone by is set with mere instincts and then set with the help of sticks but this practice leads to sever complications and different form of deformities which may lead to amputation [6]. In urban areas, different orthopedic casts and braces are employed, mostly fixed type but these type of management are not only expensive but also leads to joint stiffness, muscle atrophy and other complications thereby prolong casting and thus, longer time in recovery. Hence the solution was to develop a multi-purpose brace that is easy to use, cheap, good quality and allows certain degree of motion to avoid joint stiffness and tackles all other complications.

CHAPTER 1: INTRODUCTION & LITERATURE REVIEW

Knee and elbow joints are very crucial to general movement of our body and also for our day to day work. From walking to lifting something, every motion is possible because of these joints. Setting aside the importance, these joints are also very prone to injury and damage.

One of the most prevalent form of arthritis in the knee is Osteoarthritis (OA), and it effects the elderly the most, making the simple tasks a burden for them. In a recent study it was found that people over the age of 45 in USA had knee OA [1]. For its treatment, many non-invasive methods are being used, and one of them is to use knee brace. In many studies it has been demonstrated that the use of stabilization braces reduces pain and improves gait performance. In North America, more than 60% people require Trauma Care [2]. Between year 2008-2009 major musculoskeletal traumas were caused by accidents (79%), of which (38%) were result of fall or vehicle collision (41%) [3]. after hospitalization and during recovery phase, patients have to follow a home-based exercise which is different for each specific case. Not following these exercises results in chronic pain, limitation in range of motion or other issues. 55-75% patients retain limb impairment after 3-6 months [4]. Thus, these braces help in rehabilitation process outside the clinical settings providing effective results and preventing other unresolved issues. In the case of elbow, after surgery or minor injury braces are very helpful in the rehabilitation process as it decreases the risk of venous stasis or other regional pains as it allows to elbow to move only within a safe ROM [5].

In our project we are tackling only the one directional motion of the knee and elbow which is Extension and Flexion. Rotational motion is restricted

1.1 KNEE JOINT

Knee joint is made up of 3 main bones, Femur (upper leg), tibia and fibula (lower leg) and the kneecap (Patella)

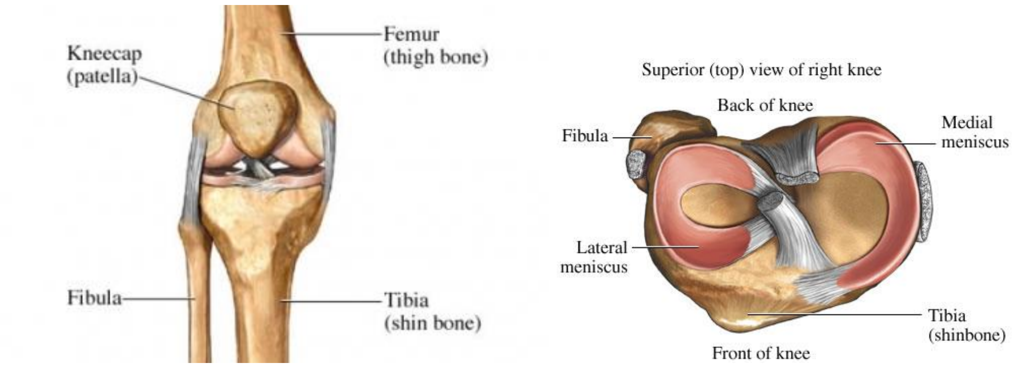

Figure 1: (left) Knee joint bones (right) Cross Sectional view of Knee joint

There are four ligaments in knee to provide the joint stability and prevent it from excessive movement [10] [11]

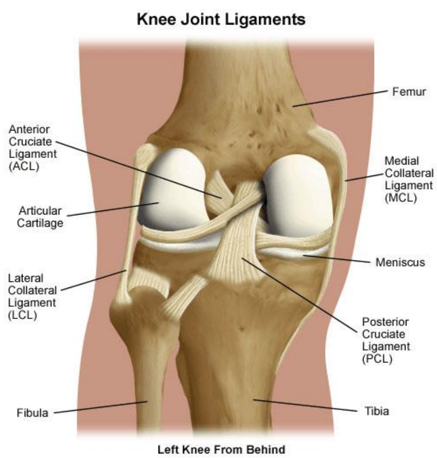

Figure 2: Knee joint ligaments

ACL - Anterior cruciate ligament: *Stops tibia from going forward*

PCL - Posterior cruciate ligament: *Stops tibia from going backward*

MCL - Medial collateral ligament: *Stops inward motion of the knee joint*

LCL - Lateral collateral ligament: *Stops outward motion of knee joint*

1.1.1 KNEE RANGE OF MOTION

Range of motion for a knee joint is as follows [12]

Flexion angle | 120-150º

Extension angle | 0-10º

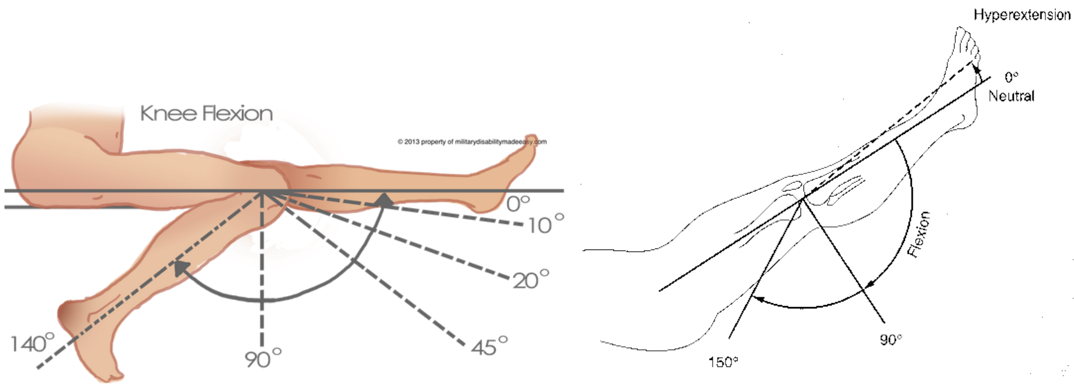

Figure 3: (left) Knee Flexion angle (right) Hyperextension in knee joint

1.1.2 KNEE PROBLEMS

In following section a few knee related injuries are discussed in which knee braces are used in rehabilitation period

1.1.2.1 MENISCUS INJURY [14]

Meniscus issues regularly identified as getting a grinding sensation in the knee. A meniscal damage can cause pain and swelling, numerous people decide on surgery to evacuate torn bits. Substantial vertical compressive burdens can affect the healing process.

Recovery:

A limited and gradually increasing range of motion is used with minimum resistance for the recovery of the joint.

1.1.2.2 LIGAMENT PROBLEMS

ACL injury (Anterior cruciate ligament) [15]

ACL injury is the most common injury in sports involving running and jumping such as football and basketball. Women are most likely to suffer from ACL injury because knee joint is looser in women

ACL repair is very difficult as it can't be sewn together, it is reconstructed with another borrowed tendon.

PCL injury (Posterior cruciate ligament) [16]

PCL is very similar to ACL and occurs when a sudden jerk or force is applied on the knee, such as falling on knee and getting pressed against something in a vehicle accident. PCL injuries make up less than 20% of total knee ligament injuries [16]

MCL & LCL injury (Medial and Lateral collateral ligament) [17]

Often known as collateral ligament sprain occurs with a stretch to the ligament or a tear in it. It occurs with a sudden force to the wither side of the knee is applied which tears or stretches the ligaments. It is very common is contact sports such as boxing or UFC. [20][21]

1.1.2.3 ARTHRITIS

Arthritis is an inflammation of the joints, which occurs with the breakdown of the cartilage with age. More than 10% of the adults over the age of 60 years are affected by it [18]. Arthritis is also due to body weight. People with BMI more than 30 have 4 times more chances to develop arthritis. [19]

1.2 ELBOW JOINT

Elbow joint is made up of three bones. Humerus or upper arm bone and two forearm bones Ulna and Radius. It is a simple hinge joint allowing extension and flexion [23]

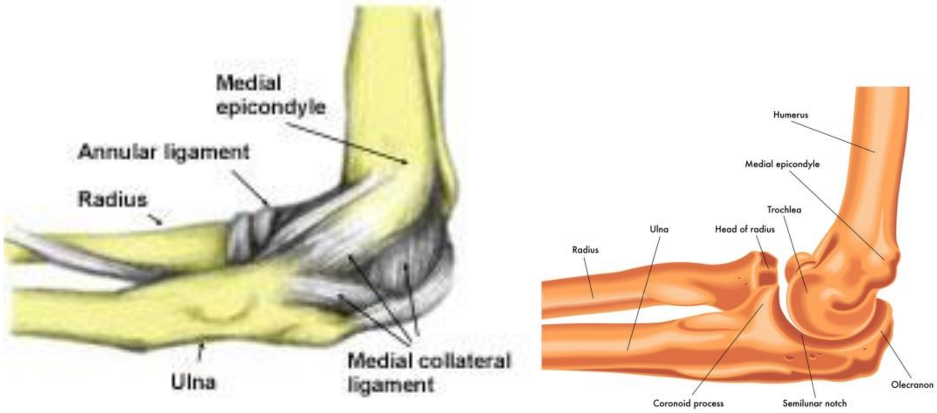

Figure 4: (left) Elbow joint ligaments (right) Bones in Elbow joint

There are three main ligaments in knee to provide the joint stability and support. [23]

MCL – Medial Collateral Ligament

Also known as ulnar collateral ligament, contains two bands, posterior and anterior.

LCL - Lateral collateral ligament

Also known as Radial Collateral Ligament. A small thin band that goes from the base of Epicondyle to annular Ligament

Annular Ligament

A fibrous band that is around the head of the Radius bone. Keeps contact between Radius and Humerus

1.2.1 ELBOW RANGE OF MOTION

Range of motion for an elbow joint is as follows [22]

- Flexion angle | 140-150º
- Extension angle | 0-10º

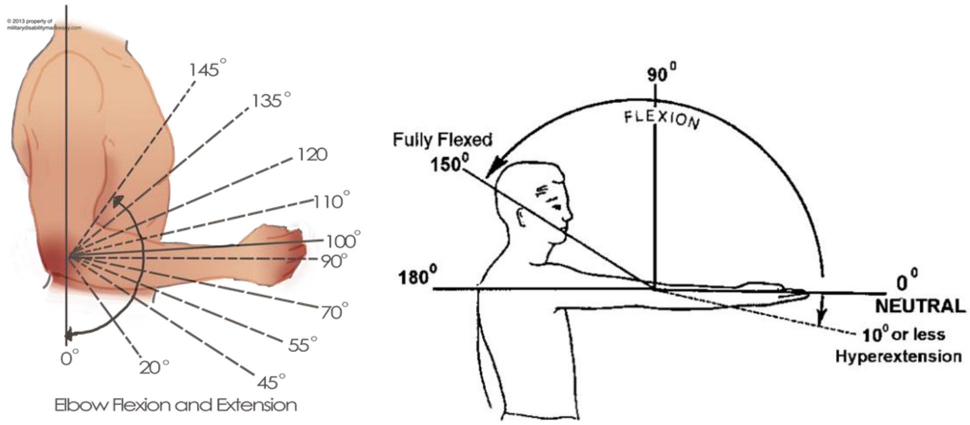

Figure 5: (left) Elbow range of motion (right) Hyperextension in elbow

1.2.2 ELBOW PROBLEMS

A few of the Elbow problems which require an elbow brace during the recovery period

1.2.2.1 BICEP TENDON TEAR [28]

A Bicep tendon tear can be either partial or complete. In partial tear, only the soft tissue is damaged in the tendon is not completely damaged. While in complete tear, tendon is detached completely from the bone. Surgery is required to reattach the tendon to the bone to regain full arm strength.

1.2.2.2 LATERAL EPICONDYLITIS OR TENNIS ELBOW [29]

As the name suggests, it is usually caused playing tennis or other related sports that involve the use of racquet. A quite painful condition which is caused due to inflammation in the tendons that join the forearm muscle. It happens because of the repetitive motion which leads to tenderness and pain on the outside of elbow.
Treatment

Physical therapy. Specific exercises for strengthening the muscles

Bracing.

1.2.2.3 OSTEOARTHRITIS [30]

It occurs when the cartilage between the elbow joints is damaged or worn out. It may happen because of fracture or dislocation but the most common cause of osteoarthritis is age and activity. It effects the parts of the joints that bear weight

1.2.2.4 UCL (ULNAR COLLATERAL LIGAMENT) INJURY [31]

Ulnar Collateral Ligament is main static constraint of the elbow. It consists of an anterior and a posterior bundle, and a transverse ligament which is also known as the Cooper ligament [32]. Injury to these ligament leads to functionality impairment and secondary intra-articular damage to the elbow

Treatments

- Bracing
- Operative

1.3 CLASSIFICATION OF BRACES

1.3.1 CLASSIFICATION OF KNEE BRACE:

There are four main types: prophylactic, functional, rehabilitative and unloader brace while there is another one known as knee sleeve which may not be technically described as a brace but sometimes referred as the main idea of the knee brace is that it doesn’t interfere with normal functioning of the knee or increase the risk of injury to any other part of the lower body.

1.3.1.1 PROPHYLACTIC BRACE:

These braces are used for sport injuries, reducing knee stiffness, protecting MCL and supporting LCL, ACL, and PCL. These braces consist of hinges, bars and adhesive straps. The purpose of this brace is to protect the knee joint prone to damage due to contact by the absorbing the valgus forces to knee. Moreover, they help in protecting MCL [37]. One study shows that they are capable of providing 20-30% in stiffness of knee and MCL strain relief [38].

Figure 6: Prophylactic Brace

1.3.1.2 FUNCTIONAL BRACE:

These braces are used for sports injuries, in rehabilitation, after surgery and following ACL surgery. These braces provide support as injury of knee heals. There are further types of functional brace and the selection of which to be used depends upon whether MCL is being treated or ACL or PCL or LCL. In any type, they apply certain forces in order to support the affected ligament. Doctors prescribe these braces to patients depending upon the severity of the injury. In case of mild to moderate injury in collateral ligament, the most common brace is made of neoprene material and has metal hinges on either side of the knee. While in server injury, the brace has a rigid frame along with hinges if necessary.

They are basically designed for the reduction of instability of knee after the injury and are suggested for the people who take part in activities like jumping, twisting, pivoting or cutting etc. but these braces are not suitable for the people with very unstable knee as it won't be helpful for them and the knee will feel unstable when exposed to high force. Moreover, patients complaint that they are hot and uncomfortable and irritates the skin (mainly due to the material of the brace)

Figure 7: Functional Brace

1.3.1.3 <u>REHABILITATION BRACE:</u>

These braces are used in rehabilitation, for sports injuries, after surgery and movement control. The design of these braces are such as to the limit the movement of the knee while it is healing after an injury. They provide protection to injured ligaments as well as controlling the movement of knee in rehabilitation phase for injured ACL, PCL, MCL, LCL, or meniscus. This brace has one of the biggest advantage that it allow space for swelling, can be removed at any time so that examination of knee can be done and also allows the knee to move in controlled range of motion. Rehabilitative braces are made up of rigid bars on both sides with adjustable hinges at the knee along with foam liners covering the calf, thigh and knee. They are usually adjustable in size and off the shelf.

Figure 8: ROM knee brace

1.3.1.4 UNLOADER BRACE:

These braces are used for knee pain, knee osteoarthritis, rheumatoid arthritis and stability. People with medial compartment knee osteoarthritis employ these braces as they remove pressure from the affected joint by putting pressure on the thigh bone which results in bending of knee from painful area. Patients who are due knee replacement surgery would find this brace helpful.

Figure 9: Unloader knee brace

1.3.1.5 KNEE SLEEVES

These brace are used for knee pain, stability and for reduction of strain in knee. It is technically not a knee brace but it is one of the cheapest type of knee support which is worn by average athlete and exerciser like joggers, walkers, tennis players' etc. knee sleeves provide compression around knee joint providing some knee stability.

Figure 10: Knee Sleeve

1.3.2 CLASSIFICATION OF ELBOW BRACES:

The ability to place the hand at varying distances is achieved with the help of the elbow and the middle joint of the upper limb along with changing the length of limb so that it can move in the space (flexion-extension) and also rotating the hand (pronation-supination) helps to grasp the object. [39][40] Per articular muscles and the soft tissues in the elbow move in a way to maintain joint homeostasis. The elbow is likely to subject to stiffness if immobilized for long time because of the complexity of neuromotor, muscular and articular muscles. Thus, in order to avoid to this, rehabilitation phase needs to be started right after the operation. The main idea of this is to protect the joint from being displaced subjected to tension during motion. Moreover, the objectives of rehabilitation is different in each phase. During inflammatory phase, it is done to control swelling and pain while in inflammatory phase, the aim is to recover muscle flexibility and ROM and in remodeling phase, the objective is recovery of neuromuscular control. One of the simplest and ready-made brace are splints consisting of cardboard or cork held in place with help of elastic bands. Due to flexibility property of cork, these cork braces allow small movement and are preferred as it doesn't allow excessive immobilization of joint.

There are several different types of elbow braces depending upon their usage. According to Jacobs, [3] some of the types of braces are:

Protective braces	Fixed
	With locked articulation
Braces with adjustable ROM	Limitation of flexion/extension
	Limitation of pronation/supination
Mobilization braces	Dynamic
	Static/progressive

Table 1: Classification of Elbow Braces and their further types

1.3.2.1 PROTECTIVE BRACES

This type of brace doesn't allow the elbow to move altogether. They are used in the post-operative or post injury periods as they help in reducing pain and edema in inflammatory phase. They have further two types: hinged and unhinged. The difference in these two is that one allows to lock the elbow at different angles while the latter doesn't give this freedom. The main disadvantage of this brace is that it cannot be used for long time as it would result in joint stiffness.

Figure 11: Protective Brace

1.3.2.2 BRACES WITH ADJUSTABLE ROM

These braces allow certain degree of motion in flexion-extension movement. In this brace, you lock the brace at certain angle of flexion and extension and the elbow you can move in between those locks. They are used in post-operative phase of rehabilitation so that the elbow can undergo early movement along with protecting the healing tissues. While treating the fracture with brace, it must compensate the possible presence of collateral ligament lesion and historical healing phase[4] since this brace allows the elbow to move in certain range of motion, it doesn't allow the joint to get stiff thereby reducing the recovery period, pain and swelling in the joint. This type of brace has the ability to perform all kinds of functions like immobilization brace when it is fully locked, a brace capable of providing different ROM and a mobilization brace when it is locked in tension. This is made possible by its ability to control articulation fixed near the axis of rotation which basically is involved in transfer of force on the forearm.

Figure 12: ROM elbow brace

1.3.2.3 MOBILIZATION BRACES:

These braces use the viscoelastic properties of soft tissues by keeping the phase of rest in tension. The alternation of the soft tissues takes place with the help of these small increase in ROM held for long period. One disadvantage of dynamic brace is that as it produces continuous stimulation, over the time, it can lead to inflammatory process. While on the other hand static braces allow biological adaption of the tissue, exerting stimulation alternated with rest and thus preferred.

Figure 13: (left) Dynamic Brace (right) Static Brace

CHAPTER 2: METHODOLOGY

2.1 DESIGN OF THE WEARABLE KNEE & ELBOW BRACE

As presented in the previous chapter, a good option for post-operative brace is Adjustable ROM brace as it does not require much physician's time to explain its working and to assess the results.

2.2 GENERAL DESIGN SPECIFICATIONS

A ROM knee & elbow brace has two major functions:

1) To restrict the motion to a certain degree of motion.

2) To bear the leg and elbow weight when the brace is in locking position.

2.3 CAD DESIGN OF THE BRACES

Following are the CAD designs of the knee and Elbow braces.
In the case of elbow, only one brace is used per elbow, while in the case of knee two braces are used because there is a lot of weight to be bear by the braces

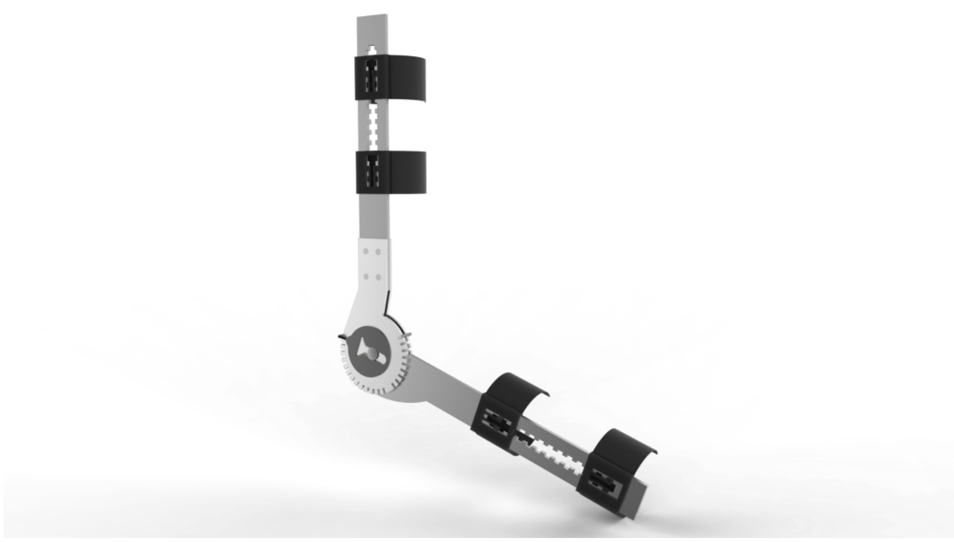

Figure 14: CAD design of Elbow Brace

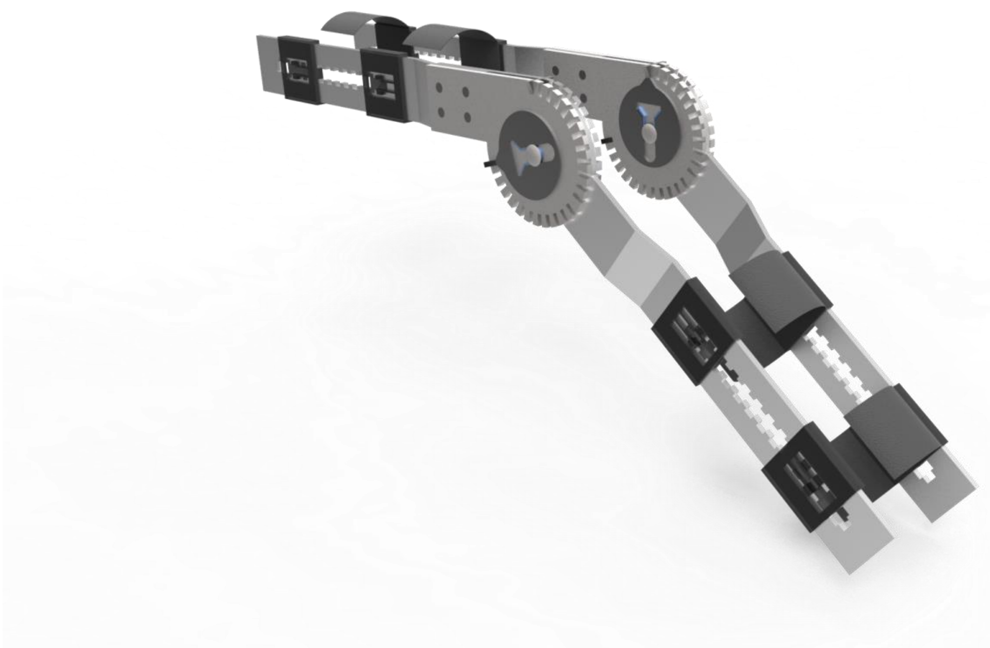

Figure 15: CAD design of Knee Brace

2.4 ADJUSTABILITY IN SIZE

For the adjustable size a moveable strap slider mechanism is designed so that fastening position of the strap can be adjusted depending on the anthropometric diversity and comfort of the patient.

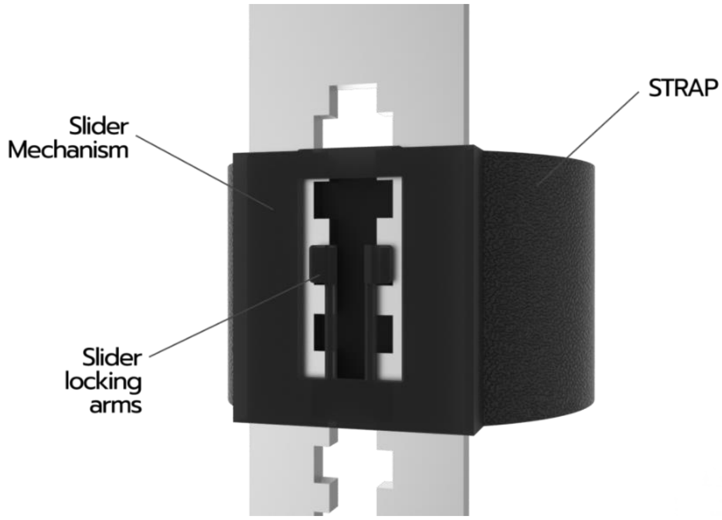

Figure 16: Adjustable Strap Slider

2.5 HINGE TYPE

The humerus, ulna and radius bones that act as a hinge form the elbow joint. While the ulna and the radius bones slide backwards and forwards along the head of the humerus, the center of rotation migrates. Displacement of the pivot point results from the 30 nature of the bone structure. Due to this fact, a polycentric hinge can be used to mimic natural elbow motion [33].

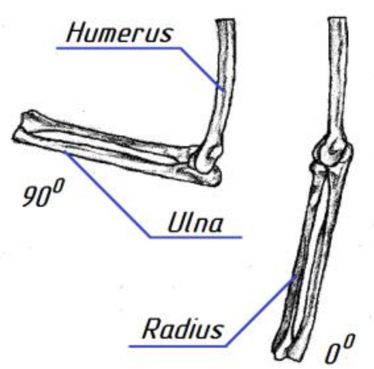

Figure 17: Elbow joint bones

Elbow motion. Although the polycentric hinge makes it relatively easy to move the arm [34], the primarily articulation of the joint is made by the ulnar-humeral coupling [35], and, therefore, the elbow can be represented as a single-axis hinge.

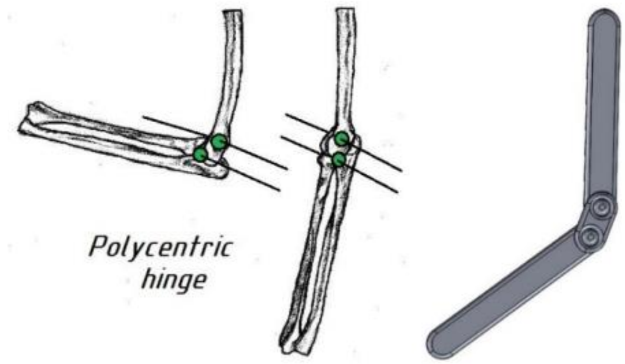

Figure 18: Elbow joint as a Polycentric hinge

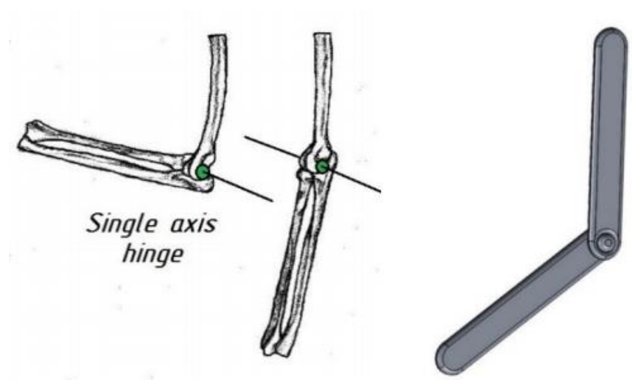

Figure 19: Elbow joint as Single axis hinge

Hence, **a single-axis hinge** was used for the design of the wearable mechatronic **elbow brace** and same is the case for **knee brace**

2.6 DOF MOTION OF THE BRACE

The main of the elbow braces is limited by the customized locking mechanism and mechanical stoppers that are coupled to the locking plates.

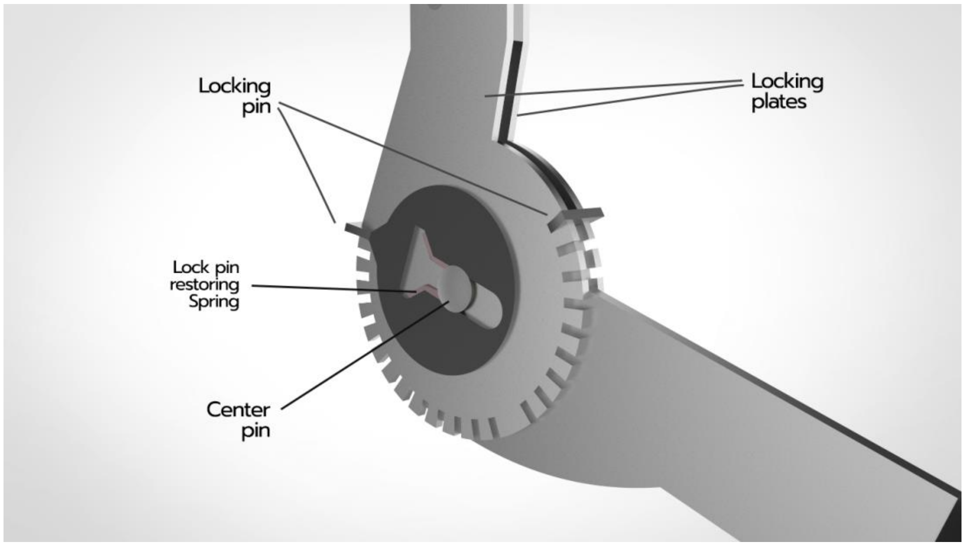

Figure 20: Locking Mechanism, Elbow Brace

Metal pins secured in the locking plates define the Range of motion for the brace. Knee brace allows Flexion and Extension from 0 to 110 Degrees with 10 Degree increment.

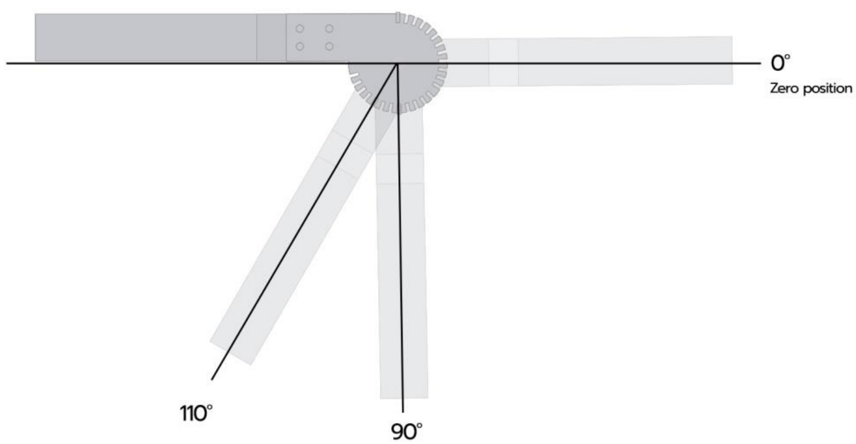

Figure 21: Range of motion of Knee brace

While Elbow brace provides flexion angles from -10 to 110 degrees while extension from -10 to 90 degrees

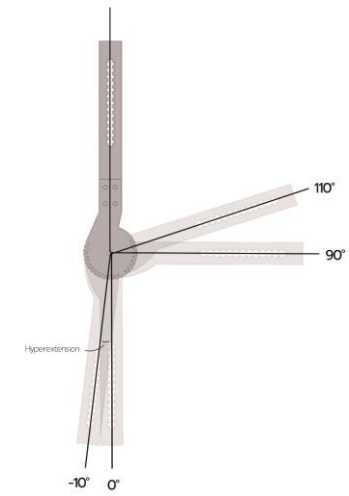

Figure 22: Range of motion of Elbow brace

2.7 LOCKING MECHANISM

The locking mechanism comprises of locking plates, locking pins and lock pin restoring spring

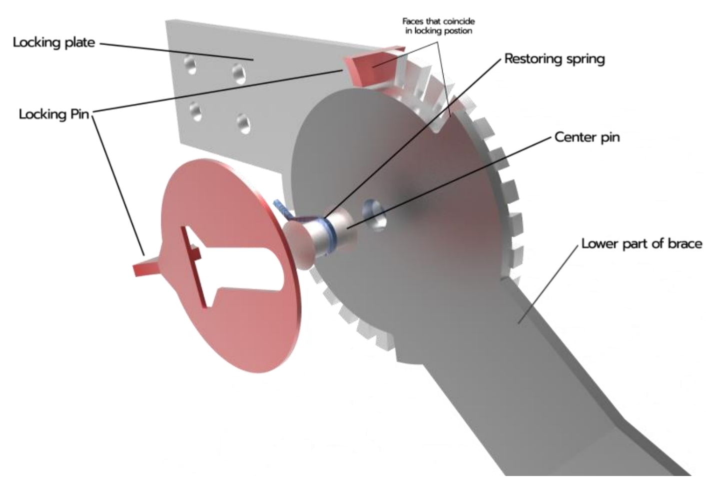

Figure 23: Exploded view of Locking Mechanism

In fig the red parts are the locking pins with a slot in them where the flat restoring spring goes.

In the locking plate, there are slots each at 10 degree increment, the locking pin goes in those slots and hence restricts the motion of the lower part of the brace depending on at which angle the locking pin is placed.

2.8 SENSOR

The main function of the sensor is to measure the angle of the motion in real time and store those values in SD card making a data base over the time which can later be used by therapists to see the patient's progress.

Following parts were used in the construction of the sensor.

1. Potentiometer
2. Arduino Nano
3. LCD module
4. SD card module
5. 9 volt battery

Schematic and Final circuit made using these components is shown in the following figures.

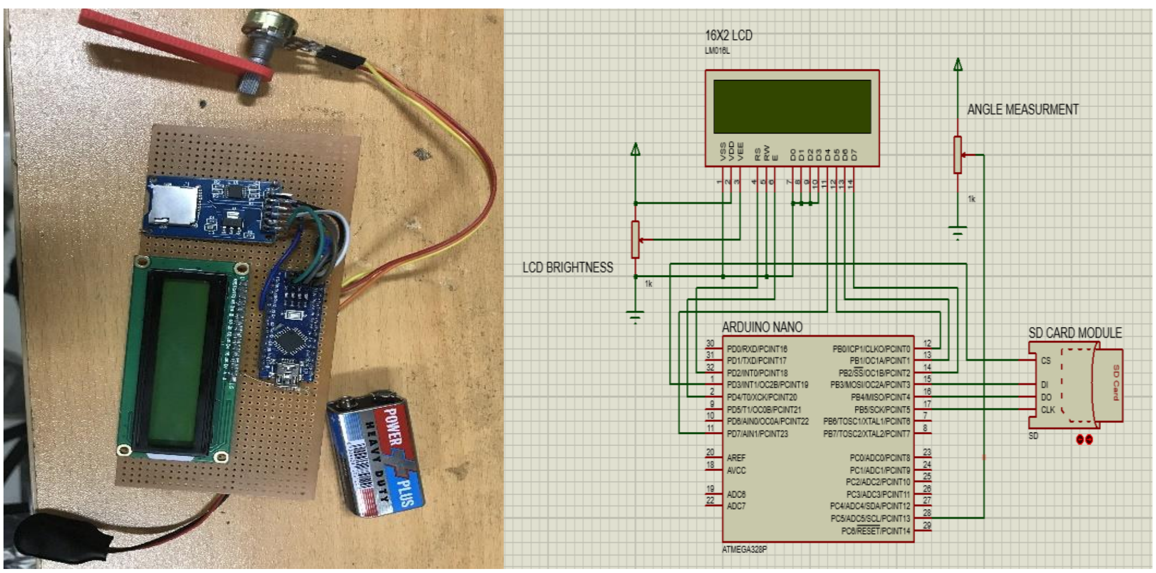

Figure 24: (left) Sensor prototype (right) Schematic

It works as follows: as the limb is rotated, the resistance of the potentiometer changes which results in changing the voltage across the terminals of potentiometer which is connected to arduino Nano, powered by 9V battery. Arduino is further connected to SD card module and LCD module. With the help of code (Appendix I) that is uploaded on the ardunio, this voltage change is related to the angles which is displayed on LCD screen as well as stored in the externally placed SD card in SD card module.

2.9 FORCE AND MOMENT CALCULATIONS:

2.9.1 ELBOW BRACE:

During rehabilitation phase, daily exercises play an important role in the recovery process. Therapist prescribe these assistive and resistive motions until patient can lift up to 1kg load. Thus the brace should be able to beat weight of lower arm, 1kg load and its own mass. In order to account for this, moment was calculated using following equation which would later be applied to the central pin:

$$M = r * F \dots\dots (1)$$

$$M = r * m_t * g \dots\dots.. (2)$$

Where

$$r = (l_a + l_h) * COM \dots\dots (3)$$

$$m_t = m_{forearm} + m_{hand} + m_{load} \dots.. (4)$$

m_t=total mass that needs to be supported by the brace.

$m_{forearm}$= mass of the arm

m_{hand}= mass of the hand

m_{load}=sum of mass 1kg load

l_a= length of forearm

l_h= length of hand

COM= center of mass of lower arm

g=9.8ms^{-2}

It might be noted that the mass of upper arm has not been included in the analysis. It is due to fact that the training in rehabilitation phase is conducted with patient sitting or standing and the upper arm is always stationary, thus it plays no role in moment.

We know that these values vary from person to person. In order to account for this diversity, brace should be able to cover most of the population i.e. up to 95^{th} percentile of the population. Values of these terms were obtained from [43]-[45] for male and female and are tabulated as follows:

Parameter	Male	Female
Lower arm length	0.312m	0.268m
Hand length	0.205m	0.189m
Lower arm mass	1.66kg	1.24kg
Hand mass	0.63kg	0.5kg
Center of mass for the lower arm and hand	31.8% (direction from fingers to elbow)	

Table 2: Anthropometric data for 95th percentile of the population

In order maintain the static equilibrium of the affected arm, the brace must supported at the center of mass of the forearm

Substituting values from table in eq. (2), the moment calculated for male was 5.3Nm while for female it was 3.9Nm.

Although, it was found while studying [46], [47], [48] that the torque value during daily activities is more than his value since elbow movements are not isolated from upper limb movement, thereby influencing the torque produced by the elbow during flexion-extension movement. Torque produced by the elbow to hold forearm at angle of 90 is 3.1Nm [46]. Torque measured during activates of daily living was 5.8Nm, max torque while reaching in the range of 0 -90 was 7Nm and in range of 90-120 it was 5Nm [47]. Range of torque produced by elbow in flexion-extension combined with rotation was from 3.88Nm to -3.22Nm.

Thus, for the brace to help the patient in the later stage of rehabilitation as well during daily activities, it was decided to use max value of 10Nm for analysis.

The central pin is basically a solid cylinder subjected mainly to shear stress. Since aluminum is ductile, it will start deformation when max shear stress will reach yield point. The max shear stress was calculated by using the following formula and it came out approximately to be 10MPa.

$$\tau_{max} = \frac{M * r}{J} \dots \dots (5)$$

While in case of locking pins force would act in case of locking position and it will deform when the max tensile stress exceeds yield point. The stress was calculated was from following formula and came out approximately to be 0.1kPa.

$$\sigma_{max} = \frac{F}{A} \dots \dots (6)$$

2.9.2 KNEE BRACE:

During the rehabilitation of the knee, one of the exercise involves making the patient to sit and move the knee in the specified range of motion. In this case, only the weight of the leg will be acting on the brace and that too in the form of the moment which will be required to move the knee with in specified range of motion.

In order to calculate the moment, the same equation which will used as that of the elbow. The parameters were obtained from [43]-[45]. The length of lower leg is 50cm approx. the center of mass from foot to knee is 64% while mass of leg is 20% of the total mass of the human. Thus, the moment applied at the central pin of one brace will be 25Nm approx. (including the extra moment will be also be generated due to the movement of upper part of leg as the lower part isn’t completed isolated. Moreover theses values represent 95^{th} percentile of the population)

In the same fashion as that of elbow, the shear max stress was calculated for central pin approximately as 15MPa and the max tensile stress for locking pin as 2kPa

2.10 FABRICATION:

The prototype of the braces had a number of parts that need to be manufactured but there were four parts which were difficult to manufacture as it required very precise machining and also machining had to be done on aluminum. The task was completed with the help of CNC machining. After their manufacturing, came the part of assembling which was done with the help of rivets/screws. Other parts include flat spring and the locking plate. The plate was initially planned to be manufactured of steel and since dimensions were very small and accuracy was important so EDM was considered but in this process there was risk of breaking the molybdenum wire thus in the end it was 3D printed with small plate as locking pin was attached at the end. The end product is shown in the figures below.

Figure 25 - Elbow Brace (prototype)

Figure 26 - Knee Brace (prototype)

CHAPTER 3: RESULTS AND DISCUSSIONS

The main function of brace is to avoid the joint stiffness during the rehabilitation phase by allowing the joint to move to certain degree depending upon how much the joint has recovered (as prescribed by the therapists and doctor). to account for this, the brace should allow smooth motion of the elbow (or knee) and should be able to bear the weight and it doesn't fail during the normal movement which means that when the elbow (or knee) is moved, a moment will be applied to the central pin and a force will be applied when it comes in contact with locking pins. Thus the main components in the brace are the central pin and locking pins and these components will be under focus during the analysis and also the selection of material will also be based on them. In order to carry out analysis, we need to know how much moment will be applied on the central pin, how much force would be applied on locking pin in full extended position and the boundary conditions and the properties of materials under focus. The analysis for both elbow and knee brace is quite similar to each other. The main difference lies in the weight each the brace would have bear and the angles of flexion and extension. Detailed discussion is given in the following sections:

3.1 MATERIAL UNDER CONSIDERATION:

Different materials were considered while carrying out analysis depending upon their availability in the market and other certain mechanical properties. But after carrying out number of analysis, aluminum alloy 6061-T6 was selected for our design as it met our basic design specifications as well as it was cheap and easily available in the market. The properties of this aluminum alloy 6061-T6 is as follows:

Properties	**Al 6061-T6[2]**
Density	$2.7 gcm^{-3}$
Young Modulus	$69 GPa$

Poisson's ratio	0.33
Tensile Yield Strength	$270MPa$
Tensile Ultimate Strength	$310MPa$

Table 3: Mechanical Properties of Al-Alloy (6061-T6)

Fatigue properties came from MIL-HDBK-5H, page 3-277.

3.2 ELBOW BRACE:

3.2.1 FEA ANALYSIS

Boundary Conditions:

- All contact regions were formulated by augmented LaGrange
- Friction coefficient for al-al is 1.05-1.35[49]. We will use average value i.e. 1.2.
- Contact region of upper bar with upper/lower plate through pins are all fixed. The contact region of locking pins and central pins with upper or lower plate are also fixed. The contact of lower bar with locking pins and central pin are frictional support with coefficient of friction equal to 1.2. The contact of lower bar with upper or lower plate is frictionless contact.
- Three new coordinate system were defined along locking and central pin which would be later used in analysis.
- A moment of 10Nm was applied around central pin

Mesh:

- Triangular surface mesh. 11863 nodes and 1687 elements.
- Small deflection theory was used.

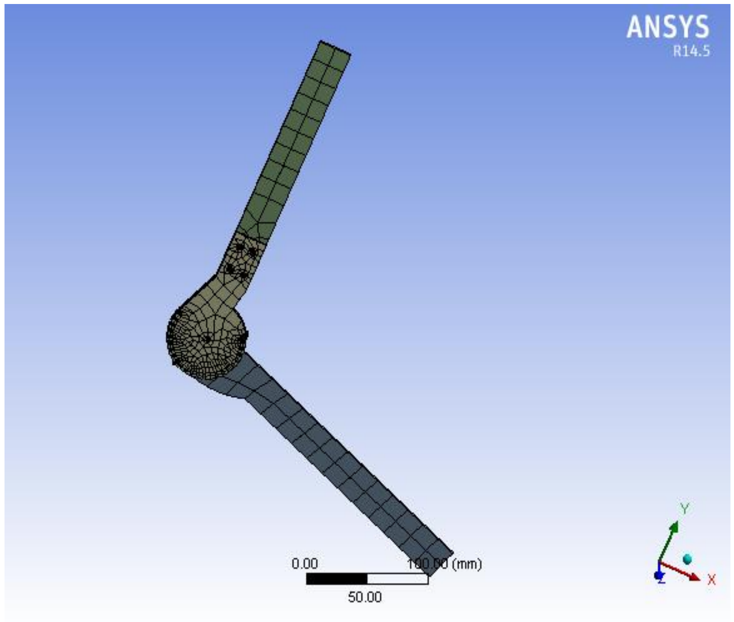

Figure 27: Mesh of Elbow Brace

Results:

For central pin (6061-T6)

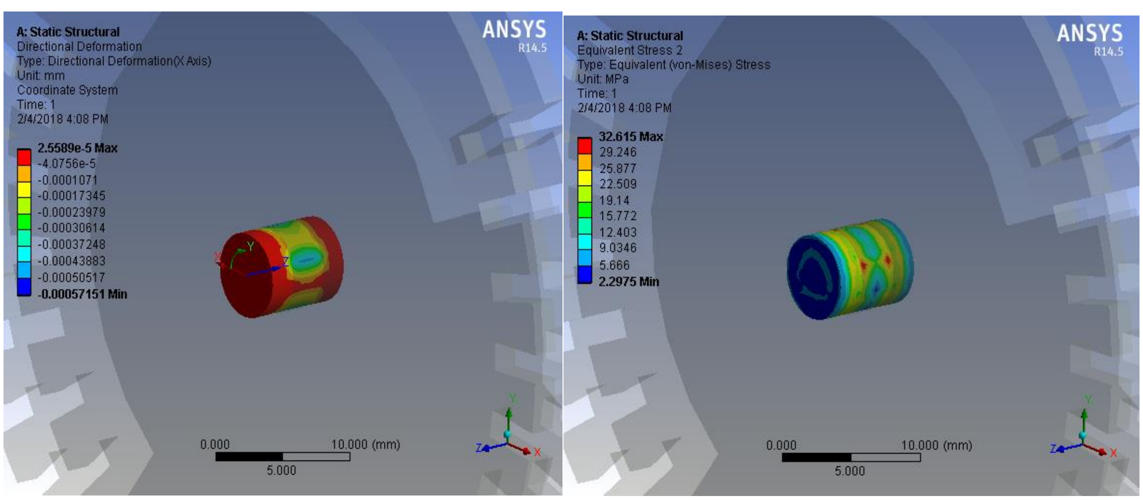

Figure 28: Central Pin Contours (Elbow Brace): (left) Directional Deformation (right) Equivalent Stress

For locking pins (6061-T6)

Locking pin 1

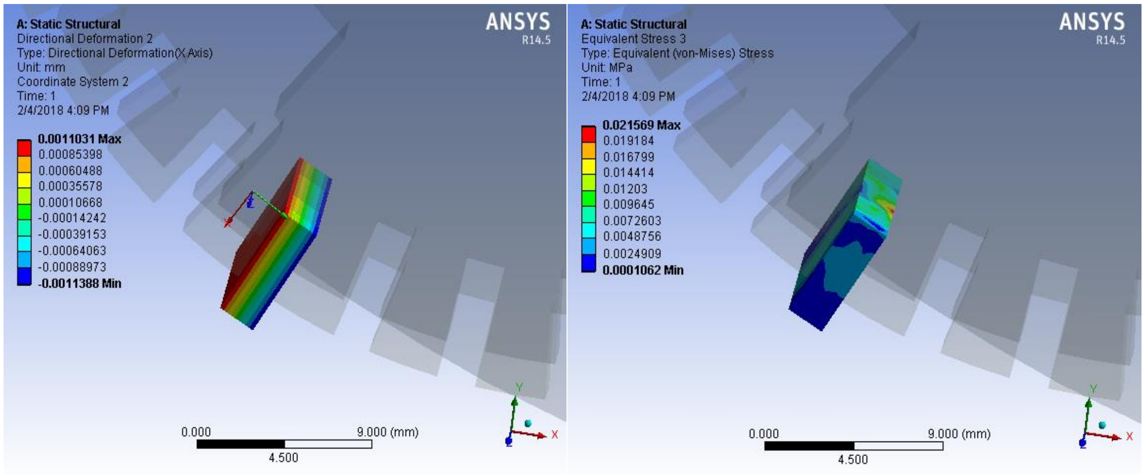

Figure 29: Locking Pin 1 Contours (Elbow Brace): (left) Directional Deformation (right) Equivalent Stress

Locking pin 2

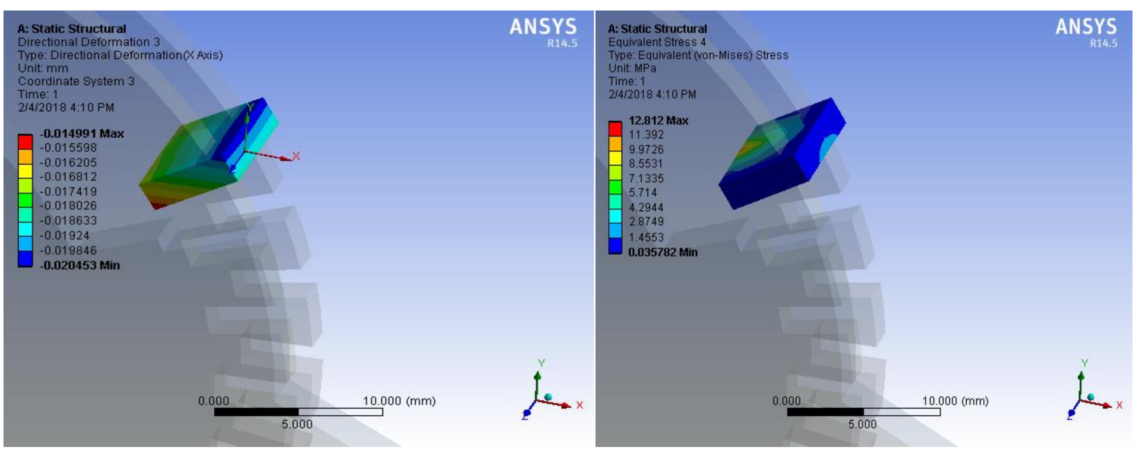

Figure 30: Locking Pin 2 Contours (Elbow Brace): (left) Directional Deformation (right) Equivalent Stres

Factor of Safety (6061-T6)

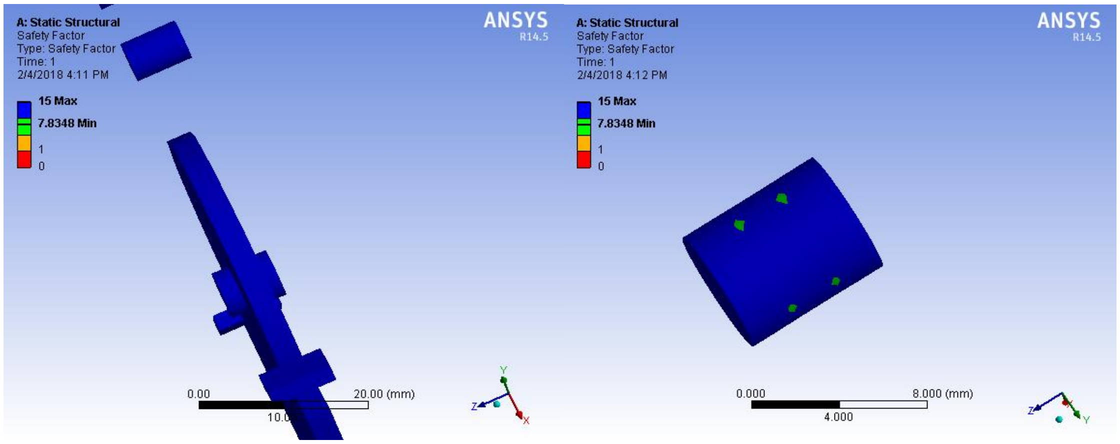

Figure 31: Factor of Safety Contours (Elbow Brace)

<u>3.2.2 DISCUSSION:</u>

The factor of safety was for the alloy came out as follows:

	6061-T6
FS	7.8348

Table 4: Factor of Safety (Elbow Brace)

It was proved both from analytical calculation and FEM analysis that the selected material would able to withstand without undergoing any deformation. And such a large factor of safety suggests that it can withstand much more than the force which was used for the analysis. Thus AL alloy 6061-T6 would be used for the elbow brace and the corresponding stress and deformation values obtained from ANSYS are as follows:

	Whole Brace (total)		**Central pin**		**Locking pin 1**		**Locking pin 2**	
	Max	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**
Stress(MPa)	34.5	7.1e-6	32.6	2.23	0.022	1.06e-4	12.8	3.58e-2
Deformation(mm)	0.41	0	2.6e-5	-5.7e-4	1.01e-3	-1.11e-3	-0.015	-0.0204

Table 5: Stress and Deformation values on different parts of Elbow Brace

It can be seen that deformations are negligible.

3.3 KNEE BRACE:

3.3.1 FEA ANALYSIS:

Boundary Conditions:

All the boundary conditions will be same as that of elbow except the moment will be 25Nm.

Mesh

- Triangular surface mesh. 13100 nodes. 3049 elements.
- Small deflection theory was used.

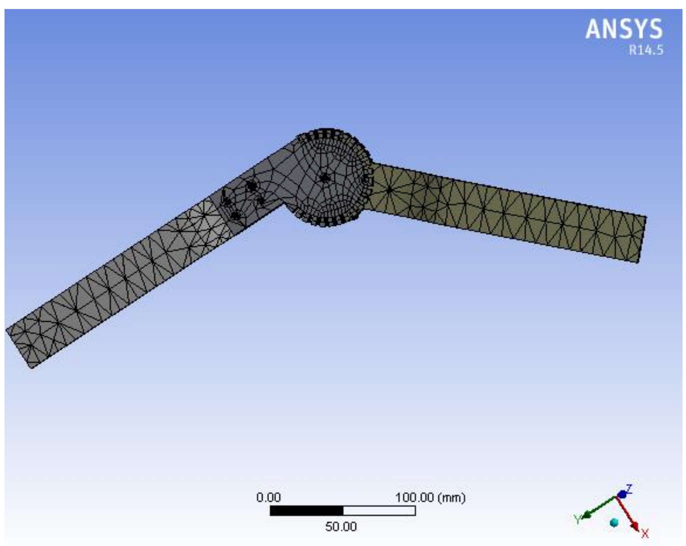

Figure 32: Mesh of Knee Brace

Results:

For central pin (6061-T6)

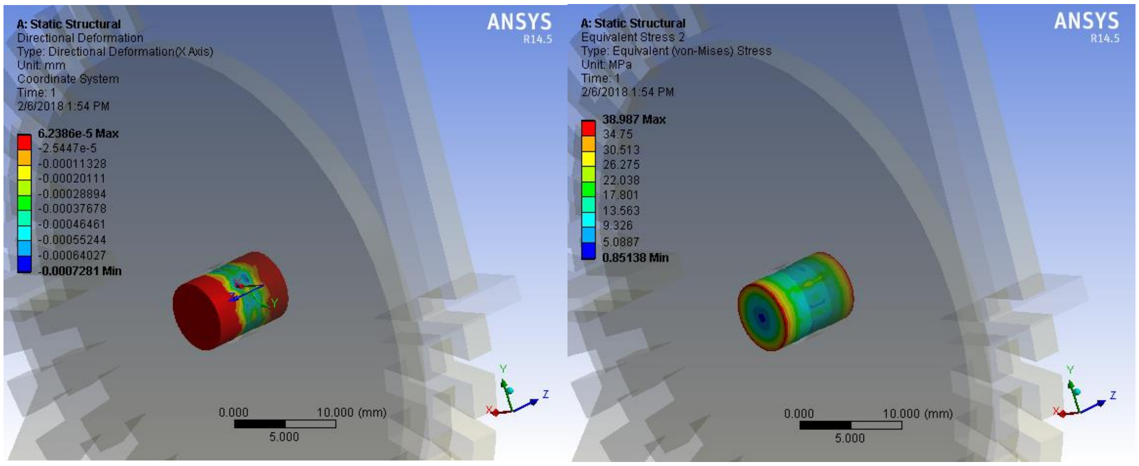

Figure 33: Central Pin Contours (Knee Brace): (left) Directional Deformation (right) Equivalent Stress

For locking pin 1(6061-T6)

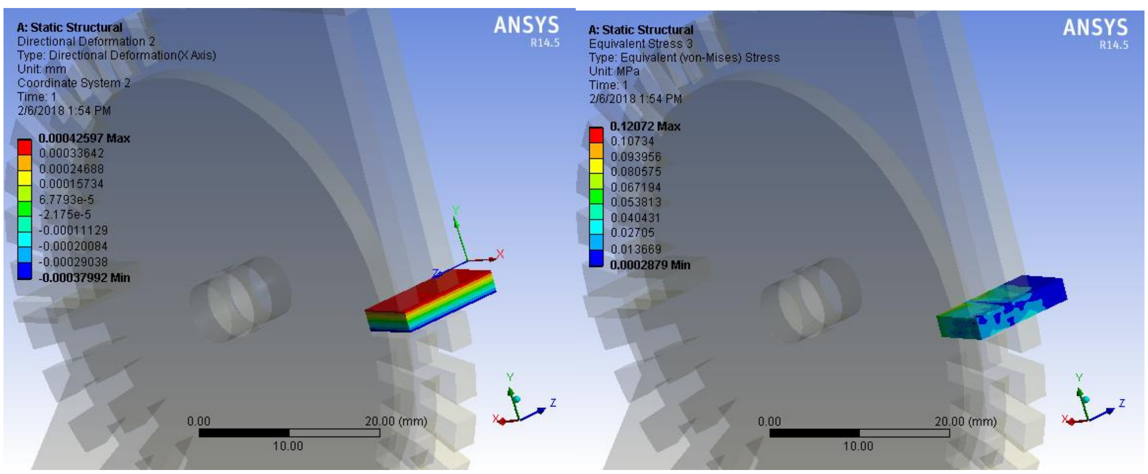

Figure 34: Locking Pin 1 Contours (Knee Brace): (left) Directional Deformation (right) Equivalent Stress

For locking pin 2(6061-T6)

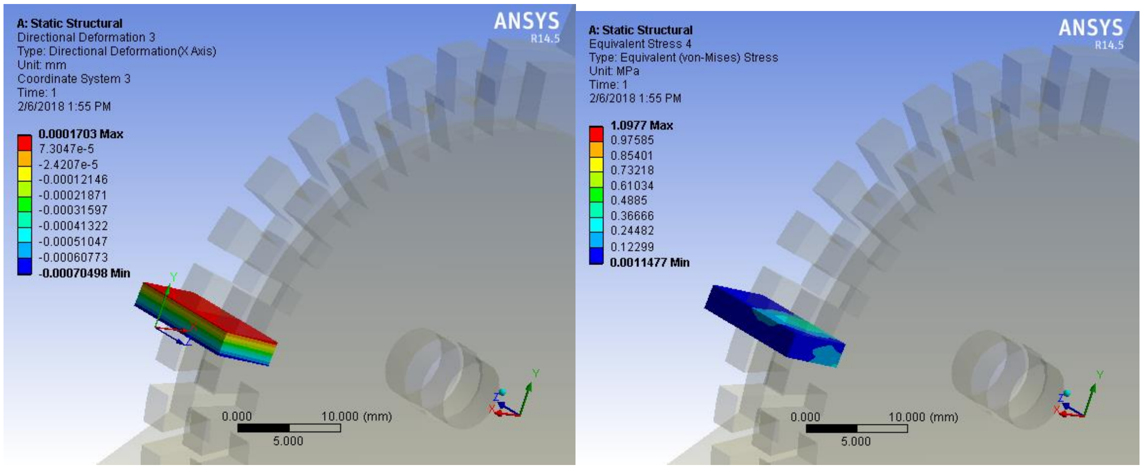

Figure 35: Locking Pin 2 Contours (Knee Brace): (left) Directional Deformation (right) Equivalent Stress

Factor of Safety (6061-T6)

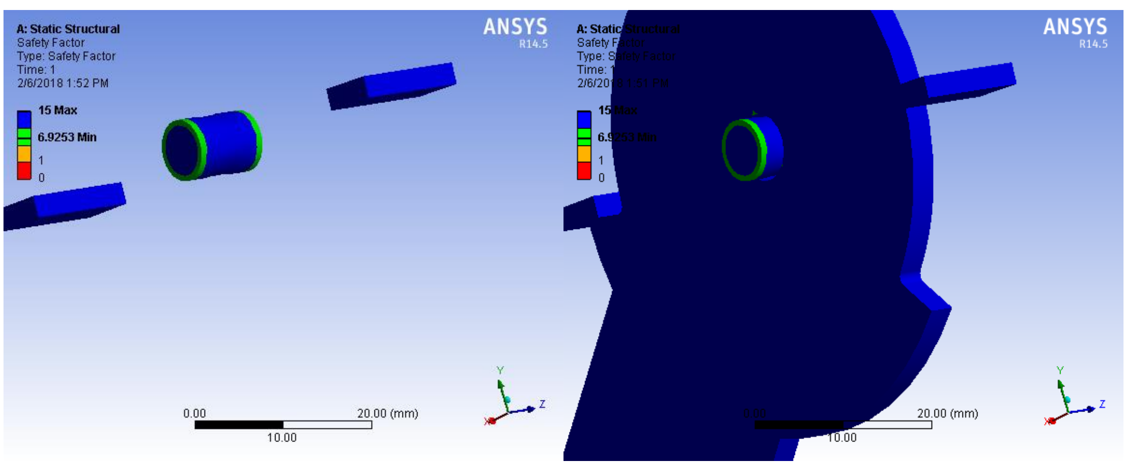

Figure 36: Factor of Safety Contours (Knee Brace)

<u>3.3.2 DISCUSSION:</u>

The factor of safety for aluminum alloy is as follows:

	6061-T6
FS	6.9253

Table 6: Factor of Safety (Knee Brace)

It was proved from both analytical calculation and FEM analysis that the selected material would able to withstand without undergoing any deformation. And such a large factor of safety suggests that it can withstand much more than the force which was used for the analysis. Thus AL alloy 6061-T6 would be used for the knee brace and the corresponding stress and deformation values are as follows:

	Whole Brace (total)		**Central pin**		**Locking pin 1**		**Locking pin 2**	
	Max	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**
Stress(MPa)	38.9	6.68e-8	38.9	0.85	0.12	2.8e-4	1.09	1.1e-3
Deformation(mm)	7.8e-2	0	6.2e-5	-7.2e-4	4.2e-4	-3.8e-4	-1.7e-4	-7.4e-4

Table 7: Stress and Deformation values on different parts of Knee Brace

It can be seen that deformations are negligible.

CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

The prototype of knee and elbow braces were fabricated using aluminum 6061-T6 with the design which included locking mechanism having an increment of 10° in flexion and extension angles, which was effective in restricting the motion of the limbs to desired angles as well as the prototype was light weight and comfortable to wear. Sensor was also designed with the help of Arduino, and SD card module which was giving the readings within the accuracy of ±2°. When the cost analysis of the project was carried out (Appendix II), it was found that elbow brace was manufactured for approx. 6500rs while knee brace was manufactured for 12540rs. These prices were almost 50-60% less as compared to braces available in the local market. Moreover, if we manufacture these braces in bulk, the prices will reduce further.

Based on the results and the fabrication limitation of the time and resources, here are some of the recommendations for improving the overall model:

1. Whole structure should be fabricated using Al sheet of less thickness making the model more light weight and comfortable to wear.
2. There was some free movement between the plate, at the end of which was attached the locking pin and the plate, which had slots as the locking pin was moved from one slot to another. It should be reduced in order to provide better locking.

APPENDIX I

```
#include <SPI.h>
#include <SD.h>
#include <LiquidCrystal.h>

File myFile;

const int rs = 2, en = 4, d4 = 7, d5 = 8, d6 = 9, d7 = 10;
LiquidCrystal lcd(rs, en, d4, d5, d6, d7);

void setup() {
  lcd.begin(16, 2);
  if (!SD.begin(3)) {
    lcd.print("No SD card.");
    while (1);
  }
  if (SD.exists("test.txt")) {
    SD.remove("test.txt");
  }
}

int x;

void loop()
```

```
{
  myFile = SD.open("test.txt", FILE_WRITE);
  x = int(map(analogRead(5), 0, 1023, 0, 270));
  if (myFile) {
    myFile.println(x);
    myFile.close();
  }
  lcd.setCursor(0, 0);
  lcd.print("Angle:");
  lcd.setCursor(8, 0);
  lcd.print(x);
  if (x < 100)
  {
    lcd.setCursor(10, 0);
    lcd.print(" ");
  }
  if (x < 10)
  {
    lcd.setCursor(10, 0);
    lcd.print(" ");
    lcd.setCursor(9, 0);
    lcd.print(" ");
  }
}
```

APPENDIX II

Elbow brace:

Material (Al-6061-T6)	1100 PKR
Cutting	4100 PKR
Arduino Nano	500 PKR
SD Card Module	150 PKR
LCD Module	250 PKR
Battery	40 PKR
3D printing	400 PKR

Knee brace:

Material (Al-6061-T6)	2200 PKR
Cutting	9000 PKR
Arduino Nano	500 PKR
SD Card Module	150 PKR
LCD Module	250 PKR
Battery	40 PKR
3D printing	400 PKR

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