Elbow Exoskeleton Mechanism for Multistage Post-Stroke Rehabilitation

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Abstract

More than three million people are suffering from stroke in England. The process of post-stroke rehabilitation consists of a series of biomechanical exercises-controlled joint movement in acute phase; external assistance in the mid phase; and variable levels of resistance in the last phase. Post-stroke rehabilitation performed by physiotherapist has many limitations including cost, time, repeatability and intensity of exercises. Although a large variety of arm exoskeletons have been developed in the last two decades to substitute the conventional exercises provided by physiotherapist, most of these systems have limitations with structural configuration, sensory data acquisition and control architecture. It is still difficult to facilitate multistage post-stroke rehabilitation to patients sited around hospital bed without expert intervention.

To support this, a framework for elbow exoskeleton has been developed that is portable and has the potential to offer all three types of exercises (external force, assistive and resistive) in a single structure. The design enhances torque to weight ratio compared to joint based actuation systems. The structural lengths of the exoskeleton are determined based on the mean anthropometric parameters of healthy users and the lengths of upperarm and forearm are determined to fit a wide range of users. The operation of the exoskeleton is divided into three regions where each type of exercise can be served in a specific way depending on the requirements of users. Electric motor provides power in the first region of operation whereas spring based assistive force is used in the second region and spring based resistive force is applied in the third region. This design concept provides an engineering solution of integrating three phases of post-stroke exercises in a single device. With this strategy, the energy source is only used in the first region to power the motor whereas the other two modes of exercise can work on the stored energy of springs. All these operations are controlled by a single motor and the maximum torque of the motor required is only 5 Nm. However, due to mechanical advantage, the exoskeleton can provide the joint torque up to 10 Nm.

To remove the dependency on biosensor, the exoskeleton has been designed with a hardware-based mechanism that can provide assistive and resistive force. All exoskeleton components are integrated into a microcontroller-based circuit for measuring three joint parameters (angle, velocity and torque) and for controlling exercises. A user-friendly, multi-purpose graphical interface has been developed for participants to control the mode of exercise and it can be managed manually or in automatic mode. To validate the conceptual design, a prototype of the exoskeleton has been developed and it has been tested with healthy subjects. The generated assistive torque can be varied up to 0.037 Nm whereas resistive torque can be varied up to 0.057 Nm. The mass of the exoskeleton is approximately 1.8 kg. Two comparative studies have been performed to assess the measurement accuracy of the exoskeleton. In the first study, data collected from two healthy participants after using the exoskeleton and Kinect sensor by keeping Kinect sensor as reference. The mean measurement errors in joint angle are within 5.18 % for participant 1 and 1.66% for participant 2; the errors in torque measurement are within 8.48% and 7.93% respectively. In the next study, the repeatability of joint measurement by exoskeleton is analysed. The exoskeleton has been used by three healthy users in two rotation cycles. It shows a strong correction (correlation coefficient: 0.99) between two consecutive joint angle measurements and standard deviation is calculated to determine the error margin which comes under acceptable range (maximum: 8.897). The research embodied in this thesis presents a design framework of a portable exoskeleton model for providing three modes of exercises, which could provide a potential solution for all stages of post-stroke rehabilitation.

Papers published out of this research

Journal publications

- Manna, S. K. and Dubey, V. N., 2019. A Portable Elbow Exoskeleton for Three Stages of Rehabilitation. *Journal of Mechanisms and Robotics,* 11, 1-10.
- Manna, S. K. and Dubey, V. N., 2019. Rehabilitation strategy for post-stroke recovery using an innovative elbow exoskeleton. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine,* 233, 668-680.
- Manna, S. K. and Dubey, V. N., 2018. Comparative study of actuation systems for portable upper limb exoskeletons. *Medical engineering & physics*, 60, 1-13.

Conference publications

- Manna, S. K. and Dubey, V. N., 2018. Design Proposal for a Portable Elbow Exoskeleton, *2018 Design of Medical Devices Conference* (pp. 1-5): American Society of Mechanical Engineers Digital Collection.
- Manna, S. K. and Dubey, V. N., 2018. A novel hardware approach to integrating active and passive rehabilitation in a single exoskeleton, *2018 International Symposium on Medical Robotics (ISMR)*(pp. 1-6): IEEE.
- Manna, S. K. and Dubey, V. N., 2017. A mechanism for elbow exoskeleton for customised training, *2017 International Conference on Rehabilitation Robotics* (pp. 1597-1602): IEEE.
- Manna, S. K. and Dubey, V. N., 2017. An innovative elbow exoskeleton for stages of post-stroke, UK-RAS Conference: 'ROBOTS WORKING FOR & AMONG US' PROCEEDINGS (pp. 106-108): UK-RAS.

Book chapter publications

- Manna, S. K. and Dubey, V. N., 2016. *Upper arm exoskeleton –what specifications will meet users' acceptability?* [online]. Nova Science Publisher, ISBN: 978-1-63485-967-7, 123-169.

Poster presented

- Manna, S. K. and Dubey, V. N., 2019.Accuracy of Kinect Sensor in Monitoring Rehabilitation Parameters, 2019 IEEE UK&I RAS Conference and 2019 IFToMM UK MO Conference on Transformative Robotics for Industries.

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List of Abbreviations

PDS – Product design specification

ADL - Activity of daily living

DOF - Degree of freedom

PAM - Pneumatic artificial muscle

EMG – Electromyography

sEMG – Surface electromyography

EEG – Electroencephalogram

3D – Three dimensional

EAP - Electroactive polymer

SMA – Shape memory alloy

FFA - Flexible fluidic actuator

HEA - Hydro-elastic actuator

MR – Magnetorheological

PD – Proportional-derivative

PI - Proportional–integral

PID - Proportional–integral–derivative

VR – Virtual reality

BCI – Brain-computer interface

EMH – Efficient market hypothesis

RGS - Rehabilitation gaming system

GUI - Graphical user interface

FMA - Fugl-Meyer motor

WMFT- Wolf-Motor function test

WHO - World Health Organization

fMRI - Functional magnetic resonance imaging

DC - Direct controlled

ISO - International organization for standardization

ABS - Acrylonitrile butadiene styrene

SD – Standard deviation

RPM – Rotation per minute

CWR – Clockwise rotation

CCWR – Counter-clockwise rotation

FTM – Forward translating motion

BTM – Backward translating motion

FL – Flexion

EX – Extension

ROM – Range of movement

FOM - Frequency of movement

PC – Personal computer

ADC – Analog to digital converter

List of nomenclatures

n	= Number of turns in the motor
θ	= Motor angle
$\dot{\theta}$	= RPM of the motor
L	= Lead of screw
N	= Gear ratio
V	= Linear velocity of the nut slider
ω	= Angular velocity of the elbow movement
x	= Position of the nut slider
f	= Frequency of the movement
S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, S_9, S_{10}	= Springs used in the exoskeleton
x_1	= Switching point between Electric motor control mode and assistive mode
x_2	= Switching point between assistive and resistive mode
x_2	= Boundary of resistive mode
f_{s1}	= Force produced by S_1
K_1	= Stiffness of S_1
x_{s1}	= Displacement covered by S_1 in fully compressed position
μ	= Coefficient of static friction
m	= Mass of the assembly connected to slider (SL_1)
g	= Acceleration due to gravity
τ'	= Required torque for rotating the elbow joint in case of joint based actuation
f_{s2}	= Assistive force provided by S_2
K_2	= Stiffness of S_2
x'_{s2}	= Free length of S_2
x_{s2}	= Displacement of S_2
f_{s3}	= Spring force exerted by S_3
f_{s4}	= Spring force exerted by S_4
T'	= Pulling force along the connecting link
K'	= Torsional stiffness of the elbow exoskeleton
f_{s5}	= Spring force exerted by S_5
f_{s6}	= Spring force exerted by S_6
K_5	= Stiffness of S_5
K_6	= Stiffness of S_6
a, b, c, d, e and h	= Lengths of solid links of the locking mechanism
φ'	= Minimum angle made by two claw type jaws at unlocking condition
α'	= $\angle MLI$ (fixed angle in the locking mechanism)
x_{s5}	= Displacement of S_5
x_{s6}	= Displacement of S_6

a'	= Width of the extension part of the nut slider
r_2	= Length of rectangular plates connected to S_7 and S_8
λ	= Angle made by those rectangular plates at maximum deflected position
r_1	= Radius of the pulley at the elbow joint
K_3	= Stiffness of S_3
K_4	= Stiffness of S_4
x'_{s3}	= Free length of S_3
x'_{s4}	= Free length of S_4
K_7	= Stiffness of S_7
K_8	= Stiffness of S_8
τ''	= Torque created by each torsional spring
F'	= Tangential force by S_7 and S_8 = Reaction force of nut slider
F_2	= Force produced by S_2 at maximum deflected position
RI_t	= Recovery index
HI_t	= Health index
L_m	= Variation of load carrying capacity
t	= Time to compute one rotation
T	= Time over a period of testing
P_l	= Load carrying capacity of the joint
$E1$, $E2$ and $E3$	= Threshold joint conditions of each recovery stage
n1 and n2	= Number of repetitions in motor control mode
τ_l	= Total torque
τ_p	= Joint torque from user
τ_D	= Desired joint torque
M	= Mass of the forearm and the supporting link
L_1	= Distance from the elbow joint to the centre of gravity of forearm and the supporting link
p	= Pitch of the leadscrew
d_1	= Pitch diameter of the leadscrew
φ	= Friction angle
β	= Elbow joint angle
δ	= Lead angle of the leadscrew
α	= Angle between connecting rod and nut-slider
P	= Effort applied to the screw to lift the load
r	= Length of the crank
R_N	= Reaction force of the nut-slider motion
W, W_1	= Force components of the effort P
τ	= Torque required for overcoming the friction of leadscrew
F	= Friction force in nut-slider movement
d	= Length of the nut-slider above the leadscrew

l	= Length of the connecting rod
K'_A	= Joint stiffness in assistive mode
K'_R	= Joint stiffness in resistive mode
τ_A	= Joint torque in assistive mode
τ_R	= Joint torque in resistive mode
X, Y, Z	= 3D position of the exoskeleton
γ	= Rotation of human arm in the transverse plane
ω_A	= Angular joint velocity in assistive mode
P_U	= User's effort
ω_R	= Angular joint velocity in resistive mode
$N_1{:}N_2$	= Gear ratio between small gear and half circular gear in arm holder
K_9	= Stiffness of S_9
K_{10}	= Stiffness of S_{10}
f_{s9}	= Spring force exerted by S_9
f_{s10}	= Spring force exerted by S_{10}
(X_1, Y_1, Z_1)	= Position of shoulder joint measured by Kinect sensor
(X_2, Y_2, Z_2)	= Position of elbow joint measured by Kinect sensor
(X_3, Y_3, Z_3)	= Position of the distal end of hand measured by Kinect sensor
$\vec{a}$	= Joint vector from elbow to shoulder joint measured by Kinect sensor
$\vec{b}$	= Joint vector from elbow to the distal end of hand measured by Kinect sensor
θ_2	= Elbow joint angle measured by Kinect sensor
T_k	= Reaching time measured by Kinect sensor
L_2	= length of forearm measured by Kinect sensor
l_2	= Distance from elbow to the centre of mass of forearm
W	= Body mass of user
τ_{elbow}	= Joint torque of elbow computed by Kinect sensor
H	= Total height of user
I_2	= Inertia of forearm with respect to the centre of mass

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Chapter 1 Introduction

In the last two decades, the mortality rate due to stroke has increased as per the statistics provided by WHO (World Health Organization)(Thrift et al. 2017). Patients suffering from stroke usually lose their muscle functions. Such occurrences may lead to loss of power or complete paralysis of limbs if left unused in the acute phase. It is recommended that intensive occupational therapy in the early stages can provide superior rehabilitation to the affected limb (McPherson and Ellis-Hill 2007). Stroke is a life-threatening event that affects not only the person who is the victim but also their family members and the caregivers. Paralysis is a condition caused by complete loss of muscle function of one or more muscle groups. In such cases, patients do not have any control of physical movement of the affected part. Also, different cognitive problems may occur due to stroke-like problems with concentration, memory and visual perception (Stroke Association 2018a) which do not allow them to do the normal activity of daily living. In general, people lose their mobility, way of communication as well as their strength, therefore, they have to go through some bio-mechanical exercises to recover their original strength. It has been proven that if patients are under rigorous and intensive rehabilitation for several months after stroke, their active range of motion as well as muscle strength can increase significantly (Krakauer and Marshall 2015). The sooner the rehabilitation training started, the more likely they are to regain the lost abilities and skills. A repetitive and early training session will improve their neuro-motor functionality. The training includes all forms of orthopaedic and neurological lessons that would be compatible with the human muscle movement. The rehabilitation training is generally performed by physiotherapist but patient has to confront a lot of socioeconomic and technological problems (Lo and Xie 2012) such as cost, time constaint and lack of intensitive therapy due to the limitations of conventional therapy which are described below.

1. It has been found that a physiotherapist can run the training for 8-10 hours a day for subacute rehabilitation (Winstein et al. 2016) and can provide the service at a very high cost (Tam et al. 2019). According to the report of Stroke Association of

the UK, the numbers of stroke-affected people are increasing day by day (Figure 1.1) which in turn also increases the demand for intensive therapy. Present Statistics shows that there are about 1.2 million stroke survivors (Stroke Association 2018b) in the UK. The annual health and social costs of caring for disabled stroke patients are estimated to be in excess of £5 billion in the UK (Sabeo Plc 2017).

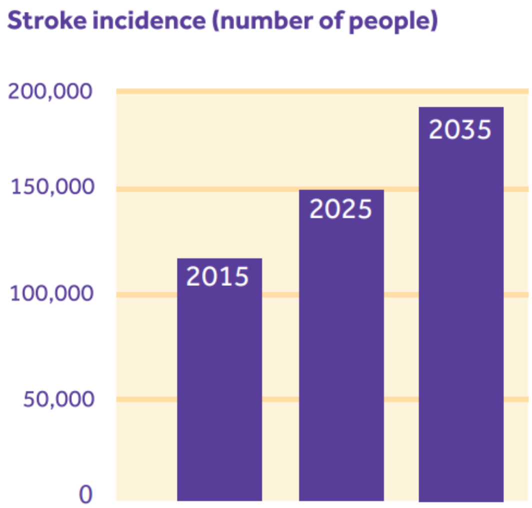


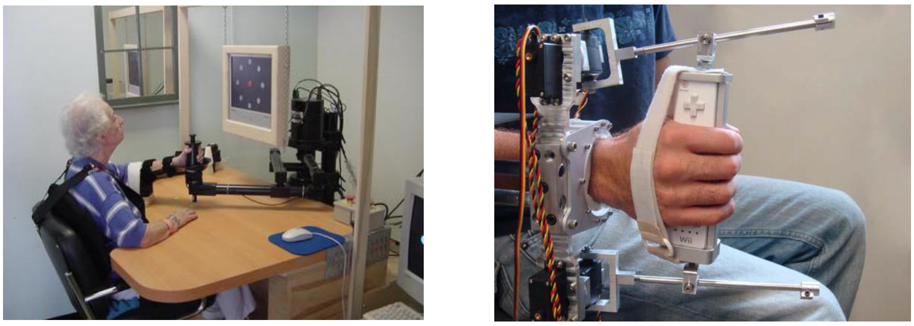
Figure 1.1. Stroke statistics (Stroke Association 2018b)

2. There is a shortage of sufficient number of trained physiotherapists (Condon and Guidon 2018) in the UK. Therefore, people with short-term training have to perform these activities which may not be effective and may cause negative effects on patients. They may even omit certain exercises which are essential for patients.
3. It is not possible for patients to receive the recommended amount of medical care from manual therapy (Clarke et al. 2015). The training session is not adequate due to the fatigue of therapists because after a few sessions of therapy, physiotherapists got tired and they are unable to support post-stroke patients with their joint movements. Patients may not get repetitive and accurate exercise sessions in case of manual intervention. On the other hand, exoskeleton could potentially provide rehabilitation training for a longer period of time without any break even without the presence of a therapist (Ren et al. 2013).
4. Due to unavailability of therapists, robotic-assisted therapy could be a possibility to provide post-stroke rehabilitation in remote areas. Any trained person can offer rehabilitation training to a patient with the help of exoskeleton from a remote location.

Considering time, cost, repeatability, reproducibility and accuracy, robotically assisted rehabilitation process could be a better option than human-assisted training (Lo et al. 2010). Robotic exoskeletons are proved to be clinically beneficial for providing rehabilitation therapy to post-stroke patients (Saha et al. 2016) in case of providing long term and intensive therapy. The purpose of exoskeleton in human rehabilitation is to strengthen motor skills, provide mobility training, constraint-induced therapy and wide range-of-motion therapy. Exoskeletons or wearable skeletons are people-oriented robots designed to be worn for training and assistance. These robots are designed based on the function and shape of human body so that users are able to control intuitively. Exoskeletons can assist in walking, running, jumping or even lifting objects one would normally not be able to. These examples are only some of the most basic ways that these robots will be used for. It may be put on to different parts of human body such as upper limb, lower limb, wrist or as full-body vest. There have been a number of research projects on human arm exoskeleton, it started with the concept of supporting military personnel in a war zone for undertaking strenuous works. However, as time moved on, the area of application has expanded to a large number of diverse applications. Broadly it can be divided into three major areas: firstly, it can be used as an assistive device for paralysed and elderly people; Secondly as a therapeutic device for patients suffering from different neuromuscular weakness; and finally it could be used as powerful muscle support for military personnel in lifting under hazardous loading conditions. So the design and development of such systems are driven by the requirements depending on the application. Most of the daily life activities are performed by upper limb of human body, for an example wheelchair based users can perform eating, picking and placing objects and grasp or push something without using their lower limb. In this research project, we have focused on upper arm exoskeletons used for post-stroke rehabilitation.

1.1 End-effector based systems for rehabilitation

Initially, end effector based systems have been used for rehabilitation therapy. It only connects the distal part of forearm with a system that looks like a serial manipulator. The movements of the end effector can change the position and orientation of whole arm since the distal part of forearm is connected to the system, all other segments automatically move with it. It is easy to design since it does not take care of the structure of human arm. But the main problem with end-effector based systems is that it is difficult to initiate a particular movement of a specific joint (Molteni et al. 2018). Dependent on the configuration, sometimes it may create a risk to a patient's arm. Notable systems in this category are MIT MANUS (Krebs et al. 2000) and CRAMER (Spencer et al. 2008) (Figure 1.2). Therefore it is difficult to provide specific joint based exercises with end effector based system (Molteni et al. 2018). To achieve a specific joint based therapy, exoskeleton based rehabilitation process needs to be engaged.

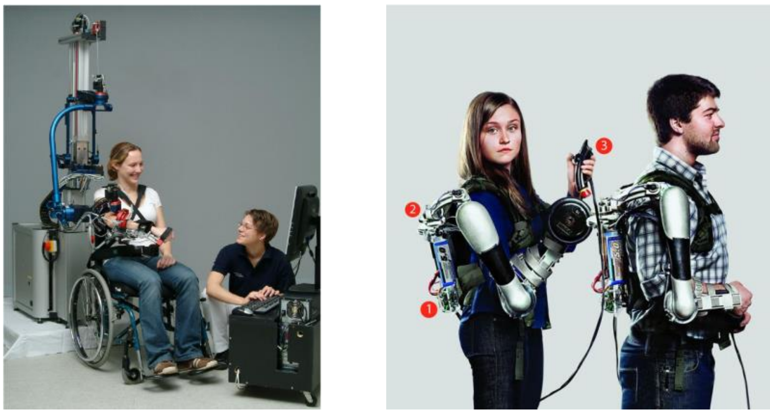


MIT MANUS (Krebs et al. 2000) CRAMER (Spencer et al. 2008)

Figure 1.2. End effector based robotic rehabilitators

1.2 Types of Exoskeleton

This particular area of research needs a complete understanding of human movements, involving the anthropometric data, its kinematics and dynamics. Mostly two types of design have been developed as shown in Figure 1.3. The first one is ground-based exoskeleton system which is attached to a base platform such as ARMin (Nef et al. 2009). The second one is body-based portable/wearable device such as Titan arm (Beattie et al. 2012).



ARMin (Nef et al. 2009) Titan arm (Beattie et al. 2012)

Figure 1.3. Arm exoskeleton systems (ground & body-based)

The question is whether rehabilitation based exoskeleton should be a complex system installed in hospitals or care centres, or it may be used in a home setting with simple and easy to use configurations. Exoskeletons like ARMin (Nef et al. 2009) and MGA exoskeleton (Carignan et al. 2007) require a large space for installation. Actuators can be fitted to human joint with structural support from the base (Nef et al. 2009) or remotely actuated by setting it on the rucksack (Beattie et al. 2012). The majority of ground-based exoskeletons have utilized brushed or brushless DC motor (Maciejasz et al. 2014) as actuators. Also, there are hydraulic driven exoskeletons (Vitiello et al. 2013), (Stienen et al. 2009a), (Otten et al. 2015) and pneumatically controlled exoskeletons (Klein et al. 2010), (Culmer et al. 2011) available. In ground-based exoskeleton, the motion transferred to human arm is very stable because the connected actuators can provide maximum torque to joint irrespective of the weight of arm. Generally, hospitals, health care centres can have this facility to accommodate a large number of patients. All required rehabilitation features have been installed into those exoskeletons making those a sophisticated and expensive device. In the body based exoskeletons, all mechanical and electronic components including energy source are mounted on a patient's body such as Titan arm (Beattie et al. 2012), shown in Figure 1.3. Human joint can be directly driven by actuator placed at joint or remotely controlled from different position like backpack or upper shoulder. The required joint torque is higher in case of joint based motor. Although there are new types of soft actuators like pneumatic muscle (Tondu and Lopez 2000) or flexible fluidic actuators (Landkammer and Hornfeck 2014) being developed for making portable and lightweight exoskeletons, there are still a number of structural limitations associated with these actuators.

Ground-based exoskeletons are generally suitable for rehabilitation purpose where the size and weight of exoskeletons are not important. But for a portable exoskeleton, the actuator should be small and lighter in weight. If the device is meant to have several degrees of freedom, this entails a lot of actuators which will increase the mass and size of the exoskeleton. Devices like WOTAS (Rocon et al. 2007) and HAL (Sankai 2010) fall under this category (Figure 1.4). Sometimes such devices have been installed on a wheelchair: MUNDUS (Pedrocchi et al. 2013) and MULOS (Johnson et al. 2001) for patients who do not have the ability to walk

(Figure 1.4). In such cases, patients can carry out exercises without worrying about the size and mass of the exoskeleton.

HAL (Sankai 2010)

WOTAS (Rocon et al. 2007)

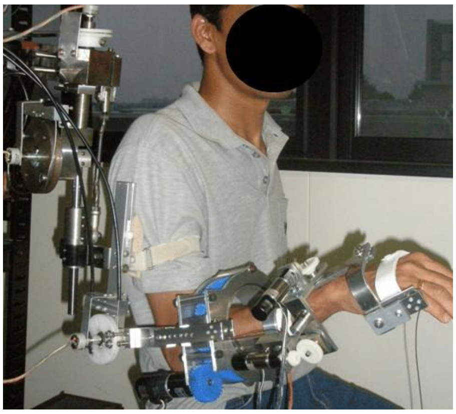
MUNDUS (Pedrocchi et al. 2013)

MULOS (Johnson et al. 2001)

Figure 1.4. Portable exoskeletons

Depending on the type of actuation, exoskeletons can be further divided into two categories such as active device and passive device.

- Active exoskeletons use actuator (electric, pneumatic, hydraulic or new type of actuation) for joint movement (Figure 1.5). As a result, the cost of such devices is comparatively higher. Since these systems use actuator, it consumes energy and requires a reliable energy source.
- Passive exoskeletons use passive elements for actuation. It may include rubber band or spring actuated mechanism to apply supportive force or resistive force (Figure 1.5). Such exoskeletons do not use actuators, therefore, lighter in weight and could be used as a portable device. These exoskeletons are less expensive because of no actuator.



Motor based active exoskeleton (Gopura et al. 2009)

Spring based passive exoskeleton (Wu and Chen 2014)

Figure 1.5. Divisions of exoskeleton based on actuators

1.3 Strategy for multistage post-stroke rehabilitation

The exercises involved in different post-stroke stages do not only recover the muscle strength to get patients back to normal life but also improves their mental health to fit into social life. Before selecting the type of exoskeleton, it is necessary to know the type of exercises required in different post-stroke stages. The rehabilitation process normally involves a series of biomechanical exercises to provide therapy from the acute phase to the full recovery phase after stroke. Variety of activity modules are followed by different organizations such as stroke.org, sabeo.com, flintrehab etc. They have shown different type of arm based exercises to improve muscle strength. Exercise may include normal arm movements as well as specific joint based training to enhance neuro-motor control and to improve the functional activities of daily living. Even different martial art technique like tai-chi is also being considered as the rehabilitation protocol for joint recovery (Zhang et al. 2014). If exoskeleton can provide all kinds of exercises aligned with the post-stroke recovery stage in a standalone model, it can be used for multistage rehab device. However, there is no standard approach documented yet for providing specific exercise from acute phase to full recovery stage. So, we have proposed a combined and comprehensive rehabilitation strategy of exercises for a single human joint that can be used as a potential standard solution for post-stroke rehabilitation from acute to full recovery stage. A few of the published guidelines are listed below (**Error! Reference source not found.**).

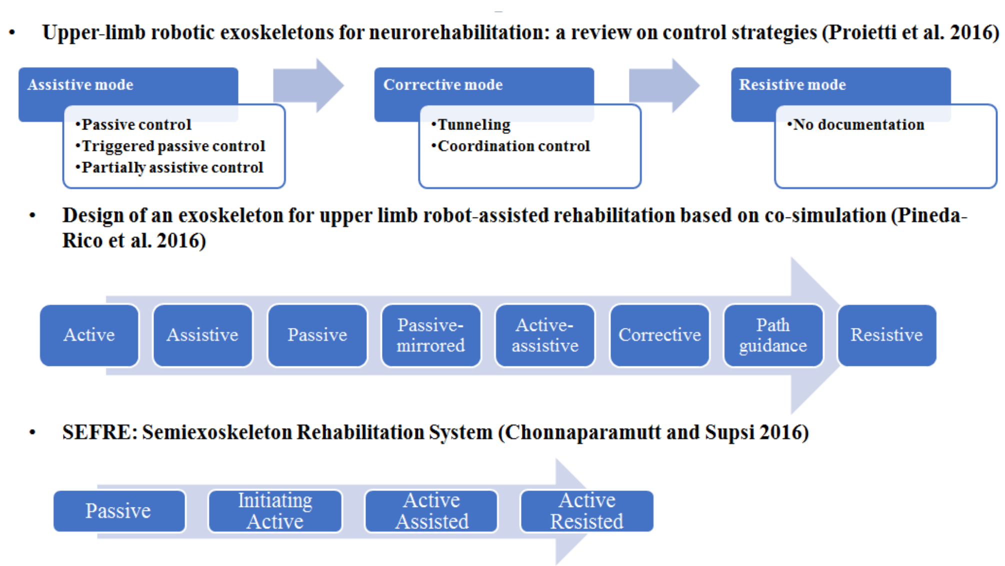


Figure 1.6. Few published guidelines for stroke rehabilitation

After analyzing the function and treatment procedure of those published guidelines (Proietti et al. 2016),(Pineda-Rico et al. 2016),(Chonnaparamutt and Supsi 2016), pathway of rehabilitation for a single human joint can be categorized into three distinct phases as per the stages of post-stroke conditions; acute, mid-stage and last stage, (Figure 1.7). Each stage may consist of a specific set of exercises which can be achieved by a specific type of mechanism. Joint conditions in each stage show the sign of recovery. Early stage exercises need an external force to move the joint due to their poor muscle strength in the acute stage. After a rigorous and intensive exercise session, patients may regain some amount of muscle strength which helps them to perform some basic movements but those are not voluntary. In this phase, spasticity continues to decrease, and patients can initiate joint movements themselves. Therefore, exercises with supportive force will assist these patients to move their arms in a desired position and orientation. Assistive force along with individual effort may help those patients to generate complex and coordinated movement in the upper limb. After a lot of repetitions of arm movements, controllability of muscle can be improved to a stage where patients are able to initiate complex voluntary movement. However, the problem remains as they may not able to apply enough force during the movement. Exercises in the last stage can be strenuous for patients. To enhance muscle strength and joint torque, exercises are normally designed to place joint motion in more difficult situations where patients would need more joint torque to achieve the goal. Such exercises may help patients to enhance their load bearing capability.

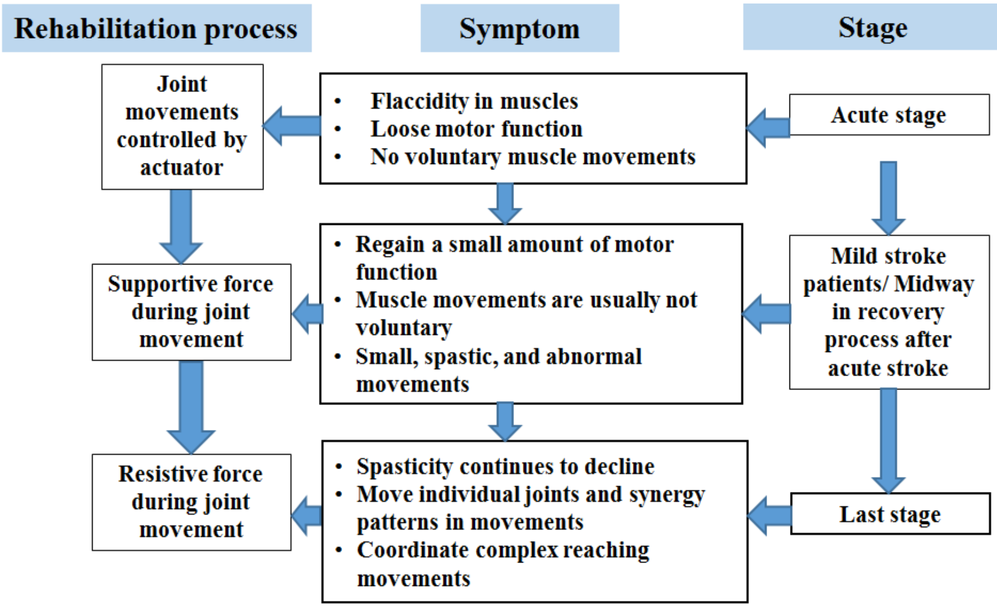
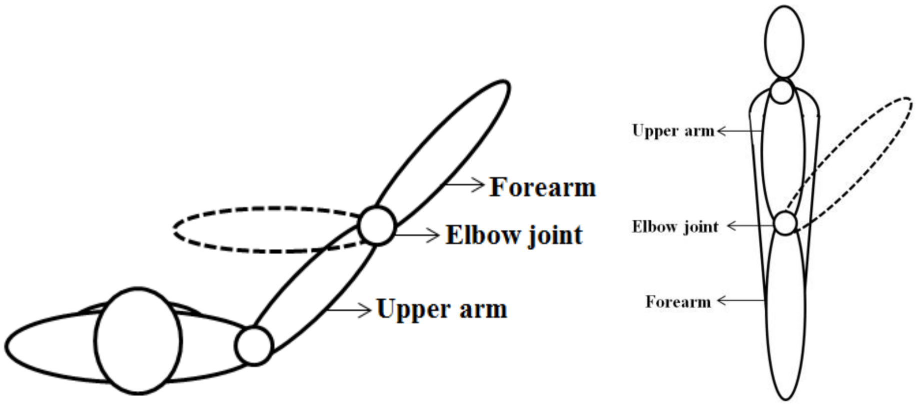


Figure 1.7. Three phases of the rehabilitation process after stroke

If exercises are performed in the transverse plane, users only need to overcome the frictional force (Figure 1.88a) due to joint stiffness. However, a lot of structural changes will be required in the mechanism if the same exercise is to be performed against gravity (Figure 1.88b). The range of reachable points with post-stroke robotic rehabilitation will improve if those exercises are performed in gravity compensated training environment (Beer et al. 2008). Postural stability can be achieved by the active holding of the body segment against an external force (Kolar 2014). In upper limb daily life activities, gravitational force seems to play a significant role because it places body segment in real-life activities. This also helps to enhance the range of motion and relative stiffness of joints. Antagonistic muscle activity against gravitational force will lead to a better clinical output.



a. Elbow rotation in transverse plane   b. Elbow rotation in sagittal plane

Figure 1.8. Exercises in different planes

1.4 Motivativation for the research

After analysing the exercises involved in post-stroke rehabilitation, three types of exercises (external force, assistive and resistive) have been proposed from acute to the last phase after stroke. It is also challenging to imitate human joint movement using exoskeleton due to its complex biomechanical structure. We could not find any standard guidelines available to design specific exoskeleton for providing multistage post-stroke rehabilitation. Most of the standard active exoskeletons (Nef et al. 2009; Rahman et al. 2010a) used electric motor placed at joint in a coaxial manner to deliver joint-oriented exercises. The internal control system can generate assistive or resistive motor torque as per the signal triggered by biosensor (EMG, EEG) (Krasin et al. 2015), however, biosensor based control may not be efficient for chronic stroke patients (Cesqui et al. 2013) because those sensors are affected by multiple factors of joint spasticity and anomalous stiffness. Fine EMG data extraction from stroke patients is difficult because of abnormal EMG-torque relations in chronic stroke (Bhadane et al. 2016). EEG based pattern recognition approach is also difficult to decode movement intention for post-stroke patients (Koyas et al. 2013). Passive exoskeletons are designed to facilitate a specific type of exercise, such as TWREX (Housman et al. 2007) can only provide assistive force. The actuation system and its associated control architecture are different for providing a particular type of exercise. Therefore it is difficult to incorporate hardware-based multistage post-stroke rehabilitation using a standalone exoskeleton model. Researchers have come up with their own customized design for their particular needs. Few developed exoskeletons have focused on the design aspect which includes portability and user-friendliness but failing on providing different types of exercises. Though few exoskeletons have proved to be beneficial in terms of clinical outcomes, still a proper guideline is unavailable to get the best out of it. Joint-based motor may require higher torque compared to those structures where joint is controlled remotely from backpack or different arm location. To provide user's joint movement consisting higher load, the specification of electric motor would change, for an example it's size and weight can be increased (Marcheschi et al. 2011) and the production cost becomes higher. These types of systems always consume energy for maintaining the range and joint torque. The size of energy source is also increased to deliver higher joint torque using motor, so the portability of the device would be compromised. The design of exoskeleton should follow human biomechanics and anthropometric data of human arm considering its safety prospectives. The existing models still have a lot of ergonomic challenges (Schiele 2008). A recent survey among the health professional and patients (Wolff et al. 2014) shows that patients would prefer a portable, simple and affordable system rather than a big complicated one. For a portable system, weight and energy consumption of the exoskeleton is another critical issue. Also, the cost of such kind of devices is too prohibitive for general public to afford. Which type of control system should be used in exoskeleton design is an important consideration. Day to day, the control system is getting improved by increasing the complexity of control algorithms with the advent of new sensors and fast computing power. When it comes to the dynamic interaction between user and exoskeleton, force or position individually is not enough to satisfy the control strategy. It must take account of different feedback parameters such as kinematic and dynamic joint parameters. The design must also consider different external force like gravitational force, frictional force etc. There should also be a provision of manual override together with local intelligence system for safety purposes. Modern adaptive control is a suitable choice for providing multistage rehabilitation using electric motor (Peternel et al. 2016) however it has a negative effect on the recovery rate such as controlling joint movement completely by making patients passive (Reinkensmeyer and Boninger 2012). The majority of these devices were platform-based and that may be one of the main inhibiting factors why users found such devices too cumbersome to use. Out of a few commercial portable exoskeletons, most are used as assistive devices for elderly people to support their ADL (Maciejasz et al. 2014), however, there is a lack of rehabilitation based exoskeletons. This opens up a question, what specifications of upper arm exoskeleton will meet users' acceptability to become a portable exoskeleton providing multistage rehabilitation? Therefore, we have focused on designing an exoskeleton model to implement three stages of rehabilitation without compromising its portability and other necessary features. A metric of user's requirement is drawn from the literature survey and shown in in Table 1.1 to map a correlation between user's demand and its solution. However, it does not involve any patients or clinical input from medical experts.

Table 1.1. Need vs solution (User's requirement based on the literature survey)

Solution / Need	Integration of three types of exercises (external control, assistive force and resistive force) in a single system	Exoskeleton can provide variable assistive and resistive torque	Production cost of exoskeleton is affordable for general public	Consistent and repeatable exercise module	Motor can provide required joint torque	Enhances torque to weight ratio	Weight of the exoskeleton is lighter	Smaller energy source for operation	Should have both control scheme: automatic and manual	Mode of exercises can be switched easily based on joint condition	Develop the control strategy using joint parameters without using biosensor	Use of universal joint instead of revolute	Compensation of Joint misalignment during rotation	Mechanical constraint to restrict the joint movement beyond anatomical limit	Software control to restrict the joint movement beyond anatomical limit	Design follows the biomechanical structure and anthropometric data of human arm	Opinion of users after using the exoskeleton	Exoskeleton can reach maximum joint angle	Control mechanism will allow users to put their effort to do joint movement	Using of passive energy source for joint actuation	Using of spring actuated mechanism for switching between mode of exercises
Exoskeleton can provide multistage post-stroke rehabilitation from acute to full recovery phase	*	*																			
Reduction of the cost of post-stroke therapy	*	*	*					*													
Intensive and long hours exercise				*																	
Exoskeleton can lift the forearm during external-force controlled mode					*																
Portable device						*	*	*												*	*
Ease of controlling the mode of exercise									*	*	*										
Joint flexibility and ergonomic property												*	*								
Safety of user														*	*						
Wearable device																*	*				
Maximum reachable workspace																		*			
Enhancement of user's participation																			*		
Minimization of energy consumption																				*	*

In order to design an upper arm exoskeleton model for implementing the metric shown in Table 1.1, we have chosen elbow joint as it is one of the simplest human arm joints having 1 DOF. Prior to constructing the elbow exoskeleton, we need to know a few parameters of human arm such as length of upperarm and forearm, mass of forearm. Length of arm segments and range of motion are required to create the structural formation of the exoskeleton and mass of the forearm decides the power of actuator used for joint movement. There is no direct method for measuring those body parameters, therefore, can be estimated based on the proportion between the segment and total body as per biomechanics rule (Table 1.2).

Table 1.2. Segment mass and lengths of human arm

Segment	Length of segment/ total height	Segment mass/ Total body mass	Length of centre of mass from proximal end (m)	Radius of gyration with respect to the centre of mass (m)
Upper arm	0.186	.028	0.436	0.322
Forearm and hand	0.254	.022	0.682	0.468

Arm parameters of five healthy subjects have been taken to get an idea for constructing the exoskeleton fitting with elbow joint (Table 1.3).

Table 1.3. Segment arm lengths and mass of five healthy subjects

Subjects	Height (m)	Mass (kg)	Upperarm length (m)	Forearm length (m)	Forearm mass (kg)
# 1	1.60	79	0.298	0.406	1.738
# 2	1.75	60	0.326	0.445	1.320
# 3	1.81	89	0.337	0.459	1.958
# 4	1.80	83	0.335	0.457	1.826
# 5	1.62	46	0.301	0.411	1.012
Mean			0.319	0.436	1.570

Anthropometric data are subjective to users, however, in order to design the project, the structural lengths of the exoskeleton were determined based on the data collected from five healthy users. The mean of upperarm and forearm lengths are found to be 0.319 m and 0.436 m, however minimum length of a user was 0.301 m and 0.411 m. Therefore, the structural lengths of the proposed exoskeleton were decided with forearm length of 0.40 m and upperarm length of 0.35 m where both lengths can be adjusted up to ±0.04 m to fit the exoskeleton for several users. The mean of forearm mass is 1.570 kg; since the forearm mass can vary for different users, the maximum motor torque is kept as 5 Nm which can create a joint torque of 10 Nm due to the mechanical advantage (discussed in section 4.4.1). The maximum joint torque would be 5.89 Nm for lifting the forearm mass of 3 kg (full body mass of 136 kg), therefore the exoskeleton can easily provide the required joint torque during motor actuated control. The ideal reachable elbow angle is 140^{o} (Manna and Bhaumik 2013), therefore the range of motion in the exoskeleton is supposed to be the same joint angle, however, due to structural limitation, the maximum reachable joint angle of the exoskeleton is designed to move the forearm up to 135^{o}. The affordable cost of exoskeleton for general public is subjective, so the aim was to keep the cost of the device below £1000. Also, we have tried to keep the mass of the exoskeleton below 2 kg so that users can easily carry it during exercises. Wearability of the exoskeleton is evaluated based on the design specifications and opinion of users after using the exoskeleton.

Based on the metric shown in Table 1.1 and calculated anthropometric parameters of healthy subjects, a product design specification (PDS) sheet has been formed where probable solutions are categorized into qualitative and quantitative solutions in Table 1.4 with ideal, target and achieved values. Most of the ideal values are subjective to user's specifications, however, based on our study (Manna and Dubey 2018), few achievable targets were set-up. A prototype of the elbow exoskeleton has been developed to achieve most of the targets by implementing those qualitative and quantitative features. Achieved targets are shown in the sixth column of Table 1.4.

Qualitative solutions have been achieved through the conceptualization and development of the exoskeleton whereas quantitative solutions have been attained through the selection of components and validated either through simulation results or experimental analysis, shown in Table 1.4.

Table 1.4. Product design specification (PDS) sheet

Property	Sl. No.	Solutions	Ideal value	Target value	Achieved value	Qualitative /quantitative	Validation method
Structural property	1	Integration of three types of exercises (external control, assistive force and resistive force) in a single system			Achieved	Qualitative	Device development and Experimental analysis
	2	Exoskeleton can provide variable assistive and resistive torque	Subjective to users		Variation of torque: 0.04 Nm in assistive mode and 0.06 Nm in resistive mode	Qualitative and Quantitative	Experimental analysis
	3	Production cost of exoskeleton is affordable for general public	Subjective to users	<£1000	£886	Quantitative	Cost estimation
	4	Consistent and repeatable exercise module	Subjective to users	Repeatability Correlation coefficient ≥ 0.9 1.96*SD of error =0	Mean measurement errors in joint angle: 5.18 % for participant 1 and 1.66 % for participant 2 Mean measurement errors in joint torque: 8.48% for participant 1 and 7.93% for participant 2 Correlation coefficient ≥ 0.99 Maximum error margin (1.96*SD of error) 8.897	Quantitative	Experimental analysis
	5	Motor can provide required joint torque	5.89 Nm (joint torque for lifting a forearm of 3 kg)	5.89 Nm	10 Nm	Quantitative	Simulation
	6	Enhances torque to weight ratio	Subjective to users		By two	Quantitative	Simulation
	7	Weight of the exoskeleton is lighter	Subjective to users	< 2 kg	1.8 kg	Quantitative	Device development
	8	Smaller energy source for operation	Subjective to users	< 5 W	5 W	Quantitative	Device development
	9	Design should follow the biomechanical structure and anthropometric data of human arm	**Elbow joint:** 1 DOF **Upperarm length:** subjective to users **Forearm length:** subjective to users	**Elbow joint:** 1 DOF **Upperarm length:** 0.35 ±0.04 m **Forearm length:** 0.40 ±0.04 m	**Elbow joint:** 1 DOF **Upperarm length:** 0.35 ±0.04 m **Forearm length:** 0.40 ±0.04 m	Quantitative	Device development

Property	Sl. No.	Solutions	Ideal value	Target value	Achieved value	Qualitative /quantitative	Validation method
Structural property	10	Opinion of users after using the exoskeleton (wearability and usability)	Subjective to users	Opinion poll from healthy users Wearability ≥ 75% Ease of use ≥ 75%	Opinion poll from 5 healthy users = Wearability ≥ 76% Ease of use ≥ 80%	Quantitative	Survey analysis
	11	Exoskeleton can reach maximum joint angle	140^{o}	140^{o}	135^{o}	Quantitative	Experimental analysis
	12	Using of passive energy source for joint actuation			Achieved	Qualitative	Device development
	13	Using of spring-actuated mechanism for switching between exercise			Achieved	Qualitative	Device development
	14	Use of universal joint instead of revolute			Achieved	Qualitative	Device development
	15	Compensation of joint misalignment during rotation			Achieved	Qualitative	Device development
Control property	16	Should have both control scheme: automatic and manual			Achieved	Qualitative	Device development
	17	Mode of exercises can be switched easily based on joint condition			Achieved	Qualitative	Device development
	18	Develop the control strategy using joint parameters without using biosensor			Achieved	Qualitative	Device development
	19	Control mechanism will allow users to put their effort to do joint movement			Achieved	Qualitative	Device development
Safety property	20	Mechanical constraint to restrict the joint movement beyond the anatomical limit			Achieved	Qualitative	Device development
	21	Software control to restrict the joint movement beyond the anatomical limit			Achieved	Qualitative	Device development

Through the PDS sheet (Table 1.4), major aspects of design-related issues of exoskeleton have been considered and the challenges can be overcome using appropriate solutions. For example, the design should consider human arm's anatomical structure and anthropometric data to justify the optimal design performance. It should also consider the reconfiguration of the exoskeleton for misalignment in the design and weight of the device to make it portable and wearable. A user-friendly control algorithm can be implemented to facilitate automatic as well as manual set up in case of insufficient sensory data. Above all, the design should maintain the safety of users using electromechanical constraints and software controlled algorithm.

1.5 Research questions and objectives

The main research hypothesis is to investigate if an exoskeleton could be designed that may offer different modes of exercise using a standalone system for providing post-stroke rehabilitation at all stages.

It is evident that a lot of advancements are still required in design and development of upper arm exoskeleton to meet these features as mentioned in PDS (Table 1.4) such as innovative mechanism, actuators, actuation system, type of exercises involved in post-stroke rehabilitation and control strategy. Therefore, the main research question addressed in this research project is qualitative which is shown below.

> **What kind of mechanism can be designed that can provide three modes of exercises (external force, assistive force and resistive force) and is also portable and wearable in a standalone system?**

Considering user's perspective, few quantitative measures have been targeted to cover many users. Table 1.4 shows the required quantitative properties with the target and achieved values. In order to satisfy the above research question, few broad objectives have been set for the project.

- **To implement three types of exercises in a single module**,
  - The function of the exoskeleton needs to be distributed into three regions of the entire operating range where each mode of exercise can be served in a specific region in coordination with the stages of post-stroke condition.

- **To build a portable and wearable system**
  - Torque to weight ratio of the exoskeleton can be enhanced compared to joint based actuation model.
  - Both electric motor and springs can be incorporated in the actuation mechanism to minimise the energy consumption to reduce the battery size. Electric motor can be used to control the joint in external force-controlled mode whereas, in rest of the two modes, joint motions can be supported by stiffness of the springs for providing assistive or resistive force.
  - Spring stiffness can be used in the switching mechanism to shift between mode of exercises; therefore, no brake or clutch is required making it an energy efficient mechanism and thus reduces battery size.
  - The actuation mechanism can be designed in a way so that a single motor is used to achieve all these features.

- **To control the mode of exercise in the exoskeleton**
  - In this design, joint range, velocity and torque can be changed since these parameters demonstrate user's reachable workspace, recurrence of movement and weightlifting limit which can be used as the feedback parameter for patient improvement.

- **To compensate joint misalignment and joint offset during movement**
  - The exoskeleton may use a universal elbow joint which can provide a slight movement in transverse plane to compensate for joint misalignment and offset.
  - Also forearm structure of the exoskeleton can have a linear passive joint to balance the joint misalignment between the centre of human arm and exoskeleton.

- **To maintain the safety of users**
  - Both hardware and software-control can be implemented to restrict the joint movement beyond the maximum anatomical range.

1.6 Research methodology

The research methodology adopted for this project is in conjunction with achieving this set of objectives. In the beginning, user's biomechanics data (weight, height and elbow joint range) is needed to design the framework of the structure. Biomechanics data of five healthy users have been considered and the mean of those data has been used to decide the structural lengths of the exoskeleton, selection of actuator and actuation system. During the experiment, the joint parameters are measured to prove the working principle. Finally, feedback from participants is taken to evaluate the usefulness of the device.

1. **Conceptualization of the design:** First of all, the existing approaches to providing post-stroke exercises have been assessed. After that, these exercises are arranged in three stages (external force, assistive and resistive) for acute to final stage of stroke, it has been analysed how those exercises provided by a therapist can be replaced by different mechanism and robotic systems (Manna and Dubey 2018). However, the main problem is how to integrate all these actuation systems in a single mechanism to facilitate all types of exercise without adding extra actuator. Therefore, different switching mechanism and clutches have been investigated. In the end, two switching mechanisms have been developed to exchange between different mode of exercise; external force to assistive mode and assistive mode to resistive mode.

   a) The first mode of exercise in the exoskeleton can be controlled by an external actuator such as electric, hydraulic or pneumatic and actuation system can be direct driven, link driven or cable driven mechanism. Now the selection of actuator and actuation system is one of the major issues as it determines the required joint torque. After analysing the advantages, specifications and control mechanism of all types of actuator, it has been found that electric motor is the most used actuator in active exoskeletons because it is easy to control and deliver high power cum bandwidth. It can be easily installed in the system. To enhance the torque to weight ratio, link driven actuation system is used instead of direct drive. So, a leadscrew-based slider-crank mechanism is used to transfer the motion from the electric motor to elbow rotation.

b) After that, a spring-based switching mechanism is developed to switch from external force-based exercise to assistive force-based region. The advantage of using this mechanism is that the same motor (used for the external force-based exercises) can be used for switching function.
c) In the second mode of exercise, variable assistive force can be generated either by the torque variation of electric motor or passive actuator like spring with a separate mechanism to vary its force. In order to reduce energy consumption, it has been decided to use spring energy for giving assistive force to users. The developed switching mechanism (used for transferring the mode of exercise from assistive to resistive force mode) is also used to facilitate a range of variable assistance to users.
d) The third mode of exercise (resistive force) can be developed either by complaint mechanism or some semi-active actuator (example magnetorheological fluid-based system). As it was not intended to use another actuator in the exoskeleton, therefore, spring-based antagonistic model (a type of complaint system) is used for varying the resistive force and motor rotation is used for changing the parameters in the proposed antagonistic spring set-up.

Following a thorough literature survey (Manna and Dubey 2018), most of the desired design parameters (shown in Table 1.4) are incorporated to build a portable exoskeleton providing three modes of exercise. Also, different kinds of mechanism have been investigated to get better performance in terms of gravity compensation, better torque to weight ratio, compensation of joint misalignment and energy efficiency.

- **Hardware and Software development**

  Considering all those parameters, a few conceptual joint models for elbow exoskeleton have been designed and 3D models (Model 1 to 10) are drawn in Solidworks platform for visualization (shown in Appendix II : Solidworks models of exoskeleton).

  i) In the first conceptual model (Model 1), a gear-driven joint mechanism is designed to give elbow rotation.

ii) In the next model (Model 2), a leadscrew-based mechanism was implemented with a motor to control the movement of elbow rotation.

iii) In the next model (Model 3), a motor is fitted at the elbow for rotation and a leadscrew based slider-crank mechanism was set-up to reduce the required joint torque compared to the direct motor-driven mechanism i.e. joint based actuation.

iv) In the fourth model (Model 4), a spring was attached between forearm and upperarm as a part of the gravity compensating mechanism, which also enhances the torque to weight ratio.

v) In the fifth model (Model 5), a spring-based assistive force model was incorporated into the exoskeleton. Previously, a separate motor was used for this purpose, however, later the motor used for external force was utilised through an innovative mechanism.

vi) In the sixth model (Model 6), spring-based actuation was combined with motor-based control in the exoskeleton model. Therefore, a switching mechanism was introduced consisting of two sliders and compression springs to divide the region of operation into two for different modes of exercise.

vii) In the seventh model (Model 7), a spring-based antagonistic model was placed into the exoskeleton to generate resistive force. The linear movement of the nut slider on the leadscrew was used to support the model. A universal elbow joint was placed for user’s flexibility.

viii) In the eighth model (Model 8), a torsional spring-based switching mechanism was incorporated in the exoskeleton to serve two functions: generation of variable assistive force and switching from assistive to resistive mode. The mechanism can be driven by the linear movement of nut-slider. The mechanism of arm holder was also designed. It can produce twisting motion to forearm. The mechanism can accommodate motor-controlled movements along with user’s originated movements to consider user’s ergonomic comfort. As it is a different kind of forearm motion, an extra motor was used for it.

The aim was to provide three types of exercise for three stages of post-stroke rehabilitation; therefore, it needs to incorporate all kinds of actuation mechanism in a standalone platform. After several iterations and models, a final exoskeleton model (Model 9) has been designed to satisfy all features. A linear passive joint at forearm supporting link is engaged to compensate joint misalignment.

- **Experimental work**

  A simulation study on the designed exoskeleton model is performed in Solidworks™ using the motion analysis tool. It includes experiments for evaluating the mechanical advantage of the design such as a comparative torque requirement for the proposed model with respect to a motor placed directly at the joint during movement, also whether the system is able to incorporate all three type of exercises or not.

2. **Development of the prototype:** A working prototype is developed to establish the working principle of the proposed exoskeleton combining electric motor and springs. Stiffness of each spring used in the exoskeleton has been determined through mathematical modelling. Besides, the manufacturing cost of the exoskeleton is also calculated to estimate the cost of implementing post-stroke rehabilitation using the exoskeleton.

- **Hardware and Software development**

  A final prototype has been manufactured using 3D printed components. ABS is the structural material. Springs and rest of the components are assembled to convert it into a working model.

- **Experimental work**

  Characteristics of all springs in the exoskeleton are evaluated and forces provided by those springs during motion have also been computed. Kinematics and dynamic analysis of the whole arm exoskeleton have been done in MATLAB based on the mathematical model of the exoskeleton. A comparative study of torque requirement is shown for the proposed model with respect to the joint axis-based motor mechanism. Forces generated by the springs have been derived. Another study is carried out for finding out the variation of elbow joint stiffness at the end of the operating region. Dexterity of the exoskeleton has also been analysed.

3. **Controlling the mode of exercises:** A joint parameter-based control strategy has been implemented to generate different exercises using the exoskeleton considering angle, velocity and torque. The exoskeleton has been tested with healthy users to verify its working principle. The wearability and usability of the exoskeleton are determined by the opinion of users through a post-experiment survey.

- **Hardware and Software development**

  A potentiometer is integrated with a microcontroller circuit to measure the joint angle and rest of the joint parameters like velocity and torque can be computed from the mathematical model of the exoskeleton. Switching conditions (specific boundary values of joint parameters) is defined to control the mode of exercise by the exoskeleton. Also, an application is developed in MATLAB to monitor joint parameters for user-friendly operation and to control the operation in two modes; in automatic sensory mode, the mode of exercise can be controlled autonomously based on the joint parameters; in the manual mode, the exercise mode can be changed manually.

- **Experimental work**

  The experiment included the elbow joint movement by healthy users after wearing the exoskeleton. They can only participate in the experiment after agreeing with the participant information sheet and signing the participant agreement form. Users are asked to move their right arm in three different modes and their elbow joint angle is recorded.

- In the first mode (electric motor-controlled mode), users are asked to keep their arm idle so that electric motor can rotate the elbow joint.
- In assistive mode, users are asked to use their normal strength to rotate their elbow joint.
- In resistive mode, users are asked to use their normal strength to rotate their elbow joint.

Joint parameters (velocity and torque) are computed at different modes of exercise. The main aim of the experiment is to analyse the working principle of the exoskeleton, whether the device can facilitate three types of exercise.

4. **Assessment of joint measurement using exoskeleton:** The measurement accuracy of the exoskeleton is assessed through two experiments. In the first experiment, the measured joint parameters from exoskeleton are compared with Kinect sensor (Microsoft XBOX V2). In the following experiment, the repeatability of joint measurement is evaluated. Users can rotate their elbow wearing the exoskeleton multiple times. Ultimately, the correlation coefficient and SD of consecutive measurements are calculated.

- **Hardware and Software development**

  A virtual platform is developed in Unity where user's right arm movement is synchronized with a basketball and a 3D avatar is placed in the environment to produce a human touch. The operation and synchronization of arm movement are programmed in Microsoft visual studio. Few audio-visual features are also integrated with the movement of right arm.

- **Experimental work**

  Healthy users can rotate their elbow joint in front of Kinect sensor wearing the exoskeleton in assistive mode. Kinect sensor can capture joint vectors of human body by its inbuilt motion capture technique therefore joint angle, velocity and acceleration can be computed with reference to time. Exoskeleton use potentiometer to measure joint angle and rest of the joint parameters are calculated from it. Euler-Lagrangian model of one degree of freedom manipulator is used for measuring joint torque and mass of the forearm is calculated from the standard biomechanics rule. The measured data from Kinect are compared with the joint parameters collected from the exoskeleton to validate the model.

Joint parameters from exoskeleton have been recorded for two full cycles of rotation (a combination of full flexion and extension) to compute the repeatability score. It is determined by the correlation coefficient of consecutive measurements and SD of measurement error.

A small post-experiment survey is conducted to prove the wearability and usability of the exoskeleton. It consists of two questions and users can give answers using a scale from 1 to 5 (strongly disagree to strongly agree).

1.7 Thesis structure

The whole thesis consists of five chapters which are described below.

1.7.1 Discovering the advantageous of robotic rehabilitation system over the manual therapy

In Chapter 1, the severity of stroke on society was explained and showed how it is difficult for physiotherapists to provide the recommended amount of therapy due to certain limitations. It was also shown how exoskeleton can provide specific joint based therapy compared to end effector-based systems. Three types of exercises external force, assistive, resistive) were proposed for post-stroke rehabilitation after analyzing several established guidelines of exercise modules to make the rehabilitation process simple and straightforward. The existing exoskeletons were divided into two categories: body-based and ground-based depending on the structural configuration; active, passive and haptic depending on the type of actuation. The properties of each type of exoskeleton were explored to find their advantages and drawbacks. After reviewing the current status of exoskeletons based on post-stroke rehabilitation, a metric (Table 1.1) is shown to analyze the market needs and probable solutions as well as a product design specification sheet (Table 1.4) has been created along with all qualitative and quantitative features. To achieve the required features, a research question and few objectives were defined. In the end, the research methodology for the project is described starting from developing the concept of the exoskeleton, making the prototype and validating the design principle.

1.7.2 Reviewing the issues and limitations of available exoskeletons

A comprehensive literature survey was carried out in Chapter 2 in order to find the existing design solutions to achieve the required features shown in PDS (Table 1.4). The advantages and shortcomings of the existing actuators and actuation systems were described with quantitative data. It was found that electric motor is the most suitable choice as actuator. It also came out from the literature survey that energy efficiency of an actuation system can be maintained by the respective ways; enhancing torque to weight ratio of an actuator, collaborative usage of energy source by an active and passive actuator. Few kinematic and dynamic joint parameters were accumulated for controlling exoskeleton. Additional structural design features were recognized like universal joint for joint flexibility and passive linear joint for enhancing the ergonomic property of exoskeleton. Several other factors such as bandwidth of rehabilitation, degreed of freedom, redundancy, hyperextension and alignment were also discussed which could influence the designing process of exoskeleton. Finally, the process of integrating three types of exercises in a standalone system had been explored through two types of solutions; one is the software-based approach where motor can generate variable joint torque based on software-controlled algorithm whereas different hardware-based passive systems can also generate assistive or resistive joint movement.

1.7.3 Design and development of a new elbow exoskeleton to overcome the shortfall of existing systems

These objectives were achieved by designing an elbow exoskeleton to facilitate three modes of exercises using an innovative mechanism. As discussed in Chapter 3, structural analysis of the developed exoskeleton was carried out to validate the model. An energy-efficient actuation system was designed to accommodate active and passive actuation system. Therefore, the electric motor was used to control joint movements for the first mode when users are unable to move their joints whereas springs were used to change the amount of assistive and resistive forces for users in next two phases when users have some residual strength to undertake exercises. All these modes were controlled by changing the region of operation which makes the exoskeleton easy to operate without implementing any complex algorithms, and it also removed the dependency on biosensors. The size of the energy source is reduced since spring force was used in assistive and resistive modes of operation without engaging any active actuator. To reduce the weight of the system and energy source, the exoskeleton was operated using a single motor and spring energy was also used for shifting from one exercise mode to another without using any electromagnetic switch. User's safety is ensured in this exoskeleton by using the switching mechanism between motor control and assistive mode which worked as a safety gate and released the joint control from motor after crossing the maximum anatomical limit (135^o). The required motor torque of the exoskeleton was reduced by two times compared to the joint based motor which allows users to use a smaller motor to generate the same torque. The exoskeleton can generate the maximum torque up to 10 Nm which is more than the required joint torque to lift a forearm mass of 3 kg. In this exoskeleton, a universal joint was used at elbow to offer flexibility to user's movement. To fit different human arm size and to increase the level of ergonomic comforts, a passive linear joint combined with a compression spring was incorporated at the forearm supporting structure. The prototype of the exoskeleton was manufactured using 3D printed components and the cost of production is estimated to be £ 886.

1.7.4 Controlling the mode of exercise in the exoskeleton

The control model of the exoskeleton was developed by combining only three joint parameters: joint angle, velocity and torque without using any biosensor signal (discussed in Chapter 4). The estimated boundary conditions of these three joint parameters were used for switching between different modes of exercise. These specific values of joint parameters can be set as a standard for estimating the post-stroke recovery rate at a particular stage. User can be promoted from external force-based exercise to assistive mode if they can rotate their elbow joint up to 135^o, self-movement at 1 Hz and joint torque up to 1.175 Nm whereas the conditions for crossing the resistive mode are reachable joint angle - 135^o, joint frequency at 2 Hz and joint torque up to 1.232 Nm. However, these switching parameters can be modified for different users as recommended by physiotherapist. The cost of electronic control was reduced by computing different joint parameters from the outcome of one sensor without using separate sensors for measurement. For example, the joint angle was measured by calibrating the potentiometer value, therefore, the joint velocity and acceleration were determined by differentiating the joint angle with respect to time. Also, the joint torque was calculated from the developed mathematical model instead of using a rotary torque sensor. In order to make a user-friendly system, the exoskeleton was controlled in two modes using the developed graphical user interface. In sensor-based automatic mode, the exoskeleton worked as a fully controlled system by integrating inbuilt microcontroller circuitry and sensor. In the manual control mode, users changed the exercise mode physically.

1.7.5 Validation of the measurement accuracy of the exoskeleton

The exoskeleton was used by healthy users and the joint parameters are recorded to see whether the developed mechanism can develop different mode of exercises or not. Also, the error between two consecutive cycles of full elbow rotation (flexion and extension) was calculated for all three modes of joint movement (motor control, assistive and resistive) to get the repeatability score of the joint measurement (discussed in Chapter 5). The correlation coefficient for all three modes was more than 0.99 which defines a strong correlation between consecutive tests. Also, the error margin was calculated by deriving 1.96 times SD of measurement error, the maximum value was 8.897. The scale of usability and wearability were determined by the data gathered from the post-experiment survey, which was happened to be 76% for wearability and 80% for ease of use. The measurement accuracy of the exoskeleton was validated by a comparative study where two healthy subjects were asked to move their elbow joint in front of Kinect sensor wearing the developed exoskeleton and the joint information collected from Kinect sensor was compared with the exoskeleton-based measurement. A virtual set-up was designed where users rotated their right arm following a basketball and Kinect sensor measured the joint angle. All the measured data from Kinect sensor were stored in an excel file and more joint features such as velocity, acceleration and torque were extracted using MATLAB. The measurement errors between the exoskeleton and Kinect sensor was turned out to be in the acceptable range; 5.18% for subject 1 and 1.66% for subject 2 in case of joint angle; 8.48% and 7.93% for subject 1 and subject 2 respectively in case of joint torque. The above results proved that joint parameters can be monitored accurately using the Kinect sensor. This contactless measurement technique will give a pathway to use these joint parameters for conducting rehabilitation with the exoskeleton in future.

Chapter 2 Design parameters of an exoskeleton

Although a large number of exoskeletons have already been developed and a lot of researches have been undertaken on it, there are some major issues which restrict their use as a portable rehabilitation device which can provide three types of exercises. There are few significant properties which should be incorporated in actuation system to get a compact and lightweight exoskeleton.

All these key features have been categorized into four divisions (Figure **2.1**): functional property, technological characteristics, financial benefits and psychological benefits.

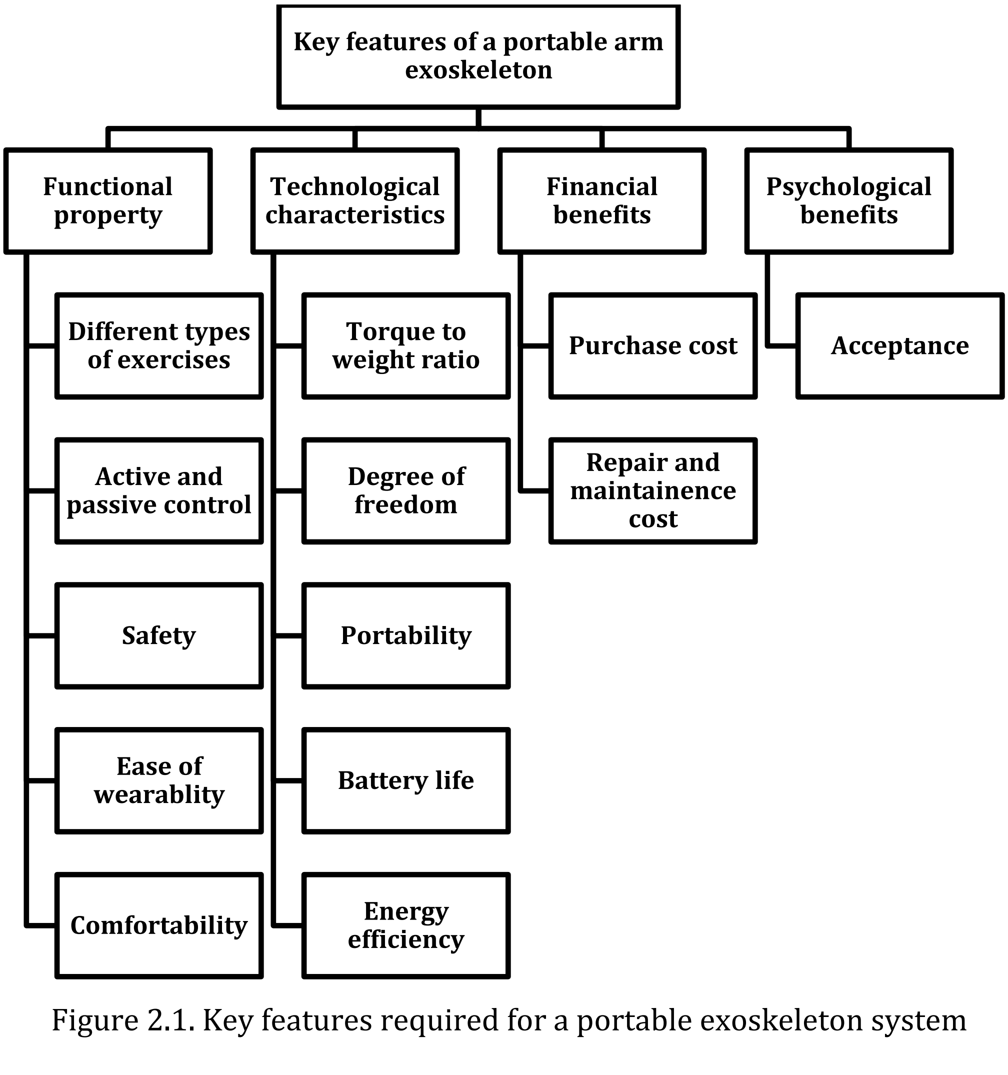


Figure 2.1. Key features required for a portable exoskeleton system

Out of the four divisions, the first two are highly important. Functional property is related to the appropriate functioning of the system to the rehabilitation process which not only includes all types of joint movement but also ensures safety and comfortability to users. The main requirement of exoskeleton is to make it a handy device which can be easily put-on and taken-off. One of the key factors of making a portable device is torque to weight ratio which should be high enough to support the maximum load during exercises. At the same time, the weight of the system should be lighter so that it will be wearable and convenient to move during exercises. The degree of freedom is another important factor of the design as the system is applied to human joint. The structural material is also essential for maintaining lightweight. Several actuation mechanisms have been designed for transferring motion from actuator to human joint. Choice of actuators and their supporting mechanical structure are mainly important for maintaining the required joint torque to rotate any joint. These mechanisms dictate the amount of energy needed for operation and ability to carry out daily exercises. Besides, the battery life is also crucial for supplying power to exoskeleton for a long time. All these attributes may require an energy-efficient mechanism to make it better than the existing models. Considerations should be given for the cost of actuator and type of sensor as it is important to make exoskeleton based rehabilitation a cost-effective therapy compared to manual treatment. Moreover, awareness should be raised amongst the patients and caregivers for utilization of exoskeleton in rehabilitation, since the acceptance level of patients to cope with new technology is very low (Van Ninhuijs et al. 2013). Sometimes patients would not go for exoskeleton based therapy due to its complicated architecture and mechanical look. Though appearance is least important among all the construction parameters of the exoskeleton, it should still provide a pleasant and aesthetic look to make it attractive to the patients.

The value of human labour rises with time whereas technical products becoming cheaper which will make these exoskeletons affordable. The prerequisites of an exoskeleton are significantly distinct for two stakeholder groups (Wolff et al. 2014). Specialists might want an exoskeleton with innovative characteristics which can deliver the finest therapeutic lessons in terms of recovery. From their perspective, the actuation mechanism of an exoskeleton should be fit for creating an assortment of joint movements. The clients' perspective is to get a customized gadget which is wearable and easy to use with an attractive and tasteful look. In this way, it is difficult to combine the perspectives of two sides in the development of exoskeleton. Safety is one of the vital factors (Wolff et al. 2014) for structuring any human-based frameworks which can be accomplished using specific mechanisms such as back-drivable system, compliant mechanism and serial elastic actuators (Maciejasz et al. 2014). The design of exoskeleton should follow the ISO 9000 standards in the European Community (Duchemin et al. 2004) where the design is safe for use from structural point of view and secured electromechanically using limit switch and mechanical restriction. Those systems are required to be programmed to hold the joint motion under anatomical range.

There are two types of movement in human arm: gross manipulation and fine manipulation (Manna and Bhaumik 2013). Shoulder and elbow joint are in charge of controlling human arm in a larger 3D space as opposed to wrist and joint joints which normally provides small manipulation task for fine movement. The weight lifting and other strenuous exercises are supported by shoulder and elbow joint whereas grasping, touching and other small-scale activities are performed by wrist and hand joints. Hence the properties of designed mechanism for facilitating movements of these joints are significantly different. For example, in case of shoulder and elbow joint, the level of joint torque and degree of freedom are the basic criteria therefore different actuation mechanism are incorporated to reduce the size and weight of the exoskeleton (includes the upper and lower arm). On the other hand, wrist and hand-based exoskeletons require very minute control for object manipulation with maximum degree of freedom. In general, an actuation mechanism for arm segments whether it is for upper arm, lower arm or hand, should produce a wide range of rehabilitation-based exercises required for post-stroke patients.

Actuators in exoskeleton can be divided into three types depending on its property; active, semi-active and passive (Figure 2.2). An active actuator can deliver a variable range of movements with various speed and torque. Electric motor, pneumatic and hydraulic systems are the most conventional active actuators which are generally used for exoskeleton (Manna and Dubey 2016). The semi-active actuator can’t provide any active torque to human joint however can apply resistive force if it has been displaced from its stable position. Normally there are two types of actuator named under this category: magnetorheological fluid based system (Oda et al. 2009) and compliant mechanisms (Van Ham et al. 2009). This type of actuator controls the joint stiffness as per the task requirement.

Passive actuators provide assistive force to the joint; these actuators are based on passive elements like spring (Sanchez et al. 2004) or rubber band (Housman et al. 2007) which uses its elastic property to generate force. There are some new kinds of actuators, for example, artificial muscle, shape memory alloy (SMA), electroactive polymer (EAP) and piezoelectric motor are also well received for exoskeleton designs (Letier et al. 2006).

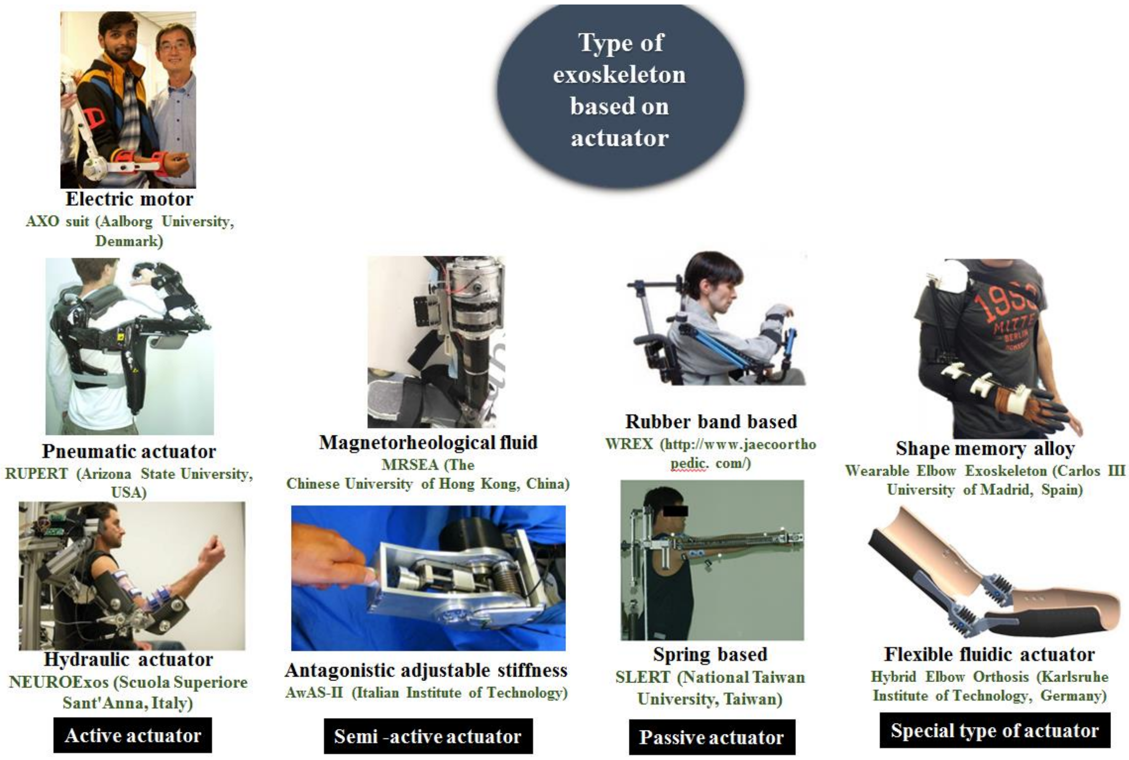


Figure 2.2. Type of actuators used in exoskeletons

After investigating 46 arm exoskeletons (Manna and Dubey 2016), it has been found that 56% of the total exoskeletons have electric motors (either brushed or brushless) as an actuator. Figure 2.3 shows the statistics of stationary and portable systems based on different actuators. According to this survey, passive actuator-based exoskeleton turns out to be the best choice for designing a portable system compared to those exoskeletons using conventional active actuators. However, it was discussed in the previous chapter that controlled joint movement is required in the acute phase of rehabilitation which cannot be achieved without active actuators. Out of all sorts of active actuators, pneumatic actuators are the favourable choice for making a portable exoskeleton, however, electric motors are still used as an actuator in most of the exoskeletons for providing actuation because of its linear and ease of control properties. Figure 2.4 shows a guide map of different actuators along with its actuation system used in the existing exoskeletons.

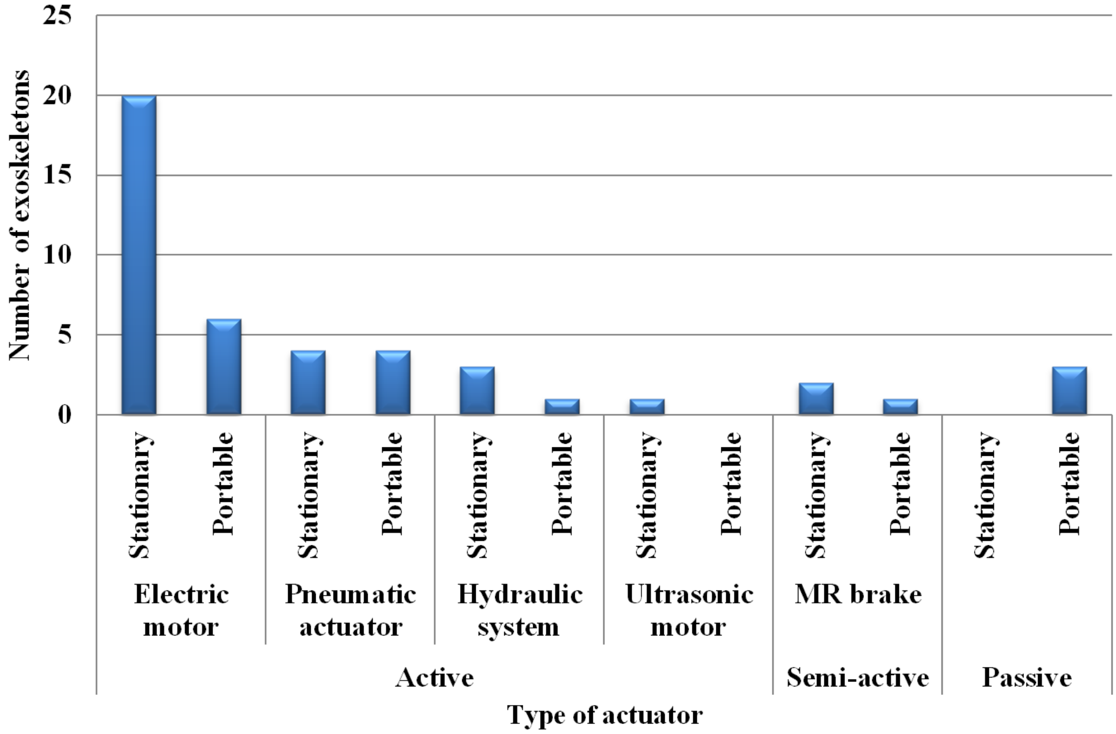


Figure 2.3. Statistics of actuator used for stationary and portable systems

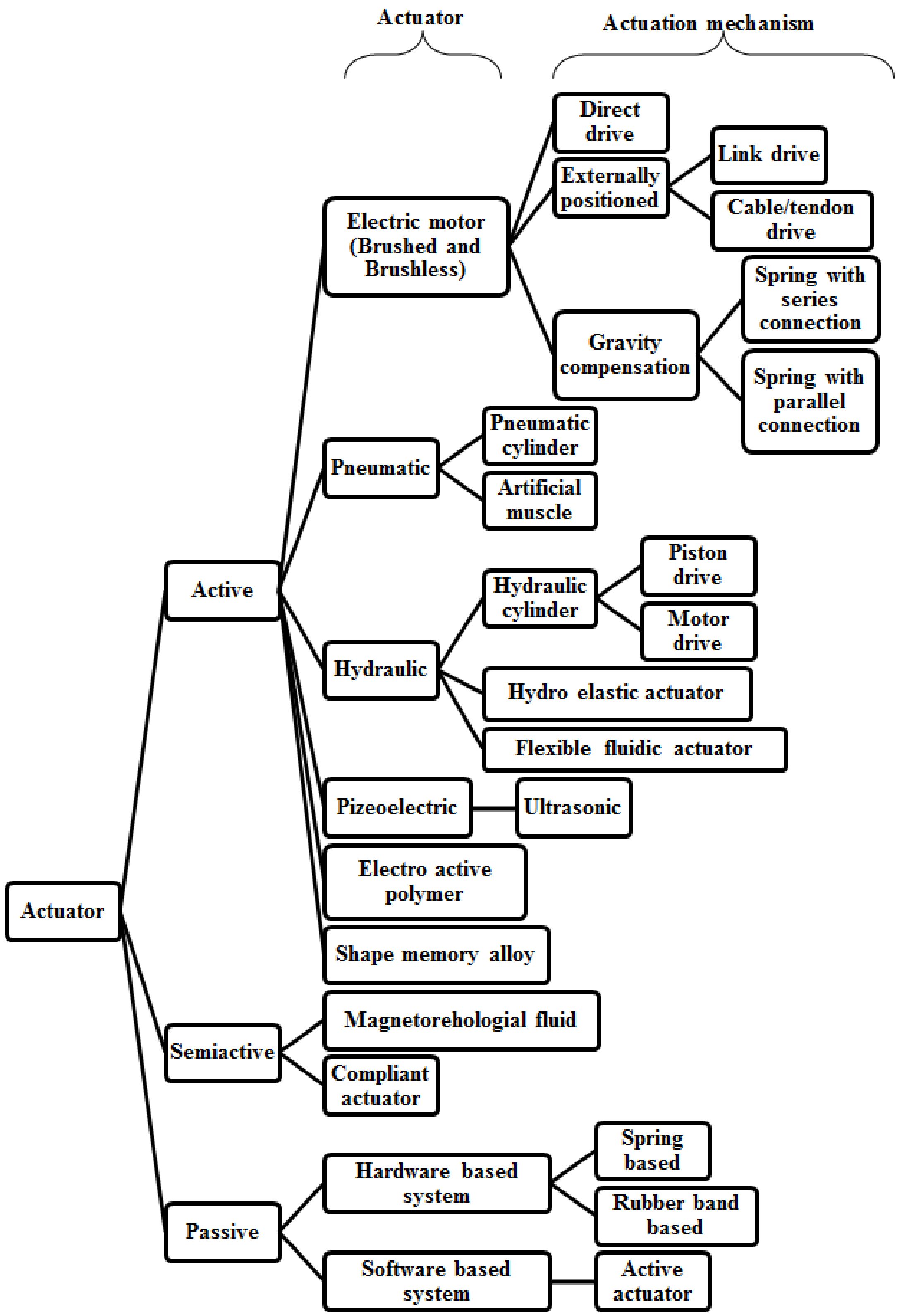


Figure 2.4. Different types of actuation systems

2.1 Actuation system for providing three types of joint movements

In this section, the existing actuators and actuation systems have been discussed to provide three types of joint movement to elbow joint. The advantages, as well as the limitations, are described with quantitative data.

2.1.1 External force-based exercise using active actuation

At the primary stage of rehabilitation, patients get joint movements comprising of some predefined orthopaedic exercises at various frequencies since they don't have any muscle control left. As patients do not have active participation, all types of arm-based activities are completely controlled by exoskeleton as a part of exercises; joint movement produced by exoskeleton is attached to affected body segment of patients. In human body, few muscles activate synergistically to deliver movement to a single joint, however, it is quite challenging to recreate human muscle structures in exoskeleton design, though it could be possible to accomplish the same level of joint torque and speed by incorporating active actuators with the proper mechanism design.

- **Electric motor**

It has been found that electric motor is the most popular actuator used in active exoskeletons because it can be controlled easily and facilitates high power cum bandwidth. In generall, brushed DC motor is used due to less complicated electronics circuit. On the other hand, brushless electric motor provides better power to weight ratio. In the majority of existing exoskeletons, motor is used as direct drive actuator which is located at human joint. The motor should have the capacity to generate enough torque to start, accelerate and control the exercises at the specific speed required for the treatment. Exercises in this phase of rehabilitation mode are performed at different loads. Motors normally behave with specific attributes to coordinate the particular speed-torque relationship in a joint. When an exoskeleton attempts to lift human arm against gravity during rehabilitation (including its own mass), it is subjected to a varying level of torque. As these activities are carried out by motor, large motors might be required to assist the human arm. Problem happens when a heavy and bulky electric motor is placed at the joint axis which needs to be carried by user. The condition could be worsened when a serial manipulator type exoskeleton is attached to human arm along with motors situated at joints. In this case, the motor used for shoulder has to take care of the load of the full arm including those motors used for elbow and wrist together attached to the mechanical structure. Sometimes more than two motors are connected in parallel as a parallel manipulator which acts more like muscle structure of human arm, for example, in MAHI (Gupta et al. 2008). The parallel mechanism also offers higher stiffness in a confined space. The motor produces high speed, low torque and is smaller in size but the frequency needed in rehabilitation is normally in the range of 1-2 Hz (Brooks 1990), therefore, those motors cannot be used. Gears are used in motor to reduce speed which typically adds more mass and decreases the efficiency level (Van Ninhuijs et al. 2013). Additionally, there is another issue with power consumption as it would fluctuate with the motor torque. The energy source of a portable exoskeleton should provide a continuous supply to the motor for a longer period. The bigger energy source meant additional mass to the exoskeleton. To improve the energy efficiency of a system, another direction of research emanating is on energy optimization techniques (Ghozzi et al. 2004).

To overcome the torque and energy-related issues, many actuation mechanisms have been created along with motor to improve the ratio of torque to volume and torque to weight which in turn enhance the possibility of developing a portable system. A system with low inertia provides better dynamic performance. The most well-known arrangement is to put the motor in a remote location and controls the joint using link-driven or cable driven systems. Actuators can be located either on the posterior attached to backpack (Rahman and Avi 2015) or on the arm structure itself (Agrawal et al. 2009). The four-bar linkage system was used to exchange the movement from one point to the next without any loss (Ching and Wang 1997). The advantage of using rigid links in mechanism is to transmit power without any loss of efficiency.

Cable tension should be maintained positive for joint actuation in cable-driven exoskeletons, however, the mechanism causes frictional loss because of cable and pulley-based systems. Joint torque is also subjective to the stiffness of cable. Cable-driven exoskeletons (Agrawal et al. 2009), (Ball et al. 2007), (Dehez and Sapin 2011) and (Perry et al. 2007) can produce a higher range of movement compared to other existing designs. Two actuators are necessary to create a bi-directional movement for a joint as it can generate motion in one direction (only pull but not push).

The dynamic range of a motor is affected if it is used in combination with a speed reducing or torque enhancing component. In the event, if an arrangement is made to offload the actuator's torque by balancing gravity, it not just reduces the power requirement of the whole system but also helps to make it compact. This type of technique is called passive gravity compensation technique. There are few approaches such as adding an extension spring with the actuator so that a portion of the required motor torque can be compensated using spring energy (Dubey and Agrawal 2011). This type of compensating model is called series elastic actuator which is developed by combining an elastic element like spring with the actuator. This type of arrangement reduces the impendence as well as provides a balancing force in gravity compensation (Crea et al. 2016). It also presents more resonances in the framework however brings down the functional bandwidth (Van Ninhuijs et al. 2013). As arm therapy doesn't need higher bandwidth, this kind of design is used in many exoskeletons (Crea et al. 2016), (Ragonesi et al. 2011). The elastic element of exoskeleton also provides safety (Chen et al. 2015) in arm movement by adding compliance.

The tension of a spring can be varied by the motor associated with it so that it can support extra load of the arm (or exercise with different loads in hand). To overcome frictional loss and backlash problem, sometimes electric motor is used along with a cable-capstan reducer (Letier et al. 2008) in place of the conventional speed reducer. A motor associated with capstan can adjust the tension between spring and joint. By using planetary gearbox with limited backlash and low reduction ratio, the frictional loss and creep in the cable-driven system can be reduced. Sometimes a slip clutch can be attached to a motor for providing safety from spastic motions (Carignan and Liszka 2005). It also functions as a torque-limiting device. If the joint torque crosses a specific limit, the slip clutch will separate the actuator from the exoskeleton structure. It enables free movement of the affected joint if spasm occurs in human arm. Clutches can be used for improving the usefulness of springs and actuators in exoskeletons (Diller et al. 2016). The clutch is connected to springs to control the spring force. The harmonic drive can provide high gear ratio and high torque in a compact space (Taghirad and Belanger 1998). It can also perform complex dynamic behaviour compared to conventional gear drives. HAL is an example of harmonic drive based commercial full-body exoskeleton (Kawamoto and Sankai 2002).

- **Hydraulic actuator**

The hydraulic joint actuator can generate the highest torque to weight ratio (Brown et al. 2003) however not appropriate for making a portable system because the entire system needs an oil pump along with a reservoir to produce compressive oil for movement. The push and pulling force are produced by the compressive fluid which is injected into a hydraulic cylinder under high pressure. Those systems have the issues of oil leakage and the control of systems is non-linear. For example, exoskeleton like NEUROEXOS (Vitiello et al. 2013) has a big chamber and pump associated with it, therefore, it is extremely difficult to move it during motion. The leadscrew based motor-driven mechanism can be also used to drive the hydraulic cylinder to provide bi-directional motion. There are some newly developed hydraulic actuators which have been developed to enhance portability like hydro-elastic actuator (HEA) (Stienen et al. 2008) and flexible fluidic actuator (FFA) (Landkammer and Hornfeck 2014). Hydro-elastic actuator generates rotational force using a motor in combination with a spring which keeps the elasticity during motion. But it has the drawback of using an individual motor for a particular joint motion whereas a single reservoir with an oil pump is sufficient to give power to all hydraulic cylinder driven joints in an exoskeleton. FFA is a new type of modular fluidic actuator which is used for elbow joint. The main component of FFA is a few reinforced flexible bellows which are connected together and inflate due to pressurization. If an FFA is attached between two links, it can generate rotational movement to the joint. It needs a small hydraulic pump as well as a small portable reservoir for its operation.

- **Pneumatic actuator**

Pneumatic actuators can also provide good power to weight ratio. There are two types of pneumatic actuators which have been developed for exoskeleton; pneumatic cylinder based actuation and pneumatic artificial muscles. The function of pneumatic cylinder is the same as hydraulic cylinder where compressed oil is replaced by air to generate motion in both directions. The artificial muscle is also known as Mckibben muscle (Tondu and Lopez 2000) which behaves like natural muscles and it is advantageous compared to existing active actuators because it can provide higher torque to weight ratio by maintaining less weight. The impedance property of pneumatic muscle is also lower than electric motors. Exoskeletons such as RUPERT (Balasubramanian et al. 2008), Pneu-Wrex (Reinkensmeyer et al. 2012), ASSIST (Sasaki et al. 2005), Salford arm (Tsagarakis and Caldwell 2003) fall under this category. The structure of pneumatic muscle consists of two layers fabricated from braided nylon. When the material is under pressure due to compressed CO_2, the braided material inflates and the axial length contracts, therefore showing similar action like human muscle. This sort of actuator facilitates smoothness, lightness and compliance in the system. For this reason, pneumatic muscle based exoskeletons are also called soft-robots. It can produce natural compliance in the mechanism which in turn improves the ergonomic property of exoskeleton and makes it more user-friendly. Exo-suit (O'Neill et al. 2017) is a standout amongst the developed models of soft-robots, designed at Harvard University where the structural material of the exoskeleton is soft fabric and small wearable sensors are attached to it for measuring joint movement. This type of exoskeleton can be fitted under garments empowering users to avoid any open exhibit. Researchers have also developed different fabric using thermal adhesive film placed inside pneumatic muscle (Yang 2017) to enhance the performance of exoskeleton. However, there are several disadvantages of artificial muscle such as low bandwidth, non-linear characteristics, unidirectional operation and bigger size. It is difficult to put this type of actuator in a small area with other components due to its size. Since it can only provide motion in one direction, a pair of pneumatic muscle is required for generating bi-directional joint movement. Human joints such as shoulder joint and wrist joint having several degrees of freedom, therefore it is difficult to recreate human joint motion using this type of actuator.

- **Electroactive polymer**

Electroactive polymer (EAP) is a recently created flexible material which has an elastic property similar to human muscles (Bar-Cohen 2005). Using the movement of ionic species in this material, actuation can be produced. However, this material can be used for micromanipulation in the exoskeleton. There are few qualities possessed by EAP for example, high bandwidth, higher electrical-to-mechanical power conversion ratio but has very low torque to weight ratio. Hence currently it is not fit for the actuation in exoskeleton. It is anticipated that the properties of EAP can be improved with further research and make it an acceptable solution for portable exoskeleton in the near future.

- **Ultrasonic motor**

Another new type of actuator providing high power to weight ratio is ultrasonic actuator which can be a suitable choice for portable exoskeletons (Choi and Choi 2000). It can generate mechanical vibration depending on the piezoelectric effect. Unlike the other motors, it consists of two parts; electrical energy is converted into mechanical vibration using stator and the rotor converts the vibration into rotational movement using friction. There are two piezoelectric elements attached serially which are used to transmit the vibration from stator to rotor. The main benefit of using ultrasonic motor is that the ratio of torque/weight and torque/volume can be enhanced up to 20 times higher than DC motors (Letier et al. 2006). The other benefits of ultrasonic motor are lightweight system and compact in size. It doesn't make any electromechanical noise during operation. This type of actuator can support rehabilitation based activities because it can also be operated at low speed. Along with few advantages, it has some disadvantages as well such as ultrasonic motor needs local force feedback to control its operation. Besides these actuators are very stiff and difficult to fabricate due to high production cost (Petit and Gonnard 2005).

- **Shape memory alloy**

The functional property of shape memory alloy (SMA) is similar to EAP and pneumatic artificial muscle because it contracts or expands with reference to heat. It can be an alternative to an activity which requires less movement. It is recognised as smart material fabricated from different metal alloy specially copper-aluminium-nickel and nickel-titanium. However, there are some materials from which it can also be created such as alloying-zinc, copper, gold and iron. SMA is normally deformed due to heating but it will return to its initial shape after cooling. It performs as a memory element by recovering from its pre-deformed shape before heating. The shifting of crystalline structure between two stages causes the movement in SMA, known as martensite and austenite. The low-temperature stage is called martensite and high-temperature stage is called austenite. The nonlinear property of SMA including hysteresis makes it difficult to control (Heo et al. 2012). Moreover, the bandwidth of SMA is very low due to the cooling cycle. Few hand exoskeletons have been developed using SMA such as hand orthosis (Dittmer et al. 1993) and a differential rotational actuator (Tang et al. 2013). A couple of exoskeletons have also been designed with SMA wire-based actuators for elbow joint (Copaci et al. 2017) and forearm cum wrist (Hope and McDaid 2017) for rehabilitation of post-stroke patients.

- **Electrostatic force**

Electrostatic force (Diller et al. 2016) can be used for actuation by applying a voltage to a pair of electrodes separated by an insulating dielectric layer. Adhesion property of insulating material can be changed by the electrostatic force. This procedure will create a different gripping force at the electrode. Table 2.1 shows technical specifications of few existing exoskeletons using active actuator.

Table 2.1. Exoskeletons with active actuator

Exoskeleton Design	Actuator	Actuation System	Degree of freedom	Attached to	Mass	Torque	Portability
ARMin (Nef et al. 2009)	Harmonic Drive	Direct drive & link drive	6	Full arm	18.76 kg	37.76 Nm	No
MGA exoskeleton (Carignan et al. 2007)	Electric Motor	Direct drive	7	Shoulder, elbow, and forearm	12 kg	137 Nm	No
ExoRob (Rahman et al. 2010a)	Harmonic Drive	Direct drive	5	Elbow joint and wrist joint	Actuator mass- 1.15 kg	5.5 Nm	No
MEDARM (Ball et al. 2007)	Electric Motor	Cable drive	3	Shoulder, elbow, wrist	115 kg	73 Nm	No
ShouldeRO (Dehez and Sapin 2011)	Linear Actuator	Bowden Cables	2	Shoulder joint	1 kg	50 Nm	No
NEUROEXOS (Vitiello et al. 2013)	Hydraulic Drive	Antagonistic Compliant actuation	3	Shoulder joint	2.30 kg (without pump , reservoir)	15 Nm	No
Multiple Joint Robotic Arms (Jang et al. 2004)	Ultrasonic motor	Direct drive	4	Shoulder, elbow, wrist	-	63 Nm	No

Exoskeleton Design	Actuator	Actuation System	Degree of freedom	Attached to	Mass	Torque	Portability
Skeleton Arm (Brackbill et al. 2009)	Electric Motor	Tendon-Driven	6	Human arm	-	-	No
BONES (Klein et al. 2010)	Pneumatic	Parallel Drive	4	Shoulder and elbow	-	22 Nm	No
Dampace (Stienen et al. 2009a)	Hydraulic Actuator	Cable & spring drive	4	Shoulder and elbow	-	50 Nm	No
Limpact (Stienen et al. 2008)	Rotational hydroelectric actuator	Direct drive, cable & spring	4	Shoulder and elbow	8 kg	36 Nm	No
Pneu-Wrex (Reinkensmeyer et al. 2012)	Pneumatic	Link drive	4	Shoulder, elbow, and finger joint	-	80 N force	No
Intelliarm (Ren et al. 2009)	Electric motor	Direct drive & cable drive	9	Shoulder, elbow, wrist and finger joint	-	10.20 Nm	No
SUEFUL-7 (Gopura et al. 2009)	DC servo motor	Direct drive & gear drive	7	Shoulder, elbow, wrist and finger joint	5 kg	5.90 Nm	No
MIME-RiceWrist (Gupta et al. 2008)	Electric Motor	Parallel Drive	3	Wrist	1.96 kg	5.08 Nm	No
Salford Rehabilitation exoskeleton (Tsagarakis and Caldwell 2003)	Pneumatic muscle	Antagonistic actuation	7	Shoulder, elbow, and wrist	2 kg	30 Nm	No
CADEN-7 (Perry et al. 2007)	DC Brushed motor	Cable drive	14	Shoulder, elbow, forearm and wrist	6.80 kg	6.20 Nm	No
WOTAS (Rocon et al. 2007)	DC motor	Direct drive	3	Elbow, forearm, wrist	0.85 kg	8 Nm	Yes
MAHI Exos-II (French et al. 2014)	Frameless DC brushless motor	Parallel Drive	5	Elbow, forearm, wrist	Motor-0.48 kg	11.61 Nm	Yes
RehabExos (Vertechy et al. 2009)	DC brushless motor	Direct drive	4	Shoulder, elbow, and forearm	Motor-3.70 kg	150 Nm	No
ARAMIS (Colizzi et al. 2009)	DC brushed motor	Direct drive	12	Shoulder, elbow, and forearm	19 kg	94 Nm	No
iPAM (Culmer et al. 2011)	Pneumatic	Link drive	6	Shoulder, elbow, and forearm	Wheelchair-based system	15 Nm	No
L-Exos (Frisoli et al. 2012)	Electric Motor	Cable and link drive	5	Shoulder, elbow, and forearm	11 kg	Torque - 3.70 Nm	No

Exoskeleton Design	Actuator	Actuation System	Degree of freedom	Attached to	Mass	Torque	Portability
MULOS (Johnson et al. 2001)	Electric Motor	Direct drive	5	Shoulder, elbow, and forearm	Wheelchair- based system	14.95 Nm	No
Hybrid Elbow Orthosis (Pylatiuk et al. 2009)	Hydraulic	Flexible fluidic actuation using bellows	1	elbow	1.20 kg	3 Nm	Yes
Exorn (Manna and Bhaumik 2013)	DC Brushed and brushless motor	Direct drive	10	Shoulder, elbow, forearm and wrist	10 kg	Motor torque-30 Nm	Yes
ALEx (Pirondini et al. 2016)	Brushless Motor	Direct drive	6	Shoulder, elbow, forearm and wrist	14.50 kg	80 Nm	Yes
ABLE (Garrec et al. 2008)	Electric Motor	Link drive	4	Shoulder, elbow, and wrist	-	18 Nm	No
SAM (Letier et al. 2008)	Electric Motor	Capstone wheel based drive	7	Shoulder, elbow, forearm and wrist	6 kg	19.70 Nm	No
Myomo (Stein et al. 2007)	DC motor	Direct drive	4	Elbow and wrist	-	-	Yes
SUE (Allington et al. 2011)	Pneumatic	Link drive	2	Forearm and wrist	0.56 kg	-	Yes
Self-aligning exoskeleton (Beekhuis et al. 2013)	Electric motor	Gear drive and direct Drive	3	Forearm and wrist	-	3 Nm	Yes
Exo-suit (O'Neill et al. 2017)	Soft textile pneumatic actuator	Direct drive	1	Shoulder	-	20 Nm	Yes
Pneumatic elbow exoskeleton (Yang 2017)	Pneumatic muscle	Direct drive	1	Elbow	0.30 kg	300 N force	Yes
ExoGlove (Yap et al. 2015)	Pneumatic actuator	Direct drive	-	Hand	0.20 kg	-	Yes
Hand rehabilitation system (Tang et al. 2013)	Shape memory alloy	Direct drive	3	Finger	-	20 N force	Yes
Soft Robotics Wearable Elbow Exoskeleton (Copaci et al. 2017)	Shape memory alloy	Bowden Cables	1	Elbow	0.60 kg	Pulling force-34.9 N	Yes

Exoskeleton Design	Actuator	Actuation System	Degree of freedom	Attached to	Mass	Torque	Portability
Wearable Wrist and Forearm Exoskeleton (Hope and McDaid 2017)	Shape memory alloy	Spring and cable drive	3	Elbow and wrist	0.95 kg	20 Nm	Yes

Short conclusion: After reviewing these actuators and actuation systems, electric motor is considered as a best suitable choice for providing the required joint torque in acute phase of post-stroke rehabilitation. Link-driven mechanism can be used to enhance the torque to weight ratio.

2.1.2 Methods for assistive force-based exercise

After rigorous external force-based exercises, patients can initiate their joint movements because they normally recover some muscle strength. But they can barely keep their arms in a balanced condition to manoeuvre it in a certain orientation. Therefore, support from exoskeleton would be useful for patients to do different exercises. Assistive force in exoskeleton can be achieved using an active actuator or passive elements.

2.1.2.1 Software based approach

The easiest solution for delivering assistive force to user is based on soft computing approach (Rahman et al. 2010a) where the controller circuit can detect patient's intention of motion using different biosensors (EMG and EEG). An intelligent control framework can produce variable motor torque depending on the patient's triggering signal extracted from sensors. In case patients are not capable enough to do physical activity on their own, the control signal regulates the required motor torque which may help to refine arm movements. Exoskeleton would reduce the amount of motor torque in case of improved health conditions of patients. However, there are a few constraints regarding the stability of sensor signals. In software based approach, exoskeleton can show dissonant behaviour on sudden effect of impact force because of delay in the signal transmission. In this type of control, electric motor is engaged to human joint constantly along with other electronic components thus may result in constant draining of energy source. This technique may not be suitable for an energy-efficient system. On the other hand, the movement of human joint is always controlled by motor where the function of motor is to maintain the rotation angle beyond the anatomical limit is not ideal from a safety perspective.

2.1.2.2 Hardware based solution

Through hardware-based mechanism, reverse forces can be generated against gravity to balance the arm in a specific position such as putting a counterweight in the exoskeleton on the opposite side of joint rotation so that the arm can be balanced by the load under gravity (White and Xu 1994). However, this type of solution is not useful for making a portable system where weight reduction is the main goal. A passive elastic material like spring or rubber band can assist human arm by reducing the joint torque for arm movement. Extension spring always reacts to get into its normal shape and due to its property, it would generate an opposite force to gravity. Therefore, passive elastic elements can create energy-free exoskeleton because joint movement does not need any involvement of active actuator.

Springs are normally attached to a mechanism made up of solid links (Wu and Chen 2014). The position of front-end or rear-end of the spring is tied between two separate links which are attached to two adjunct arm segments. Spring force may assist to deal with the arm movement that needs movement against gravity. Assistive power can be varied by modifying the connection points of the spring in the mechanism. However, the range of motion is reduced due to the free length of springs in those systems. Spring length may restrict the joint movement to a specific degree but using complex link mechanism, it may possible to enhance the efficiency of joint torque as well as the range of motion. Full range of joint motion should be obtained using zero-free-length spring which is not easy to manufacture. To expand the range of motion, cable can be attached to the end point of a spring (Herder et al. 2006). One arrangement is to put it in a remote position and provides the spring force using cables. Rubber band is also a good choice to provide assistive force without adding complexity to design such as T-WREX (Housman et al. 2007) which is a commercial exoskeleton, it is a simple and affordable device.

Rotational joint torque is different for different users based on their arm size and mass. A user requires variable joint torque for lifting different loads in therapy process. There are two different procedures to modify the spring force dynamically during the operation; one approach is to change the number of active coils in spring (Hollander et al. 2005) and another is to change its displacement range by moving the front-end or rear-end position of the spring (Kramer et al. 2007). The first procedure changes the stiffness of a specific spring while the second arrangement changes the spring force. In any case, it is important to ensure that the changing of spring dimension should not last permanently and it should restore to its original dimension. Most of the exoskeletons have used extra motors to develop the platform for providing variable spring force. This type of arrangement might be suited from a control perspective however not suitable for a compact device due to the addition of extra motor. It also increases the size of the system. Lists of few passive element based exoskeletons are shown in Table 2.2.

Table 2.2. Exoskeleton with passive element (spring & rubber band)

Exoskeleton Design	Actuating system	Passive elements	Degree of freedom	Attached to	Mass	Torque	Portability
T-WREX (Housman et al. 2007)	Link drive	Rubber band	5	Shoulder, elbow, and finger	-	-	Wheelchair -based system
Armon (Herder et al. 2006)	Link drive and cable drive	Spring based	3	Shoulder, elbow, and wrist	-	23 N force	Wheelchair -based system
SLERT (Wu and Chen 2014)	Link drive	Spring based	4	Shoulder, elbow	-	-	No
Armeospring (Sanchez et al. 2004)	Link drive	Spring based	7	Shoulder, elbow, wrist and finger	-	-	No
Hybrid arm support (Cannella 2015)	Link drive	Spring based	1	Arm support	10 kg	-	No

Short conclusion: After reviewing these actuators and actuation systems, passive spring-based system is considered as a best suitable choice for providing assistive force in mid phase of post-stroke rehabilitation because it does not need any energy source for actuation. However, there should be a provision to vary the range of the assistive force.

2.1.3 Techniques for creating variable stiffness at exoskeleton joint

The second phase of rehabilitation solely depends on patient's recovery condition and assistive force. Neuromuscular activity improves with time as patients regain their strength. Training-induced cortical activation is dependent on post-stroke rehabilitation process and the difficulty level of exercises enhances the contralesional activation. It makes them familiar with real-time force activities through different learning process. Therefore, exercises in the third phase of rehabilitation should be intense and strenuous with time.

Joint stiffness of exoskeleton is being kept constant during the first phase of rehabilitation since patients do not participate actively. Patients start participating in their exercises in the second and third phase of rehabilitation. If the joint stiffness of exoskeleton can be made stiffer, patients have to give extra torque to move the joint. There are three different ways to vary the joint stiffness.

2.1.3.1 Active actuator based joint stiffness control

Dynamic joint stiffness control can be acquired in active actuator using soft computing technique to maintain a specific resistive force in a particular environment (Kircanski and Goldenberg 1997). An exoskeleton can impose variable joint stiffness to human arm during exercises by adjusting its motor torque. The strategy is similar to the assistive force based rehabilitation process but the nature of applied force is opposite. Toward the beginning of self-movement based activities, assistive force is required to support joint movements whereas variable resistive force is imposed later on to restrict those movements. This kind of technique is purely programming-oriented and it should be adaptable according to the health status of patients. As an example, patients may experience unpredictable neurological effects due to involuntary muscular contraction resulting in undesirable joint torque.

2.1.3.2 Semi-active actuator based joint stiffness control

The semi-active actuator can also control the joint stiffness in exoskeleton. The internal design mechanism of this actuator is only suitable for the application where resistive force is required because it can't generate active force. It contains controllable fluid and its viscosity can be changed by adjusting its electromagnetic property. As a result, stiffness of the joint connected to it is also varied. One of the developed semi-active actuators is MR (Magnetorheological) brake which provides a resistive torque up to 1.1 Nm (Oda et al. 2009). The magnetorheological fluid is placed between the gap of stator and rotor. It contains a large number of micron-sized magnetic particles inside the liquid carrier and forms a structure like magnetic chain whenever exposed to the external magnetic field. Eventually, the viscosity level of the fluid is modified and as a result, the stator can impose variable frictional force to the rotor and the mechanism can apply different stiffness at the joint. The advantage of MR brake is about its intrinsic stability to the patient for keeping their arm at a specific location. In some systems, the semi-active actuator and normal actuator are combined together to provide stiffness to the joint with better efficiency and extra features which is not possible to achieve by the semi-active actuator. Normally, the operating voltage range of MR brake is 2-25 volt with a current rating of 1-2A.

2.1.3.3 Compliant actuator based joint stiffness control

It is possible to achieve variable joint stiffness using different mechanisms. This type of approach can replace the complex control system by incorporating different passive component-based mechanism in exoskeleton structure. A couple of series elastic materials, for example, spring or bending rod can be used for this purpose. There are a couple of standard mechanisms used for changing the stiffness of joint however all of those procedures can't be utilized for human applications. The most standard solution is compliant actuator (Vanderborght et al. 2013). The property of compliant actuator shows elastic behaviour when the end effector of the mechanism deviates under an external force but comes back to its original state if no force is existing. It consists of passive elements which basically keeps and releases the elastic energy for actuation. It appears in recent publications that the compliant actuator is more efficient than electromagnetic brakes for making arm based exoskeleton as far as safety and comfort are concerned (Van Ham et al. 2009). The main advantage of using this type of actuator is that it normally imposes less impact force on the joint under external shocks and keeps it intact. From a technical perspective, stiffness and compliance are reverse in nature; a stiff actuator always tries to keep a human joint at a particular position if the external force is withdrawn. A compliant mechanism is displaced from its balanced position based on the applied force. However, it restores to its stable configuration with zero potential energy. Since the compliant property of a mechanism can substitute the non-stiff behaviour of it, it can be used as differential stiffness actuator. In actual circumstances, the exercises of post-stroke rehabilitation require relatively less stiffness and the joint stiffness can be eventually increased when patients are able to regain their muscle control.

Active actuator can provide the characteristics of spring through control algorithm whereas passive compliant mechanism uses spring for generating the joint stiffness. The disadvantage of using active actuator is that it always needs power source to create any type of reaction force. On the other hand, passive compliant mechanism requires some additional components like spring and motor to vary the resistive force. A couple of existing designs are discussed here for creating compliant behaviour in a system such as:

- Antagonistic controlled stiffness (Migliore et al. 2005): The structure of the mechanism consists of two non-linear springs associated with two actuators in series which are connected to the joint antagonistically, imposing force against each other. The joint stiffness of the compliant mechanism can be controlled by changing the displacement of those springs using actuator.
- Structure controlled stiffness: A few mechanical structures such as cantilever beam or bending rod acts like a spring because of their elastic property. These material are also used to provide variations in stiffness (Speich 1999). The stiffness of those elements is decided by the structural material and dimension. The stiffness of spring can also be controlled by adjusting the effective spring length e. g. jack spring (Hollander et al. 2005) which uses a mechanism for controlling the effective number of active coils.

Majority of the mechanisms providing variable stiffness generally use spring-based system which is controlled by one or two active motors. However, the addition of extra motors or mechanism increases the mass of the exoskeleton which is one of the principal inhibiting factors of portable exoskeleton development.

Back-drivable actuators are also used for providing safety and comfort. Higher joint torque is required to actuate stiff actuator while back-drivable actuator can be actuated with a small amount of torque. In case the back-drivability of an actuator is turned out to be too low, the gearbox may be damaged because of sudden external force. The resonance of mechanical systems is increased (Van Ninhuijs et al. 2013) and the system bandwidth is reduced due to the addition of springs. A couple of exoskeletons offering variable joint stiffness are shown in Table 2.3.

Table 2.3. Exoskeleton with variable joint stiffness

Exoskeleton Design	Actuating system	Actuator	Degree of freedom	Attached to	Mass	Torque	Portability
Semi-active actuator							
MEM-MRB (Oda et al. 2009)	Link drive	Magneto-rheological fluid brake	1	Elbow	26.40 kg	27.5 Nm	No
MUNDUS (Pedrocchi et al. 2013)	Link and cable drive	Electro-magnetic DC brake	3	Shoulder, and elbow	2.20 kg	-	Wheelchair -based system
DVB orthosis (Loureiro et al. 2005)	Link drive	Magneto-rheological Fluid	1	Wrist	<0.20 kg	50 N peak force	Yes
Compliant actuation system							
Biologically Inspired Joint (Migliore et al. 2005)	Antagonistic series elastic actuation	Electric motor	1	Any joint	-	-	-
VSA-II (Schiavi et al. 2008)	Antagonistic series elastic actuation	Electric motor	1	Any joint	0.35 kg	-	Yes
AwAS-II (Jafari et al. 2011)	Lever and spring based	Electric motor	1	Any joint	1.10 kg	80 Nm	Yes
Hybrid Dual Actuator Unit (Kim and Song 2010)	Double spring based	Electric motor	1	Any joint	1.80 kg	50 Nm	Yes
CompAct-VSA (Tsagarakis et al. 2011)	Lever and spring based	Electric motor	1	Any joint	-	117 Nm	-
vsaUT-II (Groothuis et al. 2012)	Spring and belt drive	Electric motor	1	Any joint	-	-	-
HVSA (Kim and Song 2012)	Lever and spring based	Electric motor	1	Any joint	-	8.50 Nm	-
VSA-CubeBot (Catalano et al. 2011)	Spring and wire drive	Electric motor	1	Any joint	0.26 kg	3 Nm	Yes
PVSA (Nam et al. 2010)	Antagonistic actuation with cam	Electric motor	1	Any joint	0.98 kg	-	Yes
VSJ (Choi et al. 2011)	Leaf-spring based	Electric motor	1	Any joint	4.95 Kg	-	-
DLR FSJ (Wolf et al. 2011)	Roller-based cam drive	Electric motor	1	Any joint	1.41 Kg	67 Nm	Yes

Exoskeleton Design	Actuating system	Actuator	Degree of freedom	Attached to	Mass	Torque	Portability
mVSA-UT (Fumagalli et al. 2012)	Spring and gear drive	Electric motor	1	Any joint	0.10 Kg	1 Nm	Yes
CCEA (Huang et al. 2011)	Antagonistic link based spring Drive	Electric motor	1	Any joint	0.80 Kg	13 Nm	Yes
MACCEPA (Van Ham et al. 2007)	Link and spring drive	Electric motor	1	Any joint	-	-	-

Short conclusion: After reviewing these actuators and actuation systems, passive spring-based antagonistic compliant set-up can be considered for providing resistive force in last phase of post-stroke rehabilitation because it does not need any energy source for actuation. However, there should be a provision to vary the range of the resistive force.

2.2 Mechanism for forearm motion

Existing exoskeletons like ARMin (Nef et al. 2009), SUEFUL (KIGUCHI et al. 2016) can provide the twisting movement of arm using motor based operation. ShouldeRO (Dehez and Sapin 2011) use a series of motor connected serially in combination with a cable-driven mechanism to create alignment-free motion in human arm which can substitute the twisting motion. Sometimes two actuators are placed on shoulder top or remote location to control the clockwise-anticlockwise twisting motion (Mao et al. 2015). Large numbers of motor consume more energy and increase the cost of the system. Tension in Bowden cable results in frictional loss. Parallel manipulator exoskeletons such as MAHI (French et al. 2014) can generate twisting movement but the range of movement is restricted due to its mechanical structure. All these mechanisms used in those exoskeletons generate motor controlled movement without considering user's flexibility. ARMin (Nef et al. 2009) has used back drivable motor for twisting motion.

Short conclusion: The design should have twisting motion with a spring-based system to enhance user's flexibility.

2.3 Other structural factors for designing exoskeletons

Apart from the actuators and auxiliary structure of actuation systems used for upper limb exoskeleton, there are also other structural factors responsible for designing an exoskeleton which is discussed below.

2.3.1 Joint misalignment

One of the major issues in designing exoskeleton is to align its joints with human arm when attached. During joint motion, the distal point of exoskeleton will move with respect to the centre of joint at different postures. The attachment is normally shifted to a new position (Figure 2.5), as a result, the actuator of exoskeleton may move a certain segment of the arm misaligned which is not desirable (Schiele 2008). It may cause injury to patients such as scratching, attachment of exoskeleton to soft tissue may also create problems to patients (Schiele and van der Helm 2006). Therefore, a perfect coupling is necessary to place the attachments near to the neutral tissue less prone to pain. Most of the modern exoskeletons are controlled through impedance or admittance approach which is based on force feedback. Due to misalignment, the joint of human arm may not match properly with the exoskeleton joint resulting in an error in force transfer. As exoskeleton behaves like a mechanical chain connected serially with several linkages, an offset will be generated at the end of each distal end. These consecutive errors will be accumulated and transferred to the next linkage. Though the offset may be minimal for a single joint, the accumulated error may create a major problem for proper device functioning. Use of spring actuated passive joints could compensate for misalignment (Schiele and van der Helm 2006). In some exoskeletons, pneumatic artificial muscle has been used as actuator (Balasubramanian et al. 2008) which inherently acts like human muscle and may reduce the extra weight of passive joint.

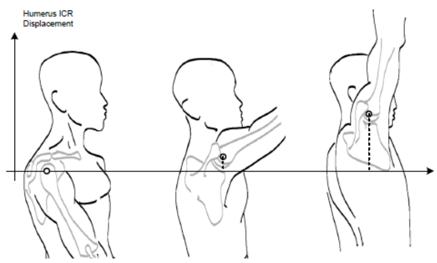


Figure 2.5. Change of centre of rotation during movement (Schiele 2008)

Short conclusion: A linear passive joint can compensate the joint misalignment between human arm and exoskeleton.

2.3.2 Degree of Freedom

Based on the bioelectric signal generated in human muscle, the activation mechanism of human joint occurs by a bunch of muscle fibres. However, it is very hard to reproduce the same kind of motion using actuators. A human arm can provide 7 independent DOF (shoulder-3 DOF, elbow-1 DOF, forearm-1 DOF, and wrist -2 DOF). Also, the structure of an exoskeleton requires passive joints to adjust joint misalignment. A couple of cable driven exoskeletons have been designed to mimic the tendon based actuation. However, large numbers of actuators will be required in cable driven exoskeletons making it complex and bulky. Shoulder and wrist possess multiple DOF from a single point. To imitate this type of characteristics using electric motors, several actuators need to be positioned in a small space and the axis of rotation of all actuators must coincide at a single point. Also the offset between all actuators should be minimum to make it an efficient joint. Parallel manipulators are designed to move its end effector in a 3D space however its end-effector motion is restricted due to structural formation (French et al. 2014). A new solution has been proposed for providing multiple DOF from a single actuator by creating spherical magnet arrays using the magnetic charge (Motoasca et al. 2013). The movement of a spherical joint cannot be controlled by a single actuator however any position in a 3D space can be accessed by creating a magnetic field on the surface of a sphere. This concept is not yet implemented and still in research. In ShouldeRO (Dehez and Sapin 2011), several actuators are moulded and supported by Bowden cable to generate motion to shoulder joint.

Short conclusion: DOF is an important consideration in exoskeleton design, for elbow exoskeleton one DOF rotational motion (flexion-extension) and forearm twisting motion (pronation-supination) should be considered

2.3.3 Structural lengths and reachable joint angle

The structural lengths of upperarm and forearm for making an elbow joint exoskeleton is decided based on the lengths of human arm. The structural lengths of the exoskeleton should be such that it will help users to reach maximum joint angle and provides comfort and flexibility to users. Most of the exoskeletons such as ARMin (Nef et al. 2009), CADEN-7(Perry et al. 2007) have considered the variation of arms length to fit with different users.

Short conclusion: Structural lengths of exoskeleton should not be fixed, and can be determined based on the collected user's anthropometric data.

2.3.4 Bandwidth

Actuator's bandwidth of an exoskeleton decides the quality of rehabilitation services. If the bandwidth of an exoskeleton is same or higher than that of a patient, it shows better performance. The natural frequency of a human is in range of 1-2 Hz for unpredicted signal, 2-5 Hz for repetitive signal and 5 Hz for learned actions (Brooks 1990). Each actuator has specific characteristics. However, additional components such as gear and spring influence its bandwidth. The control bandwidth of DC motors is generally in the range up to 200 Hz (Schiele and Hirzinger 2011), however, can be reduced to 50 Hz using gear reduction. The cable-driven system can reduce the bandwidth up to 40 Hz. Spring attached DC motor delivers lower bandwidth compared to an independent DC motor relying upon the spring stiffness. The bandwidth of pneumatic artificial muscles is 2.4 Hz which is close to human muscles, 2.2 Hz (Aaron and Stein 1976). Hydraulic disk brake works at 10 Hz (Stienen et al. 2009b) and hydro-elastic actuator associated with spring can deliver the bandwidth in between 6.5-7.2 Hz (Vitiello et al. 2013).

Short conclusion: The range of joint frequency can be varied between 1-2 Hz.

2.3.5 Energy consumption

Energy efficiency is equally important for designing a portable system. The required joint torque of shoulder, elbow, and wrist are not same as it relies on the inertia of the arm segment. Exoskeletons with gravity compensating mechanism may reduce the torque level, therefore consume less energy. Passive exoskeletons operate on the potential energy of springs for implementing assistive or resistive torque. At equilibrium condition, these systems are torque balanced with zero potential energy. WREX (Housman et al. 2007) and Armon (Herder et al. 2006) are the exoskeletons using this concept. Passive exoskeletons may be helpful for designing a portable system as they do not need any energy source to hold an arm joint in a balanced condition, but those systems can't generate active actuation force. A structurally optimized system with a combination of active and passive components can be considered to design a portable exoskeleton. It should be able to provide two phases of self-initiated exercises; one with assistance and another with resistance.

Short conclusion: A hybrid system of active and passive actuators can be combined to optimize the use of energy resources.

2.3.6 Redundancy

Redundancy of an exoskeleton is nothing but adding an extra joint to the structure. Though the extra joint adds up complexity to the system, many researchers found that it provides extra advantages as well (Ren et al. 2009), (Gopura et al. 2009). Problems such as misalignment, singularity could be reduced with additional joint. It also helps the system to get flexibility similar to human arm and increase the level of ergonomic value and comfort (Schiele 2008) shown in Figure 2.6. Also, the offset compensation in sternoclavicular joint and wrist joint is reduced using the redundant joint but at the same time, it will create complexity to the design, kinematics, and control, though these extra joints are passive in nature.

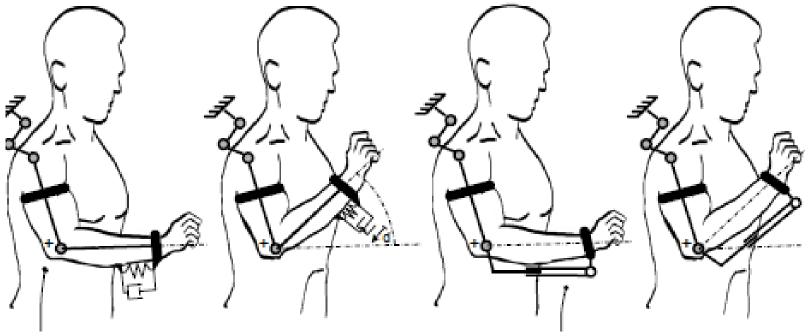


Figure 2.6. Joint offset compensation using redundant passive DOF (Schiele 2008)

Short conclusion: Redundant joint has an advantage of compensating joint misalignment.

2.3.7 Singularity

When two or more axes remain collinear, this results in unpredictable motion due to the loss of a DOF. This is called singularity configuration and occurs in a structure where revolute joints are connected serially. In an exoskeleton, internal-external rotations of shoulder sometimes align with elbow pronation-supination motion and may create this type of configuration. In these circumstances, small velocity of arm will require very large joint motions. From kinematics point of view, the solution to avoid the occurrence of singularity is to impose some constraints (joint angle limits) so that the link never reaches the singularity configurations.

Short conclusion: The structure of exoskeleton should be designed to avoid singularity condition using mechanical barrier or software-controlled motion.

2.3.8 Modularity and reconfigurability

Some exoskeletons have been designed by integrating different detachable parts and can be reconfigured for a specific joint motion. It also supports the portability and flexibility of the system. Depending on the type of rehabilitation service, the modules of the system could be changed and assembled. Therapy costs are claimed to be reduced by adopting this concept. MUNDUS (Pedrocchi et al. 2013) is a modular system. Another example such as Universal Haptic Device is used for shoulder and elbow joint however, can be used for elbow and wrist joint too (Oblak et al. 2010).

Short conclusion: Modular and reconfigurable system can be dissembled and reassembled easily and can be used for the exercise of multiple joints. A series of small components can be combined to make a bigger system.

2.3.9 Feedback signal

Initially, exoskeletons relied on position data because it was based on resolved motion rate control or independent joint control (Manna and Bhaumik 2013). Later PD (Secoli et al. 2011) and PID (Tsagarakis and Caldwell 2003) controls were implemented where velocity and acceleration data were merged with position data for better stability and lower steady state error. Since positional data cannot analyse the dynamics of a system, torque (Gupta et al. 2008) and inertial sensors (Song et al. 2012) have been introduced. Sometimes an array of sensors is used so that force extraction at human-exoskeleton interface can be monitored in case of shifting of exoskeleton with respect to muscle (Tamez-Duque et al. 2015). In impedance (Gupta et al. 2008) and admittance (Mihelj et al. 2008) control, kinematic and dynamic data of exoskeleton are the controlling parameters. An EMG (electromyogram) sensor measures the bio-electric potential generated in muscles during the contraction using non-invasive electrode. This strategy has been used for upper limb exoskeleton (Gopura et al. 2009). More recently EEG-based Brain-machine control (Viriyasaksathian et al. 2011) has been used to capture the pattern of neural activity in the brain that decides joint motion. Also visual (Secoli et al. 2011), audio (Secoli et al. 2011) and haptic (Letier et al. 2010) signals could be integrated for making a user-controlled autonomous system. Motion and physiological data can be captured from smart devices such as Mayo

Armband (Nymoen et al. 2015), Kinect sensor (Guevara et al. 2013). Figure 2.7 shows a schematic of such a possibility.

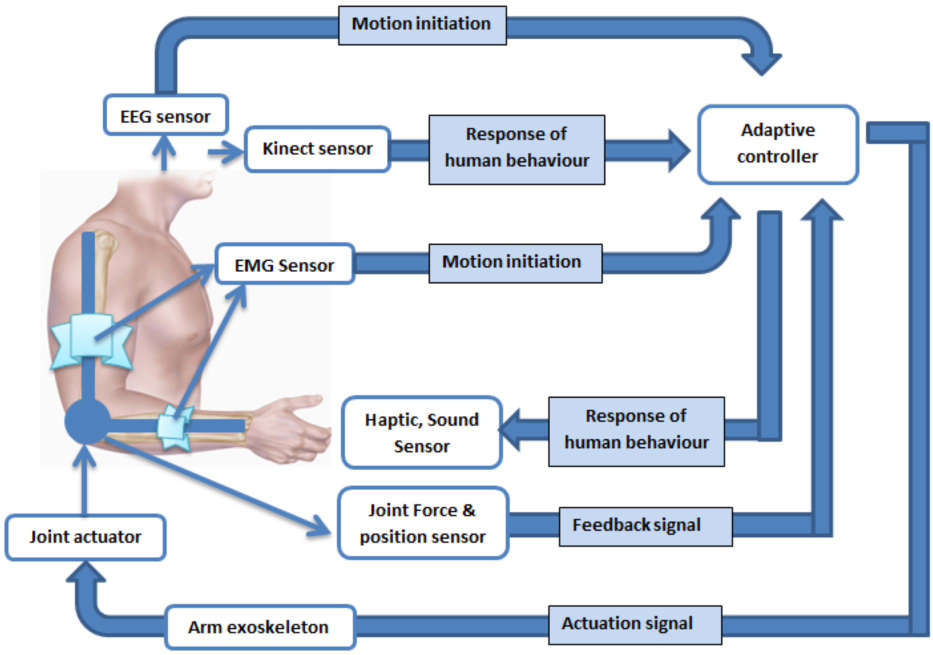


Figure 2.7. Feedback signal for an adaptive human-machine interaction

Short conclusion: Both Kinematic (position, velocity and acceleration) and dynamic (torque, spasticity and stiffness) joint parameters should be used as feedback signal for controlling dynamic force in an exoskeleton.

2.3.10 Material selection

Selection of material for building exoskeleton is directly contributing to the weight hence the portability of the design. Most of the existing designs use metal alloy such as aluminium for constructing the body of the exoskeleton. However, with the advancement of new materials which are light as well as strong, portable exoskeletons could be developed from nylon, polypropylene, ABS (Acrylonitrile butadiene styrene). Carbon fibre also has high strength to weight ratio which could be suitable for developing a portable structure.

Short conclusion: Lightweight and strong material like ABS can be used as the structural material for the exoskeleton.

2.3.11 Hyperextension

Hyperextension is the movement beyond the anatomical limit. It is one of the crucial requirements for designing exoskeletons. Every human joint has its range of motion and beyond that, it will cause injury. The exoskeleton design should be mechanically as well as electronically protected so that it operates in the safe zone.

Short conclusion: Electromechanical and software-controlled barrier should be incorporated to avoid hyperextension of joint movement.

2.3.12 Workspace

The design should cover maximum reachable points in 3D space. In an exoskeleton, workspace evolution is one of the important criteria since it shows how different rehabilitation activities can be provided. The majority of exoskeletons have limited workspace because of mechanical restrictions on link length and joints. Dexterous workspace always adds extra advantage to the ergonomic value of exoskeleton (French et al. 2014) therefore, can also avoid singular locations (Chen et al. 2007) The workspace evaluation can relate with the exoskeleton's performance.

Short conclusion: Workspace of the exoskeleton should be covering the maximum reachable range of motion with the utmost flexibility.

2.3.13 Control system design

Which type of control system should be used in exoskeleton system design is an important consideration. It should take account of different parameters like gravitational force, frictional force, and Coriolis components. Day to day the control system is enhanced by increasing the complexity of the control algorithms with the advent of new sensors and fast computing power.

When it comes to the dynamic interaction between environment and robotic exoskeleton, force or position individually is not enough to satisfy the control strategy. The impedance of a system basically depends on the task to be performed. It specifies the relation between the interaction force and the desired motion. Impedance control is based on force feedback where the error between the desired position and existing position is computed to create a force at end effector during contact. It is suited for low contact force. The main disadvantage of impedance control is that accurate force measurement requires compensation for natural dynamics of exoskeleton such as gravity loading and drives friction, it will show poor accuracy in free space due to friction. It can be improved by integrating torque sensor and joint with low friction. L-Exos is a classic example of this kind of exoskeleton (Frisoli et al. 2012). Admittance control is the opposite approach of impedance where the error of joint force is converted into the corresponding displacement which has been applied to servo controller to drive the joints to desired position. Impedance and admittance control are complementary to each other. However, admittance control has the major drawback of instability for dynamic interactions. MGA Exoskeleton (Carignan et al. 2007) is an example of this approach and the more recently ARMin Exoskeleton (Nef et al. 2009) can operate in either admittance or impedance mode. Nonlinear sliding mode technique (Rahman et al. 2010a) is also proposed for controlling an exoskeleton used for shoulder, elbow and wrist joint. In this approach, an exponential reaching law is being used along with the integral of the error signal to have better tracking performance. The new trend is to use sophisticated control regimes like neuro-fuzzy, genetic, hybrid and pattern-based control by integrating all types of bio-signal to make it an intelligent system. Both EMG and EEG-based control has been executed with neuro-fuzzy control (Gopura et al. 2009). It makes a synergistic combination of the two techniques; reasoning based fuzzy algorithm with the learning pattern of neural networks. Also in this control, some complicacy due to the cognitive behaviour of human can be incorporated (Bueno et al. 2008). As an example, Fuzzy Hybrid Force-Position Control is used for the robotic arm of an upper limb rehabilitation robot powered by pneumatic muscles (Jiang et al. 2010).

Nowadays the above control strategies have become obsolete and adaptive control is becoming popular for exoskeleton control since it can change the mode of exercises, level of difficulty and force level depending on the patient's requirement. This can also include other forms of data like visual, audio and emotions to decide the ultimate control action. There should also be a provision of manual override together with local intelligence system for safety purposes. The overall system could be a hybrid control system where master/slave, as well as automatic local control scheme, may be integrated for rehabilitation and if there is any problem in the local control system due to malfunction, it should be controlled by the master controller from outside. Table 2.4 shows a list of existing control strategies along with feedback system used in arm exoskeleton.

Table 2.4. Different control system and feedback sensor used in exoskeletons

Exoskeleton	**Sensors and Feedback**	**Control architecture**
ARMin (Nef et al. 2009)	Force & Position sensor	Labyrinth control scheme
Sarcos Mater arm (Mistry et al. 2005)	Force sensor	Independent PD servo control

Exoskeleton	Sensors and Feedback	Control architecture
HAL 5 (Sankai 2010)	Bioelectric sensor, angular & acceleration sensors, floor reaction force sensors	Cybernetic Autonomous Control
MGA exoskeleton (Carignan et al. 2007)	Force feedback & torque	Admittance control & impedance control
RehaBot (Hu et al. 2011)	Position & kinematic data controlled	Tele-rehabilitation
ExoRob (Rahman et al. 2010a), (Rahman et al. 2010b)	Force feedback	Sliding mode control
MEDARM (Ball et al. 2007)	Position & kinematic data	Independent joint control
ShouldeRO (Dehez and Sapin 2011)	Angular position data	Not defined
NEUROEXOS (Vitiello et al. 2013)	Flow controlled	Agonist-antagonist mechanical actuation system
Multiple Joint Robotic Arms (Jang et al. 2004)	piezo-deflection amplitude	Independent joint control
Skeleton Arm (Brackbill et al. 2009)	Pressure & Kinematic data	Kinematic & force based control
BONES (Klein et al. 2010)	Joint angles and cylinder pressure	Impedance control
Dampace (Stienen et al. 2009a)	Joint angles and torque	Passive system
Limpact (Stienen et al. 2008)	Joint angles and torque	compliant impedance control and stiff admittance control
Armeospring (Sanchez et al. 2004)	Joint angles and grasp force	Java Therapy*
ASSIST (Sasaki et al. 2005)	Joint angle	EMG & torque based
Pneu-Wrex (Reinkensmeyer et al. 2012)	Joint angles, grasp force	PD force control
Intelliarm (Ren et al. 2009)	Joint angles & torque	VR based impedance control
MUNDUS (Pedrocchi et al. 2013)	sEMG, Button, eye-movement or brain-computer interface	BCI based control
HEnRiE (Mihelj et al. 2008)	End-point torque, position and velocity and joint angles and end-point force	Admittance control
Gentle/G (Loureiro and Harwin 2007)	End-point torque, position and velocity and joint angles and end-point force	Admittance control
ARMOR (Mayr et al. 2008)	Joint angles	EMG based control
SUEFUL-7 (Gopura et al. 2009)	sEMG, Joint forces	EMH based fuzzy control
MIME-RiceWrist (Gupta et al. 2008)	Force Sensor	impedance-based force control
UMH (Morales et al. 2011)	Joint torque	Impedance control
RUPERT (Balasubramanian et al. 2008)	Joint torque and actuator pressure	Impedance control
Salford Rehabilitation exoskeleton (Tsagarakis and Caldwell 2003)	Joint position and torque	PID control
ESTEC exoskeleton (Schiele and van der Helm 2006)	Joint angles	Impedance control

Exoskeleton	Sensors and Feedback	Control architecture
CADEN-7 (Perry et al. 2007)	SEMG joint angles and angular velocities and torque	Force base trajectory control & Impedance control
WOTAS (Rocon et al. 2007)	Angular velocity, torque	Active tremor suppression control strategy
MAHI Exos-II (French et al. 2014)	Joint angles	Proportional control
T-WREX (Housman et al. 2007)	Joint angles, grasp force	Java Therapy*
RehabExos (Vertechy et al. 2009)	Joint torques	Force based control
W-EXOS (Gopura and Kiguchi 2008)	sEMG, torque	Fuzzy-neuro control
ARAMIS (Colizzi et al. 2009)	Joint angles and torque	Distributed force control
iPAM (Culmer et al. 2011)	Joint torques	Admittance control
L-Exos (Frisoli et al. 2012)	Force feedback	Proximal segments motor control
MULOS (Johnson et al. 2001)	Joystick	Angle oriented control
Armon (Herder et al. 2006)	Joint angles and torque	Zero gravity compensation based system
DVB orthosis (Loureiro et al. 2005)	Not defined	DRIFTS control scheme
MEM-MRB (Oda et al. 2009)	Joint angular velocity, torque	PI controller
EXOSTATION (Letier et al. 2010)	Joint torque	Joint to joint control algorithm
Hybrid Elbow Orthosis (Pylatiuk et al. 2009)	sEMG	EMG based control
Myomo (Stein et al. 2007)	sEMG	EMG based Haptic & Inertia control
ALEx (Pirondini et al. 2016)	EMG sensor	EE control
Exorn (Manna and Bhaumik 2013)	Joint position	Resolve motion rate control

Short conclusion: Impedance and admittance control are considered as a standard choice for exoskeleton. Modern adaptive control is also getting popular, however, it has a drawback of slowing down the recovery process by making patients passive during exercise.

2.3.14 Clinical parameters for arm exoskeletons

2.3.14.1 Different ways of implementing rehabilitation therapy

Exoskeletons can be evaluated in terms of structural efficacy. However, such systems are subjected to clinical trial for measuring their effectiveness in rehabilitation process. The clinical requirement of rehabilitation will depend on different grounds such as psychological, medical and ergonomic values. The task-oriented motor learning program improves motor function. Several new innovative techniques of therapy like constrained induced movement therapies have been used to improve the motor function and patient engagement during the exercises. It is patient's personal motivation to rehabilitation which will help the whole process effectively. Such as task based rehabilitation exercise will engage patients with a game in a virtual platform which may resemble with the kind of movement required for their day to day activities. The difficulty level can be varied in the game according to the level of exercises. This will create a more engaging therapy process which will motivate patients to take part in cooperatively. An example of VR based stroke neuro-rehabilitation is Rehabilitation Gaming System (RGS) (Cameirao et al. 2012). It is based on goal-oriented movement which improves the mirror neuron system. It is not ascertained how many patients could withstand in terms of intensity of the training, it is yet to be seen what intensity dose of training is the right for an individual patient and for each stage of rehabilitation process. A comparative study is examined between one exoskeleton having single DOF and another multi-DOF exoskeleton system but surprisingly after a week of exercises, the net result in terms of improvement in muscle function is the same in both cases (Milot et al. 2013). So this provides some insight that a simpler system could be as effective as a complex one if rehabilitation is planned properly.

Also, it needs to be investigated whether bilateral training or unilateral training is more beneficial for patients. Experiments in post-stroke therapy using progressive task specific in two modes-unilateral and bilateral have shown that bilateral training is more useful for patients (Byl et al. 2013). All these features of smart innovative rehabilitation process are only possible through exoskeleton therefore, exoskeleton based training can play a significant role in rehabilitation process (Otaka et al. 2015).

Short conclusion: Intensive and task-based exercise improve neuro-motor function. VR and Game based therapy can motivate patients during exercise.

2.3.14.2 Standard Clinical scale for rehabilitation evaluation

There are several scales proposed for evaluating the effectiveness of rehabilitation to measure the patient condition after stroke. However, most of the clinical scales are being used for assessment of sensory and motor function. Many organizations have made their own scale of assessment such as Nottingham sensory assessment (Milot et al. 2013), California Functional Independence Scale (Byl et al. 2013), Modified Ashworth Scale (Milot et al. 2013), however, after a thorough review, mostly two scales seem to be mainly used for evaluation of the patients conditions from different neuromuscular diseases.

1. Fugl-Meyer Motor scale(FMA)
2. Wolf-Motor Function Test (WMFT)

FMA scale is not only used for stroke assessment but for other activities such as ADL, functional mobility and pain. It includes all measurable parameters of human body for the assessment of post-rehabilitation conditions such as motor function, sensory function, balance, joint range of motion and joint pain. On the other hand, WMFT is also applicable to stroke, dexterity, strength and upper extremity function. It basically considers task based rehabilitation therapy in terms of time, functional ability and strength; all the scales developed are used for manual therapy process. Till now there is no standard scale defined especially to measure the improvement after rehabilitation using exoskeletons. So there is a need to develop some standards to analyse the clinical effectiveness of exoskeletons for rehabilitation. Most research papers have reported the study of mechanical advantage of exoskeletons however, some have reported relating the rehabilitation outcomes with fMRI of brain. If any improvement in the neuromotor function happens, it will show up in the lesson portion of brain through fMRI (Carey et al. 2007) (Figure 2.8).

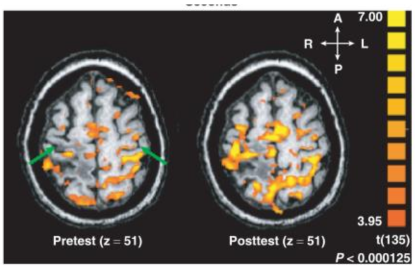


Figure 2.8. Pre and post rehabilitation of brain fMRI

Short conclusion: FMA and WMFT are considered as the standard scale of estimating post-stroke recovery condition of patients.

2.3.15 Cost of production

One of the main aims was to make post-stroke therapy using exoskeleton affordable for public. However, the purchasing cost of exoskeleton is so high that restrict people to use it. One of the reasons could be that there is no standardization of exoskeleton and the research to find the best design is still continuing. Therefore, most of the exoskeletons available in the market used as assistive device to support a specific or multiple joint movements. However, there is a sacristy of exoskeleton to provide rehabilitation service to post-stroke patients. The function of assistive exoskeleton is to provide assistive power to help in routine activities or to attempt strenuous task. However, a rehabilitation exoskeleton is mainly used to provide therapy to patients and the type of activities can be varied based on the post-stroke recovery requirements. It could be providing assistive or resistive force during rehabilitation. Table 2.5 shows the price of few commercial exoskeletons, where passive spring exoskeletons are cheaper from motor based system due to the cost of actuator.

Table 2.5. Price of few commercial exoskeletons

SL NO.	Name of the exoskeleton	Price range	Type pf actuation
1	TILTA ARM-T02 Armor Man 2.0	£2,318.40	Passive spring based system
2	WREX	£3,299.99	Passive spring based system
3	EksoVest™	$6,995.00	Passive spring based system
4	HAL	$14,000-$19,000	Motor based system
5	Myomo exoskeleton	$20,000-$50,000	Motor based system

Short conclusion: The cost of exoskeleton is generally high, however, it should be less for user acceptability.

2.4 Integration of all modes of exercises in a standalone system

As per the proposed rehabilitation strategy is shown in Figure 1.7, external force-based exercise is required in acute phase and assistive cum resistive force based self-initiated exercise is needed in the next two phases for the users who are undergoing recovery process. However, it is not a trivial task to integrate both features in a single mechanism because mechanism associated with these types of exercises are contradictory in nature. Movements entirely controlled by outside force require firm contact with human arm during activities while self-initiated movements require flexible or loose contact to carry forward the exercises according to the triggering pattern of the patient. The objective of implementing three types of exercises (external force, assistive and resistive) in a single structure can possibly be accomplished in two ways (Figure 2.9); one is the mechanism-based solution and the other is software approach.

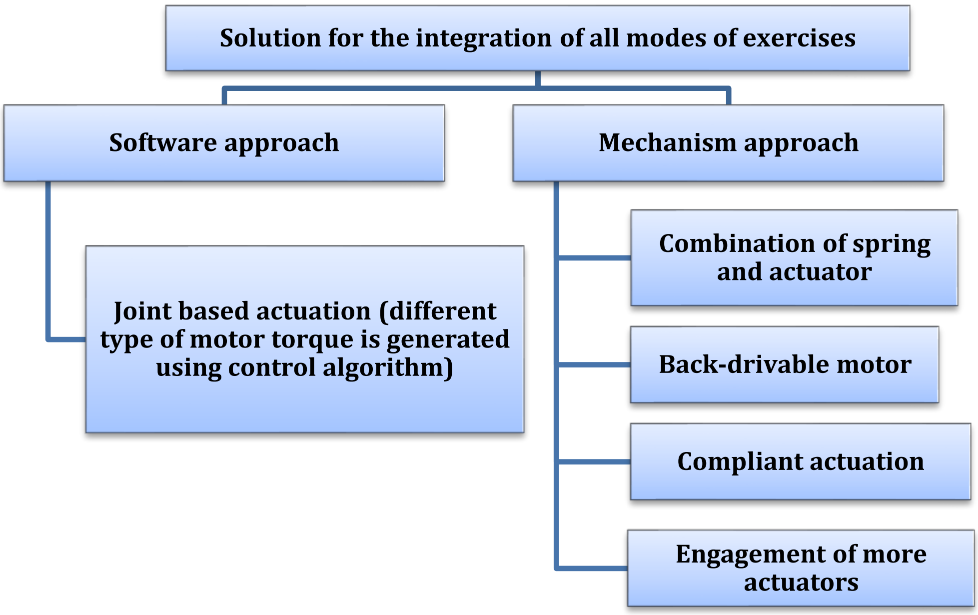


Figure 2.9. Solutions for integrating different stages of rehabilitation

In order to execute exercises using external actuator, electric motor is placed at joint in most of the exoskeletons (Nef et al. 2009; Rahman et al. 2010a). The motor torque is varied as per software-based complex control algorithm based on the signal from biosensor (Krasin et al. 2015), therefore, these exoskeletons are inoperable without those sensors. There are few limitations (Table 2.6) in software-based approach to generate different types of exercise. These biosensors are normally attached to user's body and measure user's muscle activity (Lenzi et al. 2012). Motor provides assistive or resistive torque to the affected joint as per the recommended therapy which is incorporated into the controller as a program. Joint-based actuation system requires higher torque compared to these designs where joint is remotely controlled. The requirement of joint torque is changed substantially depending on the load during exercises. To carry out the exercises with higher load, size and mass of the motor are increased (Marcheschi et al. 2011) and so is the cost. The size of the energy source is also increased to deliver higher joint torque using motor. Also, the active range of motion is not constant for each patient, therefore, the adaptive control system should satisfy all kinds of demand. A sophisticated control algorithm used for controlling the variable joint torque all the time may result in constant draining of energy. Motor-based control always consumes energy for maintaining the range and joint torque, therefore, the design requires a bigger energy source to provide uninterrupted power supply. Users cannot carry the whole system along with the energy source, as a result, most of the electric motor controlled exoskeletons are ground-based system (Manna and Dubey 2018). EMG sensor based joint control (Peternel et al. 2016) has a disadvantage that slows down the recovery rate as it controls joint movement completely by making patients passive (Reinkensmeyer and Boninger 2012). Apparently, it will reduce user's effort and affect the rehabilitation process. Muscle-based EMG sensor may not be efficient for collecting the feedback signal from chronic stroke patients (Cesqui et al. 2013) because joint spasticity and anomalous stiffness of patients influences these sensors. It is also difficult to extract fine EMG data from stroke patients due to the abnormal EMG-torque relationship in chronic stroke (Bhadane et al. 2016), therefore, it would be difficult to decode movement intention for post-stroke patients. EEG based brain-computer interface may be not affected by those factors in terms of extracting the signal, however, it is difficult to recognize the type of action required by analysing the EEG signal (Koyas et al. 2013).

Table 2.6. Limitations of Software based post-exercise using exoskeleton

Issues		**Problems of existing technology**
Structural issues	Size and mass of the system	Motor torque is higher depending on the load.
		Size and mass of the motor will be increased.
		Bigger energy source is needed for continuous power supply.
		Exoskeletons are normally ground based system.
Sensory problems	Bio-sensor (EMG, EEG) based control	Abnormal signal recorded using EMG from stroke patients can generate unexpected motor torque.
		It is also challenging to interpret EEG data for joint movement.
Control issues	Software controlled exercises	Negative effect on the recovery rate because pre-actuated control from exoskeleton reduces the user's participation in the exercise.
Other issues	Energy consumption	Motor based control always consumes energy for maintaining the range and joint torque.

There are other limitations regarding stability and feedback constraints in software solution. Users may suffer from painful and involuntary muscular contraction which may lead to a joint stiffness with undesirable joint torque. In this technique, human joint motion is always under motor control which might not be ideal from a safety point of view. If the motor will move beyond the anatomical limit of human joint due to malfunction, accident may happen.

Integration of multistage rehabilitation services can also be accomplished using different mechanisms; however, this approach reduces the complexity in control system by including different active and passive components in the structure. The actuation system of arm exoskeleton is different depending on the exercise. External force should be stable and constant throughout the exercise, so the actuator plays a vital role in providing the required torque and effective rehabilitation to patient. Passive actuation systems use elastic elements such as spring or rubber band which can provide the required joint torque for reducing gravity force during elbow movement. Spring-based exoskeletons(Housman et al. 2007),(Sanchez et al. 2004) do not need any energy source to actuate but these systems can only provide assistive force to users. A few hardware-based exoskeletons which consider both types of rehabilitation are based on hand functions such as iHandRehab (Li et al. 2011), HANDEXOS (Chiri et al. 2009). The back-drivable motor in combination with a series elastic actuator (Crea et al. 2016) is also able to provide both types of rehabilitation. Still mechanism based solutions also have lists of structural problems as illustrated in Figure 2.10.

A complex mechanism may consist of a lot of mechanical components making the mass of the system higher. Motors are designed with certain characteristics to match specific speed-torque requirement for various loads. Also, for other properties such as stiffness control and compensating gravitational force, these exoskeletons would need more actuators and additional components which would make it heavy and difficult to use. Systems can also use an electromagnetic switch for shifting from one rehabilitation mode to another and it will drain some energy and create unwanted noise during switching.

Exoskeletons actuated by passive element	•Advantage: It can create energy less system. •Disadvantage: It can only generate assistive force.
Engagement of more actuators	•Advantage: It can generate different types of exercise. •Disadvantage: It increases the weight and size of the system.
Combination of spring and actuator	•Advantage: It can generate variable assistive force for the users. •Disadvantage: To achieve different modes of rehabilitation, a complicated mechanism is required.
Back-drivable motor	•Advantage: It helps patients to do self-movement along with external control. •Disadvantage: If the back-drivability is too low, the gearbox can be damaged due to sudden external force.
Compliant mechanism	•Advantage: It is a standard solution for providing variable stiffness to the joint. It provides elastic behaviour to the joint. •Disadvantage: It can only generate resistive force.

Figure 2.10. Mechanism based solutions for different rehabilitation modes

2.5 Summary of literature survey

Though several new types of actuators such as ultrasonic motor, EAP, SMA and pneumatic muscle are developed, electric motor is still extensively used in most of the exoskeleton designs. To improve the efficiency of an actuator, hybrid systems are designed where different types of actuators are combined to get better performance such as electric-pneumatic, electric-hydraulic systems. Link based and string-based actuation systems are integrated with spring or rubber band to provide more advantages such as compensating gravity force, higher torque to weight ratio, compliance and joint flexibility. The structure of exoskeleton can be modified to improve user-experience while doing exercises. For example, incorporating a passive joint in the supporting arm link can help users to compensate joint misalignment and to improve the ergonomic property of the device. To design the control system of exoskeleton, both kinematic parameters (joint angle, velocity and acceleration) and dynamic parameters (impedance or admittance) should be included for getting an adaptive model. Though several medical scales such as FMA, WMFT are used for evaluating the recovery rate of post-stroke patients, the actual components of these clinical scales are mainly joint attributes such as functional mobility, pain, dexterity and strength. Those joint attributes can be measured from kinematic and dynamic joint parameters such as angle velocity, acceleration and torque, jerk, stiffness and so on. Therefore, these controlling joint parameters (kinematic and dynamic) can also be considered to measure the recovery rate. To make a compact and wearable design, these design features should be incorporated into the design of an exoskeleton (Figure 2.11).

Actuator	•Electric motor
Actuation system	•Attchement of spring with link driven system
Feedback signal	•Kinematic parameters: angle, velocity and acceleration •Dynamic parameters: impedance and admittance
Other deesign parameters	•Passive linear joint for compensating misalignment and improving ergonomic property
Recovery rate	•Kinematic and dynamic joint parameters
Clinical scale	•Kinematic and dynamic joint parameters

Figure 2.11. Desirable features of exoskeleton design

Though mechanism based approach requires much more complex mechanism, it is still preferable for human-machine interactions for safety reasons. The PDS is already described in the introduction chapter to meet the design requirements of the exoskeleton. After this thorough literature survey, we have gathered the existing mechanisms, parameters and design specifications to achieve the desirable solutions in PDS, shown in Table 2.7.

Table 2.7. Benchmarks achieved by the existing solutions

Property	Sl. No.	Market need	Solutions	Achieved so far
Structural property of elbow exoskeleton	1	Exoskeleton can provide multistage post-stroke rehabilitation from acute to full recovery phase	Integration of three types of exercises (external control, assistive force and resistive force) in a single system	Active exoskeletons such as ARMin (Nef et al. 2009), ExoRob (Rahman et al. 2010a) mainly generate different types of joint torque to provide assistive or resistive force. Passive exoskeletons such as T-WREX (Housman et al. 2007), Armon (Herder et al. 2006) can only provide assistive torque. Exoskeletons like VSA-II (Schiavi et al. 2008), DVB orthosis (Loureiro et al. 2005) can only provide resistive torque. Also, there is no such exoskeleton which combines the benefits of active and passive actuation in a single mechanism.
			Exoskeleton can provide variable assistive and resistive torque	Active exoskeletons such as ARMin (Nef et al. 2009), ExoRob (Rahman et al. 2010a) can vary the assistive or resistive torque based on the control signal. Passive exoskeleton such as SLERT (Wu and Chen 2014) and VSA-II (Schiavi et al. 2008) uses another motor or actuator to vary the assistive or resistive force in the structure.
	2	Reduces the cost of post-stroke therapy	Production cost of exoskeleton is affordable for general public	The cost of active exoskeletons such as HAL (Sankai 2010) comes in the range of £10,000- £15,000 whereas the cost of passive exoskeleton such as WREX (Reinkensmeyer et al. 2012) is £3,299.99
	3	Intensive and long hours therapy	Consistent and repeatable exercise module	Exoskeletons like ARMin (Nef et al. 2009), Intelliarm (Ren et al. 2009) and MGA exoskeleton (Carignan et al. 2007) can provide repeatable and consistent joint movement.

Property	Sl. No.	Market need	Solutions	Achieved so far
Structural property of elbow exoskeleton	4	Exoskeleton can lift the forearm during external-force controlled mode	Motor can provide required joint torque	ExoRob (Rahman et al. 2010a) is an elbow exoskeleton that can provide joint torque up to 5.5 Nm.
	5	Portable device	Enhances torque to weight ratio	No information is given
			Weight of the exoskeleton is lighter	Mass of ExoRob (Rahman et al. 2010a) is 1.15 kg
			Smaller energy source for operation	Most of the active exoskeletons have ground-based large energy source to provide uninterrupted power supply. Passive exoskeletons do not need any energy source.
	6	Wearable device	Design should follow the biomechanical structure and anthropometric data of human arm	The structure of elbow exoskeleton consists of 1 DOF and it can be varied for different arm length
			Opinion of users after using the exoskeleton	No information is given
	7	Maximum reachable workspace	Exoskeleton can reach maximum joint angle (wearability and usability)	140^{o}
	8	Energy consumption	Using of passive energy source for joint actuation	Passive exoskeletons like T-WREX (Housman et al. 2007), Armon (Herder et al. 2006) use spring energy for joint actuation. However, no such design has been developed so far to integrate both spring and active actuator

Property	Sl. No.	Market need	Solutions	Achieved so far
Structural property of elbow exoskeleton	8	Energy consumption	Using spring-actuated mechanism for switching between exercise	Not used so far
	9	Joint flexibility and ergonomic property	Using of universal joint instead of revolute	Universal joint is used in NEUROEXOS exoskeleton (Vitiello et al. 2013) to facilitate joint flexibility during movement
			Compensation of Joint misalignment during rotation	Linear passive joint (Schiele and van der Helm 2006) is used to compensate the misalignment between the centre of exoskeleton and human joint
Control property of elbow exoskeleton	10	Ease of controlling the mode of exercise	Should have both control scheme: automatic and manual	Active exoskeletons mostly perform in automatic mode to create different type of joint torque. Passive exoskeletons do not need any control as it depends on spring force.
			Mode of exercises can be switched easily based on joint condition	Adaptive control can detect human intension and provides assistive or resistive force as per the human bio-signal.
			Develop the control strategy using joint parameters without using biosensor	Kinematic and dynamic parameters-based control, Passive actuator-based system (spring and rubber band based).
	11	Enhance the participation of user during exercises	Control mechanism allows users to put their effort to do joint movement	PID control, Impedance and Admittance control, Adaptive control, Neuro-fuzzy control.
Safety property	12	Safety of user	Mechanical constraint to restrict joint movement up to anatomical limit	Electromechanical switch, limit switch, clutch, ISO 9000 standards in the European Community.

Property	Sl. No.	Market need	Solutions	Achieved so far
Safety property			Software control to restrict joint movement up to anatomical limit	Adaptive control algorithm, ISO 9000 standards in the European Community.
Structural property of forearm motion	13	Twisting motion in forearm	Motor controlled twisting motion with user's flexibility	Most of the active exoskeleton use motor controlled twisting movement ARMin (Nef et al. 2009) has used back drivable motor

Chapter 3 Mechanism design of the elbow exoskeleton

It was concluded that the exoskeleton should consist of a few distinct design properties to make it a cost-effective and portable system which can provide three types of joint movements. To achieve those desirable features for exoskeleton design (shown in Table 1.4) and to overcome the limitations of existing exoskeletons (shown in Table 2.7), specific material, appropriate mechanism and actuation system, actuator have been incorporated to make a portable and affordable exoskeleton which has the potential to provide multistage post-stroke exercises. The aim of this research is to design a new mechanism to allow all types of rehabilitation in a single module. With this idea in mind, elbow joint has been selected for the design of exoskeleton because it is one of the simplest human joints and majority of gross manipulation tasks cannot be performed without elbow motion. In the simplest form, it could be visualized as a revolute joint with one degree of freedom with further flexibility provided for pronation-supination motion of forearm (Figure 3.1). The following joint movements of elbow and forearm are studied to facilitate the design development.

1. Elbow flexion - The movement of bending the elbow causing the anterior surface of the arm and forearm to move toward each other.
2. Elbow extension – It is the opposite motion of flexion causing forearm to move away from each other.
3. Pronation of the forearm - This movement involves twisting the forearm and palm from a palm forward to a palm backward.
4. Supination of the forearm – It is just the opposite motion. Pronation and supination movements of the forearm occur primarily because of articulation of the radius and ulna.

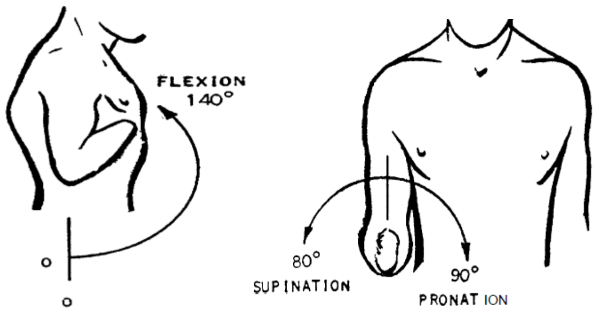


Figure 3.1. Joint movements of elbow and forearm (Manna and Bhaumik 2013)

In the first section, the mechanism is created to generate flexion-extension of elbow and then the mechanism providing pronation-supination of forearm is explained. Actuation in human arm takes place due to the ligaments and muscle-tendon movements. Biceps muscle helps forearm in elbow flexion and triceps muscle applies opposite motion-extension to straighten forearm back to its own position. The pattern of human joint movement requires a lower amount of torque compared to a motor connected at joint. The actuation mechanism of the developed exoskeleton for elbow rotation takes place due to the pulling force instead of joint based actuation, therefore it enhances the torque to weight ratio.

As per the proposed rehabilitation protocol, external forces are required in the first stage of training, after that patients have to initiate their own movements during the exercises. The last stage requires variety and difficulty of exercises. All these exercises are not performed at the same time and are followed gradually one after other. Therefore, the mode of exercise in the exoskeleton can be changed depending on user's condition. The idea is to divide the whole operating region into three sub-regions consisting of different training regimes providing specific exercise (Figure 3.2). The mechanical components related to the actuation system of the exoskeleton will be different depending on the situation whether the exercises are controlled by the exoskeleton or users themselves. All these regions are interconnected and will appear one after another automatically.

The first section controls the joint movements externally using electric motor without user's participation whereas the middle section allows users to do joint movements supported by the spring force and the level of assistance can be varied by adjusting the displacement of the spring. In the last section, a spring assembly is used to provide variable resistive force to the joint. A couple of springs (compression and torsional) have been used in the exoskeleton design for switching between different regions using their stiffness property. As a result, no extra energy source is required to move from one training regime to another making it an energy-efficient mechanism. It also removes the complexity of electromechanical switches. In the developed exoskeleton, both electric motor and passive elements have been introduced in a single structure which allows the exoskeleton to utilize the motor torque during acute phase when users may not have enough strength and to provide spring energy during self-movement for generating assistive and resistive from the exoskeleton. Therefore, the energy source is only used to provide power to the motor in the first mode. With this technique, it becomes an energy-efficient system. The aim of the designed exoskeleton is to use as much as fewer actuators for the whole operation making it a portable device. Therefore, a single motor is used in this exoskeleton to achieve all the above features with the help of springs (Manna and Dubey 2019a).

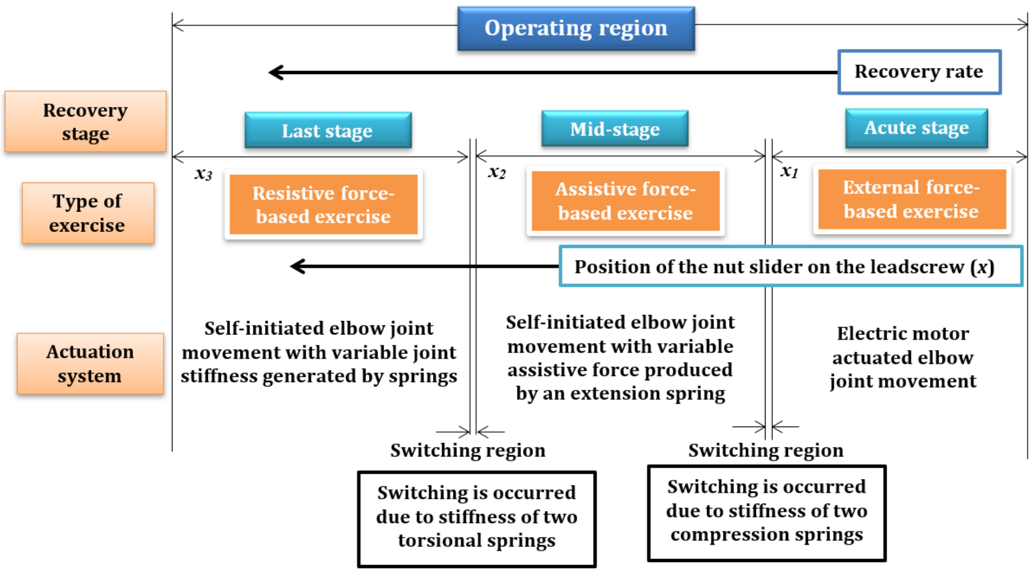


Figure 3.2. Operating region of the developed exoskeleton

In this exoskeleton, the number of rotations of the motor determines the position of the nut slider on the leadscrew. The mode of exercise is differentiated by the region of operation which is decided by the position of the nut slider on the leadscrew. The relationship between the distance covered by the nut slider (x) and the motor rotations (n, θ) is given by

$$x = \theta e \;\; \text{Where } e = \frac{nL}{2\pi N} \tag{3.1}$$

Where n = Number of turns in the motor

θ = Motor angle

L = Lead of the screw

N = Gear ratio

Mode of exercise: $0 \leq x \leq x_1$ = Electric motor based joint control

$x_1 < x \leq x_2$ = Spring based assistive force

$x_2 < x \leq x_3$ = Spring based resistive force

Where x_1, x_2 are the switching positions.

The schematic diagram of the exoskeleton and its 3D model are shown in Figure 3.3 and Figure 3.3 respectively. The final model is designed after nine initial models which have been described in the introduction part and shown in Appendix II.

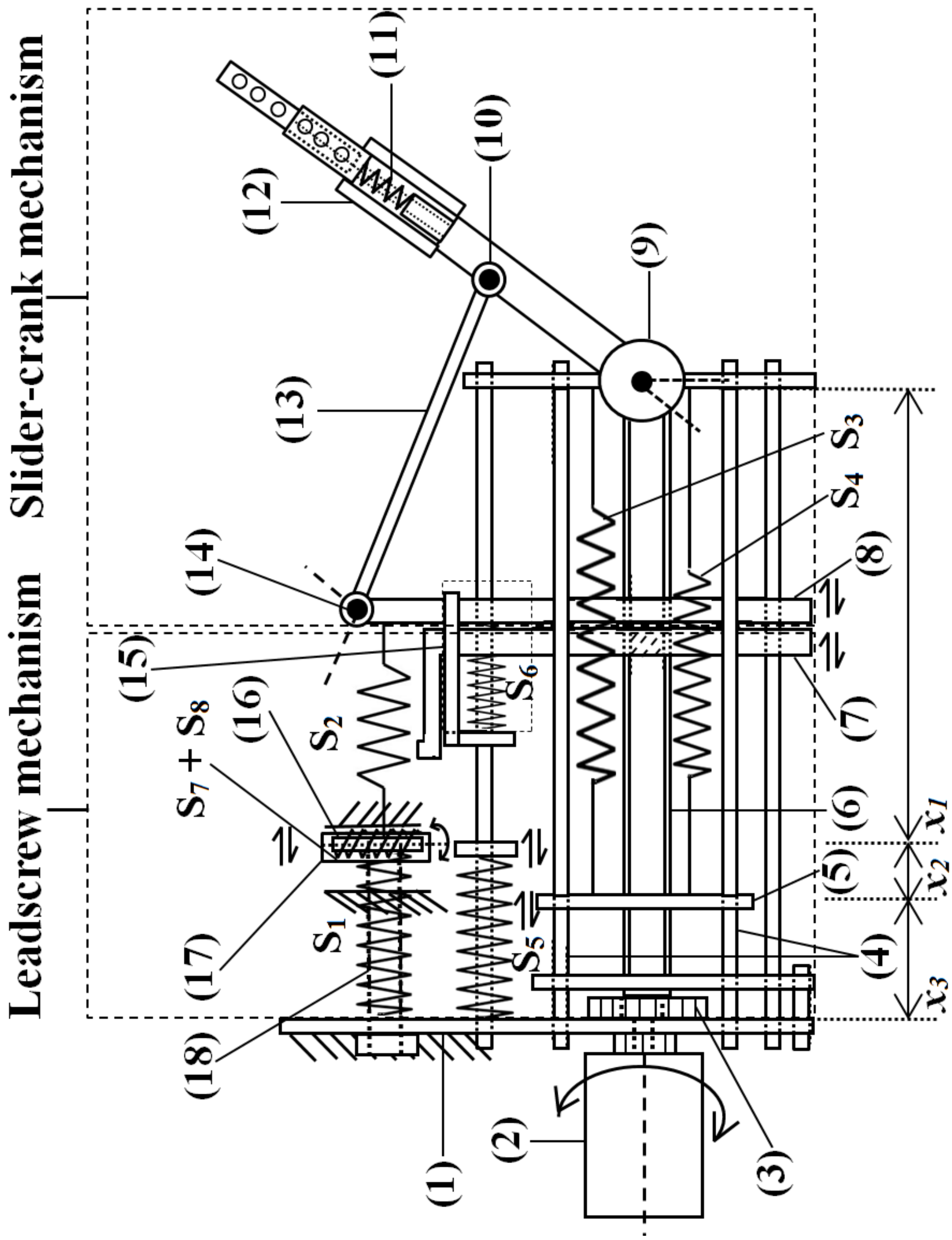


Figure 3.3. Schematic diagram of the developed exoskeleton

(1) Baseplate	(7) Nut slider	(13) Connecting link
(2) Motor	(8) Concentric slider	(14) Universal joint
(3) Gear	(9) Elbow joint	(15) Claw-type jaws
(4) Solid rods	(10) Revolute joint	(16) Rectangular slider
(5) Slider for variable stiffness	(11) Compression spring for passive translational joint	(17) Connected plates
(6) Leadscrew	(12) Forearm supporting link	(18) Small cylindrical rod

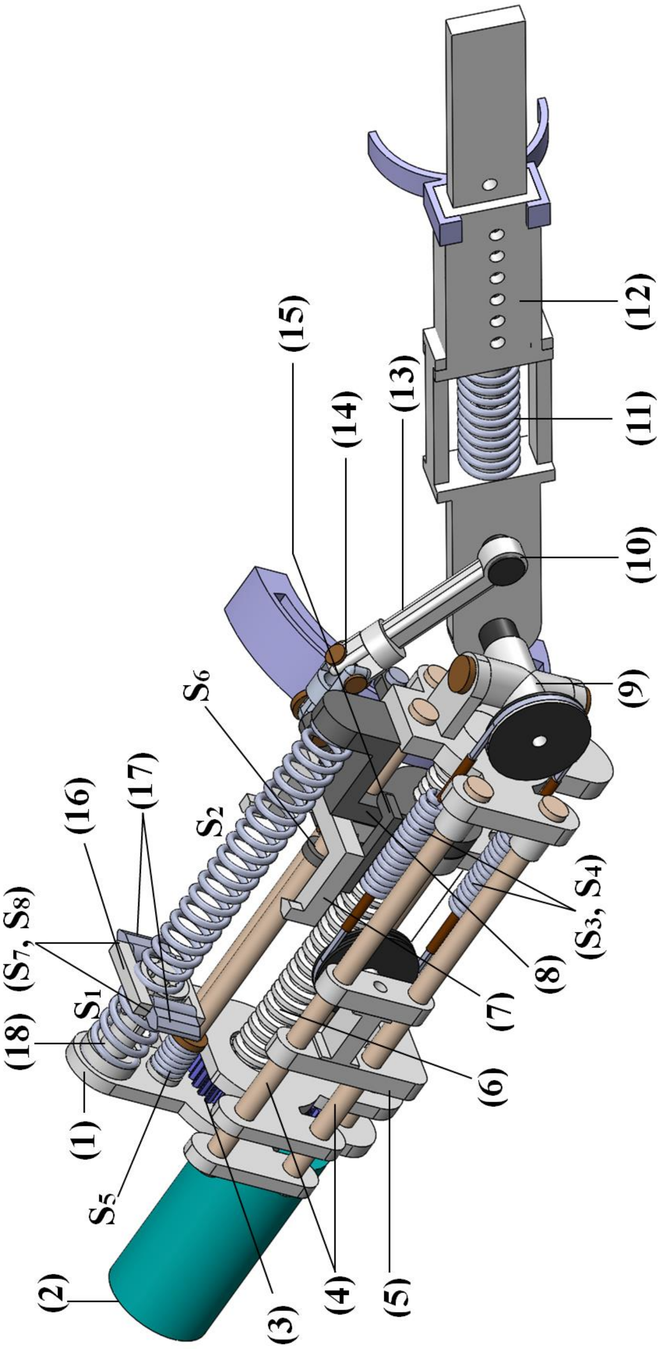


Figure 3.4. 3D model of the developed exoskeleton

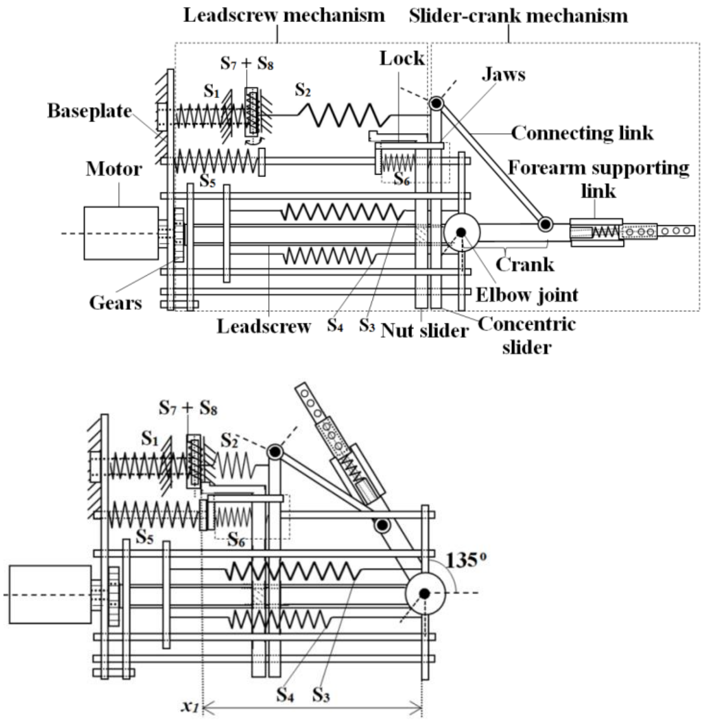
(1) Baseplate	(7) Nut slider	(13) Connecting link
(2) Motor	(8) Concentric slider	(14) Universal joint
(3) Gear	(9) Elbow joint	(15) Claw-type jaws
(4) Solid rods	(10) Revolute joint	(16) Rectangular slider
(5) Slider for variable stiffness	(11) Compression spring for passive translational joint	(17) Connected plates
(6) Leadscrew	(12) Forearm supporting link	(18) Small cylindrical rod

Table 3.1 shows the components used for each function of the exoskeleton.

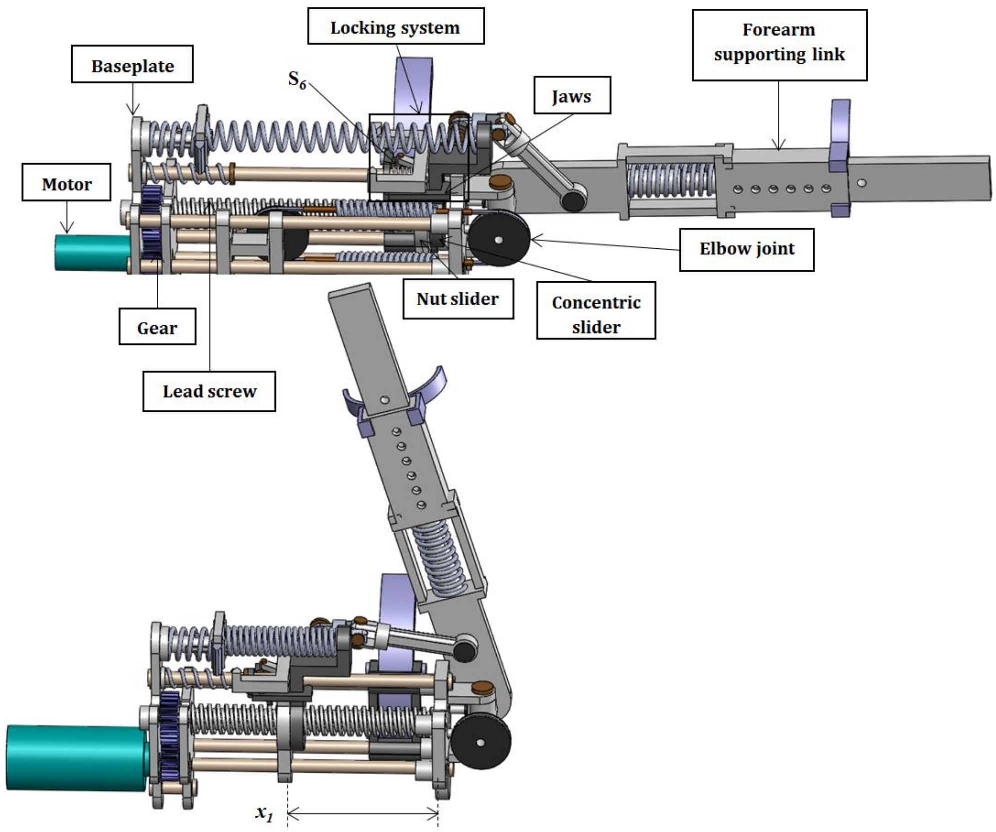
Table 3.1. Components used for each mode of exercise in the exoskeleton		
Function	**Mechanism used**	**Components involved**
Electric motor based joint movement	Lead-screw based Slider-crank mechanism	(1) Baseplate (2) Motor (3) Gear (6) Leadscrew (7) Nut slider (8) Concentric slider (9) Elbow joint (10) Revolute joint (11) Compression spring for passive translational joint (12) Forearm supporting link (13) Connecting link (14) Universal joint (15) Claw-type jaws
Switching from electric motor controlled mode to assistive mode	The stiffness of S_5 is greater than S_6. When S_5 and S_6 clash with each other, S_6 is compressed and both claw type jaws are opened to free the concentric slider from the lock.	(2) Motor (3) Gear (6) Leadscrew (7) Nut slider (8) Concentric slider (15) Claw-type jaws Compression springs (S_5 and S_6)
Assistance from the exoskeleton in assistive mode	S_2 provides assistive force during joint movement.	(6) Leadscrew (8) Concentric slider (9) Elbow joint (10) Revolute joint (11) Compression spring for passive translational joint (12) Forearm supporting link (13) Connecting link (14) Universal joint Extension spring (S_2)
Switching from assistive to resistive mode	The displacement range of S_2 is varied to provide more assistance to users.	(1) Baseplate (2) Motor (3) Gear (6) Leadscrew (7) Nut slider (16) Rectangular slider (17) Connected plates (18) Small cylindrical rod Compression spring (S_1) Torsional springs (S_7 and S_8)
Resistive force during joint movement	Both S_3 and S_4 are extended to increase joint stiffness therefore creating more resistive force	(1) Baseplate (2) Motor (3) Gear (4) Solid rods (5) Slider for variable stiffness (6) Leadscrew (8) Concentric slider (9) Elbow joint (10) Revolute joint (11) Compression spring for passive translational joint (12) Forearm supporting link (13) Connecting link (14) Universal joint

3.1 Electric motor based joint control mode

In the first operating region ($0 \leq x \leq x_1$), the electric motor controls elbow joint movement without any active participation from user. Patients are being rehabilitated with free movement consisting of some predefined orthopaedic lessons prescribed by the physiotherapist. In this exoskeleton, the actuation system consists of a leadscrew-based motion along with a slider-crank mechanism as shown in Figure 3.5 (a & b). These two mechanisms have been integrated to get a non-slipping motion during movement because leadscrew maintains unidirectional firm contact with the movable part and slider-crank mechanism allows elbow rotation. The motor is connected to the exoskeleton behind the baseplate. It doesn't occupy any extra space on either side of the exoskeleton structure. Motion from the motor is transferred to the leadscrew using two mutually coupled reduction gears. Slider-crank mechanism converts the linear motion of leadscrew into elbow joint rotation. Part of the forearm supporting link acts like the crank, therefore forearm is pulled by the connecting link. This type of actuation system requires lower amount of motor torque compared to most of the existing exoskeleton models where motor is connected directly at the joint axis. By this technique, torque to weight ratio can be enhanced by engaging a small motor to create the joint rotation.



a. Schematic diagram (Electric motor based joint control)



b. 3D model diagram

Figure 3.5. Electric motor based joint control

To incorporate assistive and resistive force in next two operating regions, the leadscrew based slider is not directly connected to the crank mechanism. There are two sliders on the leadscrew; one of which acts as a nut that translates in both directions following the guiding path of screw thread as per the rotation of the motor and another slider can only slide on the leadscrew concentrically (Figure 3.6). The inner diameter of the concentric slider is the same as the outer diameter of the leadscrew with a clearance level, as a result, the concentric slider can slide on the periphery of the leadscrew. In the first operating region, a spring-actuated locking mechanism keeps both sliders in a single unit to construct the situation where crank rotation is fully controlled by the motor but unlock them during self-movement. Two compression springs (S_5 and S_6) of different stiffness are responsible for the locking operation as shown in Figure 3.6. S_6 maintains its two claw-type jaws parallel to latch both sliders throughout the first region to provide motor controlled motion. The range of elbow joint motion during rehabilitation is 135^o.

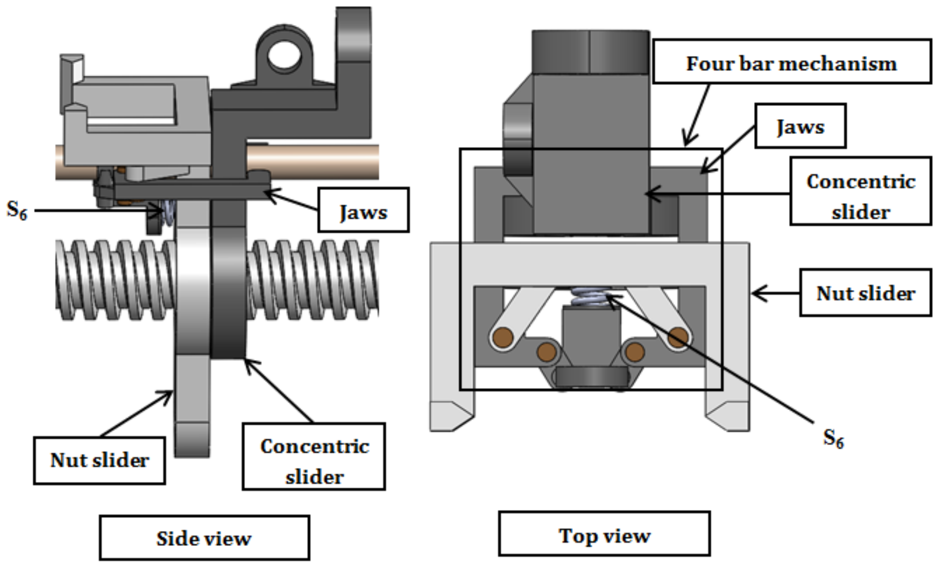


Figure 3.6. Locking mechanism

The leadscrew is placed in the middle of both sliders which are supported by two solid rods (Figure 3.5), therefore, the moment created by the pulling force will not disturb the motion of the nut along the screw. It also reduces the possibility of self-locking of the concentric slider and helps those sliders to maintain a linear sliding motion during movement. All sliding contacts have linear bearings to reduce friction.

3.2 Electric motor to assistive force mode

Switching between operating regions has been achieved using the stiffness property of springs (Figure 3.7). However, the motor rotation is also required for keeping the nut slider in a particular position to make this operation successful. Schematic diagram in Figure 3.7 of pre and post condition of the switching mechanism has been explained in detail. The locking of both sliders keeps the control of joint movement to the electric motor, however, the unlocking of the concentric slider from the nut slider allows the concentric slider to move freely on the leadscrew as a result, the elbow joint is not controlled by the motor.

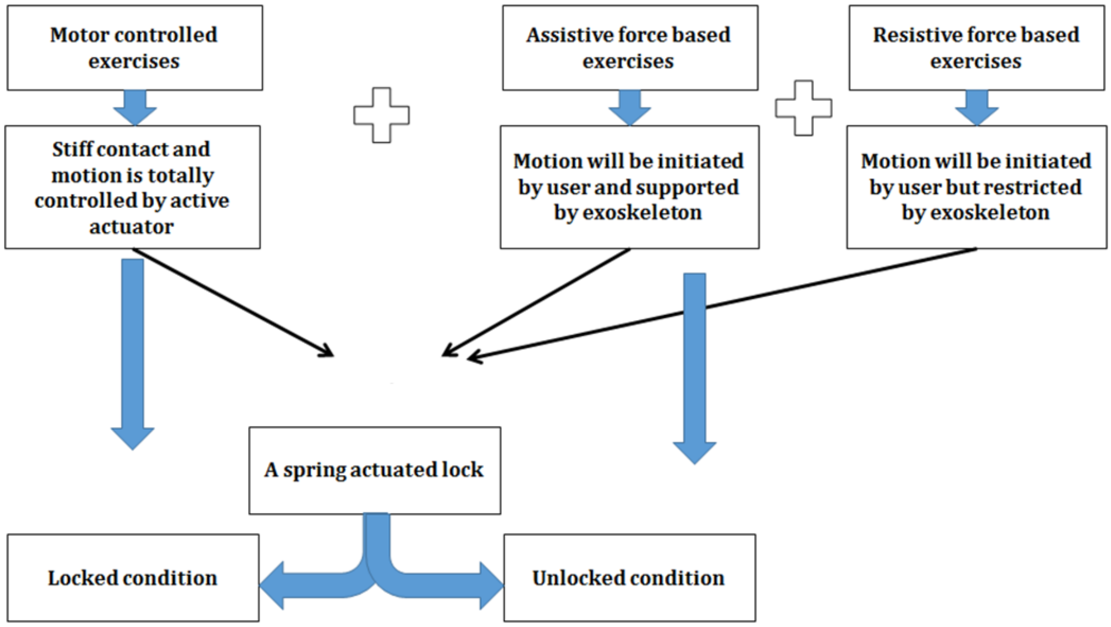
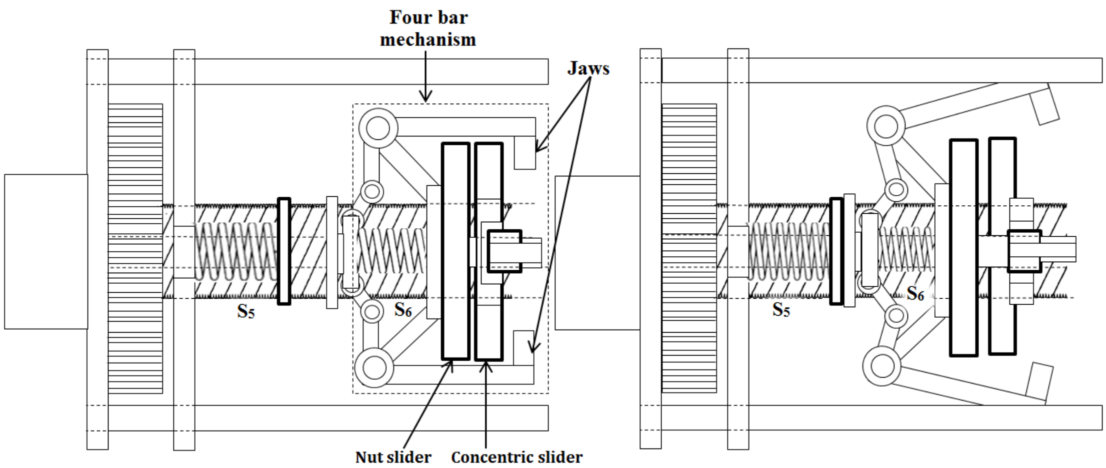
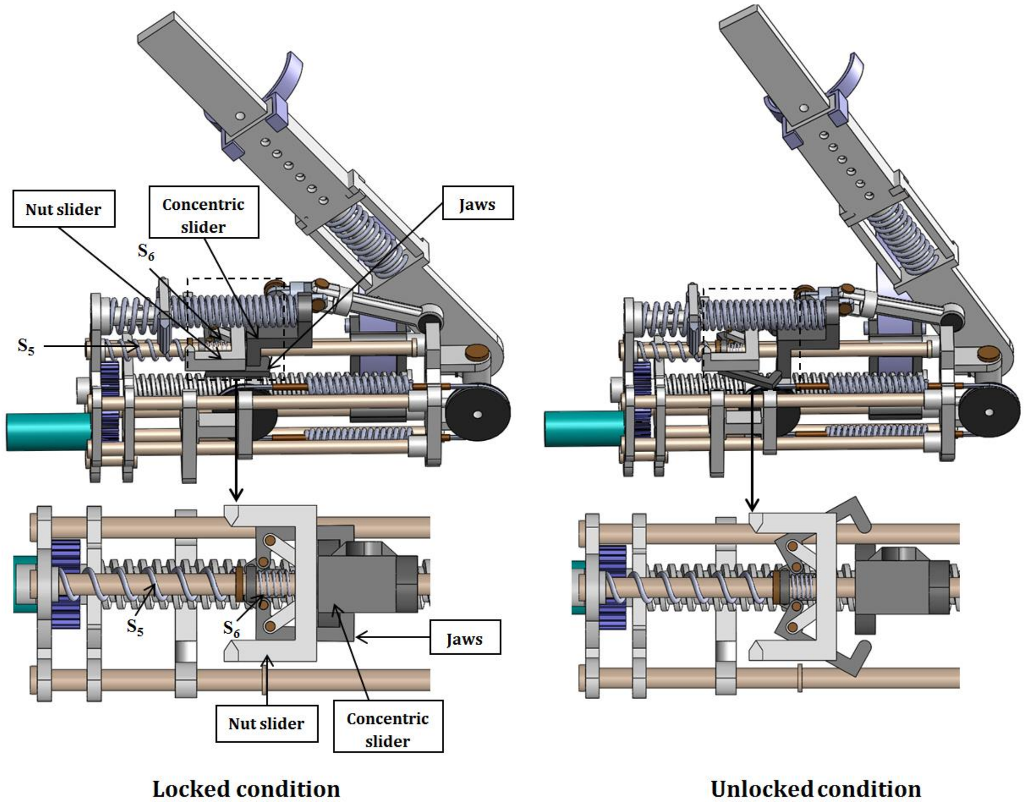


Figure 3.7. Method of switching from motor controlled to user-controlled mode

As discussed in the design section, a spring (S_6) actuated lock is required for maintaining the locking condition and another compression spring (S_5) is used to open the lock. In the locking mechanism, two claw-type jaws are connected to the nut slider in the form of a four-bar mechanism (Figure 3.8a, Locked condition). The compressive force created by S_6 attaches both leadscrew sliders (concentric and nut slider) by keeping its two jaws parallel during the motor controlled regime. Locking condition will remain the same until two compression springs S_5 and S_6 clash with each other due to backward movement of the nut slider. As soon as the nut slider crosses the switching position ($x>x_1$), two compression springs (S_5 and S_6) push each other and the switching operation takes place. The stiffness of S_5 is quite higher than that of S_6 so that a small displacement of S_5 causes a large displacement in S_6. As a result, S_6 will be compressed by the resultant force and both jaws will rotate about a fixed point, thus opening the lock to free both sliders from the single attachment (see unlocked condition, Figure 3.8b). However, forward movement of the nut slider beyond the switching point will restore the locking mechanism again. The ratio of the stiffness of S_5 and S_6 has been determined in a way that the switching region becomes as small as possible.



a. Schematic diagram of pre and post locking condition



b. 3d model of pre and post locking condition

Figure 3.8. Switching from motor based control to spring assisted force

3.3 Assistive force based exercise mode

A fixed number of motor rotations keep the joint movement in the first operating region allowing a full range of motion. A slight increment in the motor rotation shifts the working region from motor controlled mode to assistive self-controlled mode by opening the lock. In this situation, the control of joint rotation won't be under electric motor. It is shown in Figure 3.8 that the leadscrew based concentric slider is connected to an extension spring (S_2) and it can help them to rotate the elbow joint during flexion by providing assistive force. The same assistive force opposes the joint freefall during extension, therefore it balances the arm weight and slows down the joint movement to reach full extension. Joint would be torque balanced at every configuration due to spring force and only a small joint torque is required to move the forearm from the statically balanced condition. Assistive force during joint movement should be adaptable for different type of exercises and muscle strength of users. It is important to ensure that changing of spring force in S_2 is not permanent and it should restore to its normal condition after the operation. The spring force provided by S_2 can be changed in three different ways: changing the material, no of active coils or the displacement range, as shown in Figure 3.9. To change the spring force dynamically without adding any extra actuator, solution 3 is considered as the best for the developed mechanism. Therefore in this exoskeleton, the range of assistive force can be varied by changing the span of displacement.

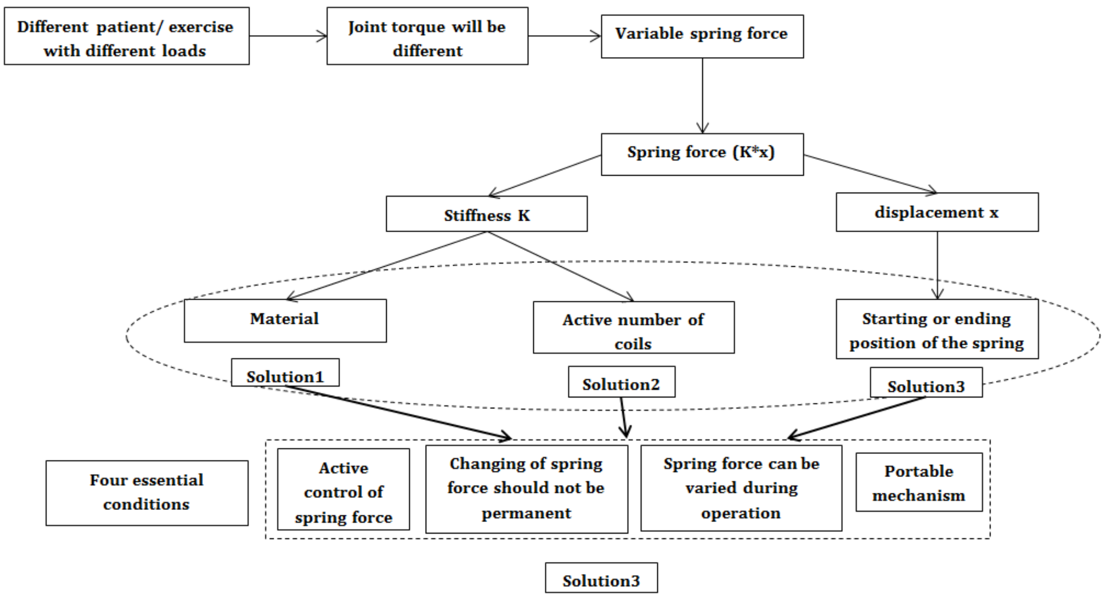
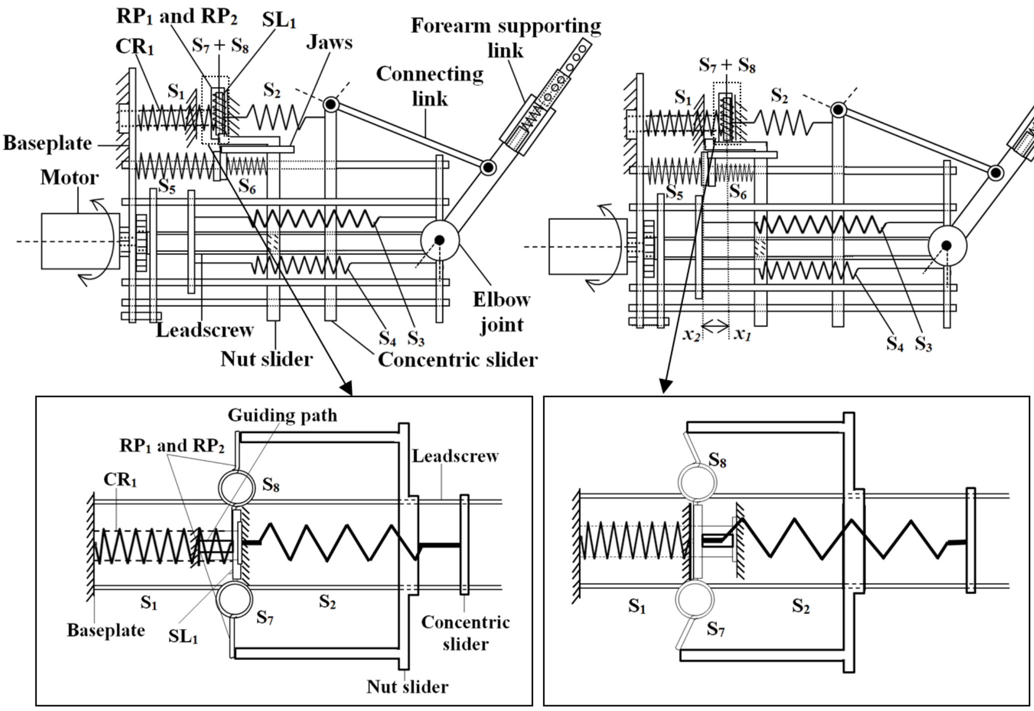


Figure 3.9. Solutions for changing the spring force in the exoskeleton

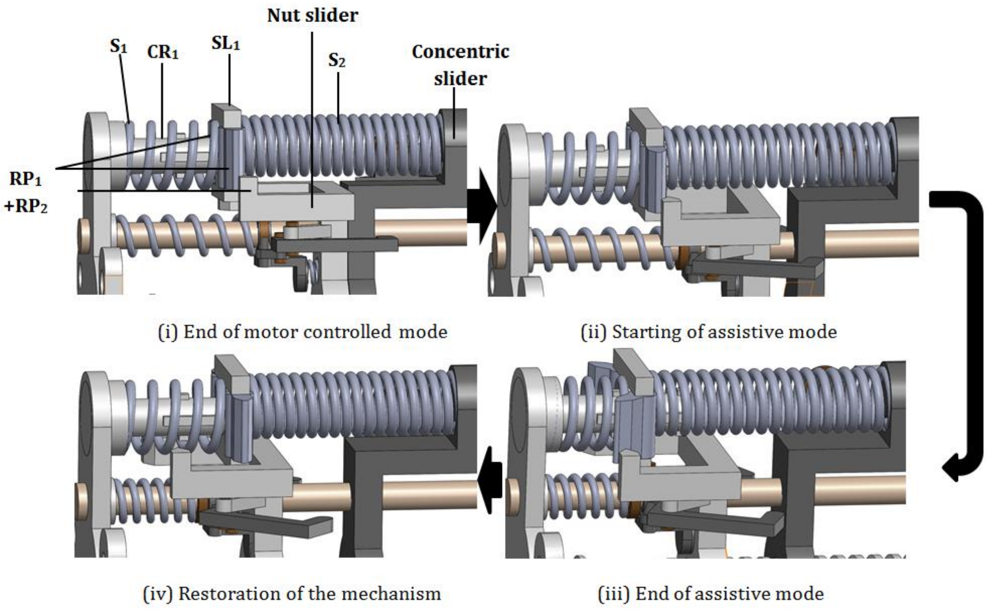
Higher assistive force reduces the effort of users. The structural part of the exoskeleton to provide variable assistive force (Figure 3.10a & b) consists of two torsional springs (S_7 and S_8), one compression spring (S_1), one small cylindrical rod (CR_1), one small rectangular slider (SL_1) and two rectangular plates (RP_1 and RP_2). SL_1 is concentric to CR_1 which is attached to the base plate. As shown in

Figure 3.10, SL_1 is also attached between S_1 and S_2. The range of spring force provided by S_2 can be amplified by changing the span of displacement. RP_1 and RP_2 are connected to SL_1 using S_7 and S_8 on both sides in such a way that those plates can rotate about the axis of these torsional springs. RP_1 and RP_2 have been used to maintain the force balancing condition during joint movement to maintain a constant supply of assistive force. CR_1 has a rectangular channel to provide a guiding path to SL_1. The guiding path has two mechanical restrictions for controlling the movement of SL_1 within a particular range ($x_1<x\leq x_2$) where different spring force can be generated by S_2. The role of S_1 is to restore the whole setup to its original position once released.

At the initial condition, the front end of S_2 is fixed which allows a fixed range of spring force. To increase the spring force dynamically, the front-end of S_2 is shifted backward near the baseplate. The extended part of the nut slider has been utilized for this purpose. The backward movement of the nut slider in this region pushes RP_1 and RP_2 connected to S_7 and S_8. The stiffness of S_7 and S_8 is high enough to be deflected by a small force, as a result, the whole arrangement connected to SL_1 will move backward along with the nut slider. Due to the torsional stiffness, S_7 and S_8 create an opposing torque which is equalized by the reaction force from the nut slider during the movement. The second mechanical restriction on the guiding path does not allow SL_1 to move further in the backward direction. This is the position where the exoskeleton can develop maximum assistive force at the joint using S_2. Therefore, further pressure from the nut slider will put S_7 and S_8 beyond their limit and RP_1 and RP_2 are deflected to come out from the range of nut slider. Because of the stiffness property of S_1, SL_1 will come to its initial position with all its arrangement after the end of the second region.



a. Schematic diagram

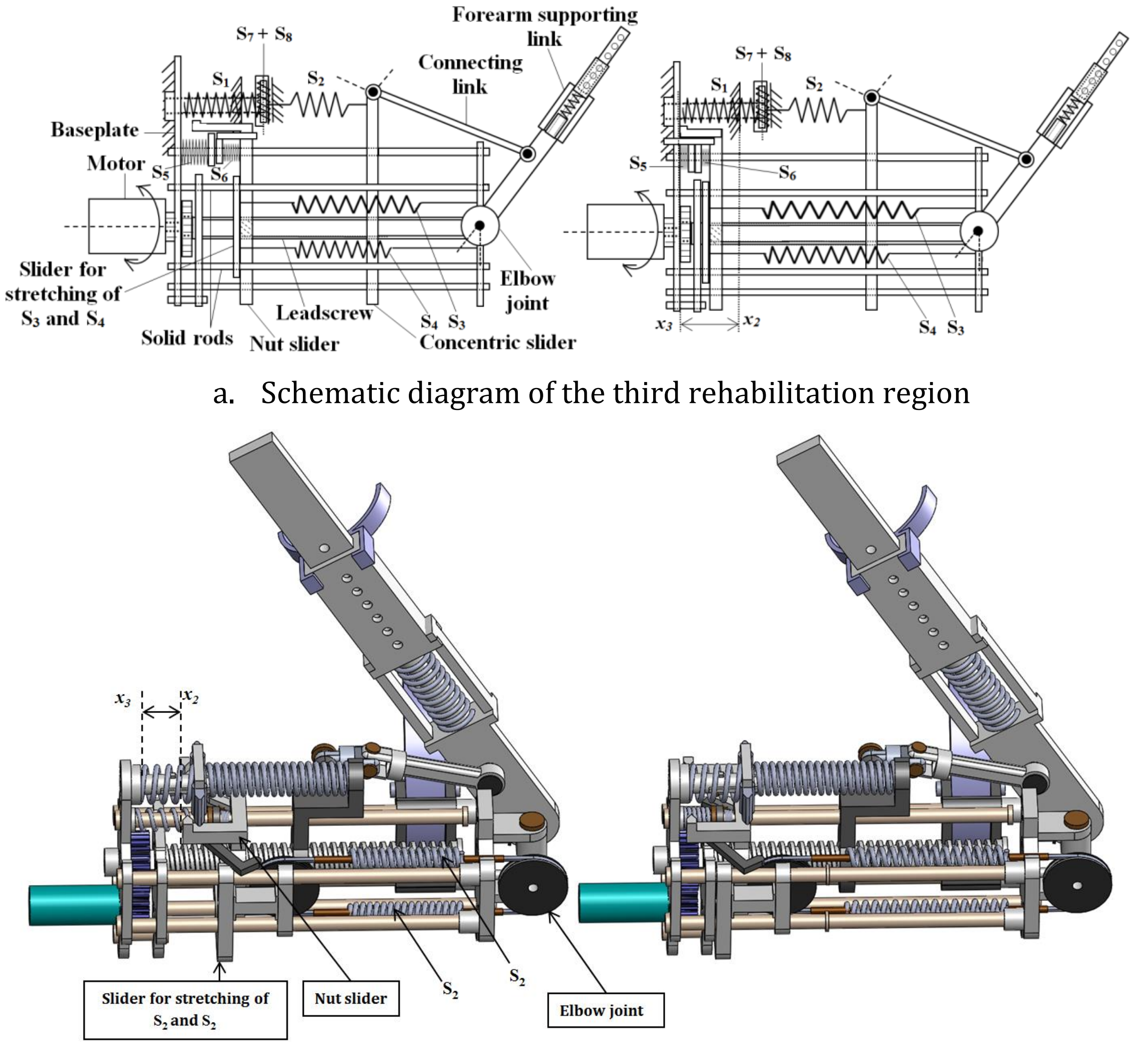


b. 3D model

Figure 3.10. Assistive force based spring configurations

3.4 Resistive force based rehabilitation mode

In this stage of the operating region, variable resistive force is imposed to restrict the movement (Figure 3.11). At this level, the level of difficulty should be increased, this could be varied by changing the joint stiffness of the exoskeleton. An additional setup of extension spring assembly (S_3 and S_4) is used for changing the joint stiffness of the exoskeleton. Further backward movement of the nut slider beyond the second region ($x_2 < x \leq x_3$) will stretch both S_3 and S_4 resulting in higher contact force at the elbow joint. As a result, joint stiffness will change. Two pairs of S_3 and S_4 are connected on both sides of the joint in parallel to maintain the elbow joint in a stable condition. In this mechanism, both S_3 and S_4 are connected to another slider which can slide on two solid parallel rods. Those solid rods are not only used for strengthening the exoskeleton but act as a guide to the slider at the time of stretching of those parallel springs (S_3 and S_4). Proper calibration is required to exert the required stiffness for the elbow joint with respect to the position of the nut slider. Two linear springs (S_3 and S_4) of different stiffness have been considered in the exoskeleton.



a. Schematic diagram of the third rehabilitation region

b. 3D model diagram of the third rehabilitation region

Figure 3.11. Resistive force based spring configuration for variable joint stiffness

3.5 Additional structural features

All sliding contacts have been developed with linear bearings to reduce the frictional loss during motion. The mechanism of the exoskeleton has also improved with other design features to get more advantages from other existing systems. In this exoskeleton, a universal joint (Figure 3.12) is used to replace the normal revolute joint. The biological structure of human forearm allows elbow joint not to be fixed during flexion and extension. If the arm segment is connected rigidly to the exoskeleton, it can cause discomfort to user and articulation. Therefore, the universal joint will provide a slight movement (±5°) laterally during elbow joint rotation. Out of its two degrees of freedom possessed by the universal joint, active one is responsible for flexion-extension of the elbow whereas the passive joint supports the flexibility during joint movement. Two mechanical stops with rubber padding are attached to restrict the joint motion in the transverse plane. Another universal joint is also connected at the junction between leadscrew based concentric slider and connecting rod to maintain joint flexibility.

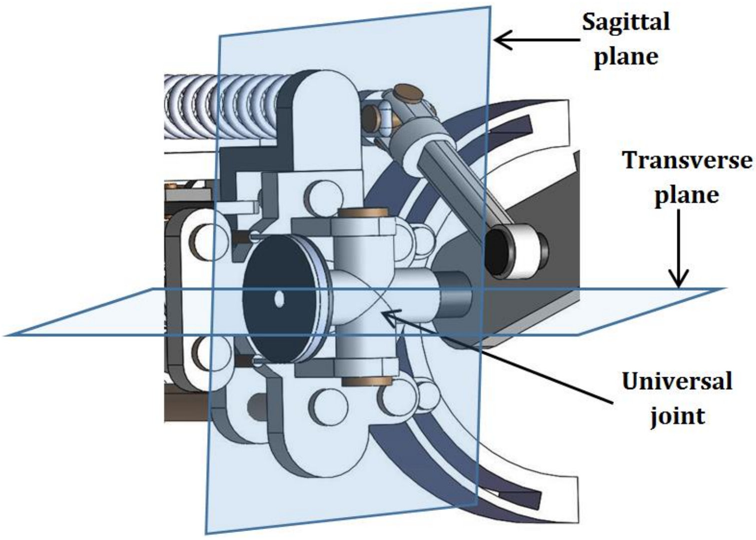


Figure 3.12. Universal joint at the elbow joint

The upperarm and forearm lengths can be varied up to 0.04 m from its fixed length of 0.35 m and 0.40 m to fit with different users. As shown in Figure 3.13, the forearm supporting link consists of two parts: the fixed link which is connected to joint has a rectangular tunnel in which the second solid part can slide. Both parts have a series of discrete holes, therefore, the length of the total forearm supporting link can be varied by matching the holes of both parts. Also, the upper arm supporting structure has different holes to configure its total length. In this way, the exoskeleton can be fitted to different arm lengths. The distance between the forearm gripper and elbow joint can be slightly varied for different postures during exercises. As a result, the centre of the exoskeleton is normally shifted from elbow joint and not aligned with it anymore. To get flexibility similar to the human arm and to increase the level of ergonomic comforts, a passive linear joint is introduced at the forearm. To maintain the alignment of the centre of rotation between exoskeleton and user, the passive linear joint has a compression spring whose length is varied to compensate for the length variation during joint rotation.

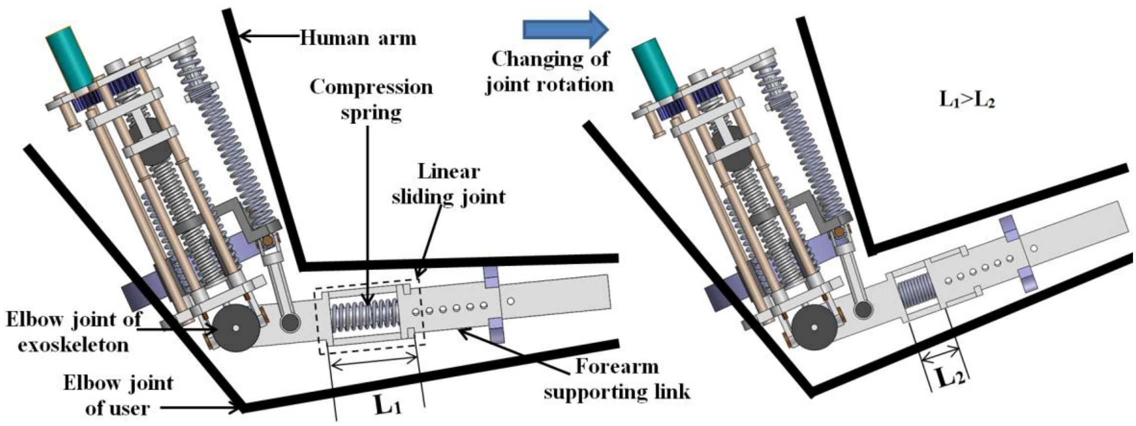
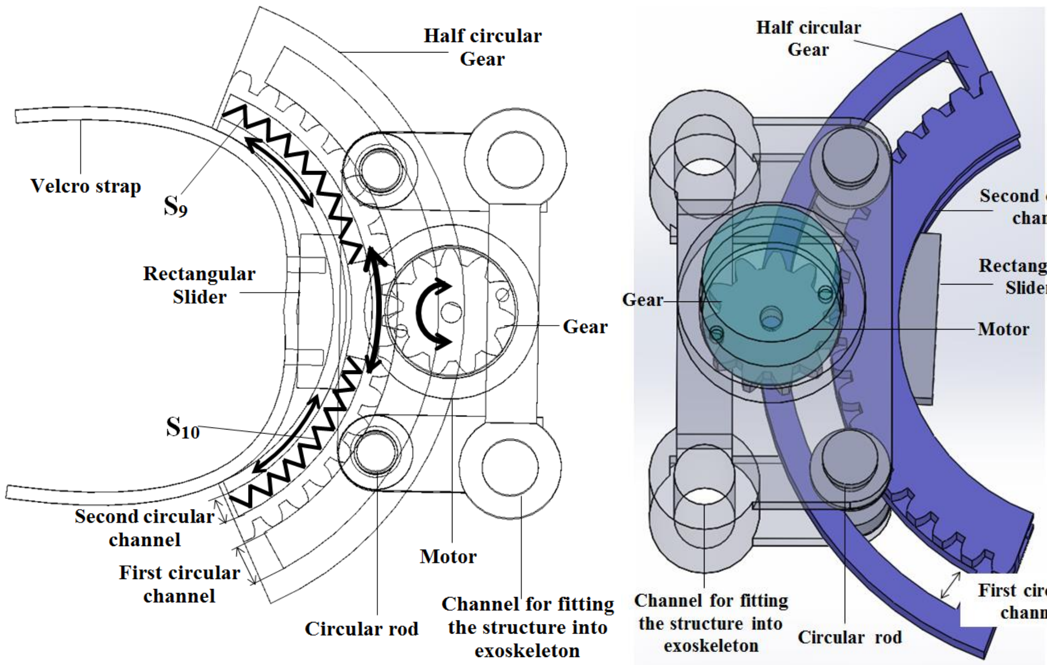


Figure 3.13. Joint misalignment compensation in the exoskeleton

3.6 Mechanism for forearm twisting motion

Most of the existing mechanisms used in exoskeletons can only provide motor based twisting movement without considering user's flexibility. In order to overcome those problems, the arm holder of the exoskeleton is designed to accommodate motor controlled activities along with user's originated movements. In this exoskeleton, the twisting motion of forearm pronation-supination is achieved using a gear-driven mechanism. A big half-circular gear is engaged to body segment and it is coupled with another small gear which is actuated by an electric motor. The electric motor controls the twisting joint angle. The ratio of both gears should be such that users can reach the full anatomical limit of joint angle. The electric motor is connected to the base structure which is used to attach the half-circular ring with the exoskeleton. The half-circular ring has two circular channels and it can slide along the first circular channel based on two circular rods during motor-controlled movement. In the second circular channel, a small rectangular slider is placed between two compression springs (S_9 and S_{10}) connected to two ends of the ring. This part of the mechanism provides free space to users for twisting their arms if they are capable of moving their joints. The stiffness and dimension of S_9 and S_{10} are same, therefore the force exerted by two springs maintain the arm in a balanced condition. If users want to twist this arm in any direction, it has to put its own effort. In that situation, the spring on the twisting side will be more compressed to allow the joint angle. Human arm is attached to the small rectangular slider with strap. The inner side of the strap is made up of fur, therefore would not create any friction during motion. The schematic diagram of and 3D model of the arm holder is shown in Figure 3.14 (a & b). It enhances the ergonomic property of the system and provides safety to users as they can twist their joint in case of arm spasticity.

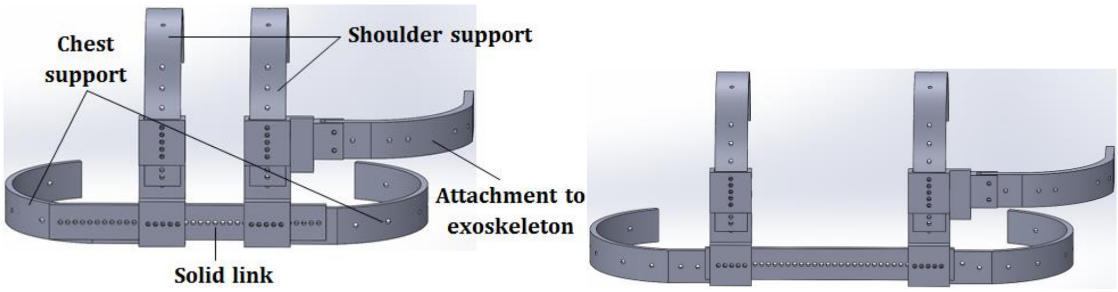


a. Schematic design b. 3D model

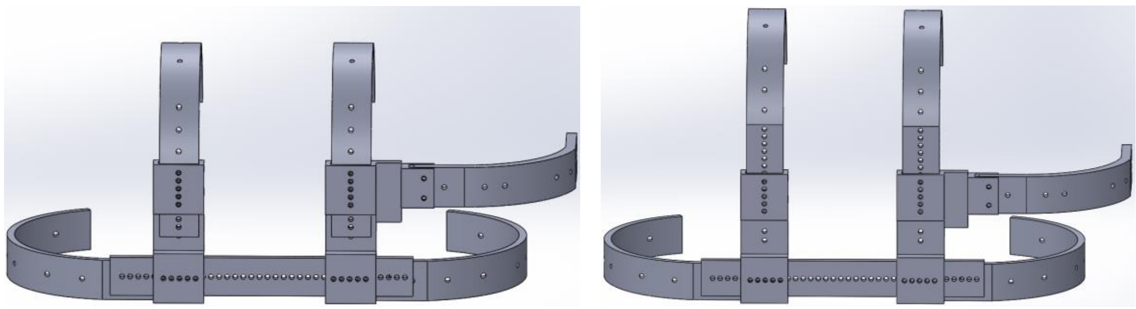
Figure 3.14. Arm holder for providing forearm motion

3.7 Supportive structure of the exoskeleton

The whole structure of elbow exoskeleton is attached to user's body to offload the weight of user's arm. The structure is made of circular holder and those holders are placed around the body tightened with belt. It helps to reduce the load on user by supporting it from two sides; two circular holders are fitted around the chest connected by a solid link and help to attach the exoskeleton with user's body in transverse plane whereas the shoulder based holder usually takes care of the weight of the exoskeleton against gravity. The supporting structure is assembled by detachable components, therefore the length of formation around the chest and shoulder can be changed as per different body shape requirements as shown in Figure 3.15 (a and b).



a. Changing of length in horizontal plane



a. Changing of length in vertical plane

Figure 3.15. Design of the flexible supportive arm structure

3.8 Selection of spring and their stiffness

All linear springs (S_1, S_2, S_3, S_4, S_5 and S_6) and torsional springs (S_7 and S_8) are used in the exoskeleton either for providing the spring force or switching from one mode of exercise to another. Therefore, the stiffness of all springs is determined for smooth functioning of the exoskeleton (Manna and Dubey 2019a).

- **Stiffness of S_1**

The function of S_1 is to restore the position of the front-end of S_2 at the end of the assistive force based region, therefore, the stiffness of S_1 needs to be high enough to overcome the frictional force between SL_1 (along with the all other components connected to it) and CR_1, see Figure 3.16.

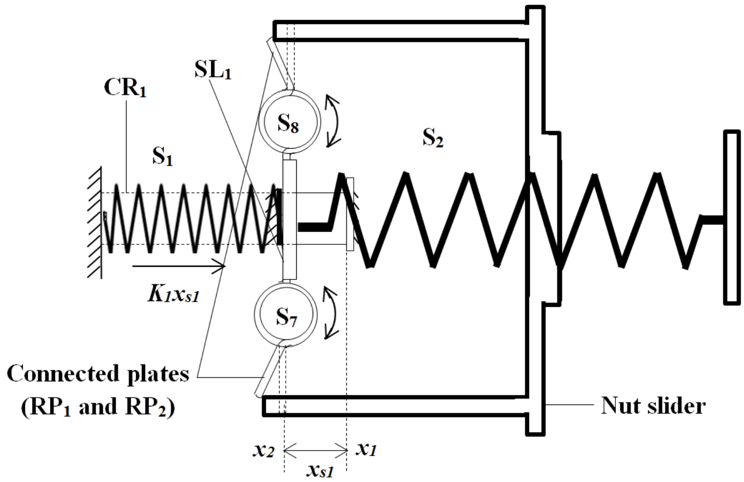


Figure 3.16. S$_1$ in fully compressed state

As per the mechanism design, $K_1 x_{s1} > \mu m g$ 3.2

The force of S$_2$ is not considered here because S$_2$ would not impose any force when elbow joint is in full flexion. However, S$_1$ should be able to overcome the frictional force.

Where K_1 = Stiffness of S$_1$

x_{s1} = Displacement covered by S$_1$ in fully compressed position = 0.02 m

μ = Coefficient of static friction between SL$_1$ and CR$_1$ = 0.45

m = Mass of the assembly connected to SL$_1$ = 0.102 kg

g = Acceleration due to gravity = 9.81 m/s^2

Substituting all these parameters, the frictional force becomes 0.451 N. We have considered the value of $K_1 x_{s1}$ as 0.5 N (>0.451 N) for safe operation to overcome the frictional force created during sliding movement by SL$_1$. The switching from assistive to resistive region starts when nut slider positioned at 0.181 m and S$_1$ produces maximum force when it is fully compressed by the nut slider (x = x_2) (Figure 3.17). Therefore, K_1 = 25 N/m where x_{s1} = 0.02 m (maximum)

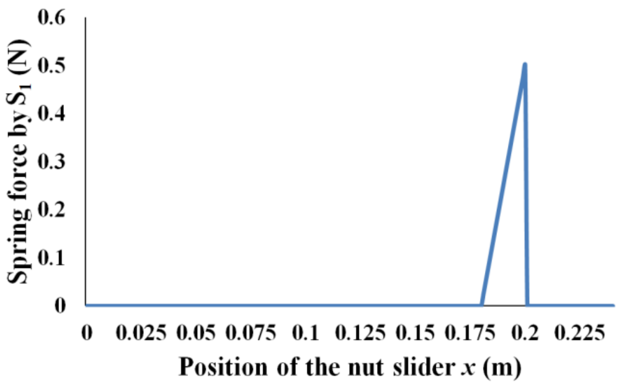


Figure 3.17. Force generated by S$_1$

- **Stiffness of S2**

Spring force of S2 is mainly responsible for assisting the elbow movement in the second operating region (Figure 3.18). In the exoskeleton, S2 will be extended for sharing the required torque used to rotate the joint against gravity.

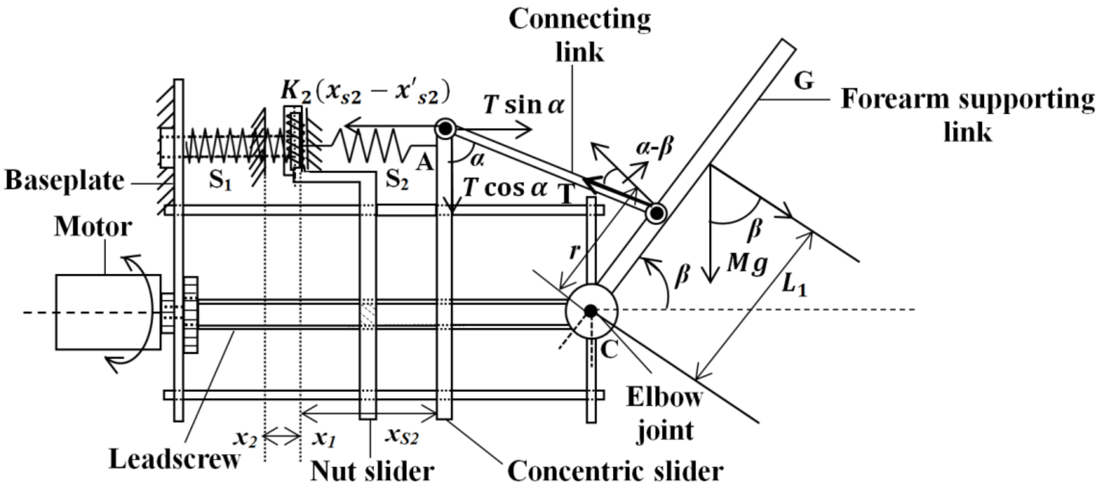


Figure 3.18. Force balancing in the assistive force region

As linear bearing is connected to the sliding contact between the concentric slider and leadscrew, the frictional force during motion is negligible compared to the elbow actuation force and is not taken into account.

In this mode, the required torque (τ') for rotating the elbow joint is given by

$$\tau' = MgL_1 \cos\beta \qquad 3.3$$

The assistive force provided by S2 is $f_{s2} = K_2(x_{s2} - x'_{s2})$ 3.4

Where K_2 = Stiffness of S2

x_{s2} = Displacement of S2

x'_{s2} = Free length of S2

Pulling force (T') along the connecting link is same as the force during the electric motor based control. The only difference is that S2 is taking care of the load in spite of the motor. Therefore, by equilibrating the forces at point 'A' in Figure 3.18, the stiffness of S2 becomes

$$K_2 = \frac{MgL_1 \cos\beta \sin\alpha}{r\cos(\alpha - \beta)\,(x_{s2} - x'_{s2})} \qquad 3.5$$

The value of K_2 is calculated for different mass of forearm (1 to 5 kg) at the maximum joint angle where the required joint torque is highest and the required stiffness of S_2 can be varied from 246.5 N/m to 739.6 N/m. The range of assistive force for an individual can be increased by changing the elongation limit of x_{s2}. The backward movement of the nut slider will shift the starting point of S_2 and the range of x_{s2} will be increased (Figure 3.19), thus providing more assistive force (Figure 3.20). In this exoskeleton, the maximum range of assistive force will be provided by the exoskeleton if the position of nut slider will be at the end of this region. The range of x_{s2} can be varied from 0.12 m to 0.14 m in the designed exoskeleton for the position of the nut slider from 0.181m to 0.20 m.

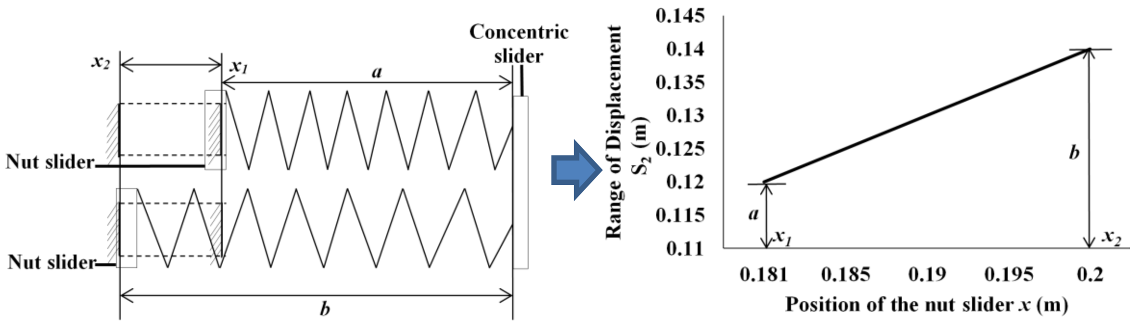


Figure 3.19. Variation of the range of S_2 with respect to the position of nut slider (x)

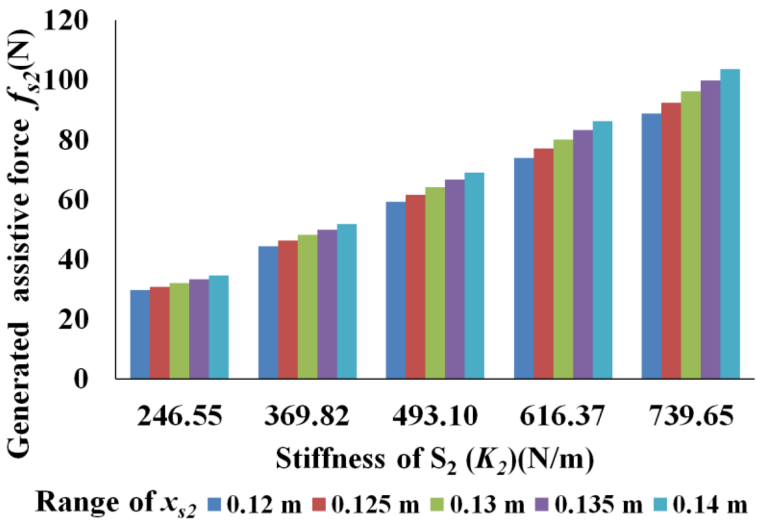


Figure 3.20. Variation of f_{s2} with the range of displacement (x_{s2})

- **Stiffness of S_3 and S_4**

The stiffness of S_3 and S_4 does not depend on any construction parameter. But those springs are mainly used for changing the joint stiffness during the third operating region as shown in Figure 3.21. The elbow joint stiffness is dependent on three springs (S_2, S_3 and S_4). The displacement of S_3 and S_4 is changed to create a variable joint stiffness in the elbow joint by moving the nut slider in the backward direction. In this configuration, the joint stiffness can be taken as a function of the distance travelled by the nut slider (x) and elbow joint angle (β). The position of the nut slider can be varied from 0.201 m (x_2) to 0.24 m (x_3) during this rehabilitation regime.

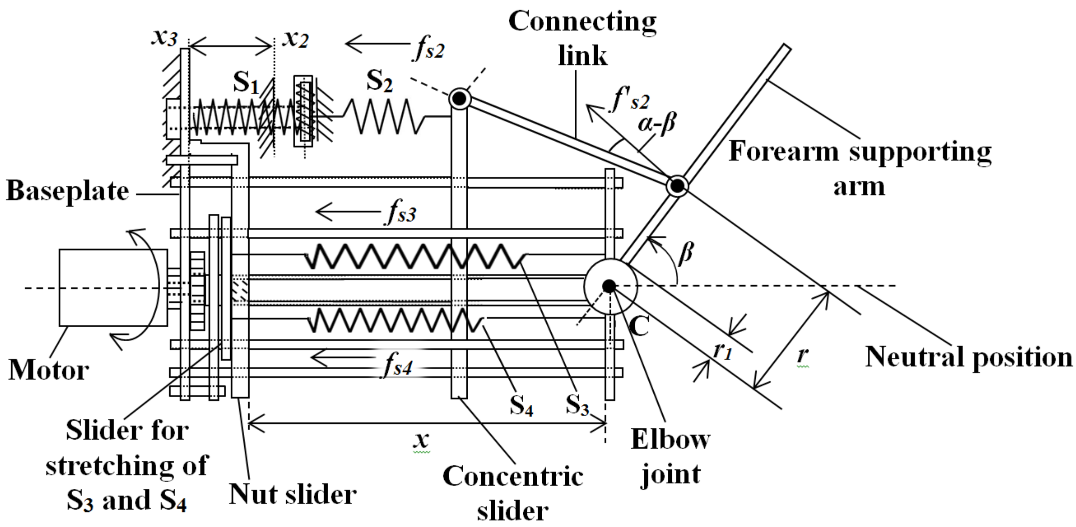


Figure 3.21. Elbow exoskeleton during variable joint stiffness control

The component of the spring force exerted by S_2 about the point C is given by,

$$f'_{s2} = \frac{K_2(x_{s2} - x'_{s2})\cos(\alpha - \beta)}{\sin \alpha} \tag{3.6}$$

Spring force exerted by S_3,

$$f_{s3} = K_3(x - r_1\beta - x'_{s3}) \tag{3.7}$$

Where K_3 = Stiffness of S_3, x'_{s3} = Free length of S_3

Spring force exerted by S_4,

$$f_{s4} = K_4(x + r_1\beta - x'_{s4}) \tag{3.8}$$

Where K_4 = Stiffness of S_4, x'_{s4} = Free length of S_4

The joint stiffness of the elbow exoskeleton is same as the torsional stiffness K' which is given by

$$K' = \frac{\tau}{\beta} = \frac{r_1(f_{s4} - f_{s3})}{\beta} - \frac{rf'_{s2}}{\beta} \tag{3.9}$$

Where r = Length of the crank

r_1 = Radius of the pulley connected at the elbow joint

Two pairs of S_3 and S_4 are connected in this mechanism, therefore, the force exerted by both springs will be doubled. Substituting the value of f'_{s2}, f_{s3} and f_{s4} in Eq. (3.9), the elbow joint stiffness is given by

$$K' = \frac{2r_1\{(K_4 - K_3)x - (K_4 x'_{s4} - K_3 x'_{s3})\} - \dfrac{K_2 r(x_{s2} - x'_{s2})\cos(\alpha - \beta)}{\sin\alpha}}{\beta} + 2r_1^2(K_4 + K_3) \qquad 3.10$$

For experimental purpose, two different extension springs are selected for the mechanism. However, those springs can be changed to get the required joint stiffness for exercises. The stiffness of S_3 and S_4 are chosen as 2.5 N/m and 10 N/m respectively. The value of K' has been calculated based on the forearm mass of 1 kg. Figure 3.22 shows the variation of elbow joint stiffness depending on the position of nut slider (x) and elbow joint angle (β) during resistive force based region.

K' = K' (minimum) when position of nut slider(x) = 0.201 m = 4.184 Nm/rad

= K' (maximum) when position of nut slider(x) = 0.24 m = 5.043 Nm/rad

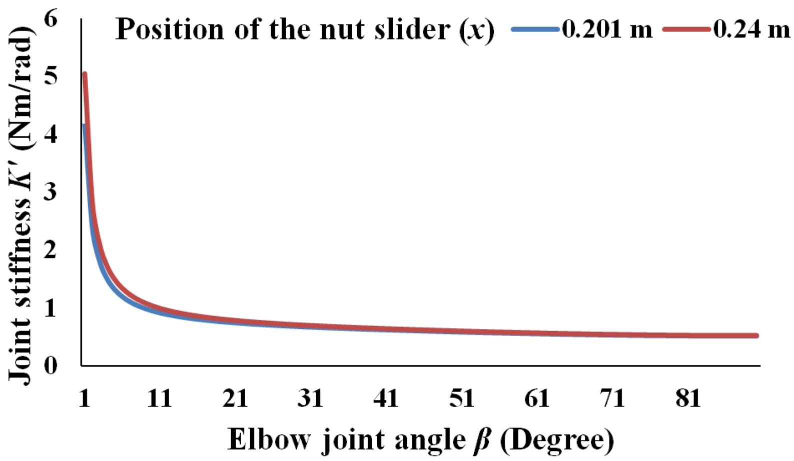


Figure 3.22. Elbow joint stiffness variation for different position of the nut slider (x)

- **Stiffness of S_5 and S_6**

The stiffness of both compression springs (S_5 and S_6) used for locking operation is equally important in switching operation between the first and second operating region. The ratio of the stiffness of S_5 and S_6 depends on the construction parameters of the locking mechanism (Figure 3.23).

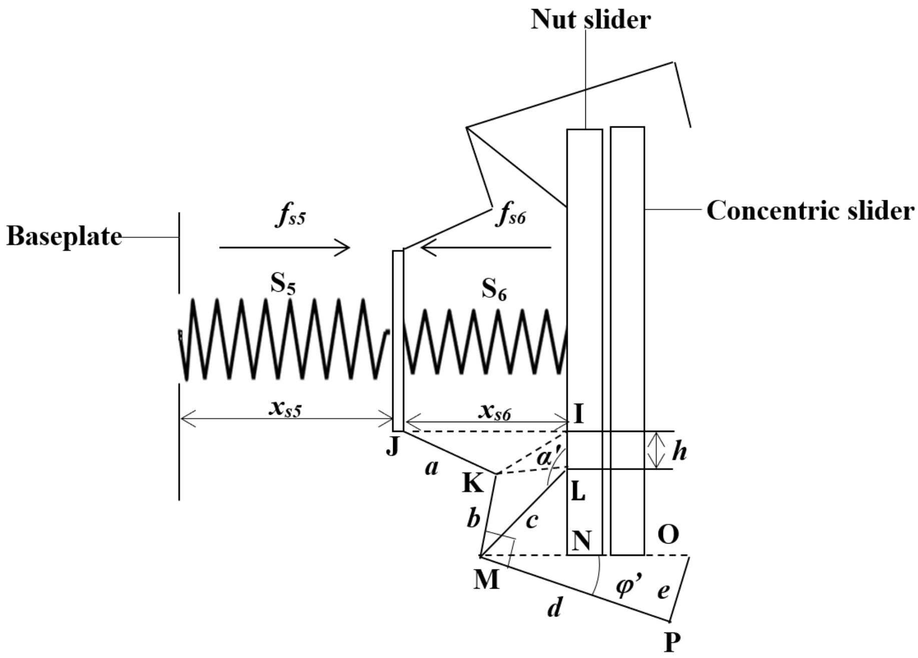


Figure 3.23. Force balancing diagram during unlocked condition

Force produced by the spring S_5,

$$f_{s5} = K_5 x_{s5} \tag{3.11}$$

Force produced by the spring S_6,

$$f_{s6} = K_6 x_{s6} \tag{3.12}$$

When the exoskeleton is unlocked, KMPO is shown here as the right-sided jaw which is deflected to free the attachment. The upper-end point of the jaw O should be outside of the region covered by these sliders (shown in dotted line OM). It is clear that these two jaws need to rotate a minimum angle φ' about point M to unlock the concentric slider from the locking range.

Here, ΔOMP is a right-angled triangle. Therefore $\varphi' = \tan^{-1}\frac{e}{d}$ 3.13

The locking mechanism has some solid links such as *a, b, c, d, e* and *h,* the length of those links are fixed. The value of ∠MLI and ∠KMP are also fixed as those are the part of the structure. Therefore, the value of φ' is constant for unlocking.

The locking mechanism can function successfully if it satisfies the following condition, $K_5 \gg K_6$ [Where K_5 = Stiffness of S_5, K_6 = Stiffness of S_6]

which means, $x_{s5} \ll x_{s6}$

At the time of opening the lock, both springs will be in equilibrium which means force exerted by S_5 and S_6 will be same at that position.

Therefore, $f_{s5} = f_{s6}$

i.e. $K_5 x_{s5} = K_6 x_{s6}$

$$K_5 = \frac{K_6\, x_{s6}}{x_{s5}} \quad 3.14$$

To achieve the defined angle of φ', S_6 moves a specific distance which is derived from the geometrical parameters.

From Figure 3.23, it shows

$$\angle \text{LMN} = (\alpha' - 90^o) \quad 3.15$$

$$\angle \text{LMK} = \left(180^o - (\alpha' + \varphi')\right) = \left(180^o - \left(\alpha' + tan^{-1}\frac{e}{d}\right)\right) \quad 3.16$$

From ΔLMK, it can be derived that,

$$\cos(\angle \text{LMK}) = \frac{b^2 + c^2 - \text{LK}^2}{2bc}$$

Substituting the value of ∠LMK taken from Eq. (3.16), the value of LK can be obtained

$$\cos\left(180^{\text{o}} - \left(\alpha' + \tan^{-1}\frac{e}{d}\right)\right) = \frac{b^2 + c^2 - \text{LK}^2}{2bc}$$

$$\text{LK}^2 = b^2 + c^2 - 2bc\cos\left(180^{\text{o}} - \left(\alpha' + \tan^{-1}\frac{e}{d}\right)\right)$$

$$\text{LK}^2 = b^2 + c^2 + 2bc\cos\left(\alpha' + \tan^{-1}\frac{e}{d}\right) \quad 3.17$$

From ΔLMK, it can also be derived that,

$$\cos \angle \text{MLK} = \frac{c^2 + \text{LK}^2 - b^2}{2c\text{LK}}$$

Substituting the value of LK taken from Eq. (3.17), it shows

$$\angle \text{MLK} = \cos^{-1}\left(\frac{c^2 + \left(b^2 + c^2 + 2bc\cos\left(\alpha' + \tan^{-1}\frac{e}{d}\right)\right) - b^2}{2c * \sqrt{b^2 + c^2 + 2bc\cos\left(\alpha' + \tan^{-1}\frac{e}{d}\right)}}\right)$$

$$\angle \mathrm{MLK} = \cos^{-1}\left(\frac{c + b\cos\left(\alpha' + \tan^{-1}\frac{e}{d}\right)}{\sqrt{b^2 + c^2 + 2bc\cos\left(\alpha' + \tan^{-1}\frac{e}{d}\right)}}\right) \qquad 3.18$$

As ∠MLI is constant, ∠KLI can be seen as

∠KLI = ∠MLI - ∠MLK

= α' - ∠MLK

Substituting the value of ∠MLK taken form Eq. (3.18) in the above equation, the value of ∠KLI will be

$$= \alpha' - cos^{-1}\left(\frac{c + bcos\left(\alpha' + tan^{-1}\frac{e}{d}\right)}{\sqrt{b^2 + c^2 + 2bccos\left(\alpha' + tan^{-1}\frac{e}{d}\right)}}\right) \qquad 3.19$$

From ΔKLI, it can be seen that,

$$\mathrm{IK}^2 = h^2 + \mathrm{LK}^2 - 2h\mathrm{LK}\cos\angle\mathrm{KLI} \qquad 3.20$$

Substituting the value of LK (from Eq. (3.17)) and ∠KLI (from Eq. (3.19)) in Eq. (3.20), it has been derived

$$\mathrm{IK}^2 = h^2 + A_1 - 2h\sqrt{A_1}\,cos\left(\alpha' - cos^{-1}\left(\frac{B_1}{\sqrt{A_1}}\right)\right) \qquad 3.21$$

Where $A_1 = b^2 + c^2 + 2bccos\left(\alpha' + tan^{-1}\frac{e}{d}\right)$

and $B_1 = c + bcos\left(\alpha' + tan^{-1}\frac{e}{d}\right)$

From ΔKLI, the value of ∠KIL can be derived as

$$\cos\angle\mathrm{KIL} = \frac{h^2 + \mathrm{IK}^2 - \mathrm{LK}^2}{2h\mathrm{IK}}$$

After substituting the value of LK and IK taken from Eqs. (3.17) and (3.21) respectively, it has been derived

$$\angle\mathrm{KIL} = cos^{-1}\left(\frac{h - \sqrt{A_1}\,cos\left(\alpha' - cos^{-1}\left(\frac{B_1}{\sqrt{A_1}}\right)\right)}{h^2 + A_1 - 2h\sqrt{A_1}\,cos\left(\alpha' - cos^{-1}\left(\frac{B_1}{\sqrt{A_1}}\right)\right)}\right) \qquad 3.22$$

During unlocking condition, the displacement made by S_6 create ΔJIK where ∠JIK can be seen as $(90^{\circ} - \angle\mathrm{KIL})$

From ΔJIK, cos ∠JIK can be calculated as

$$\frac{x_6{}^2 + \mathrm{IK}^2 - a^2}{2x_6\mathrm{IK}}$$

$$\cos(90^{\circ} - \angle\mathrm{KIL}) = \frac{x_6{}^2 + \mathrm{IK}^2 - a^2}{2x_6\mathrm{IK}} \qquad 3.23$$

After substituting the value of ∠KIL (from Eq. (3.22)) and IK (from Eq. (3.21)) in Eq. (3.23), x_{s6} can be expressed as a function of *a, b, c, d, e, h* and α'. The measured value of x_{s6} defines the condition for opening the locking system. After putting all the structural parameters as per our design in Eq. (3.23),
the value of x_{s6} will be 1.5 cm (approximately).
Where a = 1.25 cm, b = 1.375 cm, c = 1.5 cm, d = 4.6 cm, e = 1.25 cm, h = 0.75 cm and α' = 135.61°
Primary length of x_{s6} = 2 cm (before opening of the lock)
Therefore, total displacement $\Delta x_{s6} = (2 - 1.5) = 0.5$ cm (approximately)

As per the design, the value of K_5 should be higher than K_6 so that the distance covered by S_6 for the opening condition can be accomplished for a little movement of S_5. In order to make a boundary between two regions, the switching region should be as small as possible. Satisfying the criteria ($x_{s5} \ll x_{s6}$), we assume that x_{s6} moves 0.5 cm for the displacement of x_{s5} = 0.1 cm for proper functioning.
Therefore, putting the value of x_{s5} and x_{s6} in Eq. (3.14),
it has been derived $K_5 = 5K_6$ 3.24

In this exoskeleton, a small compression spring (S_6) is considered to fit into the small space of the locking system and its stiffness (K_6) is 103 N/m. Therefore, the value of K_5 should be at least 515 N/m to satisfy the unlocking condition.

The spring (S_6) connected to two jaws experience a higher and opposite force from S_5 after opening of the lock. S_6 cannot be compressed after a certain limit due to the mechanical restriction thus produces a constant force for the rest of the motion. However, due to the backward movement of the nut slider in the second operating region, S_5 will be compressed and will maintain the unlocked condition during the rest of the range as shown in Figure 3.24.

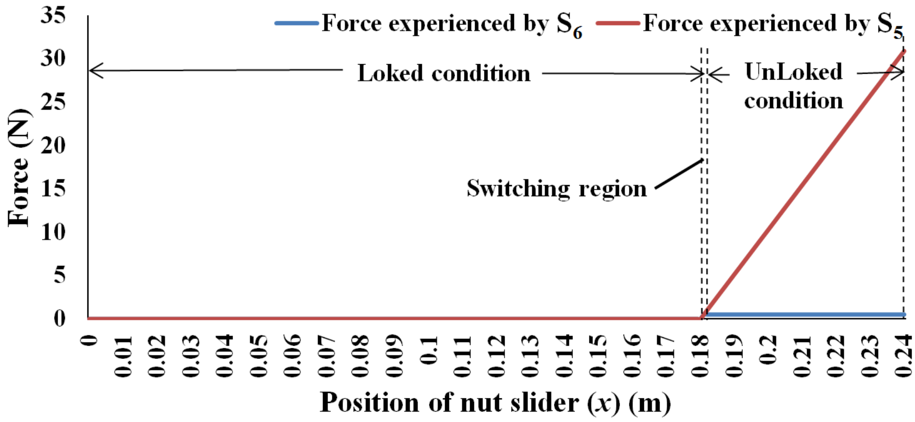


Figure 3.24. Force generation in two springs of the locking mechanism

- **Stiffness of S_7 and S_8**

Figure 3.25 shows the force balancing diagram of the mechanism during the final stage of assistive force-based region where both torsional springs S_7 and S_8 are at their maximum deflected position. The stiffness of S_2 depends on the combined weight of the arm and load which is already shown in Eq. (3.5). Compression spring S_1 is able to keep the cylinder based rectangular slider at its normal condition if no force is present. Nut slider will generate an equal and opposite force in return of the torque generated by those torsional spring (S_7 and S_8). Those two rectangular plates associated with S_7 and S_8 will be deflected to their maximum position.

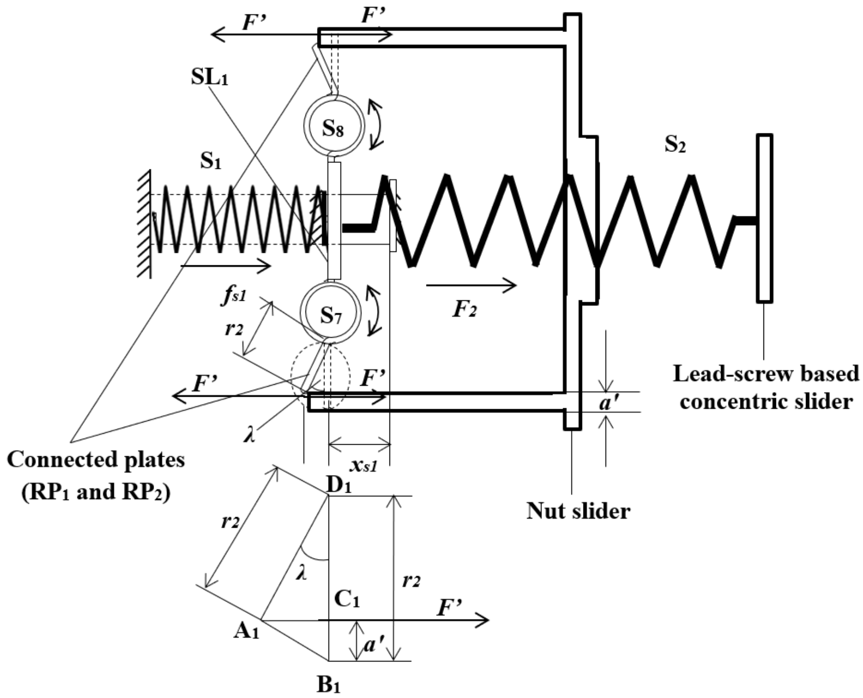


Figure 3.25. Force balancing of the mechanism in final stage of the assistive force

The reaction force produced by the nut slider should be able to balance the forces generated by S_1 and S_2. The stiffness of S_7 and S_8 can be derived from the force balancing condition of the mechanism. Both S_7 and S_8 offer equal stiffness because construction wise both springs are the same.

From $\Delta A_1B_1D_1$, it can be derived that,

$$r_2(1 - cos\,\lambda) = a'$$

$$\lambda = cos^{-1}(1 - \frac{a'}{r_2}) \qquad 3.25$$

Where a' = Width of the extension part of the nut slider

r_2 = Length of rectangular plates connected to S_7 and S_8

λ = Angle made by those rectangular plates at maximum deflected position

Force produced by S_1,

$$f_{s1} = K_1 x_{s1} \qquad 3.26$$

Force produced by S_2 at maximum deflected position,

$$F_2 = K_2(x_{s2} + x_{s1} - x'_{s2}) \qquad 3.27$$

In this mechanism, $K_7 = K_8$ [Where K_7 = Stiffness of S_7 and K_8 = Stiffness of S_8]

The torque created by each torsional spring is given by

$$\tau'' = K_7\lambda$$

$F' r_2\, cos\,\lambda = K_7\lambda$ [Where F' = Tangential force by S_7 and S_8 = Reaction force of nut slider]

$$F' = \frac{K_7\lambda}{r_2\, cos\,\lambda} \qquad 3.28$$

The force created by both torsional springs is given by $2F'$

As per the force equilibrium condition,

$$2F' = f_{s1} + F_2 \qquad 3.29$$

Substituting the value of f_{s1} (from Eq. (3.26)), F_2 (from Eq. (3.27)) and F' (from Eq. (3.28)) in Eq. (3.29), it shows

$$\frac{2K_7\lambda}{r_2\, cos\,\lambda} = K_1 x_{s1} + K_2(x_{s2} + x_{s1} - x'_{s2})$$

$$K_7 = \frac{r_2\, cos\,\lambda\left(K_1 x_{s1} + K_2(x_{s2} + x_{s1} - x'_{s2})\right)}{2\lambda} \qquad 3.30$$

After putting the value of λ (taken from Eq. (3.25)), the value of K_7 will be,

$$K_7 = \frac{(r_2 - a')\left(K_1 x_{s1} + K_2(x_{s2} + x_{s1} - x'_{s2})\right)}{2\cos^{-1}(1 - \frac{a'}{r_2})} \qquad 3.31$$

To be deflected by the nut slider, both plates RP_1 and RP_2 needs to rotate near about (λ) 31°. After substituting the structural parameters in the above equation, the value of K_7 and K_8 becomes 0.63Nm/rad. The pressure on S_7 and S_8 has been created since the starting of assistive force-based region (0.181 m) and it ends up at 0.205 m due to the angular deflexion limit of both torsional springs. Figure 3.26 shows the force generation by both springs (S_7 and S_8) during the assistive force-based spring formation.

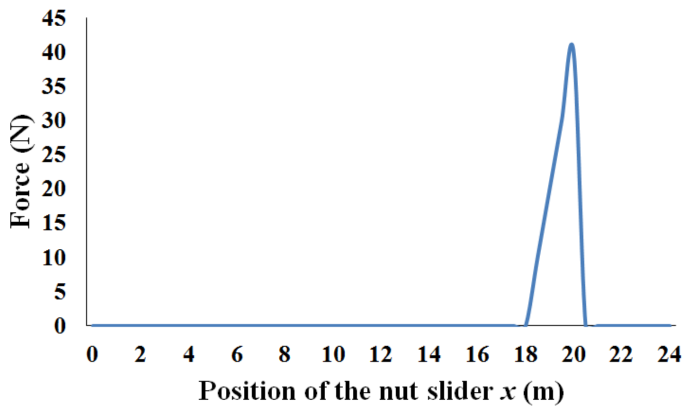


Figure 3.26. Force generated by S_7 and S_8

Specification of all compression, extension and torsional springs used in the exoskeleton are shown in Table 3.2.

Table 3.2. Specifications of the springs used in the exoskeleton

Spring number	Type of the spring	Stiffness (N/m)	No of turns	Wire diameter (m)	Material	Mean diameter (m)	Function
S_1	Compression	25 N/m	8	0.000681	ASTM music wire	0.02	Restoration of the slider (SL_1) assembly at the end of assistive force based region
S_2	Extension	246.54 N/m	35	0.0017	ASTM music wire	0.021	Generation of the assistive force during self-initiated joint movement
S_3	Extension	2.5 N/m	93	0.00054	ASTM music wire	0.01	Variation of the joint stiffness
S_4	Extension	10 N/m	122	0.00082	ASTM music wire	0.01	Variation of the joint stiffness

Spring number	Type of the spring	Stiffness (N/m)	No of turns	Wire diameter (m)	Material	Mean diameter (m)	Function
S_5	Compression	103 N/m	8	0.0005	ASTM music wire	0.01	Generation of the opposite force to open the lock
S_6	Compression	515 N/m	20	.001	ASTM music wire	0.01	Generation of the force to maintain the unlocked condition
S_7	Torsional	0.63 Nm/rad	5	.002	ASTM music wire	0.005	Switching between assistive force based region to resistive one
S_8	Torsional	0.63 Nm/rad	5	.002	ASTM music wire	0.005	Switching between assistive force based region to resistive one

3.9 Working model of the elbow exoskeleton

A working prototype has been developed to establish the working principle of the exoskeleton. The 3D model has been designed in Solidworks™ platform (shown in Appendix V) and all customized mechanical components have been manufactured using 3D printer (Manna and Dubey 2019a). All rotational and sliding contacts have been designed with a bearing to reduce the frictional loss. ABS (Acrylonitrile butadiene styrene) is used as the structural material for its hardness and lightweight. The supporting structure of the exoskeleton and its arm holder are shown in Figure 3.27 and Figure 3.28. Figure 3.29 shows how user is going to wear the exoskeleton. Different phases of exoskeleton for generating modes of exercise are shown from Figure 3.30 to Figure 3.34 with the developed prototype. The specifications of the manufactured model are shown in Table 3.3.

Table 3.3. Specification of the proposed exoskeleton

Material	ABS (Acrylonitrile butadiene styrene)
Upper arm dimension	0.35 m x 0.15 m x 0.17 m (± 0.04 m)
Forearm dimension	0.40 m x 0.02 m x 0.06 m (± 0.04 m)
Mass of the structure	1.8 kg
Motor specification	Model-DFROBOT ZYTD520
	Operating voltage-12V DC
	RPM-50 RPM
	Maximum torque-5 Nm
	Mass-0.210 kg
	Power – 5 W
Gear material	Nylon-101
Spring material	ASTM A228
Linear Ball Bearing	Model- Bosch Rexroth Linear Ball Bearing R060204010
Axial Ball bearing	HCH 62022

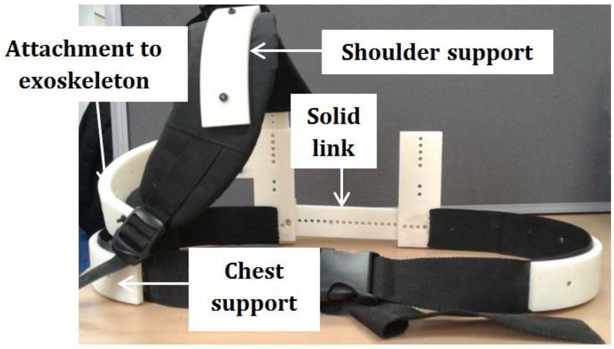


Figure 3.27. Supporting structure

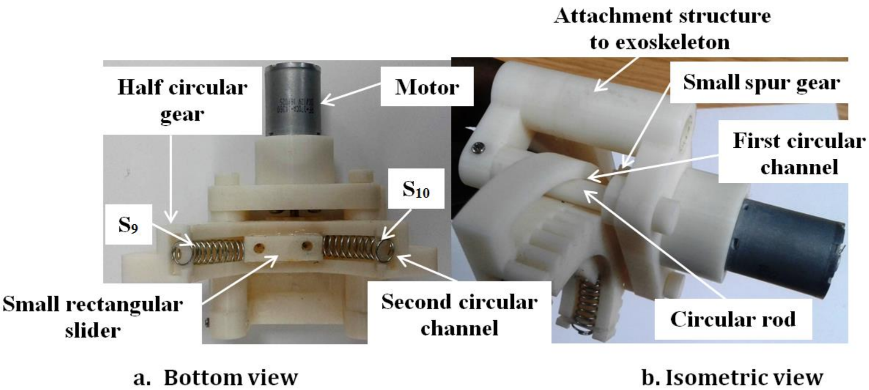


Figure 3.28. Arm holder

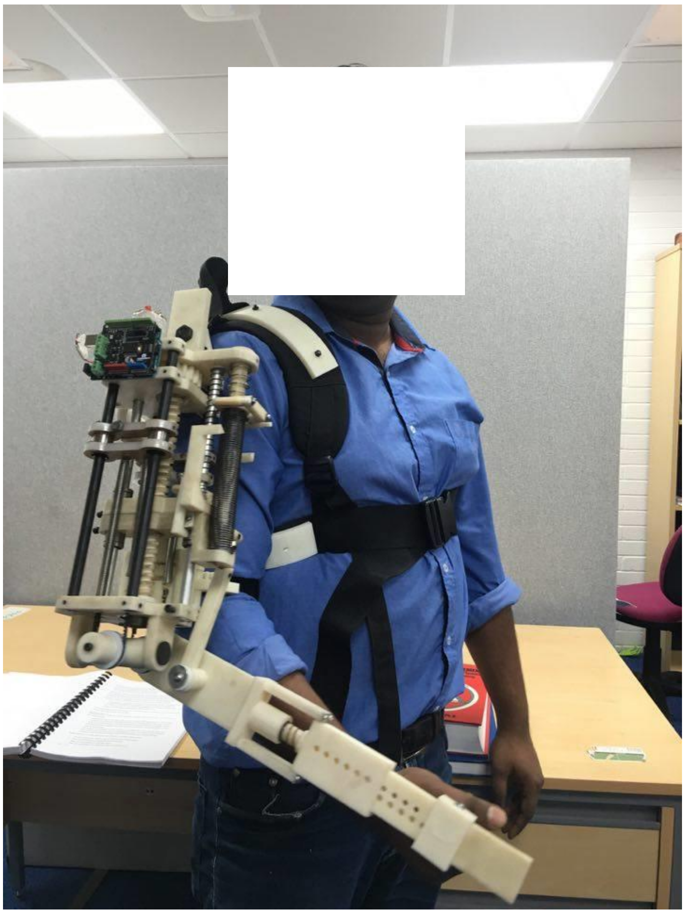
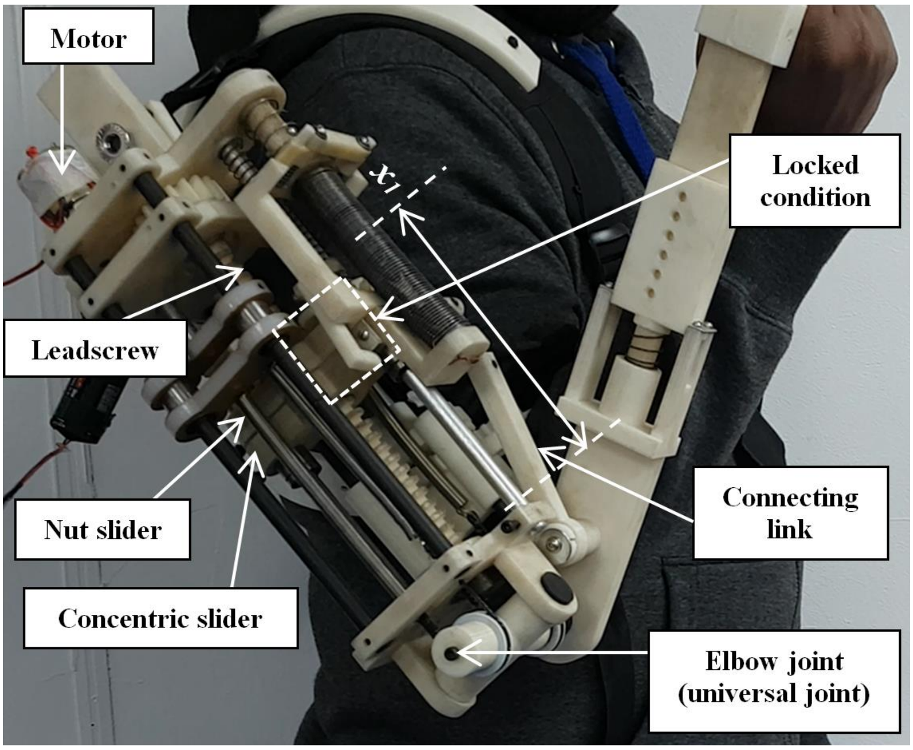
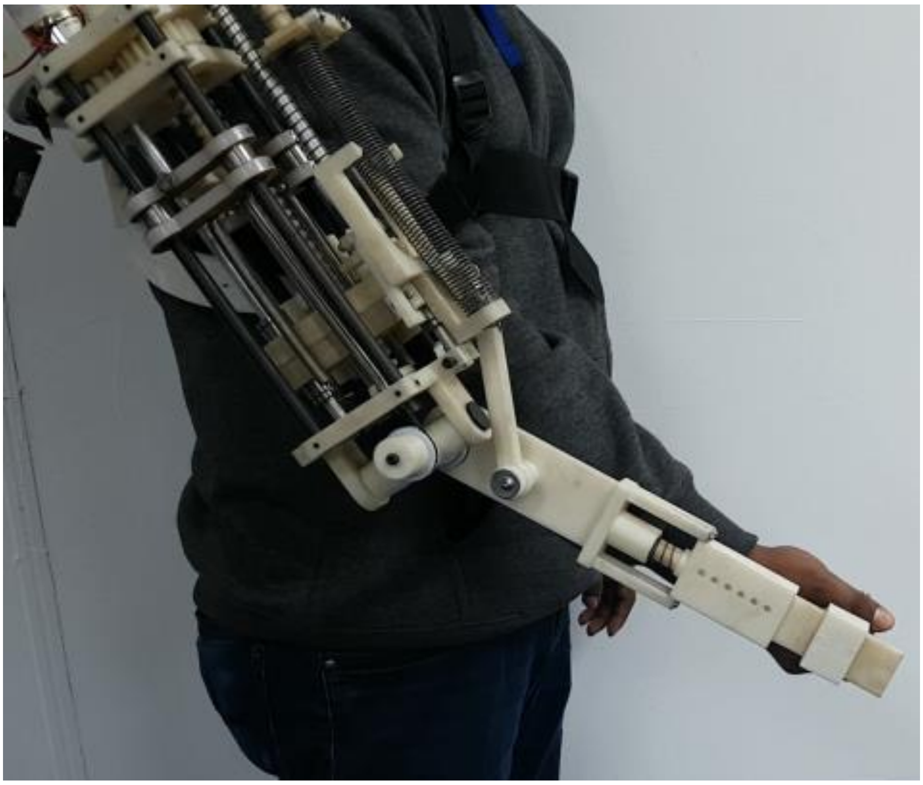


Figure 3.29. Prototype of the elbow exoskeleton

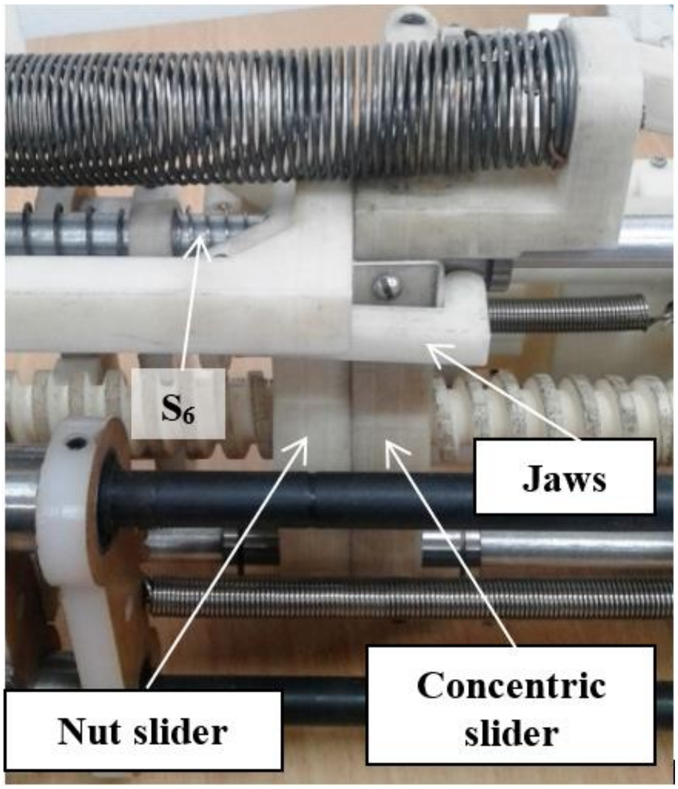


Flexion

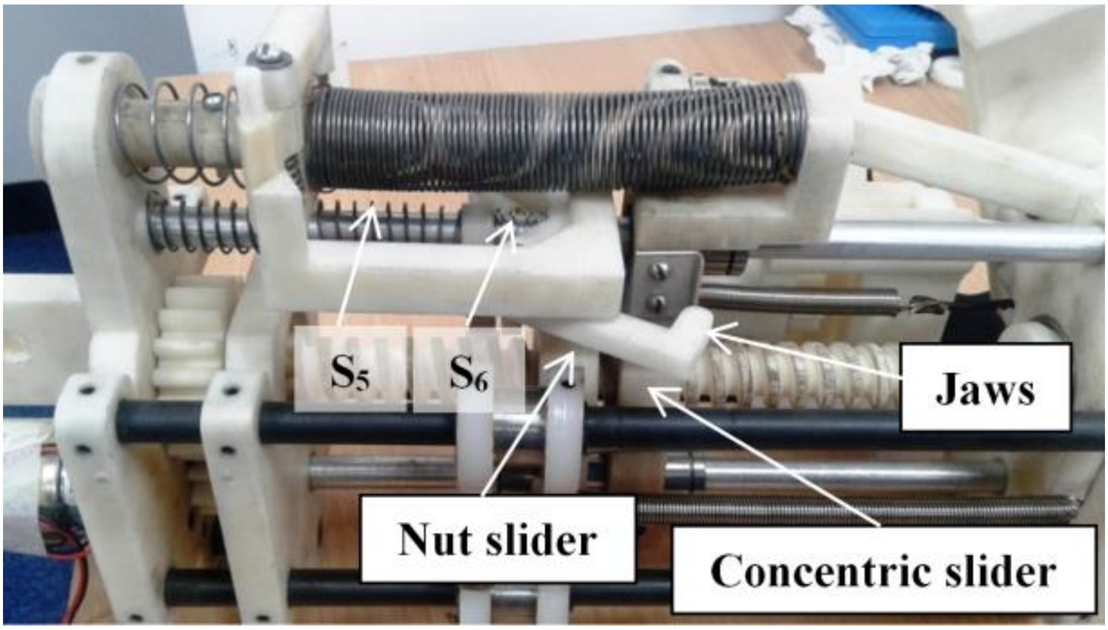


Extension

Figure 3.30. Motor controlled elbow joint motion in first operating region

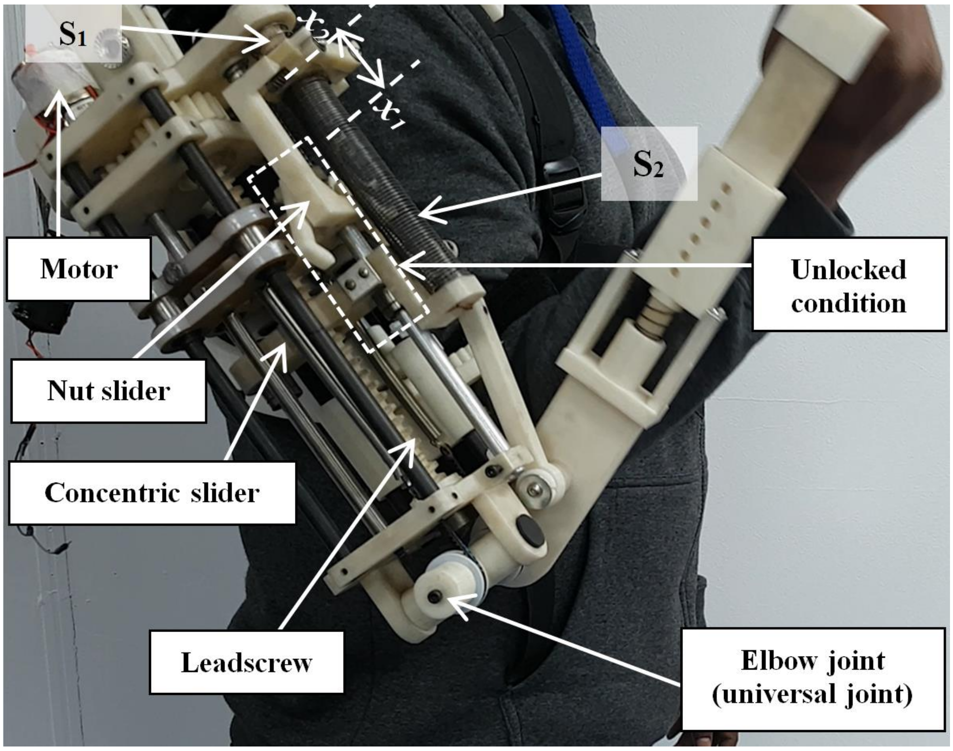


a. Locked condition

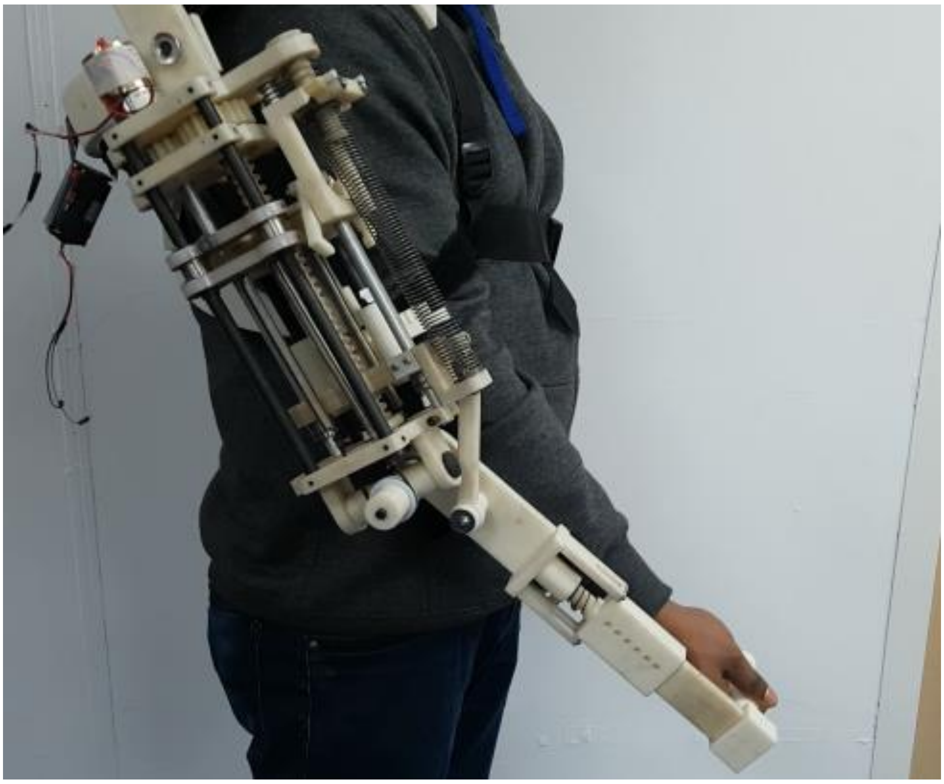


b. Unlocked condition

Figure 3.31. Pre and post locking condition for switching from motor controlled to assistive mode

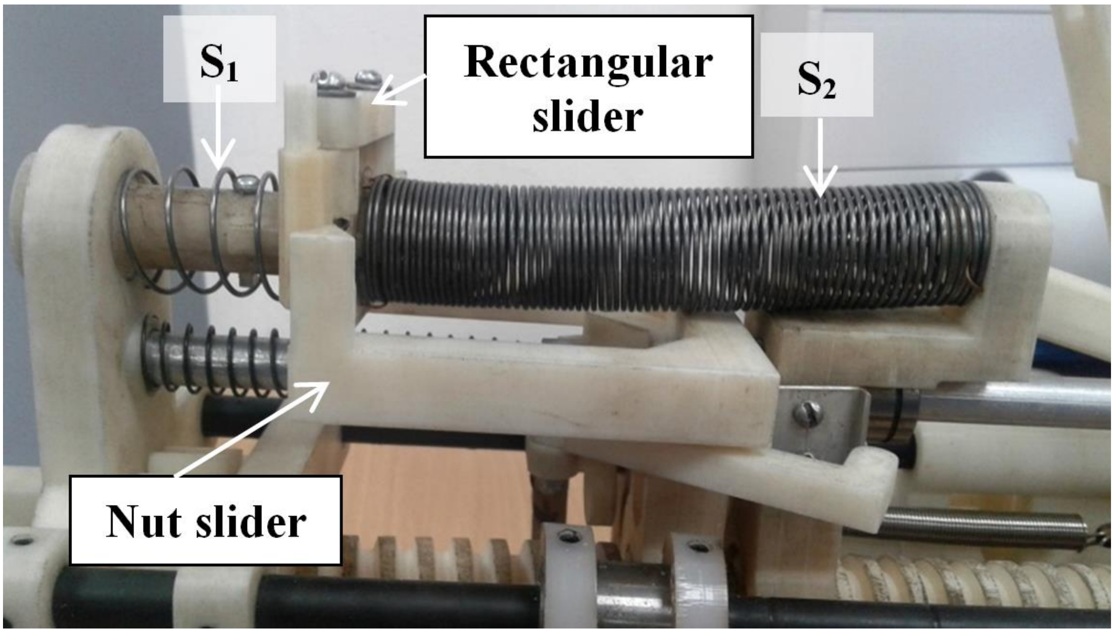


Flexion

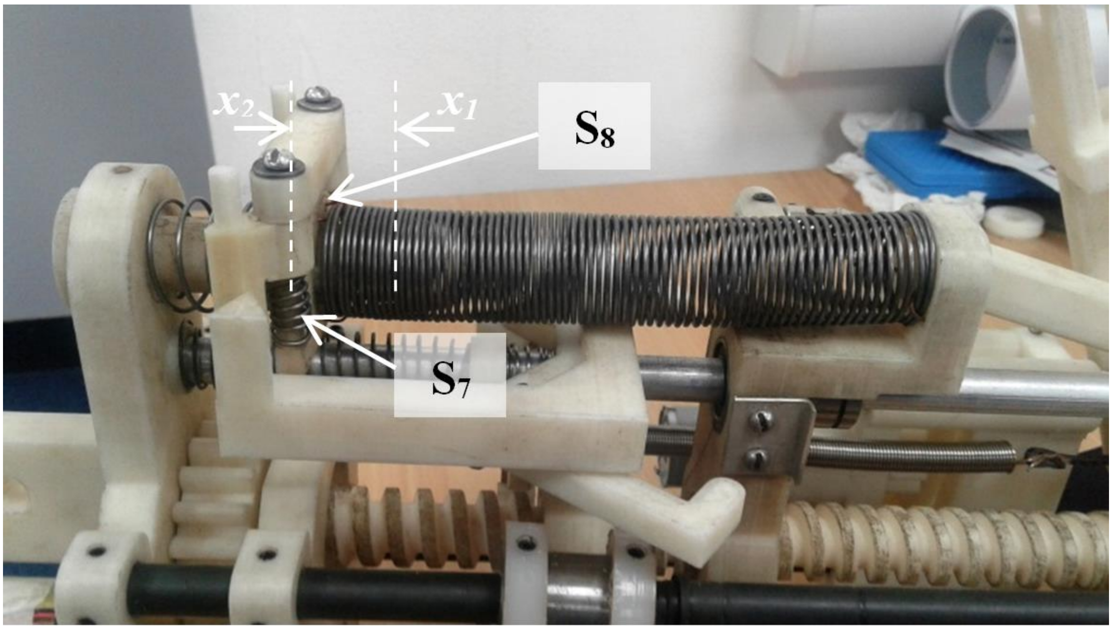


Extension

Figure 3.32. Spring assisted joint motion in the second operating region

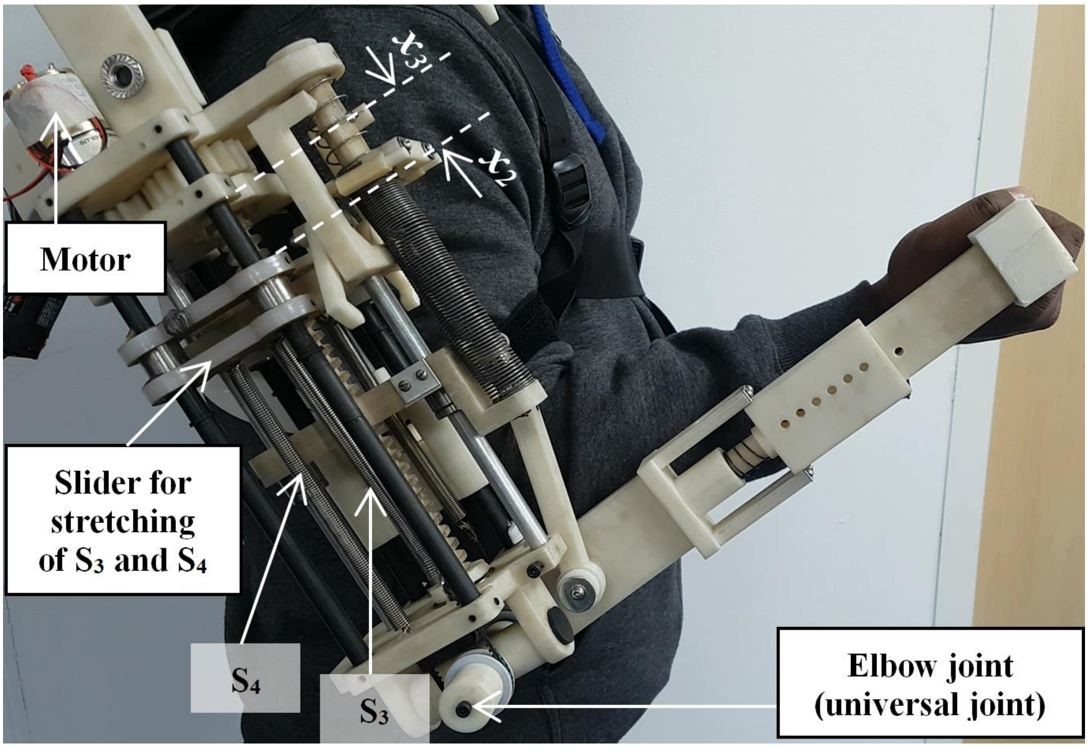


a. Starting position of assistive mode



b. End position of assistive mode

Figure 3.33. Mechanism of the exoskeleton for generating variable assistance



Flexion

Extension

Figure 3.34. Spring assisted resistive mode in the third operating region

3.10 Cost estimation

The cost of making this exoskeleton includes the manufacturing cost of all 3D printed components and purchasing cost of the mechanical and electronic components used. The price list of all components used to make this exoskeleton is shown in Table 3.4. The estimated total cost is assumed to be £886.

Table 3.4. Price list of components

Manufactured items		
Item no	**Components**	**Cost (£)**
1	60 components manufactured from 3D printers Material: ABS (Acrylonitrile butadiene styrene)	600
2	Solid rods, Material: Teflon, aluminium	10
3	Universal joint, Material: Bruss	10
4	Flange, Material: Bruss	5
5	10 Springs, Material: ASTM A228	10
6	2 Gears, Material: Nylon 101	5
7	Screw, Material: cast iron	10
8	Rivet joint, Material: Bruss	5
9	Assembling cost	123
Purchased items		
Item no	**Components**	**Market price**
Mechanical components		
1	Screw set	10
2	Linear ball bearing, Model: R060204010	10
3	Axial Ball bearing, Model: HCH 62022	10
Electronic components		
1	DC motor, Model: ZYTD520	14
2	Arduino Uno board	12
3	Arduino compatible motor driver, Model: DFR0225:V2	19
4	A reflective optical sensor Model: GP2Y0A41SK0F	6
5	4 KΩ potentiometer	2
6	12v Battery	15
7	Electronic connectors	10
	Total	**886**

3.11 Concluding remarks

An innovative mechanism of the elbow exoskeleton has been developed which can accommodate three modes of exercises that could potentially deliver different stages of post-stroke rehabilitation. In this design, we have attempted to achieve the different types of joint movements (external force based, active and passive) at mechanical level so that the device can be fine-tuned to user's requirements. Full design details of the elbow exoskeleton have been presented together with parametric relations for component selection (springs and motor specification), however, these design parameters can be tailored to suit any user-specific requirements. A prototype device has been developed to prove the principle. The present prototype can deliver the joint torque up to 10 Nm. For most exoskeletons, the motor torque is varied to generate variable joint torque depending on the signal from user's body whereas in this exoskeleton the position of the nut-slider can produce different exercise modes either under motor control or in assistive or resistive modes. The mechanism can change the amount of assistive and resistive force by simply changing the position of the nut-slider. The developed exoskeleton provides a mechanism based solution which removes the dependency of biosensor. The exoskeleton is operated using a single motor. The exoskeleton is operated using a single motor. If the joint range go beyond 135^o, the switching mechanism between motor controlled mode and assistive mode works as safety tool and transfer the joint control from motor to spring force. In assistive and resistive rehabilitation, since springs are used to provide the required forces without using any extra energy sources, this reduces the power consumption as well as the size of the energy source. Such an arrangement in a single structure offers flexibility to users to select a particular type of exercise. The cost of the exoskeleton is also under affordable range (£886) which can make it a potential solution for post-stroke patients in future.

Chapter 4 Control strategy of the developed exoskeleton

The developed exoskeleton can provide three types of joint movement (external control, assistive force and resistive force) by changing its configuration. It depends on two parameters; one is the structural parameters (dimension of the mechanical components, stiffness of springs, motor torque) which decide the working range of mechanical parts. The other is joint parameters which decide the mode of exercise and its outcome. Before considering the technical specification and dependency on joint parameters, it is important to know how different modes of exercises can be generated using the designed exoskeleton. After identifying the design specifications of the developed elbow exoskeleton, a combined three stage exercise module has been incorporated using a position-based control. To remove the dependency of muscle-based biosensor (discussed in chapter 3), different mechanisms have been used in the exoskeleton to generate variable assistive as well as resistive force.

The ability of a human joint can be evaluated based on its joint angle, angular velocity and joint torque because those three parameters show its reachable points, frequency of movement and weight lifting capacity. Therefore, these three joint parameters are considered in this exoskeleton to control the mode of exercise and can be used to evaluate the post-stroke recovery stage (acute, mid and last stage). The recovery index (RI_t) is an iterative process which can be evaluated by measuring the difference between the present and past health, quantifies the joint condition based on the joint angle (β), angular velocity of the joint (ω) and change in load carrying capacity (L_m).

$$RI_t = \frac{HI_t - HI_{t-1}}{T} \quad [HI_t \to f(\beta, \omega, L_m)] \qquad 4.1$$

T = Time over a period of testing

$$\omega = \frac{\beta(t) - \beta(t-1)}{t} \qquad 4.2$$

t = Time to complete one rotation

$$L_m = P_l(t) - P_l(t-1) \qquad 4.3$$

[P_l = Load carrying capacity of the joint]

The threshold conditions (*E1*, *E2* and *E3*) of each recovery stage can be determined based on prior information set by the physiotherapist. Each of the threshold condition consists of a specific value of three joint parameters. Users can switch from one mode of exercise to another if they cross the threshold (Manna and Dubey 2019b). The control algorithm will automatically put the nut slider in a specific position required for that exercise, as shown in Figure 4.1.

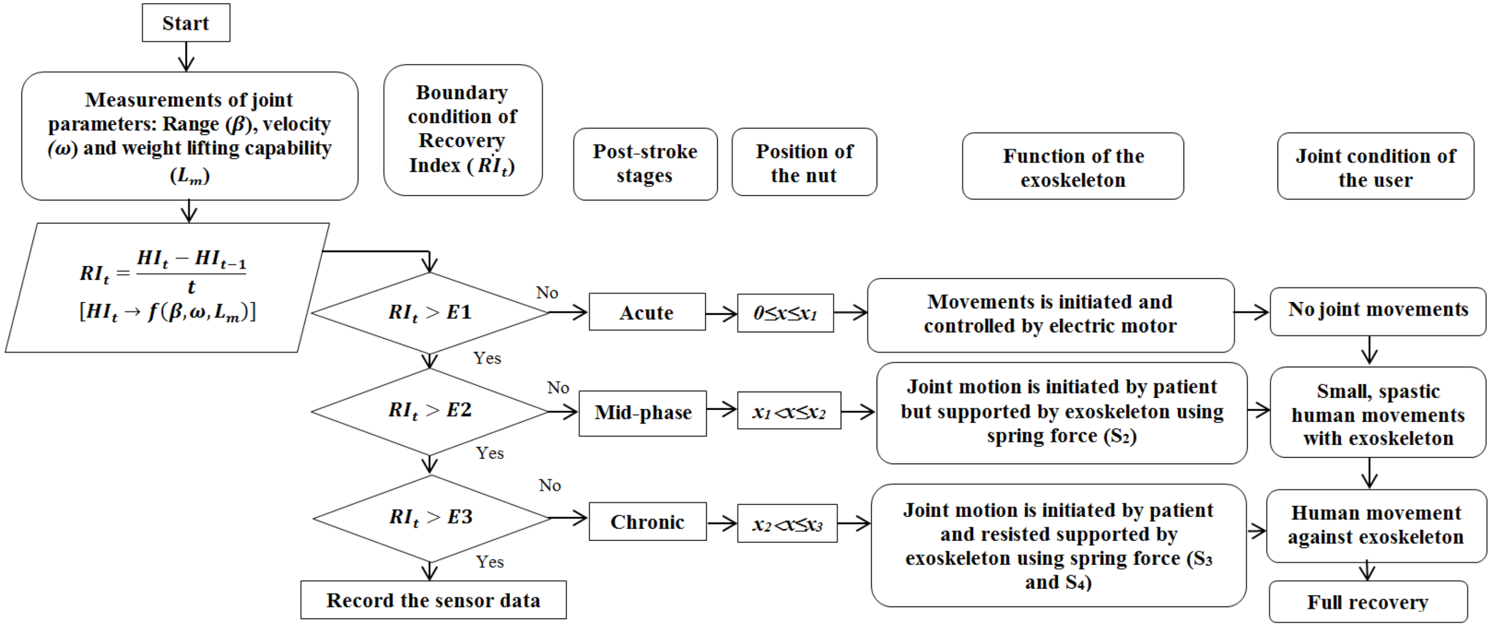


Figure 4.1. Switching of exercise modes based on recovery index

4.1 Motor controlled exercise in acute stage

Considering spasticity and joint stiffness, it is not suitable to provide a full range of motion to the affected joint at the starting phase. The range and velocity of the joint movement should be increased gradually. An oscillating motion generated by the motor by rotating it in clockwise and anticlockwise direction results in a reciprocating motion by the nut slider (x) on the leadscrew. As both leadscrew based sliders (nut slider and concentric slider) act as a single attachment in the first operating region, it controls flexion-extension of elbow joint (Figure 4.2).

If the number of rotations (n, θ) in the motor is increased, the rotation angle (β) of elbow will be simultaneously increased whilst maintaining the movement of the nut slider in the first region. On the other hand, different rpm of the motor will indirectly change the angular velocity of elbow. As the motion is based on leadscrew, the load is fixed in this mode of exercise.

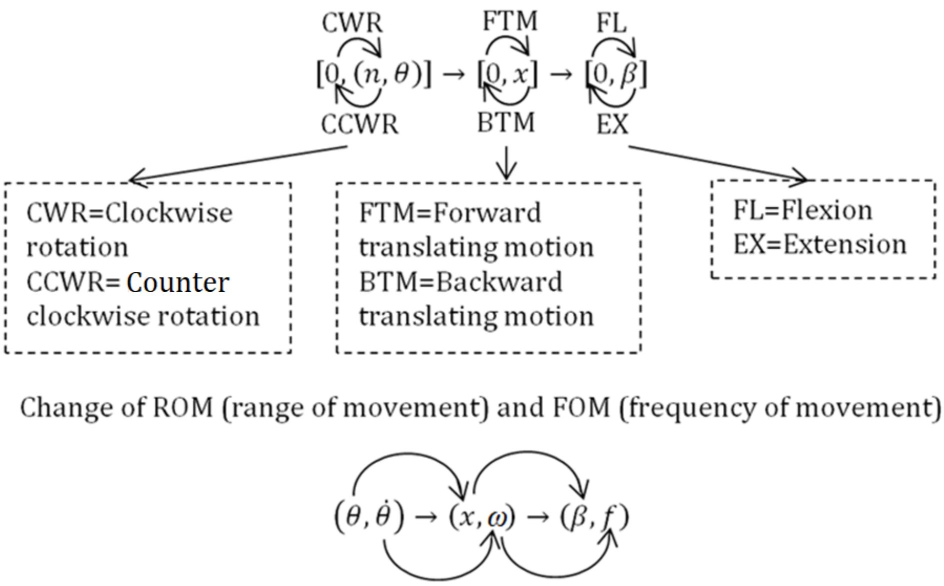


Figure 4.2. Flexion/extension of the elbow joint in motor-controlled exercise

Where n = number of turns in the motor, θ = motor angle, $\dot{\theta}$ = angular velocity of the motor, V = velocity of the nut slider, ω = angular velocity of the elbow movement, f = frequency of the movement.

In the first mode, the region covered by the electric motor ($0 \leq x \leq x_1$) is equivalent to the full range of motion by elbow joint. Continuous joint movement with different range and frequency in the acute stage may create a positive effect on patients to activate their joint and help them to initiate joint movement. However, both angular range and velocity should not be varied simultaneously. First users are habituated with joint movement up to full range using the exoskeleton, after that the same joint can be rotated with different velocity in an incremental manner. In this exercise mode, the number of repetitions (n1 and n2) for each stage as well as the incremental step size of rotation (θ_1) and angular velocity ($\dot{\theta}_2$) can be determined by physiotherapist to maintain a steady rehabilitation process (Figure 4.3).

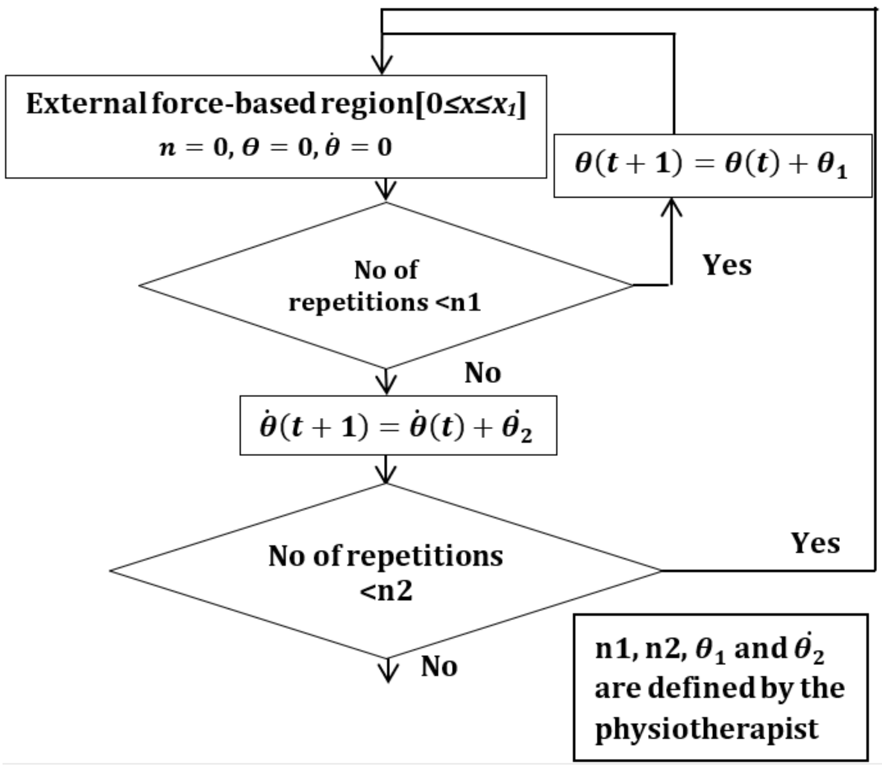


Figure 4.3. Joint parameters in motor controlled mode

4.2 Assistive mode for mid stage

Patient's effort is the most important factor in rehabilitation. The lock is opened at the starting of second operating region hence the nut slider and concentric slider are detached from each other. In the mid stage, users can rotate elbow joint themselves and the assistive force is provided by an extension spring (S_2) in this exoskeleton. The assistive force can be increased if the nut slider is pushed back to the end of this region.

The percentage of user's participation in exercise can be defined as the recovery rate of the user. Higher the percentage of participation better is the recovery rate

(Figure 4.4). Normally, the assistive spring force should be kept lower than the desired joint torque so that users endeavour to achieve it by giving more labour, thus they will practice gaining more strength at their joint. Based on the recovery status, the position of the nut slider should come forward to engage with less assistive force to encourage users to put more efforts. Theoretically, the position of the nut slider should be increased for giving more assistive force to users if they are unable to move their joints. However, this strategy is applicable at the beginning when users are initiating active joint movements, later the assistive force is decreased when users can move their joints easily, just to motivate them to put extra effort.

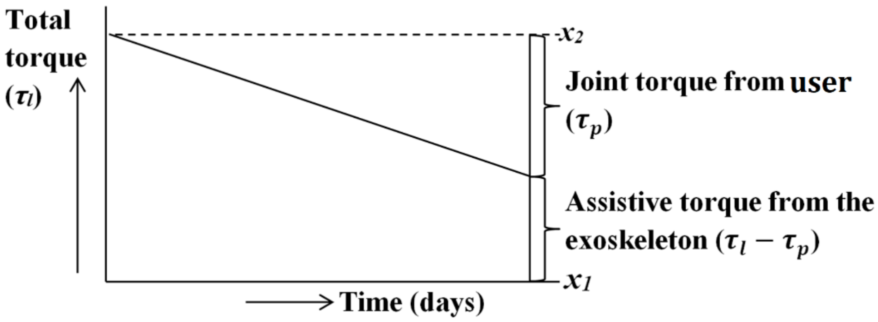


Figure 4.4. Proposed path of recovery with assistive force

We have proposed the Load sharing capacity of a user

$$P_l = \frac{\tau_p}{\tau_l} \times 100 \qquad 4.4$$

[τ_l = Total torque, τ_p = Joint torque from user]

During the assistive mode, the decrement of the distance travelled by the nut slider will be inversely proportional to the difference between the desired torque (τ_D) and the present joint torque provided by the user (τ_p) as shown in Figure 4.5.

$$\Delta x \propto \frac{1}{(\tau_D - \tau_p)} \qquad 4.5$$

Δx = Change of displacement in the nut slider

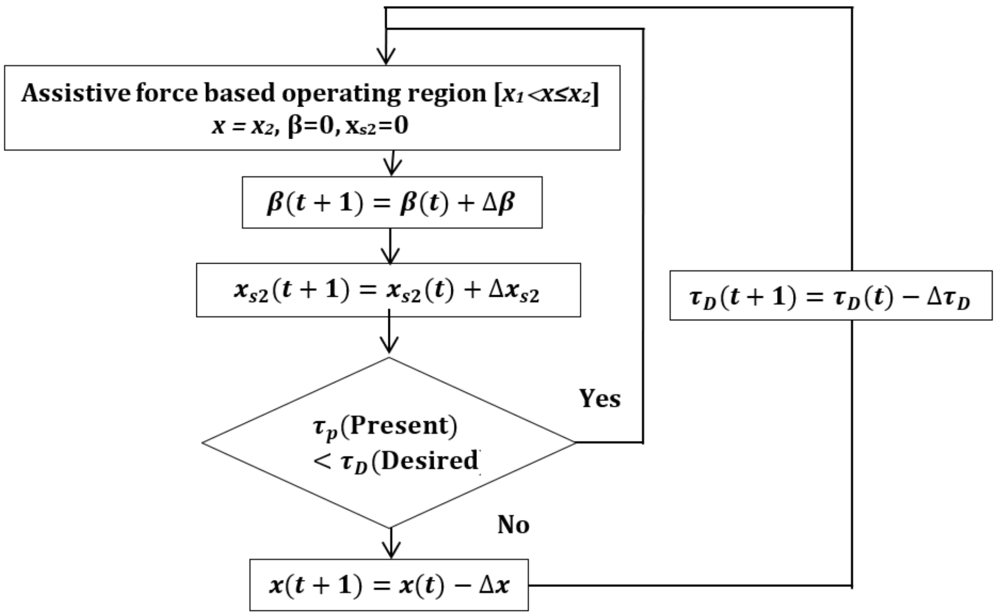


Figure 4.5. Parameters of assistive mode

4.3 Resistive mode for last stage

In the first two stages of active joint movements, no extra load is applied to the joint just to improve the muscle function so that users would be able to do their normal joint movement. In this mode, a variable resistive force is applied to elbow joint in terms of changing its joint stiffness. This mode of exercise is analogous to the exercise with variable load where the difficulty level in therapy is increased with time. As per the mechanism design, the joint stiffness is increased by moving the nut slider backward to the end of the third region.

The required joint torque of elbow increases with the joint stiffness.

Therefore, $\tau_l \propto K'$ 4.6

Where τ_l = Required joint torque to overcome the stiffness and K' = Joint stiffness

As the total amount of torque is carried out by user,

therefore $\tau_l = \tau_p$ 4.7

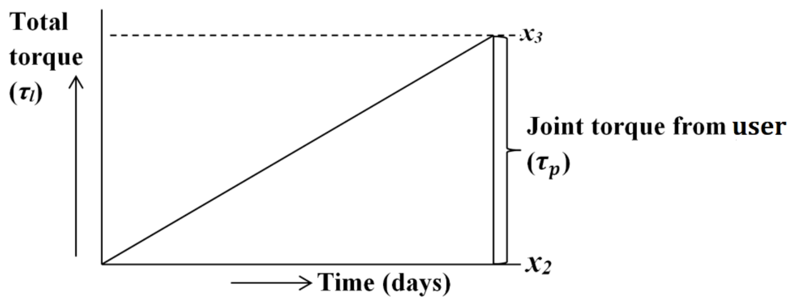


Figure 4.6. Proposed path of recovery with resistive force

In the second stage, the external assistive force is decreased with time if users are able to carry out joint movement, however, in this phase, the external resistive force is increased with time if users can rotate their joints with the existing stiffness (Figure 4.6). If users can overcome the resistive force by engaging with more joint torque, it shows the sign of recovery. In this mode of exercise, the increment of the distance (Δx) traveled by the nut slider is proportional to the difference between the desired torque (τ_D) and the present joint torque (τ_p) as shown in Figure 4.7.

Therefore $\Delta x \propto (\tau_D - \tau_p)$ 4.8

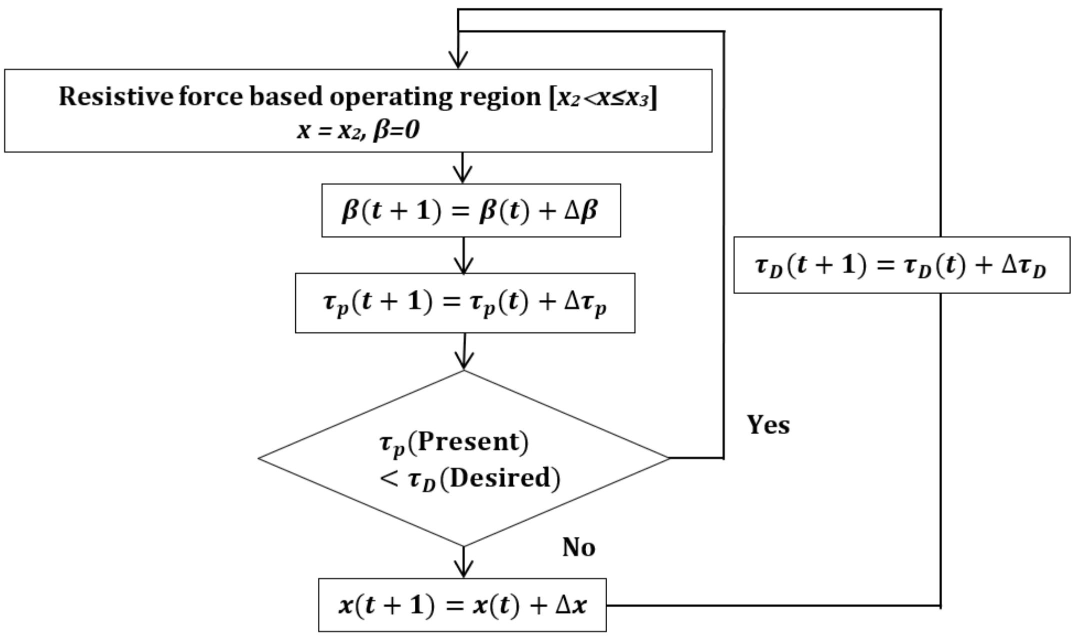


Figure 4.7. Parameters in resistive mode

4.4 Computation of elbow joint parameters

Mode of exercise in this exoskeleton is determined by three joint parameters: torque, angle and velocity.

4.4.1 Computation of joint torque

4.4.1.1 Joint torque in motor controlled mode

In the first region, the required motor torque to actuate elbow joint is equivalent to the torque needed to overcome the frictional force created between the leadscrew and the nut slider. Due to the slider-crank mechanism, the elbow joint is actuated by pulling the connecting link (Figure 4.8).

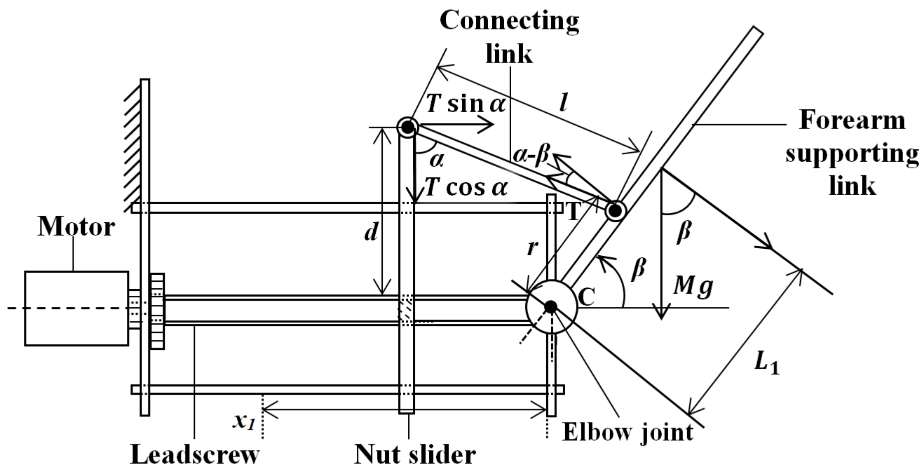


Figure 4.8. Slider crank mechanism during electric motor control

The required tension (T) for lifting up the mass of the forearm is given by

$$T' = \frac{MgL_1 \cos\beta}{r\cos(\alpha-\beta)} \qquad 4.9$$

Where, M = Mass of the forearm and the supporting link

L_1 = Distance from the elbow joint to the centre of gravity of forearm and the supporting link

β = Elbow joint angle

α = Angle made by the connecting link and nut slider

r = Length of the crank

g = Acceleration due to gravity

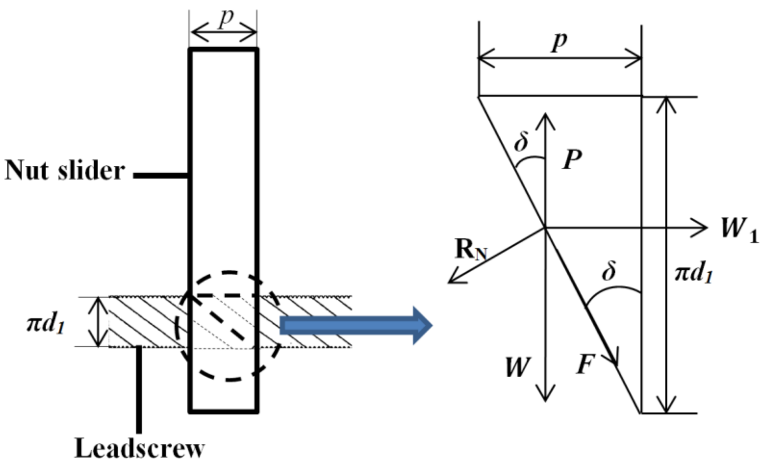


Figure 4.9. Frictional model of the leadscrew

From the frictional model of the leadscrew (Figure 4.9), it can be shown

$$\tan\delta = \frac{p}{\pi d_1} \qquad 4.10$$

Where p = Pitch of the leadscrew

πd_1 = circumference of the leadscrew

δ = Lead angle of the leadscrew

In Figure 4.9, P is the effort applied to the screw to lift the load. Taking the force equilibrium in the frictional model,

It shows, $P\cos\delta = W\cos\delta + W_1\sin\delta + F$ 4.11

Where $T\cos\alpha = W$ and $T\sin\alpha = W_1$ [taken from Figure 4.8]

Frictional force (F) during motion is

$F = \mu R_N = \mu(W\sin\delta - W_1\cos\delta - P\sin\delta)$ [μ=Coefficient of friction] 4.12

After substituting the value of F and μ = tan φ [φ = friction angle)] in Eq. (4.11), It has been derived

$$P = W + W_1\frac{(\sin\delta - \mu\cos\delta)}{(\cos\delta + \mu\sin\delta)} \qquad 4.13$$

Substituting μ = tan φ [φ = friction angle] in Eq. (4.13),

$$P = W + W_1\tan(\delta - \varphi) \qquad 4.14$$

After substituting the value of W and W_1, Torque (τ) required for overcoming the friction of leadscrew is

$$\tau = P \times \frac{d_1}{2} = \frac{T(\cos\alpha + \sin\alpha\tan(\delta - \varphi))d_1}{2} \qquad 4.15$$

Putting the value of T from Eq. (4.9), the final equation of required motor torque (τ) for the exoskeleton is

$$\tau = \frac{MgL_1\cos\beta\,(\cos\alpha + \sin\alpha\tan(\delta - \varphi))d_1}{2r\cos(\alpha - \beta)} \qquad 4.16$$

The relation between α and β can be derived from Eq. (4.29) where

$$\alpha = \cos^{-1}\left(\frac{d - r\sin\beta}{l}\right) \qquad 4.17$$

The mass of the forearm can be varied for different users. A range of the forearm mass (1 kg to 3 kg) has been considered and the required motor torque level has been evaluated as shown in Figure 4.10.

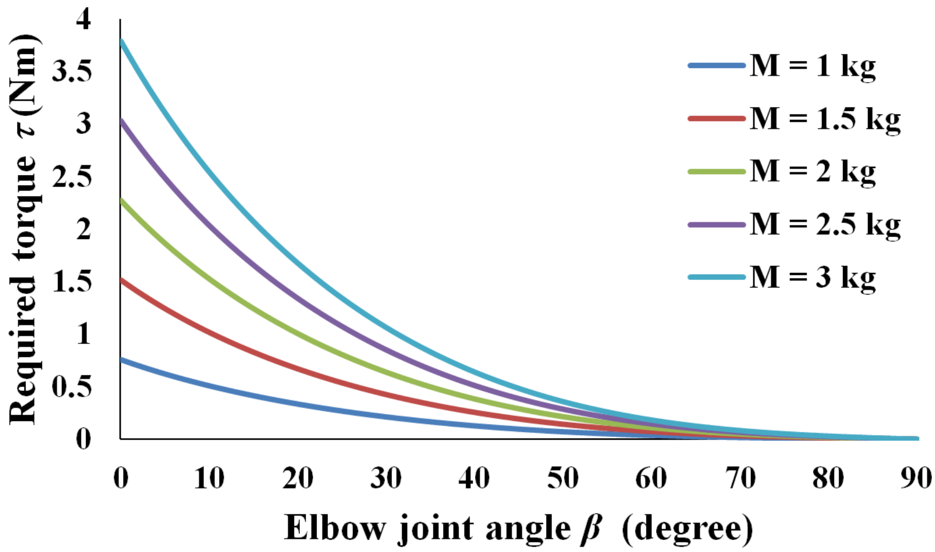


Figure 4.10. Motor torque for different forearm mass

If the motor is connected to elbow joint, the required motor torque (τ_j) is $\tau_j = MgL_1 \cos \beta$ 4.18

Figure 4.11 shows that the required motor torque of the exoskeleton is reduced almost two times compared to the joint based motor actuation for 1 kg of forearm mass. Therefore, the exoskeleton can provide joint torque up to 10 Nm due to the mechanical advantage as the motor torque is 5 Nm.

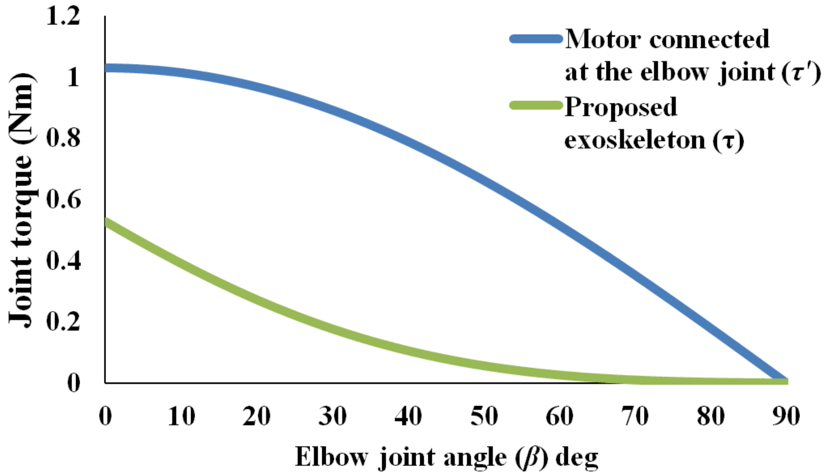


Figure 4.11. Comparison of the motor torque in two frameworks

In the next two modes (assistive and resistive), activities are performed by users hence the joint torque of users depends on their muscle strength. The value of the joint stiffness is almost constant for the first two modes (motor controlled and assistive) because the nut slider does not affect those two extension springs (S_3 and S_4) which are mainly responsible for changing the joint stiffness. However, in resistive mode, the joint stiffness is significantly changed because it increases the contact force around the elbow joint by stretching S_3 and S_4.

As shown in section 3.8, the joint stiffness is given by Eq. (3.10)

$$K' = \frac{2r_1\{(K_4 - K_3)x - (K_3 x'_{s3} - K_4 x'_{s4})\} - \dfrac{K_2 r(x_{s2} - x'_{s2})\cos(\alpha - \beta)}{\sin\alpha}}{\beta} + 2r_1^2(K_4 + K_3)$$

4.4.1.2 Joint torque in assistive mode

In this mode, the required joint torque is reduced by the spring force (S_2) which can be enhanced by moving the nut slider in this region ($x_1 < x \le x_2$) as shown in Figure 3.18.

As per the mechanism, $\Delta F_A = \Delta f_{s2}$ 4.19

Due to the spring force (f_{s2}), there is a reduction of joint torque which is given by

$$\Delta\tau = \frac{K_2 r(x_{s2} - x'_{s2})\cos(\alpha - \beta)}{\sin\alpha} \quad 4.20$$

In this mode, the nut slider moves between x_1 and x_2, therefore the maximum value of x_{s2} can also be varied simultaneously. As a result, the joint torque is reduced more due to higher spring force.

$$\Delta\tau = \text{maximum when } x = x_2$$
$$= \text{mimimum when } x = x_1$$

Taking the Eq. (3.10), the joint stiffness in assistive mode (K'_A) becomes

$$K'_A = \frac{A - rK_2(x_{s2} - x'_{s2})}{\beta} + B \quad 4.21$$

Where A and B are constant

$$A = 2r_1\{(K_4 - K_3)x - (K_4 x'_{s4} - K_3 x'_{s3})\} \quad 4.22$$

$$B = 2r_1^2(K_4 + K_3) \quad 4.23$$

The resultant joint torque of user in assistive mode (τ_A) is

$$= (MgL_1 \cos\beta) - \left(\frac{K_2 r(x_{s2} - x'_{s2})\cos(\alpha - \beta)}{\sin\alpha}\right) + K'_A\beta \quad 4.24$$

4.4.1.3 Joint torque in resistive mode

In resistive mode, the nut slider is in the third operating region ($x_2 < x \le x_3$) therefore, the value of assistive force is fixed and the displacement of both extension springs (S_3 and S_4) are changed.

Taking the Eq. (3.10), the joint stiffness (K'_R) in resistive mode becomes

$$K'_R = \frac{2r_1\{(K_4 - K_3)x - C\} - rK_2(x_{s2} - x'_{s2})}{\beta} + B \qquad 4.25$$

where C is constant

$$C = (K_3 x'_{s3} - K_4 x'_{s4}) \qquad 4.26$$

The resultant joint torque of user in resistive mode (τ_R) is

$$= (MgL_1 \cos\beta) - \left(\frac{K_2 r(x_{s2} - x'_{s2})\cos(\alpha - \beta)}{\sin\alpha}\right) + K'_R\beta \qquad 4.27$$

4.4.2 Computation of joint range and angular velocity

4.4.2.1 Motor controlled mode

In electric motor controlled mode, elbow joint's range and velocity are controlled by the rotation angle and speed of the motor. Both leadscrew based sliders (nut slider and concentric slider) are considered as a single slider as shown in Figure 4.12.

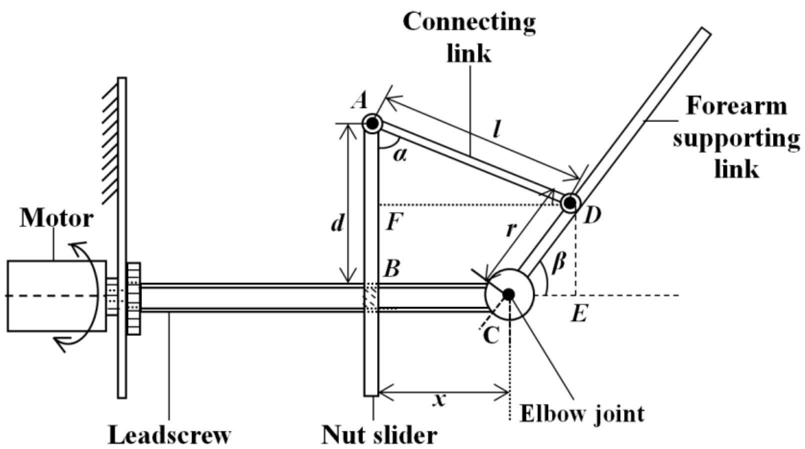


Figure 4.12. Joint angle computation in motor controlled mode

From Figure 4.12,

$\mathrm{BE} = \mathrm{BC} + \mathrm{CE}$,

$$l \sin\alpha = x + r\cos\beta \qquad 4.28$$

$\mathrm{AF} = \mathrm{AB} - \mathrm{FB}$

$$l\cos\alpha = d - r\sin\beta \qquad 4.29$$

Where x = Position of the nut slider and β = Elbow joint angle

Taking the square of both Eqs. (4.28) & (4.29) and adding them, it shows

$$l^2\sin^2\alpha + l^2\cos^2\alpha = (x + r\cos\beta)^2 + (d - r\sin\beta)^2$$

$$2dr\sin\beta = x^2 + 2xr\cos\beta + \sigma \qquad 4.30$$

Where $\sigma = r^2 + d^2 - l^2$ and the value of σ is constant since r, d and l are solid links

Squaring both the sides of Eq. (4.30), it has been derived

$$(x^2r^2 + d^2r^2)\cos^2\beta + (x^3r + xr\sigma)\cos\beta + \text{C} = 0 \quad \left[\text{Where C} = \frac{x^4+2x^2\sigma+\sigma^2-4d^2r^2}{4}\right]$$

The relation between β and x can be derived as

$$\beta = \cos^{-1}\left(\frac{-(x^3r + xr\sigma) \pm \sqrt{(x^3r + xr\sigma)^2 - 4(x^2r^2 + d^2r^2)\text{C}}}{2(x^2r^2 + d^2r^2)}\right) \qquad 4.31$$

The linear relationship between the displacement covered by the nut slider (x) and motor rotation (n, θ) is shown as Eq. (3.1) as $x = \theta e$ where $e = \frac{nL}{2\pi N}$

Substituting the value of x, σ and C in Eq. (4.31), it shows

$$\beta = \cos^{-1}\left(\frac{-(\theta^3e^3r + \theta erc) \pm \sqrt{\begin{matrix}(\theta^3e^3r + \theta erc)^2 - (\theta^2e^2r^2 + d^2r^2)\\(\theta^4e^4 + 2\theta^2e^2c + c^2 - 4d^2r^2)\end{matrix}}}{2(\theta^2e^2r^2 + d^2r^2)}\right) \qquad 4.32$$

As shown in Figure 4.14, the Cartesian coordinates of the distal end of forearm supporting link are derived as G (X, Y, Z) = ($L\cos\beta/\cos\gamma$, $L\cos\beta\tan\gamma$, $L\sin\beta$) where $\beta = f(n,\theta)$ and γ is the rotation in the transverse plane. Lateral movement of the exoskeleton has been improved due to the universal joint (Figure 4.14); the normal revolute joint can only provide a fixed planner rotation but universal joint reduces that constraint by allowing a slight lateral movement across the sagittal plane. The joint flexibility is zero at 90° due to singularity.

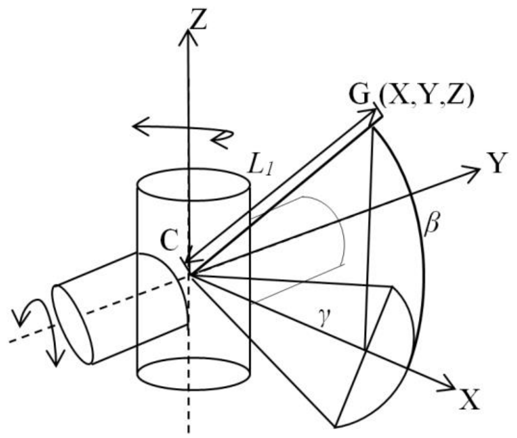


Figure 4.13. Cartesian coordinates of the distal end of forearm

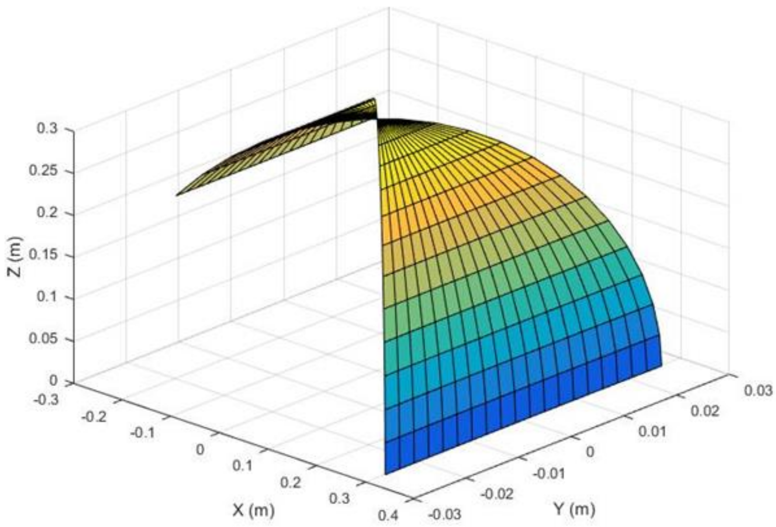
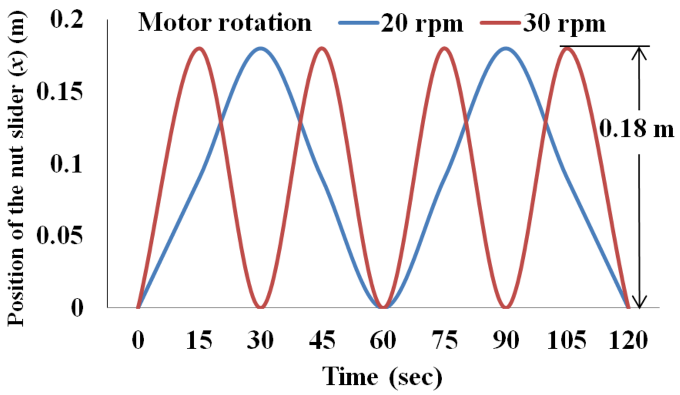
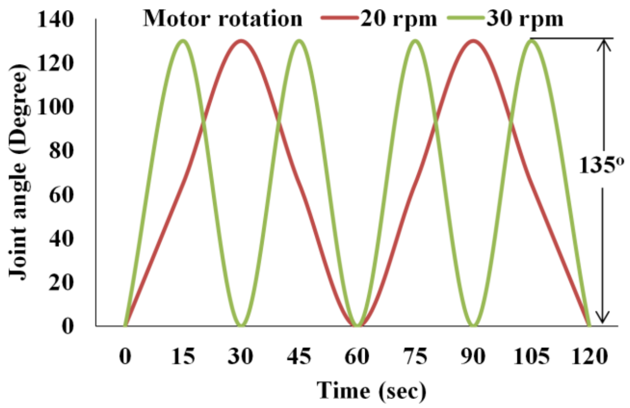


Figure 4.14. Workspace covered by the elbow joint

In this mechanism, the required number of motor rotations is 15 (clockwise & anticlockwise) in the first region for translating the nut slider in the range of 0 to 0.18 m which can generate a rotation angle of 135^0 (flexion & extension) at elbow joint, shown in Figure 4.15 for different rpm of the motor.



a. Position of the nut slider for different rpm of the motor



b. Variation of the elbow angle for different rpm of the motor

Figure 4.15. Elbow joint motion in motor controlled mode

Therefore, the angular velocity of elbow in this mode is

$$\dot{\theta} \rightarrow f(\dot{\beta}) \tag{4.33}$$

4.4.2.2 Assistive mode

The unlocking condition allows the concentric slider to move freely on the leadscrew in this region. As the concentric slider is connected to the elbow joint using the connecting link, therefore the position of the concentric slider (x_{s2}) varies as per elbow joint angle (β) which is given by Eq. (4.34).

$$\beta = cos^{-1}\left(\frac{-({x_{s2}}^3 r + x_{s2} r\sigma) \pm \sqrt{({x_{s2}}^3 r + x_{s2} r\sigma)^2 - 4({x_{s2}}^2 r^2 + d^2 r^2)C}}{2({x_{s2}}^2 r^2 + d^2 r^2)}\right) \tag{4.34}$$

Therefore angular joint velocity in assistive mode (ω_A) becomes

$$\omega_A = \frac{P_U}{\tau_A} = \dot{\beta}_A \tag{4.35}$$

The value of P_U is depending on the user's effort

And τ_A is derived from Eq. 4.24

Angular joint velocity of user is increased in flexion because the required joint torque is reduced due to the addition of higher assistive force to the user's effort. The same assistive force opposes the joint freefall during extension. Therefore, angular joint velocity is decreased during extension.

4.4.2.3 Resistive mode

In resistive mode, more resistive force increases the required joint torque in both flexion and extension hence angular joint velocity is decreased.

Therefore angular joint velocity (ω_R) becomes

$$\omega_R = \frac{P_U}{\tau_R} = \dot{\beta}_R \tag{4.36}$$

τ_R is derived from Eq. 4.27

4.5 Computation of forearm motion

4.5.1 Motor controlled mode

In motor controlled mode, the angle made by the half circular gear (Figure 4.16) is given by

$$\theta = \frac{N_1 \times \text{Rotation angle made by motor}}{N_2} \tag{4.37}$$

$N_1:N_2$ = Gear ratio between small gear and half circular gear

4.5.2 User controlled mode

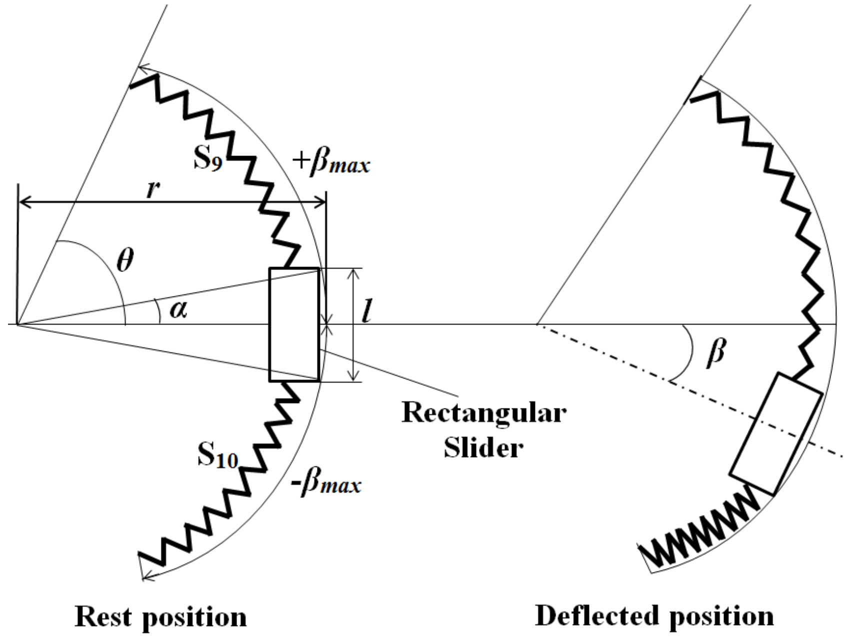


Figure 4.16. Spring arrangement of the arm holder

As shown in Figure 4.16,

$$\alpha = \tan^{-1}\frac{l}{2r} \qquad 4.38$$

l = Length of the rectangular slider

r = Radius of the second circular channel in half-circular gear

The free length of both compression springs (S_9 and S_{10}) is the same as the arc covered by angle $2\beta_{max}$ where β_{max} is the maximum angle of the half-circular gear on each side. Therefore in rest condition, both springs are compressed by an angle $(\beta_{max} + \alpha)$.

When user twists the rectangular slider by an angle β, the force provided by S_9,

$$f_{s9} = K_9\frac{2\pi r}{360}(\beta_{max} - \beta + \alpha) \qquad 4.39$$

Force provided by S_{10},

$$f_{s10} = K_{10}\frac{2\pi r}{360}(\beta_{max} + \beta + \alpha) \qquad 4.40$$

The required joint torque of a user to move the specific angle (β) in the clockwise direction is given by

$$\tau = r(f_{s10} - f_{s9}) = K_9 \frac{\pi r^2 \beta}{90} \qquad 4.41$$

To cover 110°, there should be a space where user can reach up to 55° in clockwise and anticlockwise rotation from the rest position.

Therefore, the length of the half circular ring is

$$\frac{4\pi r \beta_{max}}{360} = \frac{4 \times 3.14 \times 0.04 \times 110}{360} = 0.141 \text{ m}$$

In normal condition, the equal and opposite force from S_9 and S_{10} balance each other to keep the forearm in stable condition. The stiffness of S_9 and S_{10} used in this mechanism is 200 N/m. As it is a twisting movement, there will be no impact of forearm mass on the spring. In user-initiated joint movement, user requires the same but opposite torque as per clockwise or anticlockwise rotation (Figure 4.17).

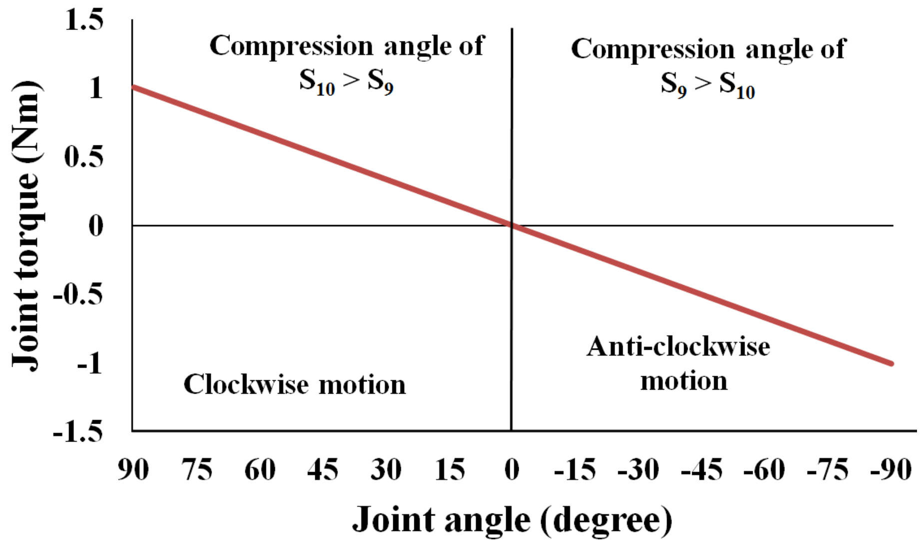


Figure 4.17. Required torque of a user in twisting forearm motion

4.6 Electronic circuit for monitoring joint parameters

All components are interfaced with Arduino Uno board (Operating voltage: 5 V, RAM: 2 KB, Clock Speed: 16 MHz) for collecting the joint parameters and controlling exercise (Figure 4.18). A DC motor (Model: ZYTD520, mass: 0.210 kg, Power: 5W) is used for moving the nut slider on the leadscrew. The motor is operated at 12V and it can provide maximum torque up to 5 Nm. Arduino Uno board consists of ATmega328P microcontroller for data processing. A 4 KΩ potentiometer is used for measuring the elbow joint angle (β) in terms of change in resistance. The cost of making the controlling circuit is minimized by computing a lot of joint parameters indirectly from the outcome of one sensor instead of using another physical sensor (Manna and Dubey 2019b). The joint angular velocity (ω) can be calculated based on the differentiation of joint angle (β) with reference to the timeframe. Joint frequency of elbow is evaluated from the relation between joint velocity and frequency (shown in Figure 4.17). A current sensor module (GY-471) is used to measure the motor current during rotation. It has a MAX471 current amplifier which can measure current up to ±3 A. The output of the current sensor is 1 V/A. The position of the concentric slider (x_{s2}) is measured from the relationship between β and x_{s2} (Eq. (4.34)). A reflective optical sensor (Model: GP2Y0A41SK0F, (Operating voltage: 5 V, mass: 0.003 kg)) is used to measure the position of the nut slider (x). There are other non-contact types of displacement sensors such as inductive, proximity or ultrasonic, however, considering the cost and linearity, the optical sensor is selected. The range of the optical sensor is 4 to 30 mm. The joint torque is evaluated from other parameters such as from computed joint torque, assistive torque and joint stiffness. All these joint parameters depend on the position of the nut slider (x), concentric slider (x_{s2}) and measured joint angle (β), as shown in Eqs. (4.24) and (4.27). All sensors' output pins are connected to the analogue inputs of the Arduino board from pin A0 to A1. The DC motor is connected to Arduino using an Arduino compatible motor driver (Model: DFR0225: V2, Operating voltage: 12 V, mass: 0.080 kg). It consists of an L298 to enhance the current level for driving the motor. The maximum speed of the DC motor is 50 rpm, however, due to the facility of PWM signal, the speed of the motor can be controlled. The microcontroller transfers the sensor data to a PC based system to monitor the joint parameters using a developed GUI. If those joint parameters cross a particular limit set for a recovery mode (*EI*, *E2* and *E3*), the microcontroller sends a command to the motor to change the position of nut slider for changing the exercise mode. Detailed technical specifications of all electronic components used in the exoskeleton are shown in Appendix III.

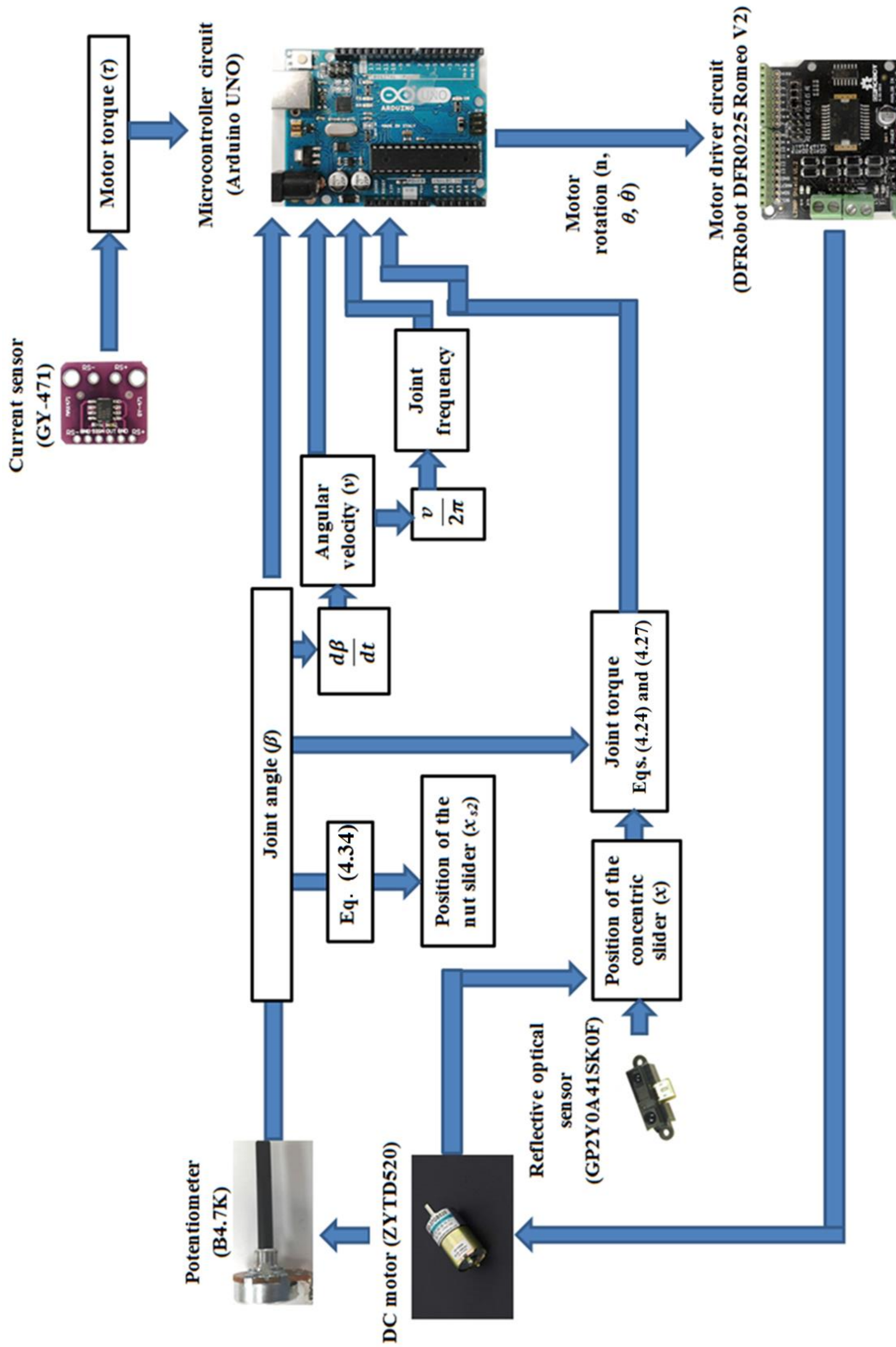


Figure 4.18. Components of the electronic circuit for operating the exoskeleton

4.7 Graphical user interface for operating different rehabilitation modes

A user-friendly graphical user interface (GUI) is designed in MATLAB platform for communicating between the controller board (Arduino) and the exoskeleton. Arduino board constantly collects all sensors data and transmitted to the PC through serial communication (Figure 4.19). Users can visualize the real time sensor value using the developed GUI (Figure 4.20). The GUI has been made simpler by connecting the available serial port to Arduino and fix the Baudrate to a specific value (9600 baud). 9600 Baudrate is used as the standard data transfer rate between microcontroller and PC in order to avoid any data loss. Arduino reads the equivalent voltage of those sensors through its inbuilt Analog to digital converter. These sensor values are calibrated from their datasheet in relation to the voltage output. It comprises two control modes; sensor-based control and manual control. Selection of one option will deactivate the other option.

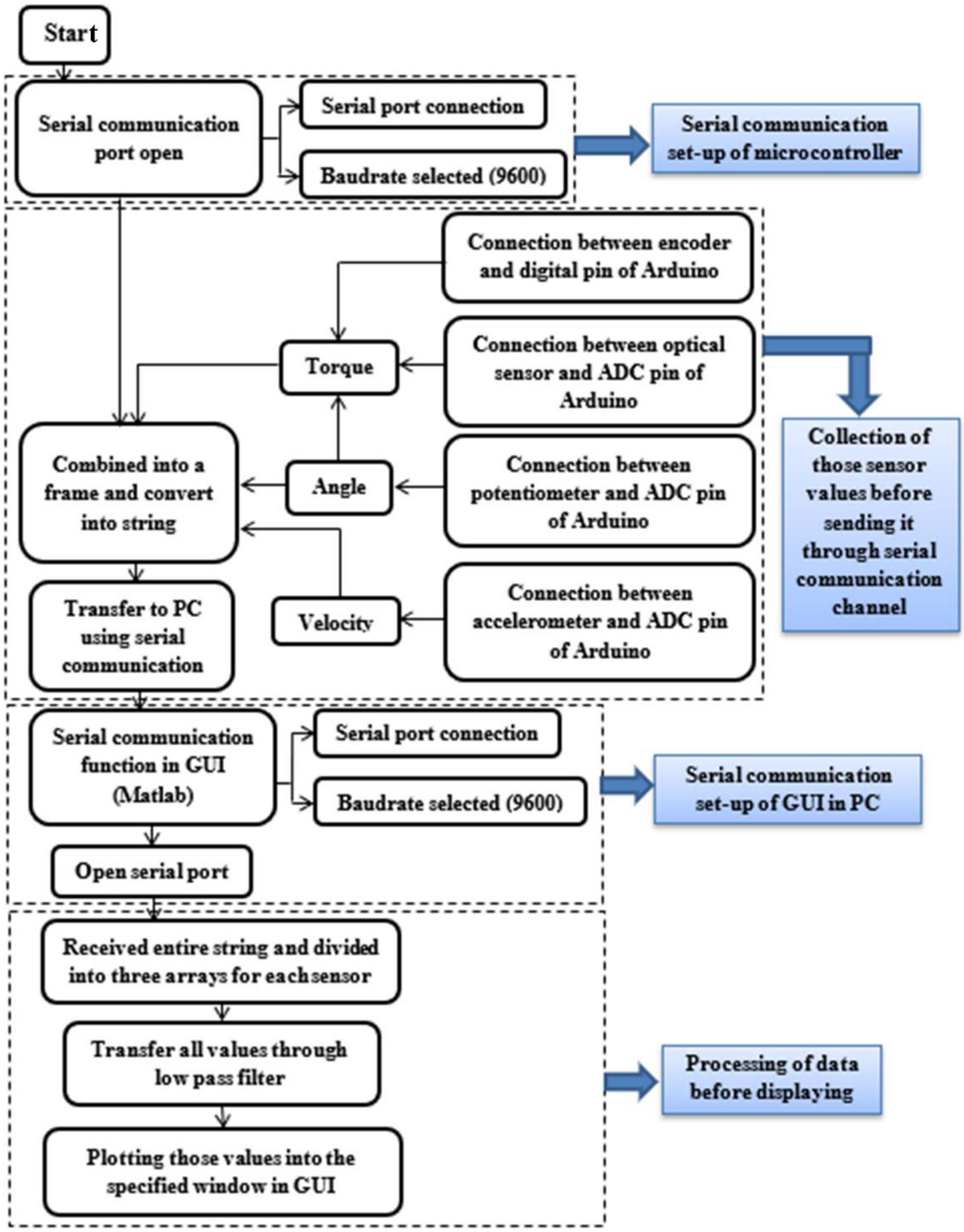


Figure 4.19. Steps for collecting sensor data using serial commutation

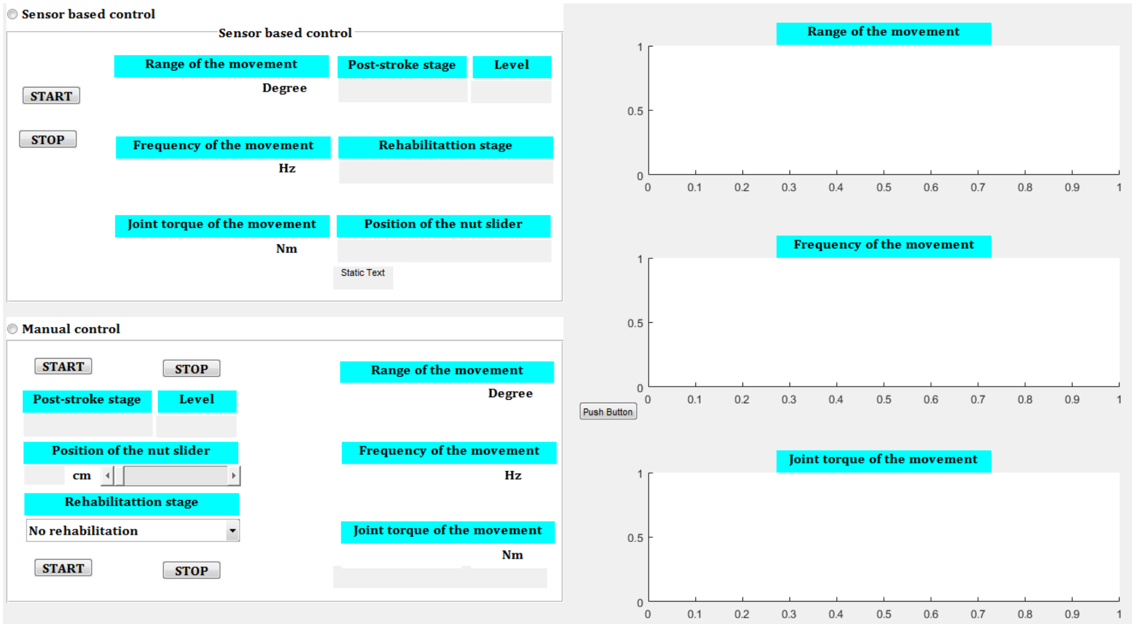


Figure 4.20. Developed graphical user interface

4.7.1 Sensor based control

In sensor based control (Figure 4.21), exercises are automatically executed to users as soon as users select the sensor based control on the GUI and the control is taken over by Arduino where the mode of exercise is controlled by the microcontroller. As discussed before, those specific joint values of boundary condition are stored into the controller, it changes the number of motor rotations to place the nut slider in a position providing specific exercise mode.

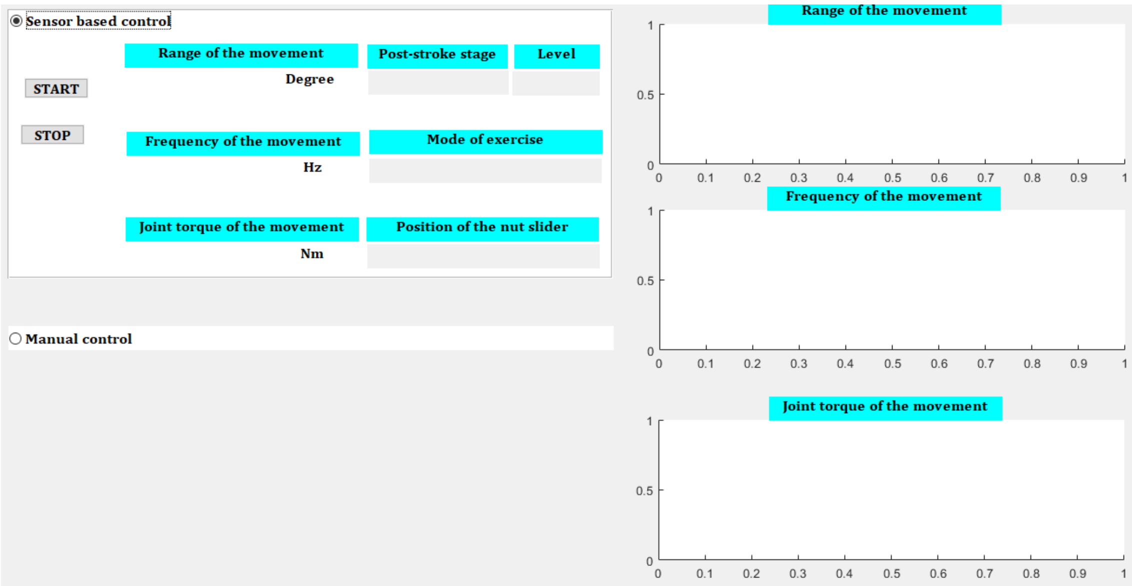


Figure 4.21. Window for sensor based control

4.7.2 Manual control

In manual mode, users can select a particular exercise manually. The manual mode can be performed in two ways. In first option, any of the three exercises modes can be selected from a popup menu and in other option, the position of the nut slider can be changed to select a specific joint movement (Figure 4.22). In electric motor controlled manual mode, users can generate three types of joint motion using GUI.

- **Orthopaedic lessons:** There are some specific joint movements which are recommended by the physiotherapist. Those joint movements are programmed in memory. Those movements are updated with time.
- **Isolateral exercises:** Isolateral exercises are the standard motions of any human joint. In this exoskeleton, elbow flexion-extension and pronation-supination are performed with variable angle and speed.
- **Activity of daily living:** In this configuration, the elbow joint actuates to do some household activities to improve the joint control.

In manual controlled assistive and resistive modes, users are allowed to move their joint with a variable assistive or resistive force. Therefore no command will be sent to the controller to deliver any movement. Joint parameters are monitored and recorded during movements.

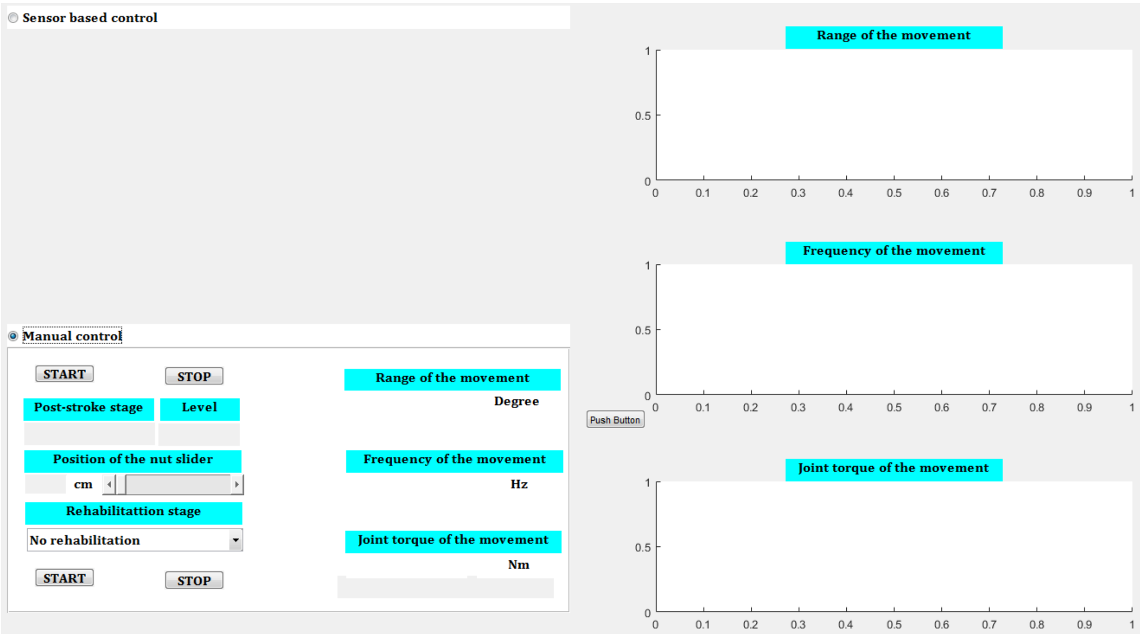


Figure 4.22. Window for Manual control

Flowchart of the working principle of GUI providing sensor based control and manual control is shown in Figure 4.23.

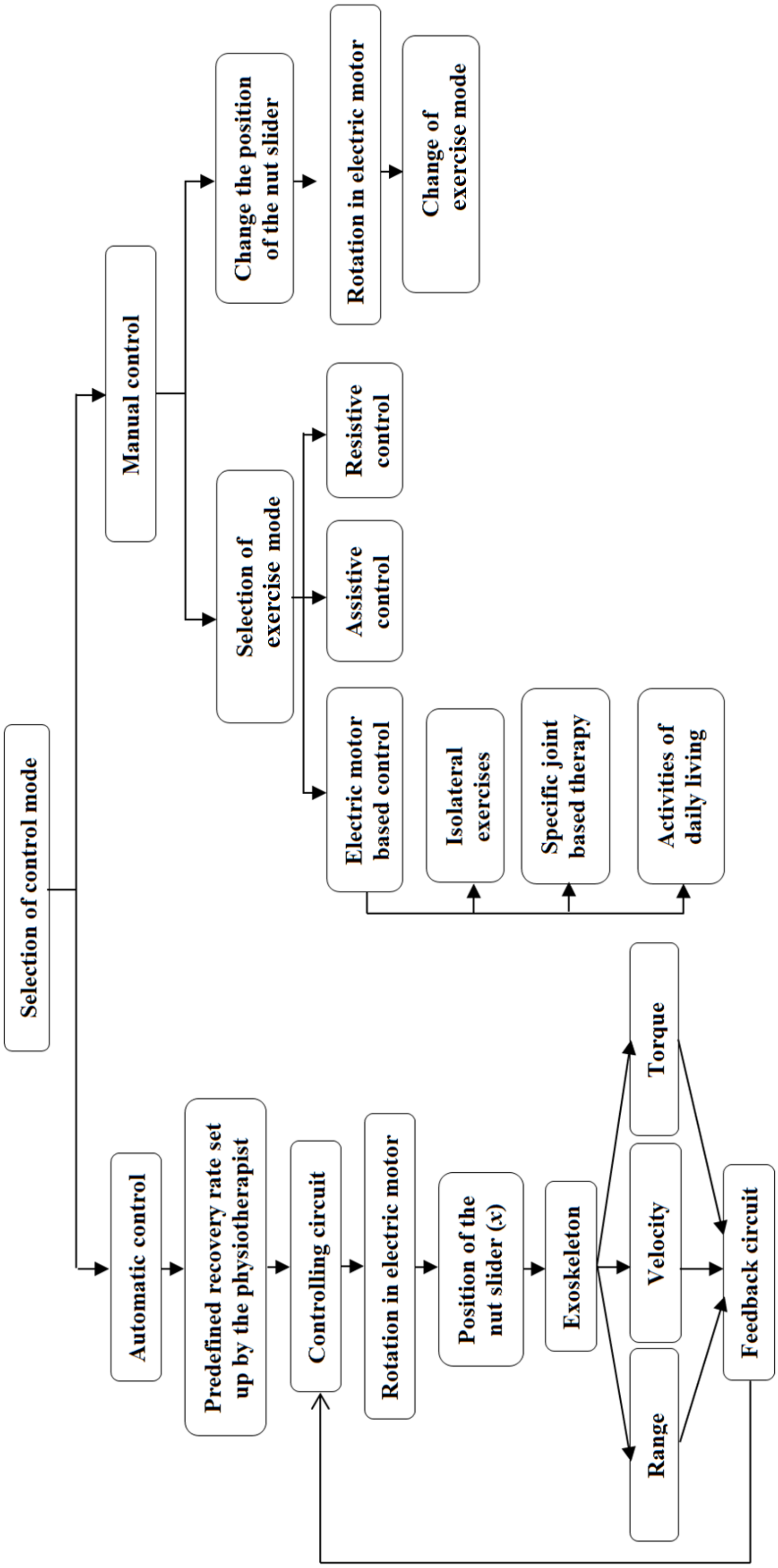


Figure 4.23. Function of the graphical user interface

4.8 Mode of exercise based on joint parameters

In this exoskeleton, the variation of the position of nut slider changes the joint angle in the first region, adjusts the amount of assistive force in the second region and the level of resistive force in the third region. The exoskeleton has been tested with a healthy subject (participant #5) of approximately 1 kg of forearm mass to evaluate the operational validity of the design. After wearing the exoskeleton, the user rotates the elbow joint in three different modes using normal strength. The joint angle is measured from the potentiometer, angular joint velocity and torque are derived from the mathematical model shown in Eq. (4.24) and Eq. (4.25). The main aim of the experiment is to analyse the working principle of the exoskeleton, whether the device can facilitate three types of exercise.

- In the electric motor-controlled mode, electric motor provides the required torque to move the user's right elbow.
- In assistive mode, the user used his normal strength to rotate the elbow joint (same effort for different positions of the nut slider).
- In resistive mode, the user used his normal strength to rotate the elbow joint (same effort for different positions of the nut slider).

The starting position is the rest position where elbow is in full extended state (making an angle of 180° between upperarm and forearm). In the final position, elbow rotates up to its maximum limit identical to full flexion state where the angle between upper arm and forearm is 45° as shown in Figure 4.24.

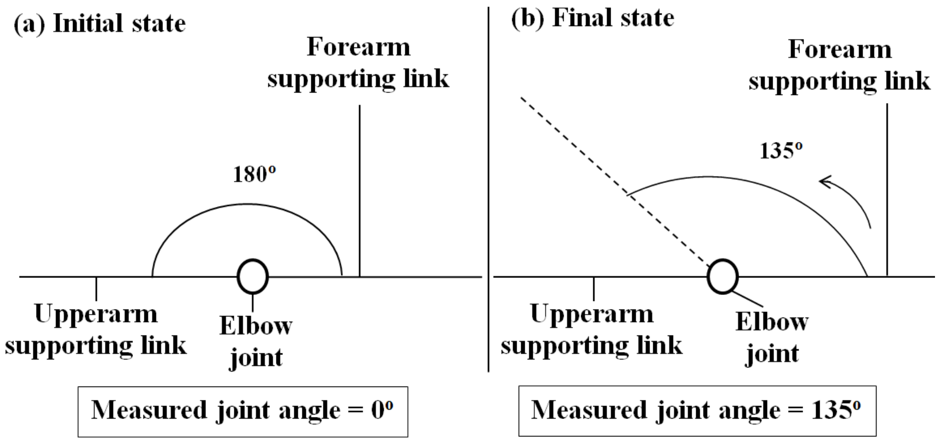


Figure 4.24. Measurement of elbow joint rotation

In all modes, the maximum range of elbow joint angle is the same because the subject can move to full anatomical limit whether actuated by the motor or by itself. The motor torque (derived from the frictional model of the leadscrew as per Eq. (4.16)) and the reading of the current sensor are following the similar pattern as shown in Figure 4.25. Ideally, the current sensor reading should be zero when the joint angle is 90° but the motor needs a minimum current for functioning and maintaining the joint at 90°. The output of the current sensor is measured in terms of voltage appeared across the output resistance.

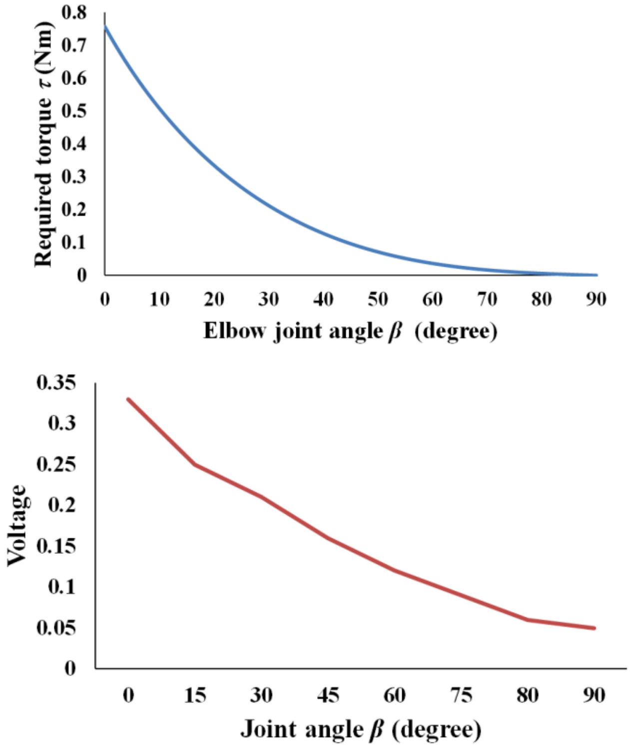
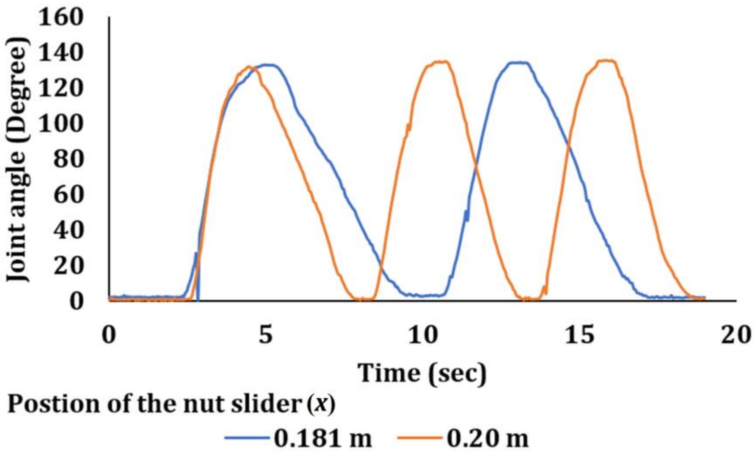
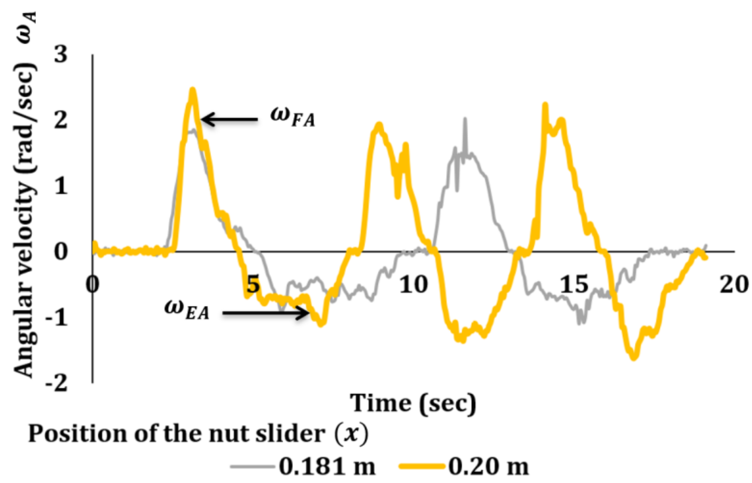


Figure 4.25. Motor torque and the voltage output of the current sensor

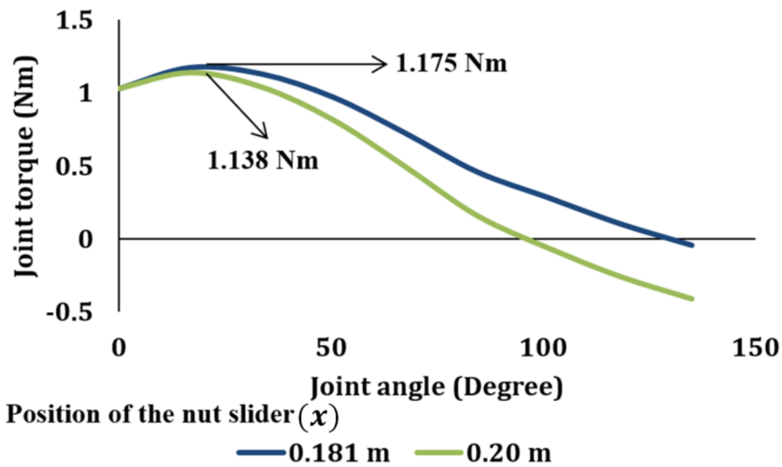
Figure 4.26a shows the joint angle made by the user for variable assistive spring force at the starting position (0.181 m) and ending position (0.20 m) of nut-slider position in assistive force-based region. It clearly shows that time required for completing a full cycle of joint movement (flexion and extension) is decreased due to the addition of more assistive force along with the linear movement of the nut slider. Figure 4.26b shows the variation of joint velocity in the assistive region (Eq. (4.34)). Depending on the measurement of joint angle from the potentiometer, joint angular velocity is calculated by differentiating the joint angle. It has been found that the maximum joint velocity of flexion (ω_{FA}) is higher than extension (ω_{EA}) in assistive mode because the spring force helps the subject to reach quicker (Figure 4.26b). In this mode, the user's effort can be reduced by the spring force (Eq. (4.24)), therefore the required joint torque for moving the joint is also reduced. In assistive mode, shifting of the nut slider from 0.181 m to 0.20 m produces more assistive force, therefore, joint velocity is increased and the maximum joint torque of the healthy subject is decreased from 1.175 Nm to 1.138 Nm (torque variation 0.037 Nm) (Figure 4.26c).



a. Variation of joint angle at different nut slider position



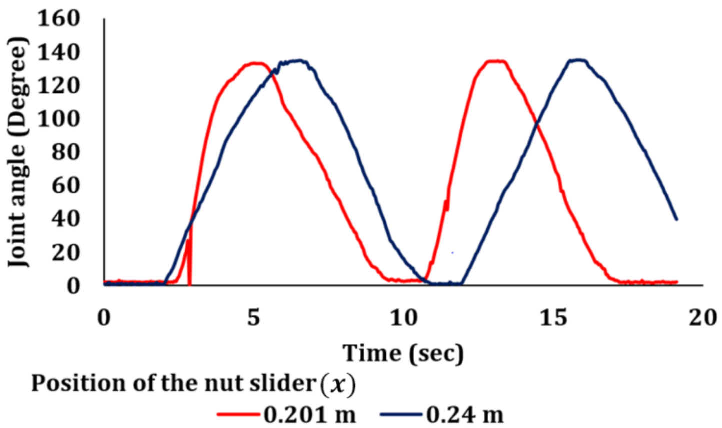
b. Variation of joint velocity at different nut slider position



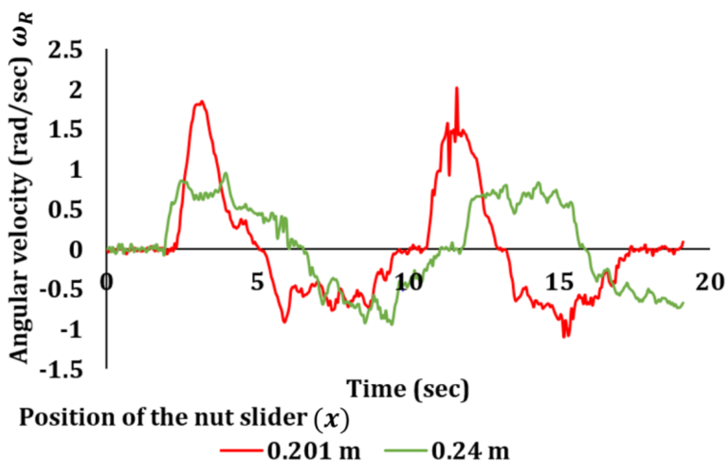
c. Reduction of joint torque (τ_l) in assistive mode of rehabilitation

Figure 4.26. Joint parameters of the exoskeleton in assistive mode

Figure 4.27a shows the variable joint angle for variable resistive force by the user at the starting position (0.201 m) and ending position (0.24 m) of nut-slider position in resistive force-based region. Because of adding more resistive force due to linear movement of the nut slider, the joint stiffness is increased, therefore, the time period of joint movement (flexion and extension) is also increased. The angular joint velocity is computed in the same way by differentiating the measured joint angle. Movement of the nut slider from 0.201 m to 0.24 m increases resistive force which reduces the angular joint velocity ((Eq. (4.35))) and increases the required joint torque ((Eq. (4.25))). Figure 4.27b shows the increment of angular joint velocity (ω_R) and Figure 4.27c shows that the maximum value of joint torque is increased from 1.175 Nm to 1.232 Nm (torque variation 0.057 Nm) due to the addition of more resistive force. At the beginning of resistive mode (x = 0.201 m), the extension spring (S_2) returns to its previous condition hence the joint torque of the user is same as the starting period of assistive mode (x = 0.181 m).

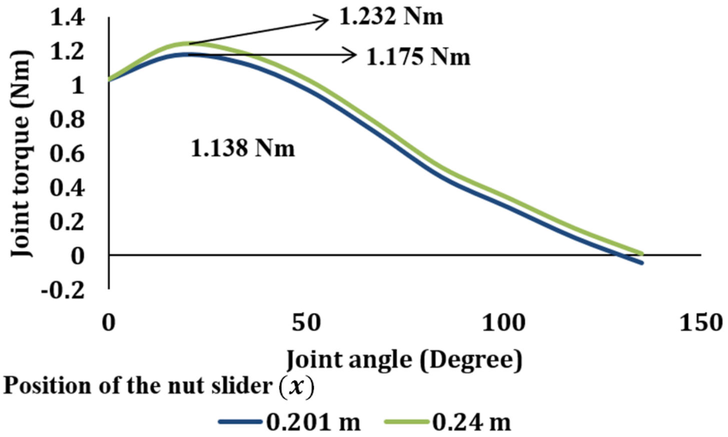


a. Variation of joint angle at different nut slider position



b. Variation of joint velocity at different nut slider position

Joint parameters of the exoskeleton in resistive mode



c. Enhancement of required joint torque (τ_l) at different nut slider position

Figure 4.27. Joint parameters of the exoskeleton in resistive mode

The joint torque of individual user can be varied, so is the range and velocity because these joint parameters depend on their individual effort. In this exoskeleton, the switching of exercise modes is decided as per some predefined joint values. Joint velocity of the movement can be measured in terms of joint frequency (a full clockwise and anticlockwise rotation). Figure 4.28 shows the region-wise variation of joint parameters and switching condition (Manna and Dubey 2019b). Due to the reciprocating linear displacement of the nut slider between 0 and 0.18 m, the rotation of elbow joint is controlled by the fixed value of motor speed which can be changed based on the requirement. This part of the region can be used for the post-stroke patients enduring in their early stage where their strength is too low to start the joint movement. Consequently, the exoskeleton needs full hold on user's joint movement. The switching region between motor controlled and assistive mode is sufficiently small (approximately 0.001m) without interrupting the operation of the exoskeleton. In this region, the control of joint movement is transferred from motor to user. The user can start the joint movement in assistive mode with their normal strength. That's why the middle region is configured to provide support to users. In the beginning, minimum assistive force is involved with the user's joint movement when the nut slider is positioned at 0.181 m. As it moves back up to 0.20 m, the assistive force increases, and joint torque of the user is gradually decreased (from 1.175 Nm to 1.138 Nm). In this exoskeleton, the boundary condition of the starting and ending phase of the assistive region is configured as per the joint frequency level of 1-2

Hz. In normal condition, the user can move its joint at 1 Hz which can be improved with time. User will be promoted to the last mode of exercise (resistive mode) if they are able to cross the frequency limit of 2 Hz. As discussed in the design section, the last region is used to enable the user to do joint movements with enhanced joint stiffness which may be needed in the last stage of recovery. The switching region between assistive and resistive mode is also approximately 0.001 m. As the nut slider translates backwards in this region from 0.201 m to 0.24 m, the required joint torque increases from 1.175 Nm to 1.232 Nm however the joint frequency decreases due to more resistive force. The switching value of joint torque is decided as per the forearm mass of the user and the springs used in the exoskeleton.

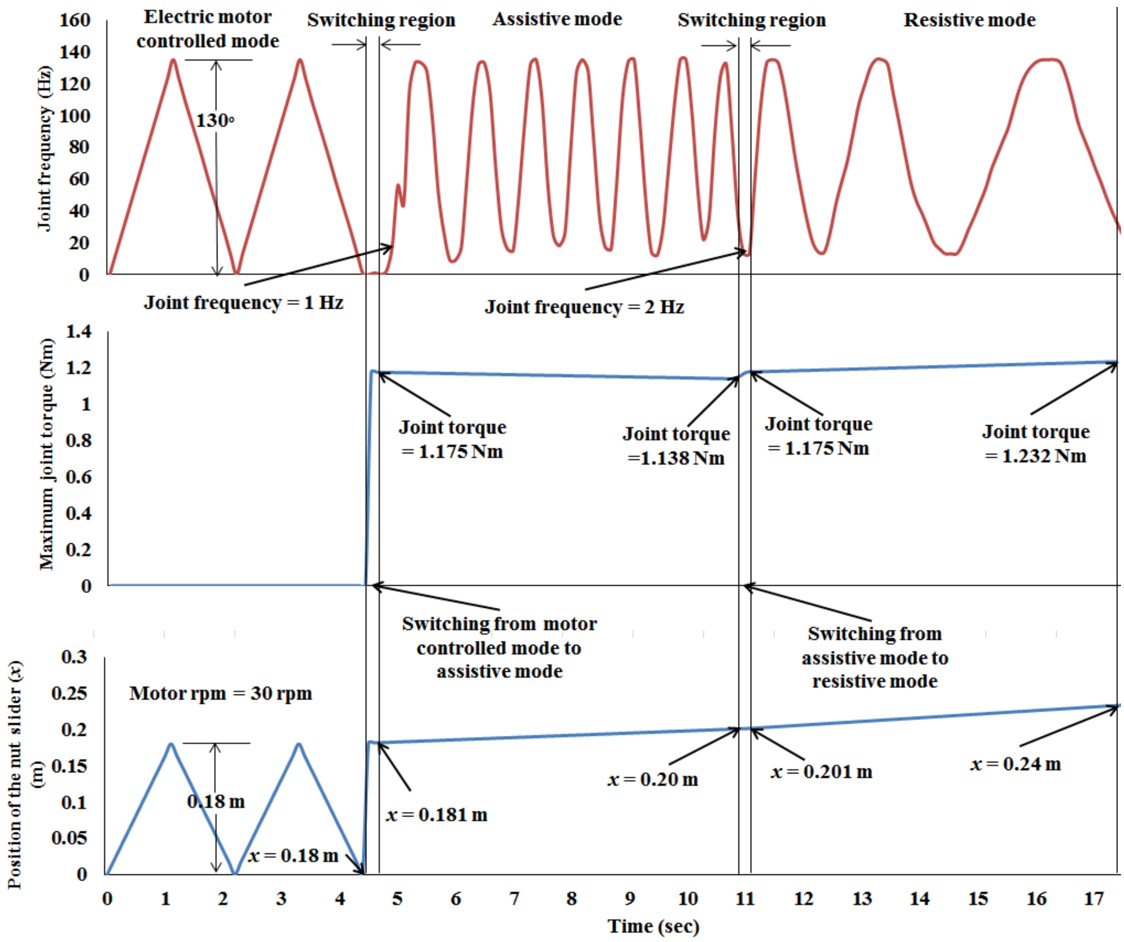


Figure 4.28. Switching of exercise modes for different joint parameters

4.9 Concluding remarks

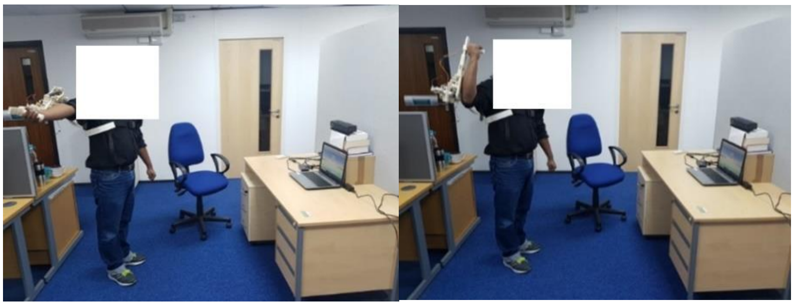
The sensor model for measuring and controlling the joint parameters of the exoskeleton is developed. After analysing the results, it is shown that the joint movement related to three stages of rehabilitation are feasible with the developed exoskeleton. The mechanical requirements related to actuation system of the exoskeleton are different depending on the situation whether the exoskeleton provides the exercise or user itself controls rehabilitation. In motor controlled mode, the joint angle and speed of the joint movement can be increased with time by changing the parameter of motor rotation. The mechanism of the exoskeleton can change the amount of assistive and resistive force as per the user's need. However, all these modes of exercises can be controlled by changing the region of operation. The aim of assistive and resistive rehabilitation is to improve the joint effort either by decreasing the assistive force or increasing the resistive force over time. The switching of rehabilitation mode is automatically happened due to the stiffness property of few springs in the exoskeleton. It is also possible to change the rehabilitation mode by just changing the position of the nut slider unlike torque control of the joint based motor; therefore, the device is mechanically tuneable to users need. The developed prototype is functional and the size and weight of the system can be further reduced with suitable materials. The paper describes a control therapy by integrating three types of exercises in a single exoskeleton. Three joint parameters: joint angle, angular velocity and joint torque are incorporated into the exoskeleton. Based on the requirements of users, any exercise mode can be chosen. In the developed prototype, the joint frequency of switching between motor control and assistive mode is fixed at 1 Hz whereas the boundary value between assistive mode and resistive mode is fixed at 2 Hz. Also the joint angle, velocity and static torque of the exoskeleton in different mode are decided based on a specific user of 1 kg forearm weight and mechanical property of springs. However, those switching parameters can be modified for different users as recommended by physiotherapist.

Chapter 5 Measurement accuracy of the exoskeleton

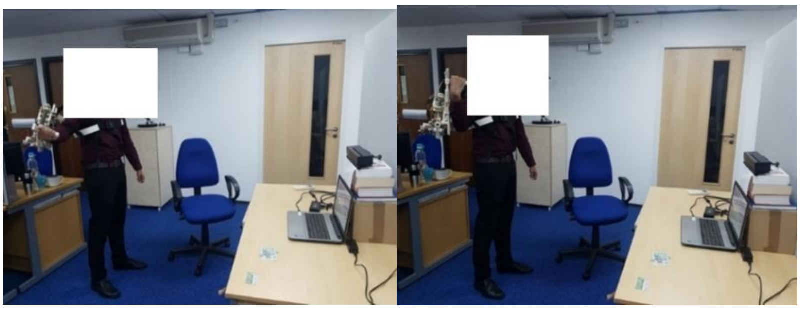
The performance of the exoskeleton is covered using three investigations. Measurement accuracy of the exoskeleton is analysed through a comparative study of joint parameters between the exoskeleton and Kinect sensor considering Kinect sensor data as the reference. Repeatability of joint measurement by exoskeleton is evaluated by computing the correlation coefficient between two consecutive measured joint angles and standard deviation of the error. Also, post-experiment survey from participants was included to satisfy the wearability of the exoskeleton.

5.1 Comparison of joint parameters with Kinect sensor

It is necessary to determine the measurement accuracy of the exoskeleton for delivering the specific mode of exercise based on the condition of joint parameters. Therefore, a comparative study is performed between the sensor data of exoskeleton and Kinect sensor considering Kinect sensor data as the reference. Two healthy subjects (#1 and #2) are selected for this experiment and they turned their elbow joint in front of Kinect camera wearing the elbow exoskeleton (Figure 5.1). Subjects can only initiate elbow rotation when they can initiate free movements wearing the exoskeleton. As the first exercise mode of the exoskeleton is controlled by motor, therefore users can rotate joint in assistive mode.



Subject #1



Subject #2

Figure 5.1. Elbow rotation of user wearing exoskeleton in front of Kinect

The joint angle is measured using the exoskeleton and other joint parameters are calculated from the mathematical model. On the other hand, those joint parameters are also recorded by Kinect sensor using the developed motion capturing method. For getting dynamic elbow joint torque, movement of forearm is considered as one DOF manipulator. The amount of assistive spring force and joint stiffness of exoskeleton have been ignored in this assessment.

The whole setup is designed around a basketball game in which the movement of the ball is controlled by the user's hand position in 3D space and user can drop the ball in basket using voice control. Kinect sensor basically tracks human body joint based on two-stage process: first compute a depth map, then infer body position. Together by combining this data, it reflects the joint vector of user. In this environment, many software tools are combined in a single platform such as Unity3D, Microsoft visual studio, Microsoft SDK (Kinect V2) and MATLAB (Figure 5.2). The setup helps in guiding users to do exercises where user is persuaded to put their effort.

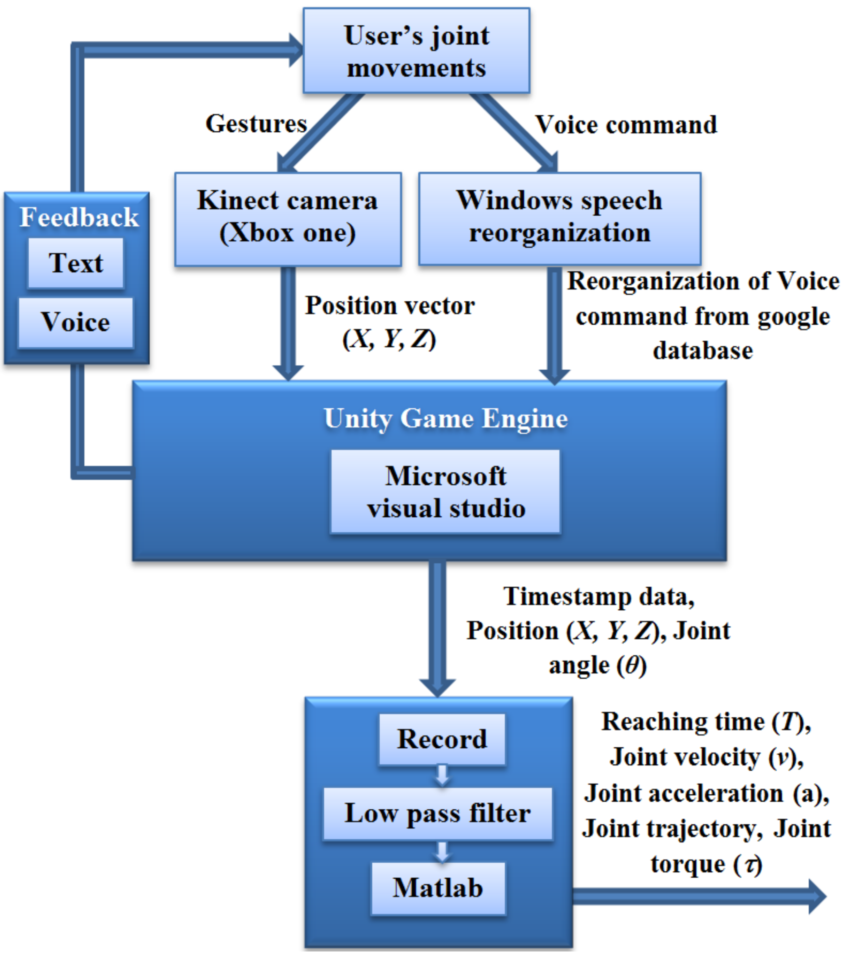


Figure 5.2. Structure of the Kinect sensor setup

The joint parameters are simultaneously recorded during movements. The environment has been designed in Unity Game engine where the position of arm joints is tracked using the Kinect sensor. The position of the ball (considered as a game object in unity) is synchronized with the movement of the hand using available API of Kinect. The voice control algorithm is implemented in this game using Windows speech reorganization technique (under Windows Speech library). Also, to implement a real feel of joint movement, an avatar is installed into the game platform. A male character pack 'FCG_Male_Char_Adam_Rig' from unity free asset store is downloaded and imported into the scenario. The arm movement of the avatar is also synchronized with the user's motion by putting the same Kinect based body tracking algorithm into it, therefore the behaviour of basketball movement and avatar motion are the same. All motions, measurement of joint vectors and reorganization of voice command are programmed in C# (shown in Appendix IV) through Microsoft visual studio. Microsoft XBOX-one is used which is compatible with Kinect V2 and it has direct plug-in interface available within Unity3D. The joint vectors and angles are measured and recorded using Windows SDK 2.0 interface with reference to the timestamp data. The recorded data can be further analysed to generate some useful information about joint parameters (velocity and torque). Rest of the analysis is performed in MATLAB based on the recorded data. In this system, Kinect's reference frame is used as the main coordinate system. Reaching time from the rest position to the goal position is calculated using the difference of the starting time to the ending time taken from timestamp data. The joint velocity and acceleration can be calculated from the differentiation of joint angle with respect to timestamp data. To reduce the noise in the calculation of joint parameters, a low pass filter is used to smoothen the data. Joint torque of the user is calculated from the information of segment mass of user, distance of centre of gravity and joint angle. Microsoft XBOX one needs a specific Xbox Kinect adaptor for connecting it to a personal computer (Figure 5.3). It used USB 3.0 cable for interfacing. The working condition of Kinect is verified by a red LED on it. If it is on, it means Kinect sensor is working fine.

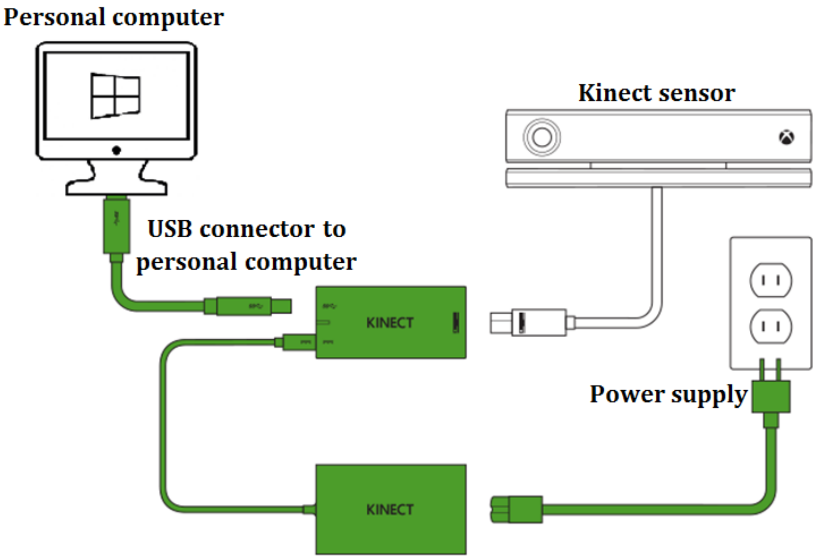


Figure 5.3. Connection between personal computer and Kinect

The distance between users and Kinect is 1.5 m and sensor is placed at 1.05 m from ground level (Figure 5.4). The game is tested on healthy subjects to see the operational validity of exoskeleton while playing the game.

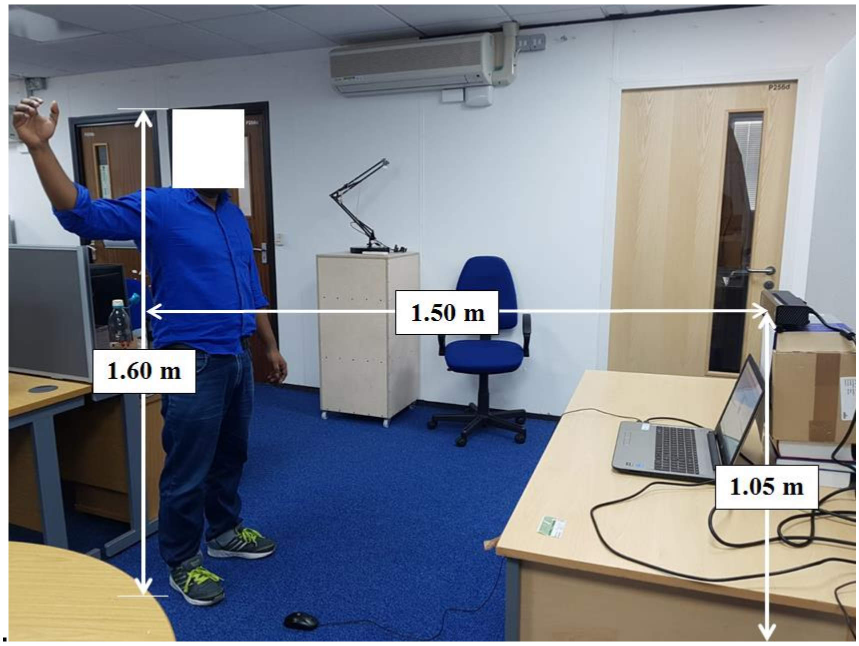
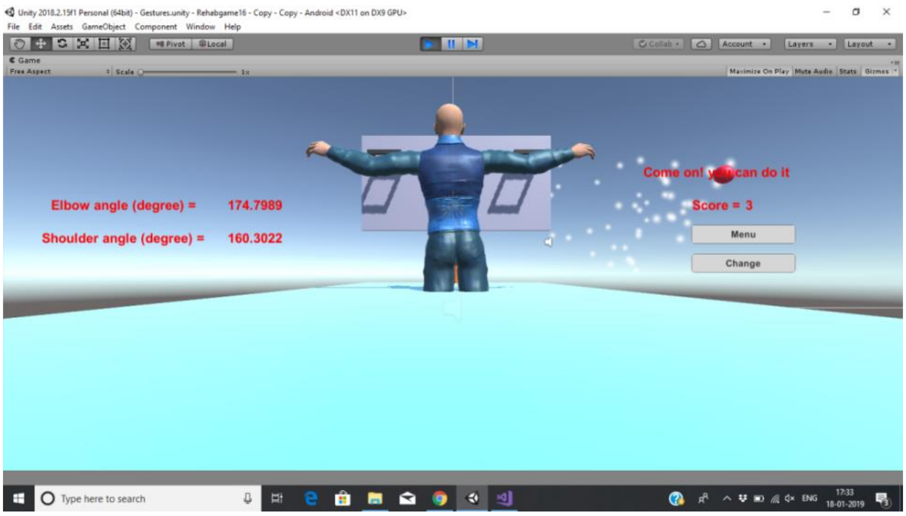


Figure 5.4. The Kinect sensor set-up

Joint angle of elbow, interactive communications between game engine and avatar appear on the game screen. After completing each stage, some motivating words and winning points will appear on the screen. The whole environment is programmed in such a way that gravity force is applied to each gameobject. After hearing the 'drop' word from the user, the holding contact between human hand and ball become zero, therefore it releases the ball. In this way, user can basket the ball from the top of the basket. There are two baskets in the game as shown in Figure 5.5. The basket on left side is allocated for left arm movement and the basket on right side is for the right arm.



a. Starting of the game

b. Ending of the game

Figure 5.5. Working setup of the game

5.2.1 Measurement of joint parameters using Kinect sensor

As, the 3D joint vectors (Figure 5.6) of hand, elbow and shoulder are recorded using Kinect sensor with respect to the timestamp data, all necessary joint parameters can be computed from the recorded data.

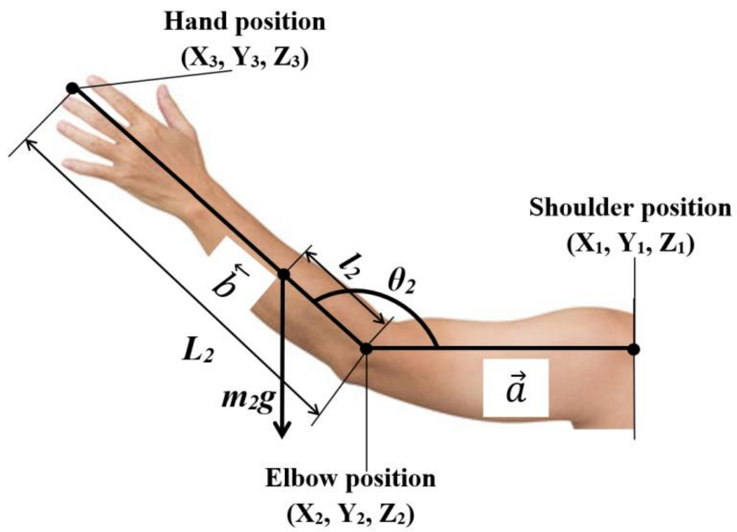


Figure 5.6. Kinematic model of human arm

Joint positions

Positions of shoulder joint (X_1, Y_1, Z_1), elbow joint (X_2, Y_2, Z_2), and the distal end of hand (X_3, Y_3, Z_3) of right arm of user are measured using Kinect SDK body tracking interface (Figure 5.6). The built-in API of Kinect provides the position vector with respect to the position of Kinect sensor (considered as reference (0, 0, 0) point).

Joint angle measurement

From Figure 5.6, $\vec{a} = [(X_2-X_1), (Y_2-Y_1), (Z_2-Z_1)]$ 5.1

$$\vec{b} = [(X_2-X_3), (Y_2-Y_2), (Z_2-Z_3)] \quad 5.2$$

$$\cos\theta_2 = \frac{a.b}{(|a||b|)} \quad 5.3$$

$$\sin\theta_2 = \frac{|a \text{ x } b|}{(|a||b|)} \quad 5.4$$

Therefore, the calculated elbow joint angle becomes

$$\theta_2 = \tan^{-1}\frac{|a \text{ x } b|}{a.b} \quad 5.5$$

Reaching time

T_k = Timestamp data (end time (T_2) – start time (T_1)) 5.6

Joint torque

Movement of elbow joint can be considered as one DOF manipulator where normal rigid body dynamics can be applied. To compute the dynamic joint torque of elbow joint, static parameters like mass of each arm segments and dynamic parameters such as joint angle, velocity and acceleration should be taken into account. The length of forearm is computed from the difference between Kinect based joint vectors. The hand is considered as a part of forearm. There is no direct method of measuring the centre of mass of each arm segment as well as the mass of each arm segments, therefore these are estimated based on the ratio between the segment and total body as per biomechanics rule (Winter 1990).

So the length of forearm

$$L_2 = \sqrt{(X_2 - X_3)^2 + (Y_2 - Y_3)^2 + (Z_2 - Z_3)^2} \qquad 5.7$$

The distance from elbow to the centre of mass of forearm (l_2) = 0.682 × L_2

Mass of forearm (m_2) = 0.022 × W

W = Body mass of the user (kg)

In human arm, each arm segments are considered as a point mass. Therefore

and inertia of forearm with respect to the centre of mass is

$I_2 = m_2(L_2 \times 0.468)^2$ kg.m^2

where $(L_2 \times 0.468)$ = Radius of gyration with respect to the centre of mass

As per Euler-Lagrange formulation of one DOF manipulator,

joint torque of elbow is $\tau_{elbow} = \left[m_2 {l_2}^2 + I_2\right]\ddot{\alpha}_2 + m_2 g l_2 \cos\alpha_2$ 5.8

Where $\alpha_2 = (180 - \theta_2)$

For measuring the length of forearm segment from exoskeleton is considered as 0.254× H Where H=total height

Mass of forearm is same for both measurements: exoskeleton and Kinect whereas the values of forearm length and joint parameters are different (Table 5.1).

Table 5.1. Comparison of arm parameters of two healthy subjects

Method	**Subjects**	**Forearm mass (kg)**	**Forearm length (m)**	**Length of centre of mass from proximal end (m)**	**Radius of gyration with respect to the centre of mass (m)**
Exoskeleton	#1	1.738	0.40	0.28	0.19
	#2	1.32	0.44	0.30	0.21
Kinect	#1	1.738	0.37	0.25	0.17
	#2	1.32	0.40	0.273	0.19

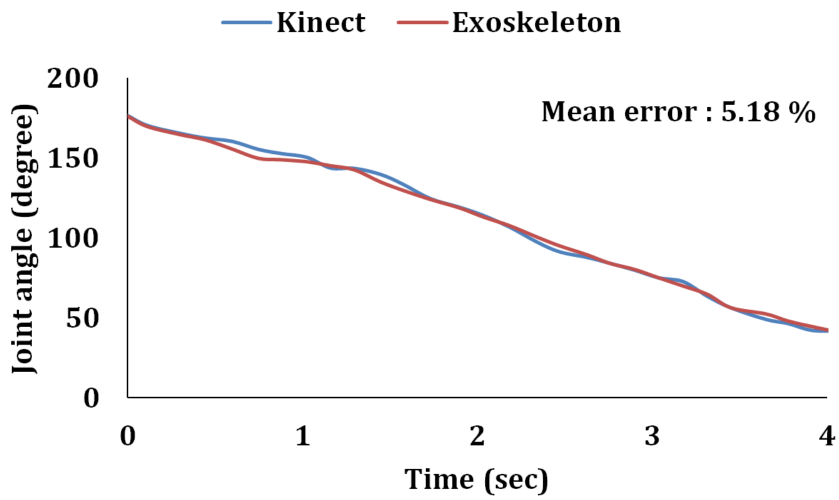
Joint torque is computed based on the mathematical model as per the Eq. (5.8), shown in Figure 5.8 for both subjects. The frictional force and muscle stiffness have been ignored in the formulation of joint torque.

As the measured joint parameters from Kinect sensor are considered as reference, measurement error in the exoskeleton is calculated as per Eq. (5.9).

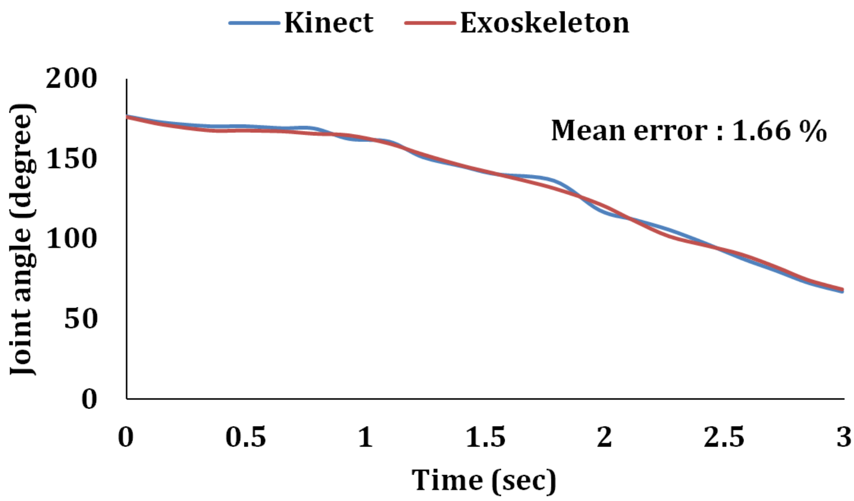
Error in measurement (%)

$$= \left|\frac{\text{Measurement(Kinect)} - \text{Measurement(Exoskeleton)}}{\text{Measurement(Kinect)}}\right| \times 100 \qquad 5.9$$

The comparison between the sensor data of exoskeleton and Kinect measurement is shown in Figure 5.7 and Figure 5.8.

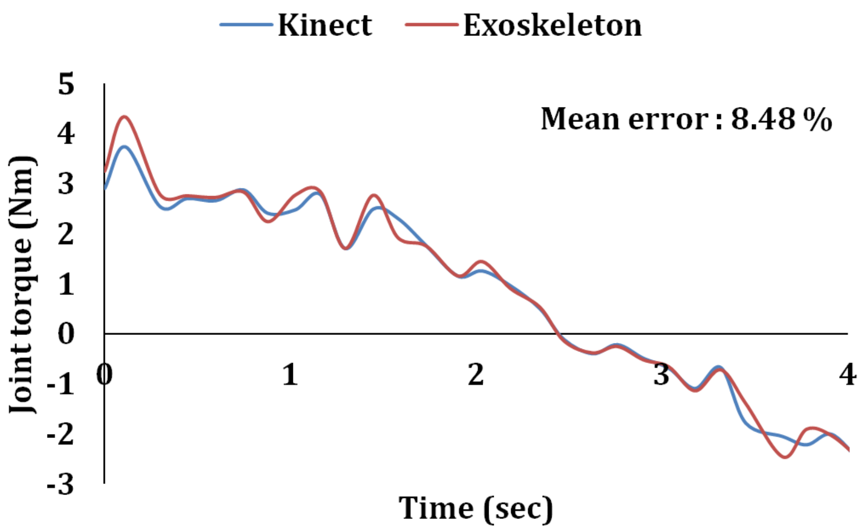


Subject 1

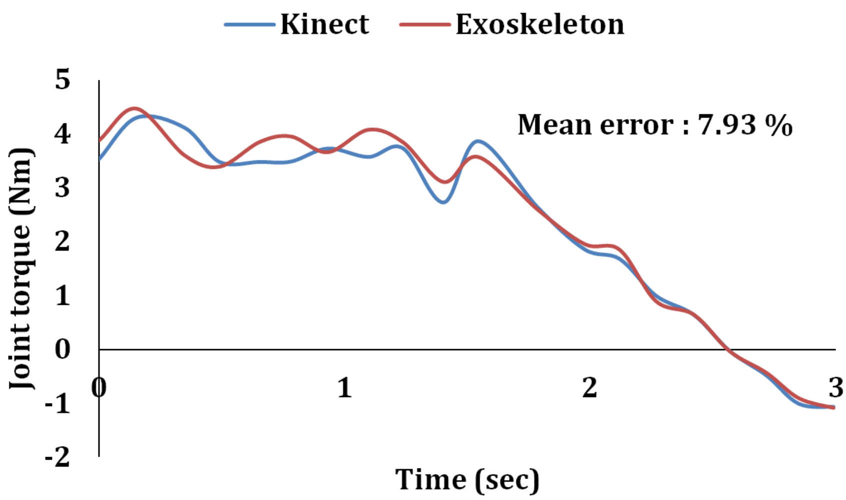


Subject 2

Figure 5.7. Comparison of the joint angle measured by Kinect and exoskeleton



Subject 1



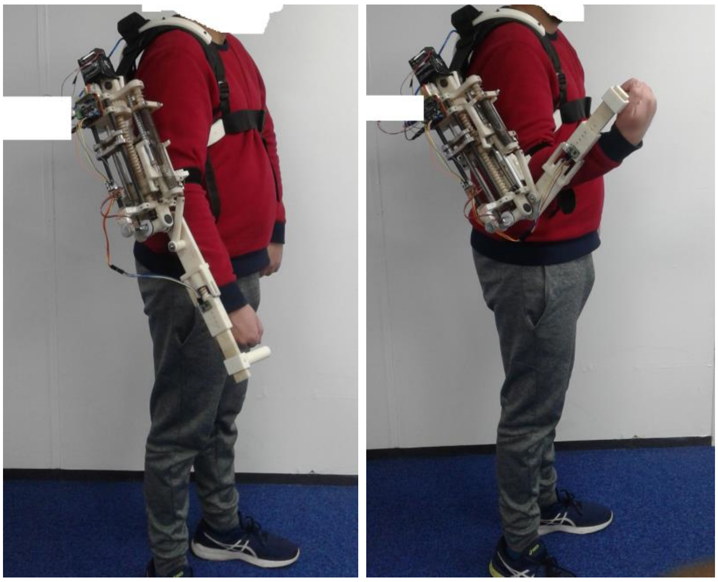
Subject 2

Figure 5.8. Comparison of the joint torque measured by Kinect and exoskeleton

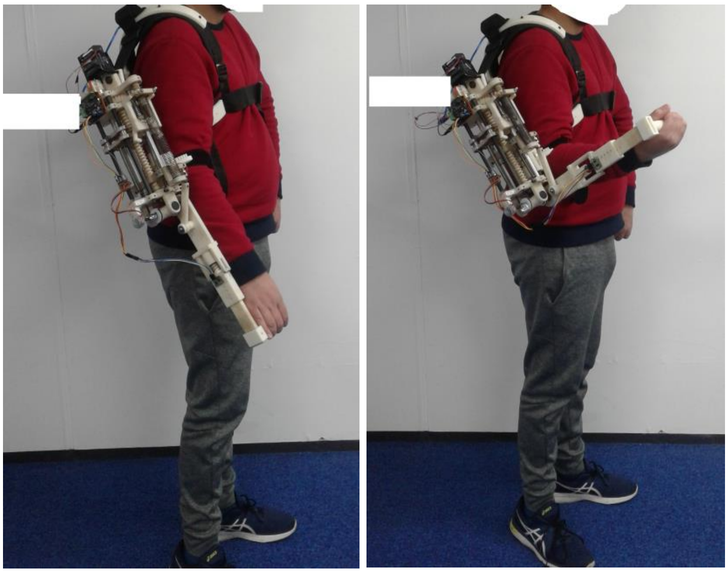
Figure 5.7 shows that the mean error in the joint angle is within 5.18% for subject 1 and 1.66% for subject 2. Therefore, it proves that the exoskeleton can also measure joint angle quite accurately. The comparison of joint torque from both measurements is shown in Figure 5.8. The mean error in joint torque is also within an acceptable range for both subjects: 8.48% for subject 1 and 7.93% for subject 2.

5.2 Repeatability of joint measurement by the exoskeleton

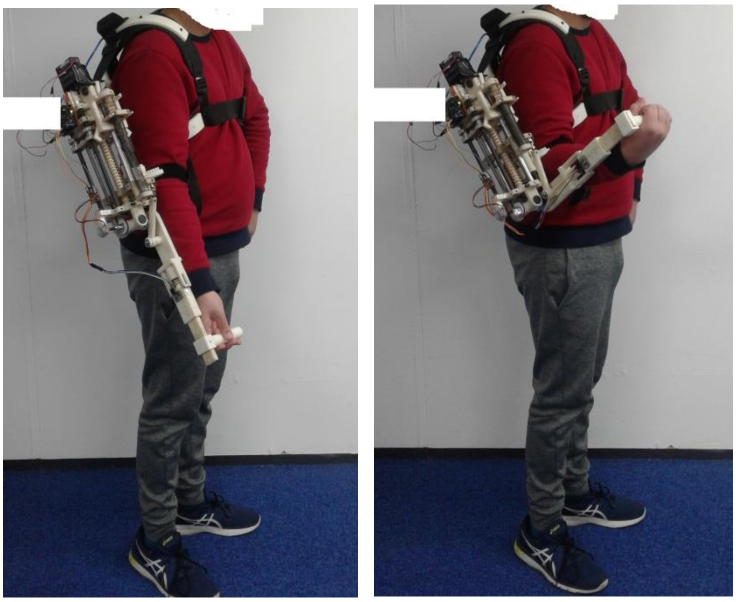
Three healthy participants (#3, #4 and #5) have participated in the repeatability test where they rotated their elbow joint in three different modes wearing the exoskeleton, as shown in Figure 5.9, Figure 5.10 and Figure 5.11. The participants completed two full cycles of flexion-extension at the same frequency.



Motor controlled mode
Joint frequency 0.06 Hz
Min joint angle: 0.223 degree
Max joint angle: 98.869 degree



Assistive mode
(Nut-slider position 0.19 m)
Joint frequency 0.1 Hz
Min joint angle: 5 degree
Max joint angle: 90 degree



Resistive mode
(Nut-slider position 0.22 m)
Joint frequency 0.08 Hz
Min joint angle: 3.608 degree
Max joint angle: 93.608 degree

Figure 5.9. Repetitive measurement of participant #3 in three modes

Motor-controlled mode
Joint frequency 0.06 Hz
Min joint angle: 10.543 degree
Max joint angle: 90.45 degree

Assistive mode (Nut-slider position 0.19 m)
Joint frequency 0.09 Hz
Min joint angle: 15 degree
Max joint angle: 129.167 degree

Resistive mode (Nut-slider position 0.22 m)
Joint frequency 0.09 Hz
Min joint angle: 20 degree
Max joint angle: 130 degree

Figure 5.10. Repetitive measurement of participant #4 in three modes

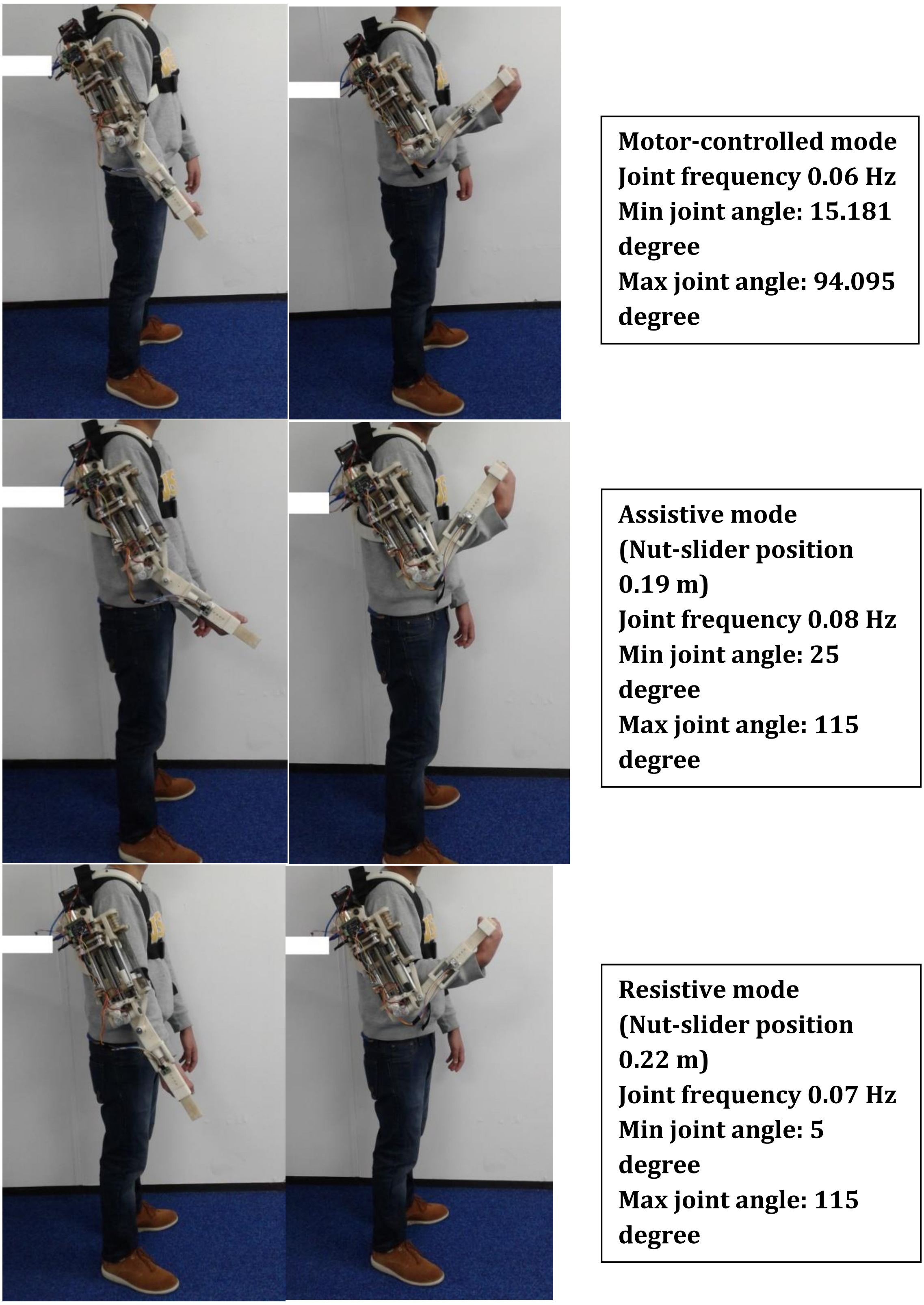
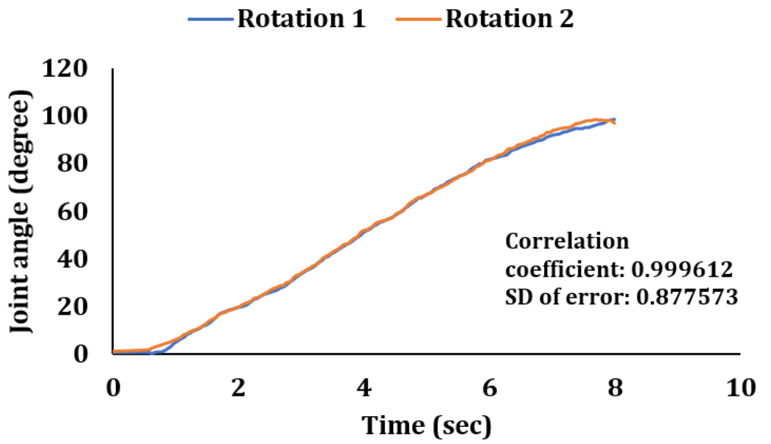
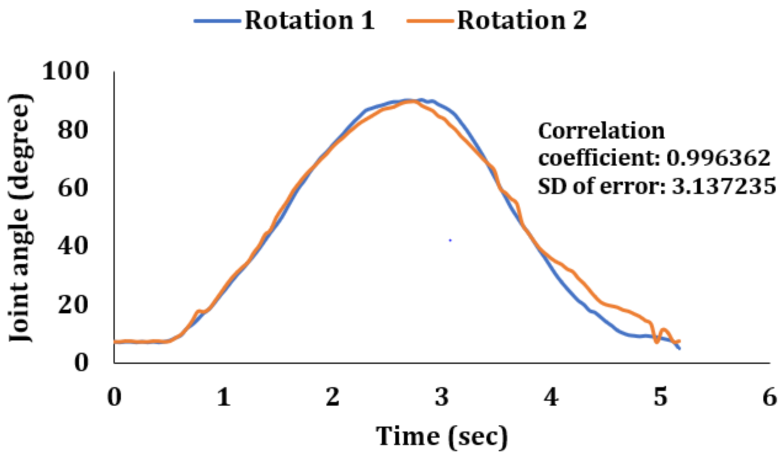


Figure 5.11. Repetitive measurement of participant #5 in three modes

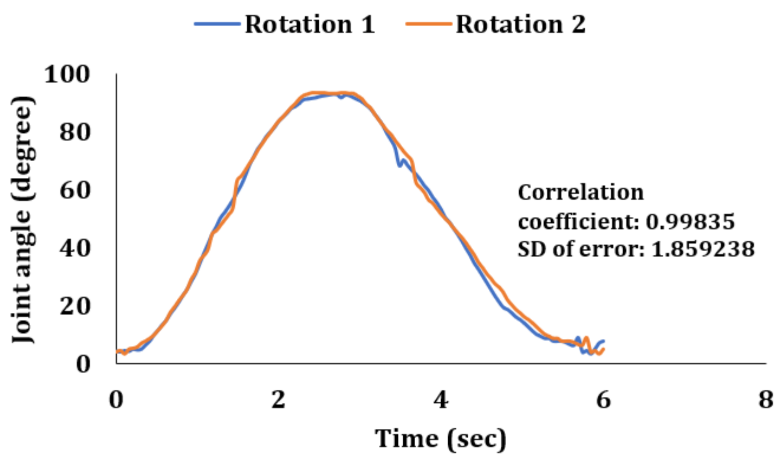
To measure the repeatability, the correlation coefficient between the two successive measurements is computed (shown in Figure 5.12, Figure 5.13 and Figure 5.14). To validate the test-retest reliability and margin of error, the absolute error between two repeated test results are computed to get SD of error. Standard deviation (SD) is multiplied by 1.96 to show a range in which the true measurement lies.



a. Motor controlled mode

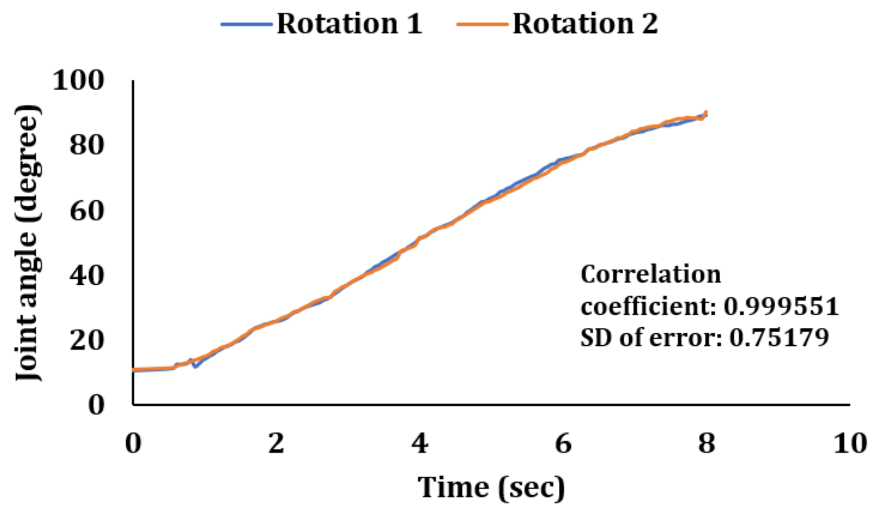


b. Assistive mode

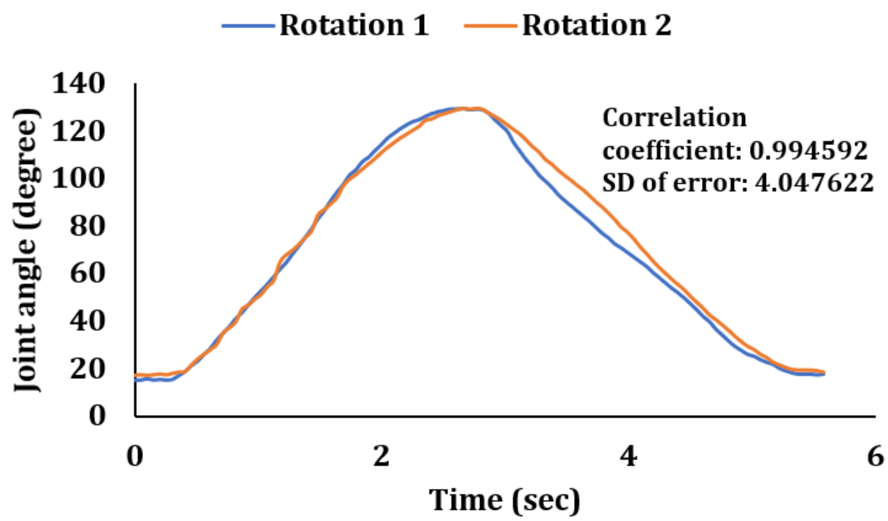


c. Resistive mode

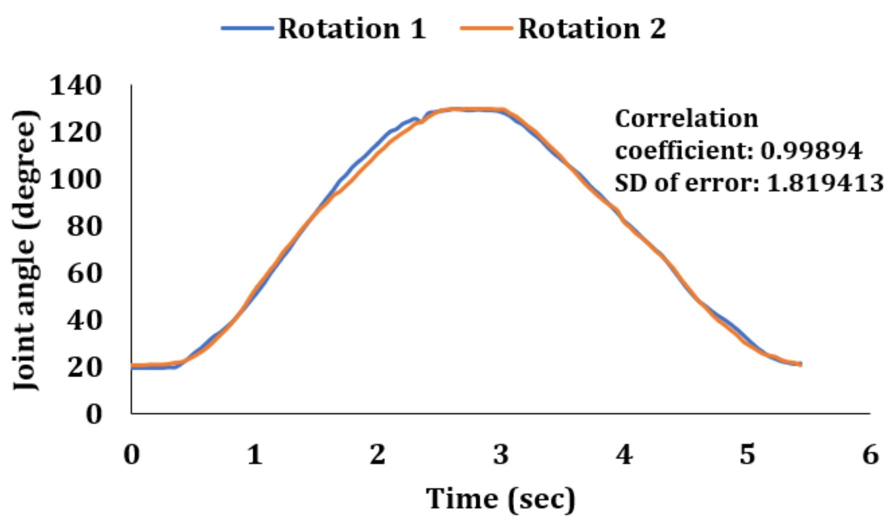
Figure 5.12. Comparison of joint angle in three modes for participant #3



a. Motor controlled mode

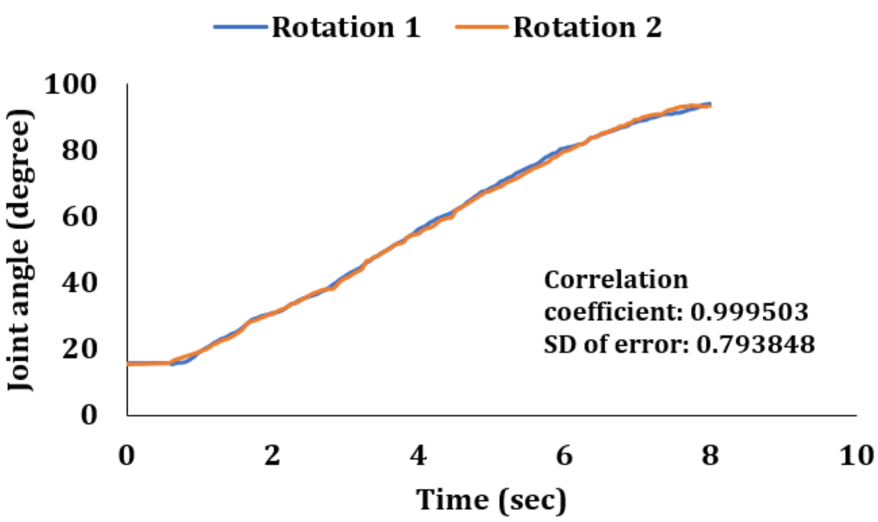


b. Assistive mode

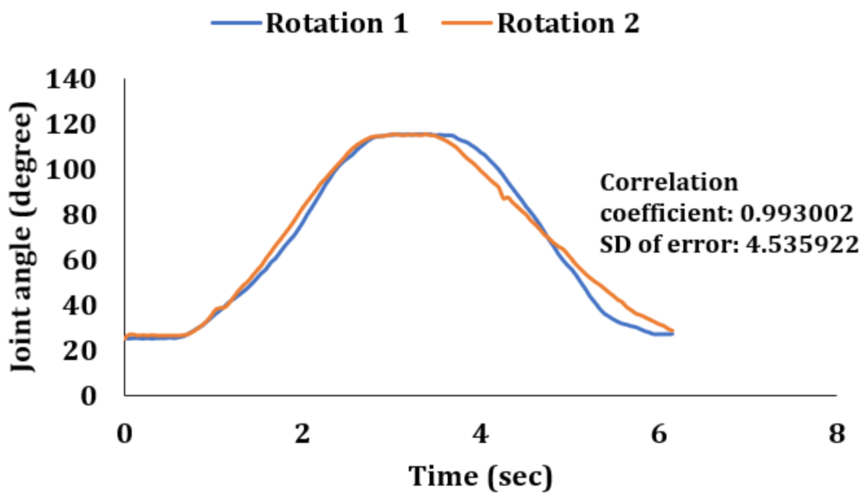


c. Resistive mode

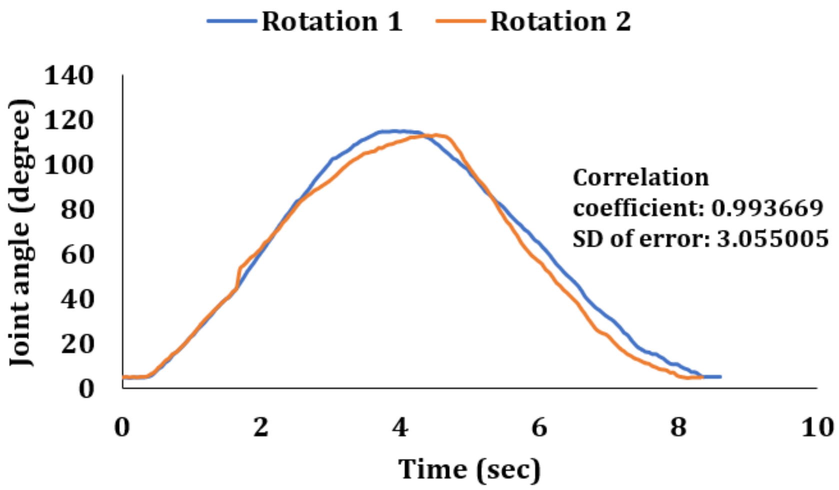
Figure 5.13. Comparison of joint angle in three modes for participant #4



a. Motor controlled mode



b. Assistive mode



c. Resistive mode

Figure 5.14. Comparison of joint angle in three modes for participant #5

Participants performed joint movement under motor-controlled mode when the position of the nut-slider is between 0 and 0.18 m. However, the positions of the nut slider for assistive mode and resistive mode are fixed at 0.19 m and 0.22 m respectively. Joint frequency of participants is almost fixed for each exercise mode. Participant 3 rotates his elbow joint at 0.06 Hz, 0.1 Hz and 0.08 Hz for motor -controlled mode, assistive mode and resistive mode respectively. Participant 4 rotates his elbow joint at 0.06 Hz, 0.09 Hz and 0.09 Hz for motor -controlled mode, assistive mode and resistive mode respectively. Participant 5 rotates his elbow joint at 0.06 Hz, 0.08 Hz and 0.07 Hz for motor -controlled mode, assistive mode and resistive mode respectively. Ranges of joint angle (minimum and maximum) of three participants are shown in Table 5.2 for three different modes.

Table 5.2. Range of joint angle for three participants

	Minimum joint angle			Maximum joint angle		
Participants	**Motor controlled mode**	**Assisitve mode**	**Resisitve mode**	**Motor controlled mode**	**Assisitve mode**	**Resisitve mode**
#3	0.223	5	3.608	98.869	90	93.608
#4	10.43	15	20	90.45	129.167	130
#5	1.181	25	5	94.095	115	115

The correlation coefficient of two consecutive rotation cycles is calculated and shown in Table 5.3. The value of correlation coefficient comes in the range from 0.99367 to 0.99961 for all three modes. As per Cronbach's alpha-internal consistency-table, if the correlation coefficient is 0.7 or above, it defines a high correlation and if the correlation coefficient is 0.9 or above, it defines an excellent correlation. From the above results, it has been proved that there is a strong correlation between two consecutive rotation cycles which indirectly shows high repeatability of the measurement. Also, if we investigate the correlation coefficient values (Table 5.3), it has been found out that the value of correlation coefficient for motor-controlled mode is higher than assistive and resistive mode because participants under motor based joint movement are fully under control of motorized mechanism. In case of assistive and resistive mode, participants rotate their joint themselves, therefore, it is difficult to maintain the symmetry between two consecutive rotation cycles, so, the correlation coefficient is reduced due to the delay in joint rotation. Also, the SD of absolute error between two consecutive joint angles is computed and shown in Table 5.3. it is then multiplied by 1.96 to get the 95% confidence interval which gives a range in which the true measurement lies and the margin of error. The maximum value of the margin of error is also in an acceptable range which is 8.897.

Table 5.3. Calculation of Correlation coefficient and 1.96*SD

	Correlation coefficient			1.96*SD (Error in jont angle)		
Subjects	**Motor controlled mode**	**Assisitve mode**	**Resisitve mode**	**Motor controlled mode**	**Assisitve mode**	**Resisitve mode**
Subject 3	0.99961	0.99636	0.99835	1.72	6.145	3.644
Subject 4	0.99955	0.99459	0.99894	1.474	7.933	3.566
Subject 5	0.99950	0.99300	0.99367	1.556	8.897	5.988

5.3 Wearability and usability of the exoskeleton

At the end of the experiment, participants filled up a small survey of two questions related to the wearability and ease of using the exoskeleton. Users response will be recorded on a scale from 1 to 5 where 1 will be considered as strongly disagree and 5 will be considered as strongly agree. Those feedback points have been used to evaluate the usefulness of the device.

The questions of the post-experiment survey are given as attached.

Q1. Did you feel the exoskeleton is wearable?

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

Q2. Did you find it easy to use the exoskeleton?

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

Maximum point for a section will be 5 (Strongly agree).

As the number of participants is 5, the user satisfaction ratio is calculated as

$$= \frac{(\textbf{Summation of total pints})}{\mathbf{5 \times No\ of\ participants}} \times \mathbf{100} \qquad 5.10$$

The exoskeleton has been used by five users. One user for using the exoskeleton to prove the conceptual design, two users for the comparative study between exoskeleton and Kinect based joint measurement and three users for repeatability test, therefore, their opinions are recorded after using the exoskeleton, shown in Table 5.4.

Table 5.4. Recording of wearability and ease of use score

Participants number	Scale received (wearability)	Scale received (ease of use)
#1	4	4
#2	4	4
#3	3	3
#4	4	5
#5	4	4

User satisfaction ratio of wearability is

$$\frac{18}{5 \times 5} \times 100 = 76\%$$

User satisfaction ratio of ease of using the exoskeleton is

$$\frac{20}{5 \times 5} \times 100 = 80\%$$

The user satisfaction ratio for wearability and ease of using the exoskeleton are 76% and 80% respectively for five users. Therefore, it may be considered for using the exoskeleton for delivering different types of exercise in future.

5.4 Concluding remarks

In this chapter, the performance of the exoskeleton is evaluated by conducting three investigations.

- The measurement accuracy of the exoskeleton is demonstrated through a comparative study of joint parameters between the exoskeleton and Kinect sensor considering Kinect sensor data as reference. The mean measurement error of joint angle and toque was calculated and that were: 5.18 % for participant 1 and 1.66 % for participant 2 (for joint angle); 8.48% for participant 1 and 7.93% for participant 2 (for joint torque). It was found that the mean error of measurements was in a considerable range.

- The repeatability of joint measurement from exoskeleton is analysed by computing the correlation coefficient between two consecutive measured joint angles and standard deviation of the error. After calculating the correlation coefficient between two consecutive joint rotation, it was found to be greater than 0.99 which proved a high correlation and repeatability. Also, the value 1.96*SD of error was 8.897 which proved that the margin of error was in an acceptable range.

- Post-trial survey from participants was included to satisfy the wearability and ease of using the exoskeleton. All five users filled up a small survey and scale it from 1 to 5 (strongly disagree to strongly agree) for evaluation wearability and ease of using of the exoskeleton. The results were quite effective as the Wearability score was 76% and score of Ease of use was 80% which proved that the exoskeleton is wearable by users as we kept the satisfaction range 75% as the desired level.

Chapter 6 Conclusions and future scope

After analyzing the joint movements required in different stages of the post-stroke condition and consulting various published works (Proietti et al. 2016),(Pineda-Rico et al. 2016),(Chonnaparamutt and Supsi 2016), the pathway of posts-stroke rehabilitation was categorized into three distinct phases; acute, mid-stage and last stage. The specific needs for multi-stages are external force-based control in the acute stage, assistive force-based exercise in the midway of recovery and resistive force based exercise in the last stage. These are well reported requirements so, in acute stage, external force is applied during rehabilitation because patients are unable to move their joints themselves. Assistive force is helpful at mid stage to support such patients. To enhance muscle strength and joint torque, more resistance is provided to meet the multi-stage rehabilitation requirements. Exercises provided by physiotherapist results in many functional and skill-based problems such as costly therapy due to the lack of time and shortage of therapist; discoordination in the exercise module due to the fatigue of therapist. To overcome these problems, it is required to configure the exoskeleton in a way so that it can provide three modes of exercises as per the recovery status of patients. After investigating several actuators and actuation systems used in the existing exoskeletons (Manna and Dubey 2018), many limitations were identified such as lack of multistage exercises in a single model, dependency on biosensor, stationary structure and the ability to provide only a specific type of exercise. Therefore, the main aim of this research was to build an exoskeleton model that may offer different modes of exercise using a standalone system for providing post-stroke rehabilitation at all stages.

The key research question is what kind of mechanism can be designed that can provide three modes of exercises (external force, assistive force and resistive force) and is also portable and wearable in a standalone system?

The solutions presented from my research address some of these possibilities. A metric of user's requirement (Table 1.1) was formed for using the exoskeleton in post-stroke rehabilitation. Based on the metric shown in Table 1.1 and calculated anthropometric parameters of five healthy subjects, a product design specification

(PDS) sheet was developed where probable solutions were categorized into qualitative and quantitative solutions, shown in Table 1.4 with ideal, target and achieved values. Table 2.7 shows a brief summary of existing solutions available for the user's requirements mentioned in PDS. Combining the existing solutions and my own research, an innovative mechanism of exoskeleton was developed to achieve all the required features.

The structural formation of the exoskeleton is based on the anthropometric parameters of five healthy users and the length of upperarm and forearm supporting structure can be varied to fit with different users. This hardware-based exoskeleton has the potential to offer better outcomes than the existing exoskeletons. It not only offers all three modes of exercises in a single structure but also preserves portability and safety of users. The developed exoskeleton incorporates the benefits of motor control and passive actuation in a single model. The cost of providing post-stroke therapy can be reduced as the production cost of the prototype was quite low (£ 886) which can be further reduced using suitable material and mass production. The mathematical model of the mechanism was analyzed for different configurations to know the motor torque and stiffness requirements for springs. The mass of exoskeleton is 1.8 kg. The exoskeleton offers three modes of exercises in such a way that the relationship between the recovery rate and the mode of exercise is directly associated. Two hardware-based switching mechanism is introduced in the exoskeleton to move between different modes of exercise. The boundary condition of the recovery index for switching from one mode of exercise to another was determined by the specific values of three joint parameters angle, velocity and torque. If users can cross the boundary, the switching mechanism will be activated and the mode of exercise will be transferred from one to another.

To validate its mechanism and proposed methodology, this exoskeleton was tested with five healthy subjects. These experiments proved its working principle, measured accuracy and repeatability. Also, feedback from participants was collected to assess the wearability and usability of the exoskeleton. The process of doing the experiment is explained in the participant information sheet (shown in Appendix I).

As described in the participant information sheet

The experiment consists of the elbow joint movement by healthy users in front of Kinect sensor after wearing the exoskeleton. They can only participate in the experiment after agreeing with the participant information sheet and signed the participant agreement form. Users are asked to move their right arm in three different modes and their elbow joint angle is recorded by the exoskeleton and Kinect sensor.

- **In the first mode (electric motor-controlled mode), users are asked to keep their arm idle so that electric motor can rotate the elbow joint.**
- **In assistive mode, users are asked to use their normal strength to rotate their elbow joint.**
- **In resistive mode, users are asked to use their normal strength to rotate their elbow joint.**

A small post-experiment survey is conducted to prove the wearability and usability of the exoskeleton. It consists of two questions and users can give answers using a scale from 1 to 5 (strongly disagree to strongly agree).

Detailed experimental analysis:

- In the first experiment, one healthy user used the exoskeleton in three different modes (at different positions of the operating region) where he was asked to move his right arm. Joint parameters from each mode were recorded for all three modes. Through this experiment, the design principle of the exoskeleton was proved, whether the mechanism can provide variable assistive or resistive torque and if yes, the range of assistive and resistive torque.
    - In the first mode (electric motor-controlled mode), the participant was asked to keep his arm idle so that electric motor can support fully to rotate his elbow joint. The maximum joint torque of the exoskeleton was 10 Nm.
    - In assistive mode, the participant was asked to use his normal strength to rotate his elbow (same effort for different positions of the nut slider). The position of nut slider was moved from 0.181 m to 0.20 m to vary the assistive force. The assistive torque was varied up to 0.037 Nm.
    - In resistive mode, the participant was asked to use his normal strength to rotate his elbow (same effort for different positions of the nut slider). The position of nut slider was moved from 0.201 m to 0.24 m to vary the resistive force. The resistive torque was varied up to 0.057 Nm.

- In the next experiment, two healthy users rotated their elbow joint in front of Kinect camera wearing the elbow exoskeleton in assistive mode. Therefore, a comparative study was performed between the sensor data of exoskeleton and Kinect sensor considering Kinect sensor data as reference. Mean measurement error in joint angle was: 5.18 % for participant 1 and 1.66% for participant 2. Mean measurement error in joint torque was: 8.48% for participant 1 and 7.93% for participant 2. The mean error of measurements was in a considerable range which proved that exoskeleton can measure the joint parameters quite accurately.

- In the last experiment, the exoskeleton was used by three healthy subjects who rotated their elbow joint in three modes at fixed operating points and joint parameters from each mode were recorded for consecutive two rotations (a complete cycle of flexion and extension). Joint frequency of participants was almost fixed for each exercise mode. Therefore, the repeatability of measurements was verified by calculating the correlation coefficient between two consecutive joint measurements and standard deviation (SD) of error. SD was multiplied by 1.96 to show a range in which the true measurement lies. The correlation coefficient was greater than 0.99 which showed a high correlation between consecutive joint measurements and 1.96*SD of error was 8.897, proved that the margin of error was in an acceptable range.

- At the end of the experiment, all five users were asked to fill up a small survey. Users gave answers using a scale from 1 to 5 (strongly disagree to strongly agree). The opinion polls from 5 healthy users were; Wearability ≥ 76% and Ease of use ≥ 80% which proved that the exoskeleton is wearable by users as we kept the satisfaction range 75% as the desired level. This test helped us to prove the efficiency of the developed exoskeleton and this may lead to finding a better robotic solution for providing post-stroke rehabilitation.

Table 6.1 shows the achieved design solutions using appropriate mechanism, actuator and material.

Table 6.1. Archived design solutions

Property	Sl. No.	Solutions	Achieved value	Design specification
Structural property	1	Integration of three types of exercises (external control, assistive force and resistive force) in a single system	Features have been implemented	• The operating region of the exoskeleton is divided into three specific regions to provide specific exercise. • The whole operating region is 0.24 m where the motor controlled joint movement is delivered within 0.18 m. Therefore, assistive and resistive force by the exoskeleton is delivered within 0.181 to 0.20 m and 0.201 to 0.24 m respectively.
	2	Exoskeleton can provide variable assistive and resistive torque	Variation of assistive torque: 0.037 Nm Variation of resistive torque: 0.057 Nm	• The exoskeleton has two operation regions consisting of spring-based mechanism for delivering assistive and resistive force to user's experience during exercise. • The assistive torque can be varied up to 0.037 Nm by changing the displacement of a compression spring. • The resistive torque can be varied up to 0.057 Nm by using the stiffness of two extension springs. • The joint measurements were collected after it was used by a healthy user for validating the mechanism.
	3	Production cost of exoskeleton is affordable for public	£886	• The cost of components (mechanical, electrical, electronic) and manufacturing the whole system have been included.

Property	Sl. No.	Solutions	Achieved value	Design specification
Structural property	4	Consistent and repeatable exercise module	Mean measurement errors of joint angle: 5.18 % for participant 1 and 1.66% for participant 2 Mean measurement errors of joint torque: 8.48% for participant 1 and 7.93% for participant 2 Correlation coefficient ≥ 0.99 (High correlation between joint measurement) 1.96*SD of error =8.897 (Margin of error is in an acceptable range)	• The exoskeleton was used by two healthy users in front of the Kinect sensor to validate the measurement accuracy of the exoskeleton. • The measured and computed joint parameters from the exoskeleton and Kinect sensor are compared by considering Kinect sensor value as reference. The mean error of joint angle and torque from both healthy subjects are in the considerable range which proves that exoskeleton can measure the joint parameters quite accurately. • The exoskeleton was used by three healthy users for two rotation cycles and the correlation coefficient between two consecutive measured joint angles was computed. • Also, the repeatability of joint measurement is calculated by the error between two consecutive measured joint angles and SD of error, in the end, it was multiplied by 1.96 to get the margin of error i.e. the range within which the true measurement lies.

Property	Sl. No.	Solutions	Achieved value	Design specification
Structural property	5	Motor can provide required joint torque	10 Nm	• A specific DC motor has been selected to provide maximum stall torque up to 5 Nm which can generate maximum joint torque up to 10 Nm due to mechanical advantage.
	6	Enhances torque to weight ratio	Required joint torque is reduced twice compared to joint based actuation	• Gear is engaged to the motor to reduce its speed. The gear ratio used here is 1:1.5. • The torque to weight ratio of the exoskeleton is enhanced using a leadscrew-based slider crank mechanism instead of joint-based actuation. Mathematically it was proved that the required joint torque of the exoskeleton is reduced two times compared to joint based actuation where motor is directly connected at the joint.
	7	Weight of the exoskeleton is lighter	1.8 kg	• ABS is used as the structural material for the exoskeleton as it is lighter in weight and hard in strength. • The structural materials of the gear and springs are nylon 101 and ASTM respectively.

Property	Sl. No.	Solutions	Achieved value	Design specification
Structural property	8	Smaller energy source for operation	Feature has been implemented	• The energy consumption is also reduced so as the battery size by using a hybrid model of electric motor and springs in the actuation mechanism. Electric motor is used to control the joint in the first mode whereas, in rest of the two modes, joint motions are supported by the stiffness of the springs for providing assistive or resistive force. • Spring-based mechanism is also used for switching between different operating regions instead of using electromagnetic switch, brakes or clutches. • The exoskeleton model used a single motor (5 W) for delivering all kinds of functions. The enhanced torque to weight ratio decreases energy consumption.
	9	Design should follow the biomechanical structure and anthropometric data of human arm	**Elbow joint:** 1 DOF **Upperarm length:** 0.35 ±0.04 m **Forearm length:** 0.40 ±0.04 m	• The mean anthropometric data of five healthy users are considered to design the framework of the exoskeleton.
	10	Opinion of users after using the exoskeleton	Opinion poll from 5 healthy users = Wearability ≥ 76% Ease of use ≥ 80%	• The exoskeleton was used by five healthy users for different purpose. • At the end of the experiment, a small survey is taken from users related to wearability and ease of using the exoskeleton. Users gave answers using a scale from 1 to 5 (strongly disagree to strongly agree).

Property	Sl. No.	Solutions	Achieved value	Design specification
Structural property	11	Exoskeleton can reach maximum joint angle	135^o	• The actuation mechanism of the exoskeleton is based on leadscrew-based slider-crank mechanism which allows users to rotate up to 135^o.
	12	Using of passive energy source for joint actuation	Feature has been implemented	• The exoskeleton uses spring-based mechanism to generate variable assistive force and spring-based antagonistic setup to vary joint stiffness to generate variable resistive force. • A compression spring (246.5 N/m) is connected at the exoskeleton to give assistance to users. • Two extension springs (2.5 N/m and 10 N/m) are set up in an antagonistic way to vary the joint stiffness, which indirectly changes the resistance during the joint movement.
	13	Using of spring-actuated mechanism for switching between exercise	Feature has been implemented	• A passive switching mechanism is developed where stiffness of springs is used to switch between different operating regions.
	14	Using of universal joint instead of revolute	Feature has been implemented	• The exoskeleton has used a universal joint model for elbow for providing a flexibility in transverse plane. • The universal joint allows the active movement of elbow joint up to 135^o in sagittal place and passive movement up to $\pm 5^o$ in the transverse plane.
Control property	15	Compensation of joint misalignment during rotation	Feature has been implemented	• Forearm supporting structure of the exoskeleton has a spring-based linear passive joint to balance the joint misalignment between the centre of rotation for elbow and exoskeleton.

Property	Sl. No.	Solutions	Achieved value	Design specification
Control property	16	Should have both control scheme: automatic and manual	Feature has been implemented	• This feature is achieved by developing a GUI in MATLAB having two options; automatic and manual where users can select one of those options.
	17	Mode of exercises can be switched easily based on joint condition	Feature has been implemented	• Mode of exercises can be controlled by a novel mechanism which can change the amount of assistive and resistive force as per user's need. • The exoskeleton can be controlled by the post-stroke recovery stage which is determined based on joint parameters; angle, velocity and torque (no biosensor is used).
	18	Develop the control strategy using joint parameters without using biosensor	Feature has been implemented	• User joint' range, velocity and torque used as feedback parameters in the exoskeleton. The threshold conditions (E1, E2 and E3) of each recovery stage can be determined based on the specific value of three joint parameters. Users can switch from one mode of exercise to another if they cross the threshold. The exoskeleton automatically changes the configuration of the exoskeleton to provide the specific exercise. User can be promoted from external force-based exercise to assistive mode if they can rotate their elbow joint up to 135^{o}, self-movement at 1 Hz and joint torque up to 1.175 Nm whereas the conditions for crossing the resistive mode are reachable joint angle - 135^{o}, joint frequency at 2 Hz and joint torque up to 1.232 Nm.

Property	Sl. No.	Solutions	Achieved value	Design specification
Control property	19	Control mechanism will allow users to put their effort to do joint movement	Feature has been implemented	• The control algorithm will keep the assistive spring power lower than the ideal joint torque with the goal that users endeavour to move. • Also, the exoskeleton controls all types assistive and resistive force using hardware-based mechanism, therefore, can be manually manoeuvred.
Safety property	20	Mechanical constraint to restrict the joint movement beyond the anatomical limit	Feature has been implemented	• Spring-based switching mechanism is used in the exoskeleton as a safety tool to restrict joint movement. When joint rotates up to the maximum anatomical range (135^{o}) in motor-controlled mode, mode of exercise will be transferred from motor-controlled to user-controlled mode.
	21	Software control to restrict the joint movement beyond the anatomical limit	Feature has been implemented	• The control algorithm of the exoskeleton is programmed to limit the number of rotations in motor to control joint movement up to the anatomical range.

Limitations and Future scope

In this research project, there was no involvement of patients and medical experts, therefore opinions from stroke patients (for checking if they accept it) and medical experts are purely literature based. This will be considered in any future development of the exoskeleton. The user's requirement for designing the exoskeleton and the design specifications were determined solely based on literature survey. All types of design features mentioned in the metric (Table 1.1) and PDS (Table 1.4) were collected from research articles. The cost-effectiveness and wearability of the developed exoskeleton can be improved by clinical trials of the exoskeleton with stroke patients.

- The cost of manufacturing the prototype was £886 which can be further reduced using mass manufacturing facility. Future research will involve cost-optimization of each components to make the exoskeleton affordable.
- The wearability of the exoskeleton was analyzed based on a post-experiment survey with limited questionnaires. Future research would include more neurological and psychological questions in the user's survey to judge the viability of the device.
- The developed prototype can be further modified to make it a compact and user-friendly system. The current prototype can be miniaturized and the size can be reduced with the appropriate use of structural materials such as a composite of carbon fibre or stainless steel. The structural material used in the developed prototype is acrylonitrile butadiene styrene (ABS). By using these materials, the size of each component of the exoskeleton structure can be smaller to exhibit the same function. The spring parameters can be changed to offer a wide range of assistive and resistive forces for different users.
- The final arm model is also conceptualized for delivering exercises to shoulder, elbow and wrist joint using the same hardware based mechanism approach which is shown in Appendix II (page no: 215).
- Currently, three joint parameters (joint angle, velocity and torque) are used in order to control the rehabilitation modes of the exoskeleton. More joint parameters can be incorporated into the control system to make it a robust system such that it may allow the exoskeleton to monitor patient's joint spasticity and

pain. The control of the exoskeleton can be made more adaptive since it can help to change the mode of exercises, level of difficulty depending on the patient's requirement. Usually in early stage, post-stroke patients suffer from joint spasticity. Sometimes due to abnormal involuntary movement, muscle becomes stiff and patients may feel joint pain during exercises. Therefore, a feedforward control (Figure 6.1) can be implemented where these three joint parameters are used for feedback control and the additional parameters like spasticity and pain can be considered as disturbances. As a result, the control algorithm can improve the performance of the exoskeleton over simple feedback control because it will consider major disturbances before giving the final control output.

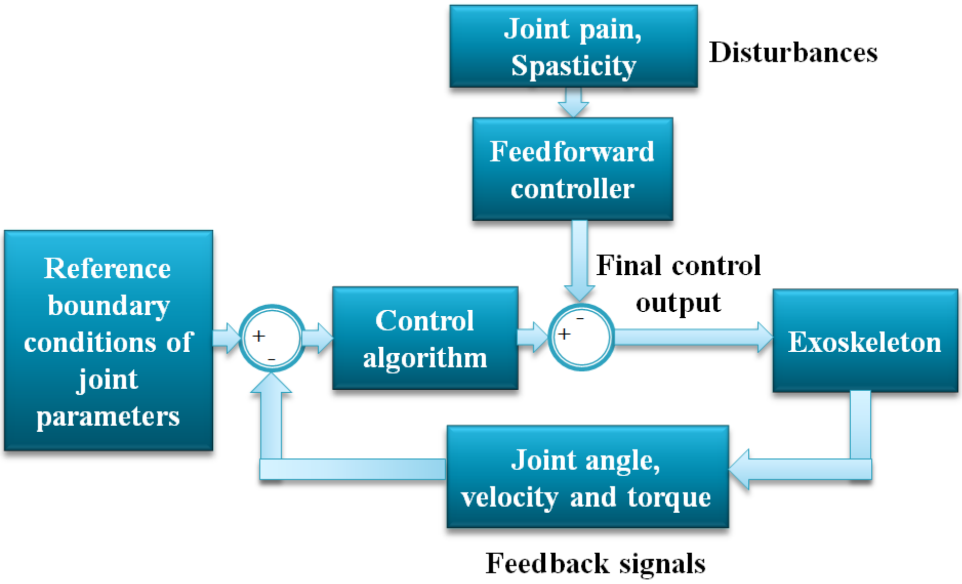


Figure 6.1. Controller with unmeasured disturbances

- Further research on Kinect-based therapy will make those exercises more acceptable and clinically useful for patients. More intriguing features (Table 6.2) can be added to the platform to enhance patient engagement in exercises. Also, more attributes like joint stiffness, jerk, spasticity and other useful rehabilitation information (Table 6.3) can be extracted from Kinect sensor to evaluate patient's recovery rate.

Table 6.2. Future user-friendly features of the game

Useful user-interface	**Advantages**
New type of interesting and simple game suitable for post-stroke patients	These types of game can create more interest among the post-stroke patients to drive them back to the exercises.

Useful user-interface	Advantages
Adding a gif or video file showing the standard way of doing exercise	This type of interface will help patients to follow the correct way of practising exercises during post-stroke rehabilitation.
Comparison of measured joint parameters with stored standard database	If a medical database is stored in the game platform based on the demographic parameters of patients, the measured data can be compared with that standard data for a specific user. It will generate a clinical report showing the recovery rate of the patient based on the comparison.
Online connection to the expert	During exercises, this facility can help patients to seek online help from the physiotherapist sitting at a remote clinic.
Group based game activities	The majority of post-stroke patients are usually in old age group (≥60) who are more interested in group based activities rather than alone. If the game window can show the performance scores of all the people involved in a group exercise, it will motivate each other during exercises and also create a competitive environment among them.
Design of clinical scale based on Kinect based joint parameters	Based on the Kinect based joint measurement, a standard clinical scale can be developed for measuring the recovery rate of patients.

Table 6.3. Other useful joint attributes

Joint parameters	Measurement using Kinect sensor
Jerk	It can be measured from the sudden change of joint torque over time.
Stiffness	It can be measured from joint torque and rotation angle.
Spasticity	It can be measured from muscle contraction which depends on the stiffness or tightness of muscles.

- Based on this research, it was shown that Kinect sensor can measure the activity of joint movement with a minimum error of margin. In future, Kinect based joint parameters can be used for controlling the rehabilitation modes of the exoskeleton instead of using physical sensors (Figure 6.2). It can also be used solo for guiding rehabilitation exercise at advanced stages of recovery without using any exoskeleton. It will create a contactless system and self-motivating.

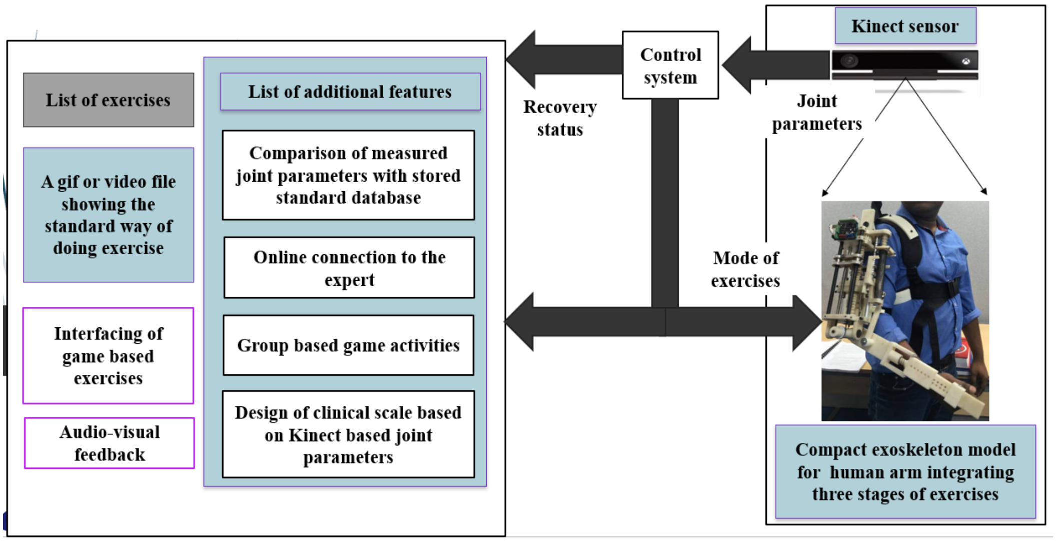


Figure 6.2. A compact exoskeleton model with Kinect based exercises

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Appendix I : Approval of Ethical application

Approved ethical checklist from Bournemouth University

Bournemouth University

Research Ethics Checklist

About Your Checklist	
Ethics ID	27850
Date Created	09/08/2019 16:18:05
Status	Approved
Date Approved	19/12/2019 12:45:46
Date Submitted	19/12/2019 12:41:37
Risk	High

Researcher Details	
Name	Soumya Manna
Faculty	Faculty of Science & Technology
Status	Postgraduate Research (MRes, MPhil, PhD, DProf, EngD, EdD)
Course	Postgraduate Research - FST
Have you received funding to support this research project?	No

Project Details	
Title	Elbow Exoskeleton Mechanism for Multistage Post-Stroke Rehabilitation
Start Date of Project	01/02/2016
End Date of Project	05/04/2020
Proposed Start Date of Data Collection	24/09/2019
Original Supervisor	Venky Dubey
Approver	Research Ethics Panel

Summary - no more than 500 words (including detail on background methodology, sample, outcomes, etc.)

In the last two decades, the mortality rate due to stroke has increased as per the statistics provided by WHO (World Health Organization). Patients suffering from stroke usually lose their muscle functions. Such occurrences may lead to loss of power or complete paralysis of limbs if left unused in the acute phase. It is recommended that intensive occupational therapy in the early stages can provide superior rehabilitation to the affected limb. The process of post-stroke rehabilitation consists of a series of biomechanical exercises, however, it can be categorized into three phases: controlled joint movement in acute phase; external assistance in the mid phase; and variable levels of resistance in the last phase. Post-stroke rehabilitation performed by physiotherapist has many limitations including cost, time, repeatability and intensity of exercises. Although a large variety of arm exoskeletons (external robotic device fitted to human body) have been developed in the last two decades to substitute the conventional exercises provided by physiotherapist, most of these systems have limitations with structural configuration, sensory data acquisition and control architecture. Therefore, it is very difficult to facilitate multistage post-stroke exercises using existing exoskeletons for the patients suffering from acute to the last stage after stroke.

So, a framework for elbow exoskeleton has been developed for upper arm exoskeleton that has the potential to offer better outcomes than the existing exoskeletons because it does not only deliver all three types of exercises (external force, assistive and resistive) in a

single structure but makes it portable and energy-efficient system. This design concept could lead to an engineering solution of integrating three phases of post-stroke exercises in a single device. Joint angle during movement can be measured by a sensor connected to the exoskeleton and by a Kinect sensor (Microsoft XBOX) using motion capture technique. All exoskeleton components are integrated into a microcontroller for measuring the joint parameters and controlling the exercises. To evaluate the efficiency of the developed exoskeleton and to proof the design concept, we would like to test the exoskeleton with few healthy users. Users can move their elbow joint in front of the Kinect sensor by wearing the exoskeleton. Kinect sensor is used to estimate the measurement accuracy of the exoskeleton. The main aim of the experiment is to analyse the working principle of the exoskeleton, whether the device can facilitate three types of exercise in different modes. The wearability of the exoskeleton can be determined by the opinion of the users through a post-experiment survey.

Filter Question: Does your study involve Human Participants?

Participants	
Describe the number of participants and specify any inclusion/exclusion criteria to be used	
Maximum number of participants: FiveEligibility criteria: The participant1.is above 18 years old.2.should not have any medical history for the last 5 years (stroke, Parkinson, neurological disorder, fatal accident, brain damage)3.should not have any problem with arm movement4.should not have any injury on both arms	
Do your participants include minors (under 16)?	
Are your participants considered adults who are competent to give consent but considered vulnerable?	No
Is a Disclosure and Barring Service (DBS) check required for the research activity?	No

Recruitment	
Please provide details on intended recruitment methods, include copies of any advertisements.	
We will only recruit healthy subjects without having any medical complicacy and they will be contacted via email address to take part in the experiment. All data (users email addresses and names) will be kept confidential at a BU password-protected secure network as the current experiment takes place. After the experiment, names and email addresses of the participants will be made anonymised by assigning a participant number.	
Do you need a Gatekeeper to access your participants?	No

Data Collection Activity	
Will the research involve questionnaire/online survey? If yes, don't forget to attach a copy of the questionnaire/survey or sample of questions.	Yes
How do you intend to distribute the questionnaire?	
face to face	
Will the research involve interviews? If Yes, don't forget to attach a copy of the interview questions or sample of questions	No
Will the research involve a focus group? If yes, don't forget to attach a copy of the focus group questions or sample of questions.	No
Will the research involve the collection of audio materials?	No
Will your research involve the collection of photographic materials?	Yes
Will your research involve the collection of video materials/film?	Yes
Will any photographs, video recordings or film identify an individual?	Yes

Please provide details	
The original photographs will include the room set-up which consist the image of the participant , however, the face will be blurred in any images including any outputs.	
Will any audio recordings (or non-anonymised transcript), photographs, video recordings or film be used in any outputs or otherwise made publicly available?	No
Will the study involve discussions of sensitive topics (e.g. sexual activity, drug use, criminal activity)?	No
Will any drugs, placebos or other substances (e.g. food substances, vitamins) be administered to the participants?	No
Will the study involve invasive, intrusive or potential harmful procedures of any kind?	No
Could your research induce psychological stress or anxiety, cause harm or have negative consequences for the participants or researchers (beyond the risks encountered in normal life)?	No
Will your research involve prolonged or repetitive testing?	No

Consent

Describe the process that you will be using to obtain valid consent for participation in the research activities. If consent is not to be obtained explain why.	
First of all, participants will be provided with the Participant Information Sheet before taking part in the experiment. Participant Agreement Form will be collected from the participants once they confirm to take part in the experiment after reading and agreeing with the terms & condition provided in the Participant Information Sheet.	
Do your participants include adults who lack/may lack capacity to give consent (at any point in the study)?	
Will it be necessary for participants to take part in your study without their knowledge and consent?	No

Participant Withdrawal

At what point and how will it be possible for participants to exercise their rights to withdraw from the study?	All information will be provided in the Participant Information Sheet and participants will be provided with that information before taking part in the experiment. It is clearly mentioned that participants can withdraw from participation at any time without giving any reason, where the data are processed and become anonymous, so their identity cannot be determined. Deciding to take part or not will not affect their treatment/care /education or studies at BU.
If a participant withdraws from the study, what will be done with their data?	Participant's data will be deleted immediately.

Participant Compensation

Will participants receive financial compensation (or course credits) for their participation?	No
Will financial or other inducements (other than reasonable expenses) be offered to participants?	No

Research Data

Will identifiable personal information be collected, i.e. at an individualised level in a form that identifies or could enable identification of the participant?	Yes
Please give details of the types of information to be collected, e.g. personal characteristics, education, work role, opinions or experiences	

The original photographs of the participants. some demographic information will be collected such as weight and height.

Will the personal data collected include any special category data, or any information about actual or alleged criminal activity or criminal convictions which are not already in the public domain?	Yes
If Yes, please give details of the information you will be collecting	
Height and weight only	
Will the information be anonymised/de-identified at any stage during the study?	Yes
Will research outputs include any identifiable personal information i.e. data at an individualised level in a form which identifies or could enable identification of the individual?	No

Storage, Access and Disposal of Research Data

During the study, what data relating to the participants will be stored and where?	The original photographs and few demographic data (Height and Weight only) of the participants will be collected and stored in the BU PC and data will be backed up to the BU one-cloud network (password-protected). The participants will be assigned by number so will not be identifiable by any means.
How long will the data relating to participants be stored?	The data will be stored until the PhD thesis is re-examined (5th May 2020 approx).
During the study, who will have access to the data relating to participants?	Researcher (my-self) and Supervisor
After the study has finished, what data relating to participants will be stored and where? Please indicate whether data will be retained in identifiable form.	The identifiable photographs and demographic data (Height and Weight only) of the participants will be stored in the BU PC and backed up by BU one-cloud (password - protected).
After the study has finished, how long will data relating to participants be stored?	The data will be stored until the PhD thesis is re-examined (5th May 2020 approx).
After the study has finished, who will have access to the data relating to participants?	Researcher (my-self) and Supervisor
Will any identifiable participant data be transferred outside of the European Economic Area (EEA)?	No
How and when will the data relating to participants be deleted/destroyed?	After the PhD thesis is re-examined, the data related to the participants will be deleted/destroyed (5th May 2020 approx).
Once your project completes, will any anonymised research data be stored on BU's Online Research Data Repository "BORDaR"?	No
Please explain why you do not intend to deposit your research data on BORDaR? E.g. do you intend to deposit your research data in another data repository (discipline or funder specific)? If so, please provide details.	
The data will not be required after the thesis is re-examined, no plans for the anonymized data to be stored.	

Dissemination Plans

How do you intend to report and disseminate the results of the study?
Peer reviewed journals,Conference presentation,Other Publication,Other

If Other, please provide details.	
Thesis	
Will you inform participants of the results?	No
If Yes or No, please give details of how you will inform participants or justify if not doing so	
No formal plans to inform them. There will be option if they contact regarding the experiment.	

Final Review	
Are there any other ethical considerations relating to your project which have not been covered above?	No

Risk Assessment	
Have you undertaken an appropriate Risk Assessment?	Yes

Attached documents
Participant Information Sheet.docx - attached on 11/08/2019 14:32:04
Participant Agreement Form.docx - attached on 11/08/2019 14:32:10
Post Experiment Survey.docx - attached on 11/08/2019 14:33:02

Participant Information Sheet

The title of the research project

Elbow Exoskeleton Mechanism for Multistage Post-Stroke Rehabilitation

Invitation to take part

You are being invited to take part in a research project. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Who is organising/funding the research?

This research is being funded by Bournemouth University.

What is the purpose of the project?

The purpose of this project is to design a structural framework of exoskeleton for providing three different types of exercise: external force, assistive force and resistive force using a mechanical model which could be a potential solution for providing post-stroke rehabilitation in future.

As per the report of Stroke Association UK, there are about 1.2 million stroke survivors in the UK. The annual health and social costs of caring for disabled stroke patients are estimated to be more than £5 billion in the UK. People who suffered from stroke, part of their body may be paralysed. Arm disability is very common when the sufferer is not able to conduct their activities of daily living. In the initial phases of paralysis, they have been provided with physical movement by physiotherapists to regain the lost arm functions. Such physical movements are varied over time for early recovery. However, there is always inadequate therapy and lack of trained staff to provide a wide range of arm movement.

My research provides a design concept for developing a support system (called Exoskeleton) that can be mounted on the arm to facilitate therapy. The device operates in three modes (external force, assistive force and resistive force) as required by physiotherapist. To validate the mechanism and proposed methodology, we would like to test this device with healthy subjects (maximum five participants). The main motive of the experiment is to prove the design principle of the developed exoskeleton.

At the end of the experiment, users will be asked to fill up a small survey of two questions related to the wearability and ease of using the exoskeleton.

Why have I been chosen?

You have been approached to take part in this study as an adult volunteer without any medical complicacy. The maximum number of participants is five.

You are eligible to participate in this study only if you are

1. above 18 years old.

2. Should not have any medical history for the last 5 years (stroke, Parkinson, neurological disorder, fatal accident, brain damage)
3. Should not have any problem with arm movement
4. Should not have any injury on both arms

Do I have to take part?

It is up to you to decide whether or not to take part. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a participant agreement form. We want you to understand what participation involves, before you make a decision on whether to participate.
If you or any family member have an on-going relationship with BU or the research team, e.g. as a member of staff, as student or other service user, your decision on whether to take part (or continue to take part) will not affect this relationship in any way.

Can I change my mind about taking part?
Yes, you can stop participating in study activities at any time and without giving a reason.

If I change my mind, what happens to my information?
After you decide to withdraw from the study, we will not collect any further information from or about you.
As regards information we have already collected before this point, your rights to access, change or move that information are limited. This is because we need to manage your information in specific ways in order for the research to be reliable and accurate. Further explanation about this is in the Personal Information section below.

What would taking part involve?

Before the experiment

- You will be asked to relax.
- Once you are relaxed and ready, the test will start which will take approximately 5 minutes.

During the experiment

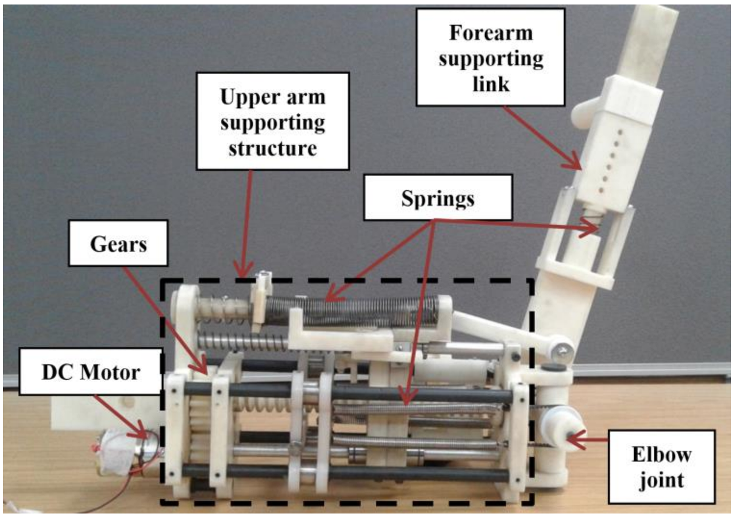
- You will be given a Participant Information Sheet (this form) about the study.
- You will be given the consent form to be agreed with the terms and condition of the experiment.
- Once you are agreed, you will be invited to take part in an experiment where the joint movement of your right arm will be recorded using an exoskeleton (Figure 1 a & b) and Kinect sensor (Microsoft XBOX, Figure 2).

Once ready

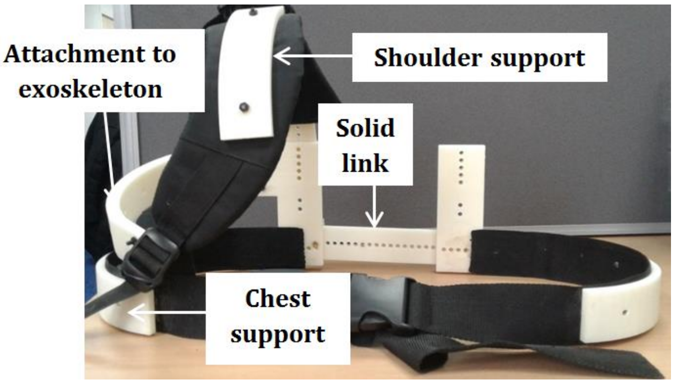
- You will wear the developed elbow exoskeleton on your right arm and be standing in front of the Kinect sensor (Microsoft XBOX), as shown in Figure 2.
- You will be asked to move your right arm in three conditions: data from each mode of exercise will be recorded three times.

1. In the first mode (electric motor-controlled mode), you will be asked to keep your arm idle so that electric motor will support fully to rotate your elbow joint.
2. In assistive mode, you will be asked to use your normal strength to rotate your elbow.
3. In resistive mode, you will be asked to use your normal strength to rotate your elbow.

A typical experiment will consist of about 20 minutes of joint movements. The experiments will be performed by experienced university researchers.



a) Elbow exoskeleton



b) Shoulder-based holder

Figure1. Developed prototype of the exoskeleton

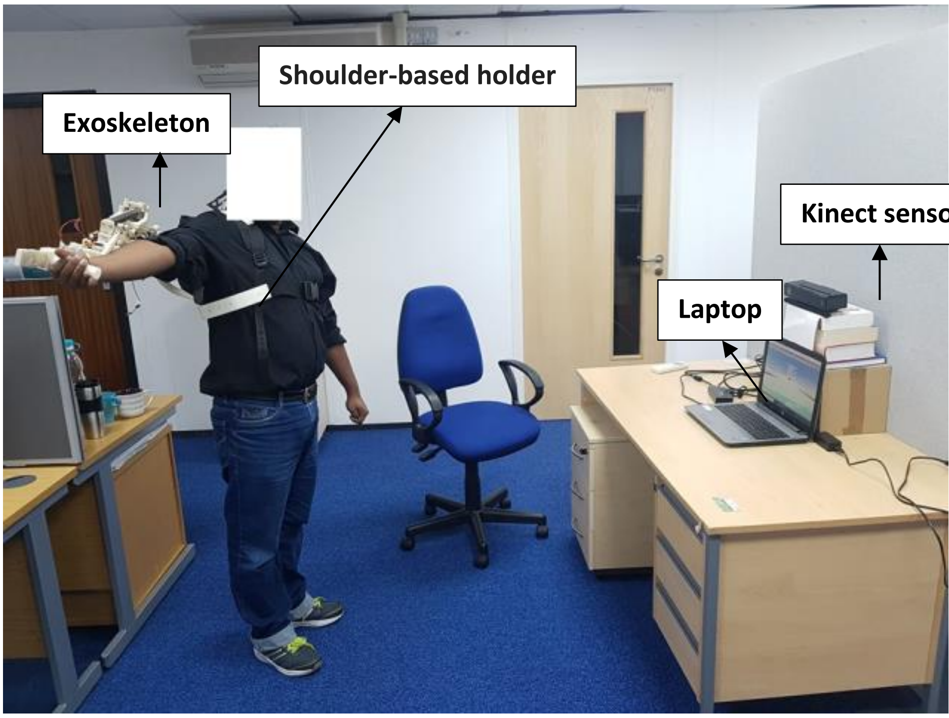


Figure 2. Joint movement of user wearing the exoskeleton in front of Kinect sensor

After the experiment
The exoskeleton will be detached from your body and you will be asked to answer two simple questions related to the use of exoskeleton and then you are free to go.

How long will the questionnaire/online survey take to complete?

It will take maximum 2-3 mins to answer both questions.

What are the advantages and possible disadvantages or risks of taking part?

Whilst there are no immediate benefits for those people participating in the project, it is hoped that this work will provide a long term benefit to post-stroke patients once the efficiency of the developed exoskeleton is proven.
There is a very low risk in the experiment since no physical sensor will be attached to your body and the mechanism is supported by electromechanical safety features (mechanical safety switch and software-controlled protection). The electronic circuit of the developed exoskeleton is driven by battery, so no AC power is involved. The Kinect sensor is connected to the laptop for monitoring joint movement without making any physical contact. You can withdraw at any time if feeling uncomfortable.

What type of information will be sought from me and why is the collection of this information relevant for achieving the research project's objectives?

The data collected are not going to be of a sensitive nature.
During the test, we will collect two types of data; static parameters (weight, height) and dynamic parameters (elbow joint angle of right arm during movement). The small survey consisting of two questions which are based on the wearability and usability of the

exoskeleton. Users can give answers using a scale from 1 to 5 (strongly disagree to strongly agree).
In the beginning, we need user's biomechanics data (weight, height) to design the framework of the structure. During the experiment, we need to measure the joint parameters to prove its working principle. Finally, we need their feedback to evaluate the usefulness of the device.
This test will help us to prove the efficiency of the developed device and this may lead to finding a better robotic solution to provide post-stroke rehabilitation. Your participation is very important in analysing the proof of concept of the developed exoskeleton.

Will I be recorded, and how will the recorded media be used?

The picture and/or video recordings of your activities made during this research will be used only for analysis and the transcription of the recording(s) for illustration in conference presentations and lectures. No other use will be made of them without your written permission, and no one outside the project will be allowed access to the original recordings. We will not collect any identifiable or sensitive information from participants and the participants will be made anonymised by assigning a participant number. In recorded pictures or videos, the face of the participant or any body part which is recognizable will be blurred or removed so that the person participating in the experiment will not be identifiable.

How will my information be managed?

Bournemouth University (BU) is the organisation with overall responsibility for this study and the Data Controller of your personal information, which means that we are responsible for looking after your information and using it appropriately. Research is a task that we perform in the public interest, as part of our core function as a university.

Undertaking this research study involves collecting and/or generating information about you. We manage research data strictly in accordance with:

- Ethical requirements; and
- Current data protection laws. These control use of information about identifiable individuals, but do not apply to anonymous research data: "anonymous" means that we have either removed or not collected any pieces of data or links to other data which identify a specific person as the subject or source of a research result.

BU's Research Participant Privacy Notice sets out more information about how we fulfil our responsibilities as a data controller and about your rights as an individual under the data protection legislation. We ask you to read this Notice so that you can fully understand the basis on which we will process your personal information.

Research data will be used only for the purposes of the study or related uses identified in the Privacy Notice or this Information Sheet. To safeguard your rights in relation to your personal information, we will use the minimum personally-identifiable information possible and control access to that data as described below.

Publication
You will not be able to be identified in any external reports or publications about the research means your information will only be included in these materials in an anonymous form.

Research results will be published in academic articles (conferences and journals).

Security and access controls
BU will hold the information we collect about you in hard copy in a secure location and on a BU password protected secure network where held electronically.

Further use of your information
The information collected about you may be used in an anonymous form to support other research projects in the future and access to it in this form will not be restricted. It will not be possible for you to be identified from this data. To enable this use, anonymised data will be added to BU's Data Repository: this is a central location where data is stored, which is accessible to the public.

Keeping your information if you withdraw from the study
If you withdraw from active participation in the study we will keep information which we have already collected from or about you, if this has on-going relevance or value to the study. This may include your personal identifiable information. As explained above, your legal rights to access, change, delete or move this information are limited as we need to manage your information in specific ways in order for the research to be reliable and accurate. However if you have concerns about how this will affect you personally, you can raise these with the research team when you withdraw from the study.

You can find out more about your rights in relation to your data and how to raise queries or complaints in our Privacy Notice.

Retention of research data

Project governance documentation, including copies of signed **participant agreements**: we keep this documentation for a long period after completion of the research, so that we have records of how we conducted the research and who took part. The only personal information in this documentation will be your name and signature, and we will not be able to link this to any anonymised research results.

Research results:
As described above, during the course of the study we will anonymise the information we have collected information about you as an individual. This means that we will not hold your personal information in identifiable form after we have completed the research activities.

You can find more specific information about retention periods for personal information in our Privacy Notice.

We keep anonymised research data indefinitely, so that it can be used for other research as described above.

Contact for further information

If you have any questions or would like further information, please contact
Prof. Venky Dubey by email on VDubey@bournmeouth.ac.uk or by phone on 01202 965986 or by post to:

Prof. Venky Dubey
Faculty of Science and Technology
Bournemouth University
BH12 5BB

In case of complaints
Any concerns about the study should be directed to Prof. Venky Dubey. If your concern has not been answered by Prof. Venky Dubey, you should contact Professor Tiantian Zhang, Deputy Dean - Research & Professional Practice, Faculty of Science and Technology, Bournemouth University by email to researchgovernance@bournemouth.ac.uk.

Finally

If you decide to take part, you will be given a copy of the information sheet and a signed participant agreement form to keep.

Thank you for considering taking part in this research project.

Participant Agreement Form

Full title of project: Elbow Exoskeleton Mechanism for Multistage Post-Stroke Rehabilitation

Name, position and contact details of researcher: Soumya Kanti Manna, Postgraduate researcher, Department of Design & Engineering, Faculty of Science & Technology, Bournemouth University
Email: smanna@bournemouth.ac.uk

Name, position and contact details of supervisor: Prof. Venky Dubey, Faculty of Science & Technology, Bournemouth University
Email: VDubey@bournmeouth.ac.uk

To be completed prior to data collection activity
Section A: Agreement to participate in the study

You should only agree to participate in the study if you agree with all of the statements in this table and accept that participating will involve the listed activities.

I have read and understood the Participant Information Sheet (STAFF_PGR & v 6) and have been given access to the BU Research Participant Privacy Notice which sets out how we collect and use personal information (https://www1.bournemouth.ac.uk/about/governance/access-information/data-protection-privacy).	
I have had an opportunity to ask questions.	
I understand that my participation is voluntary. I can stop participating in research activities at any time without giving a reason and I am free to decline to answer any particular question(s).	
I agree that BU researchers may access information my medical records as described in the Participant Information Sheet	
I understand that, if I withdraw from the study, I will also be able to withdraw my data from further use in the study **except** where my data has been anonymised (as I cannot be identified) or it will be harmful to the project to have my data removed.	
I understand that my data may be used in an anonymised form by the research team to support other research projects in the future, including future publications, reports or presentations.	
	Initial box to agree
I consent to take part in the project on the basis set out above (Section A)	

Section B: The following parts of the study are optional

You can decide about each of these activities separately. Even if you do not agree to any of these activities you can still take part in the study. If you do not wish to give permission for an activity, do not initial the box next to it.

		Initial boxes to agree
	I agree to being filmed during the Project.	
	I agree to being photographed during the Project.	
	I agree for my photograph to be included in research outputs.	
	I agree to being featured in any film which will be made as part of this research Project and may be broadcast publicly or shown to third parties.	

I confirm my agreement to take part in the project on the basis set out above.

Name of participant (BLOCK CAPITALS)	Date (dd/mm/yyyy)	Signature
Name of researcher (BLOCK CAPITALS)	Date (dd/mm/yyyy)	Signature

Post experiment survey

Full title of project: Elbow Exoskeleton Mechanism for Multistage Post-Stroke Rehabilitation

Name, position and contact details of researcher: Soumya Kanti Manna, Postgraduate researcher, Department of Design & Engineering, Faculty of Science & Technology, Bournemouth University. Email: smanna@bournemouth.ac.uk

Participant no.--------

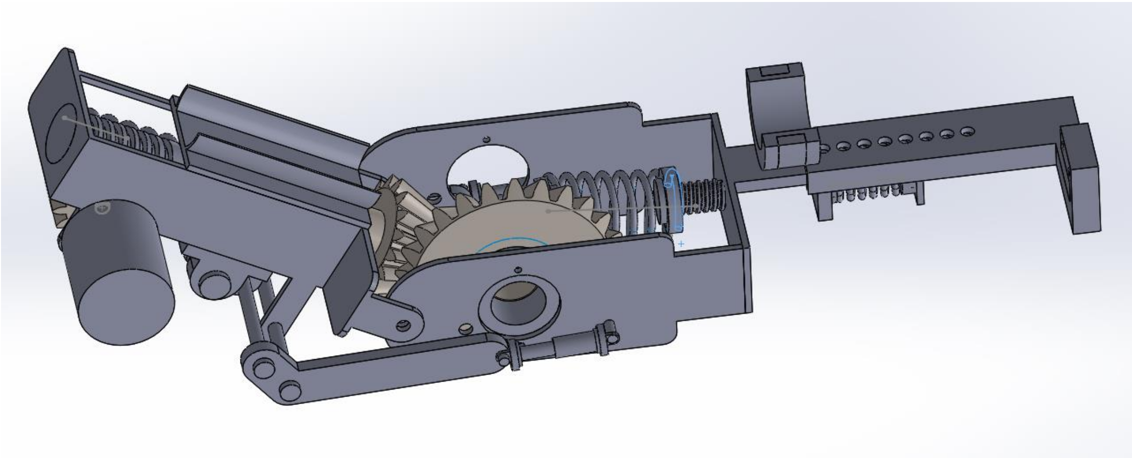
Did you feel the exoskeleton is wearable?

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

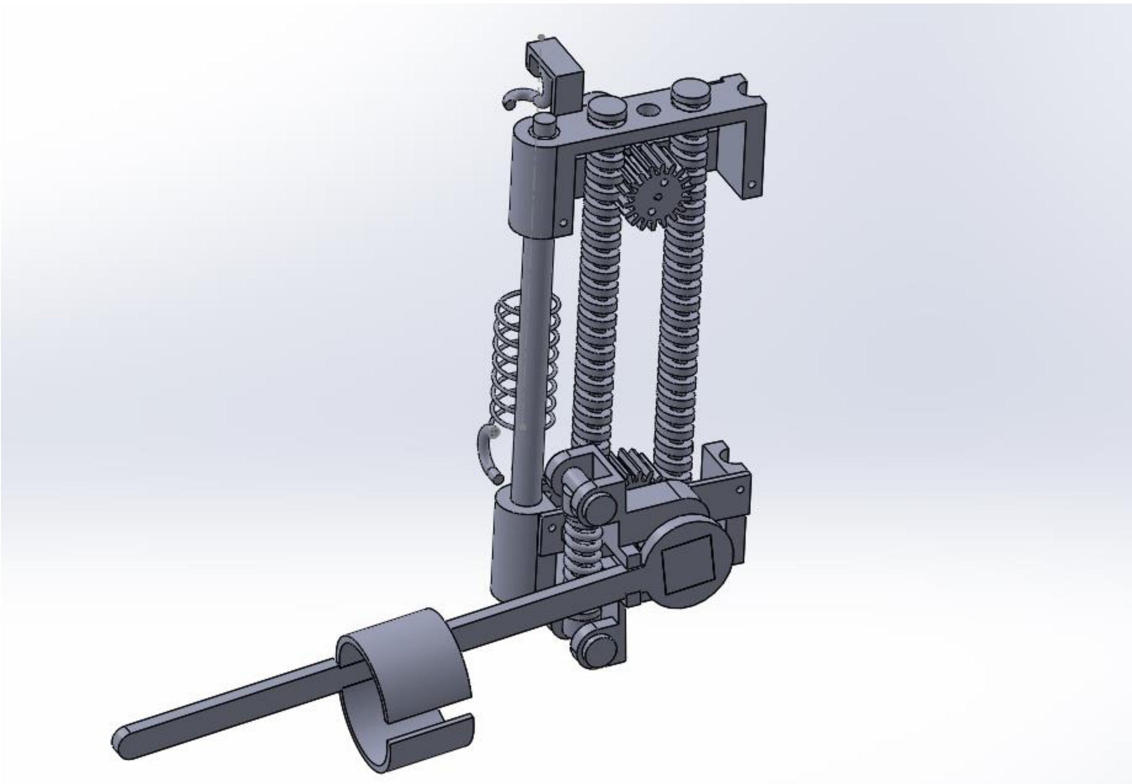
Did you find it easy to use the exoskeleton?

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

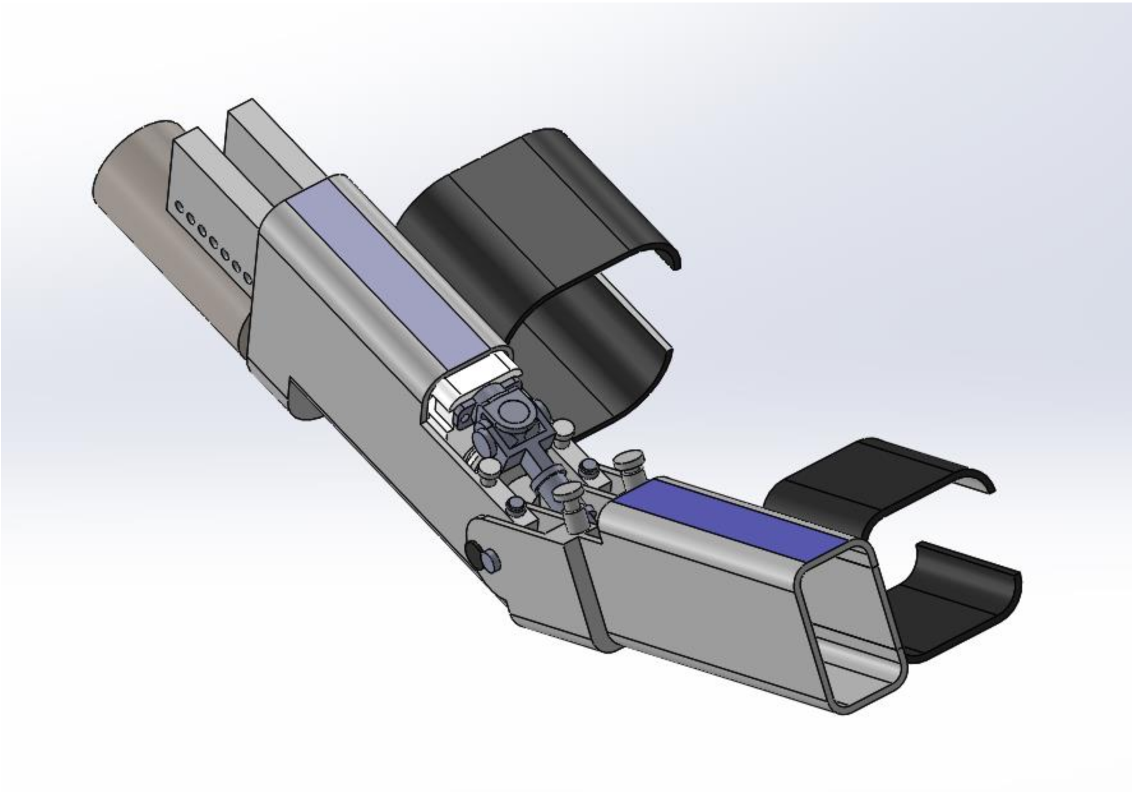
Appendix II : Solidworks models of exoskeleton



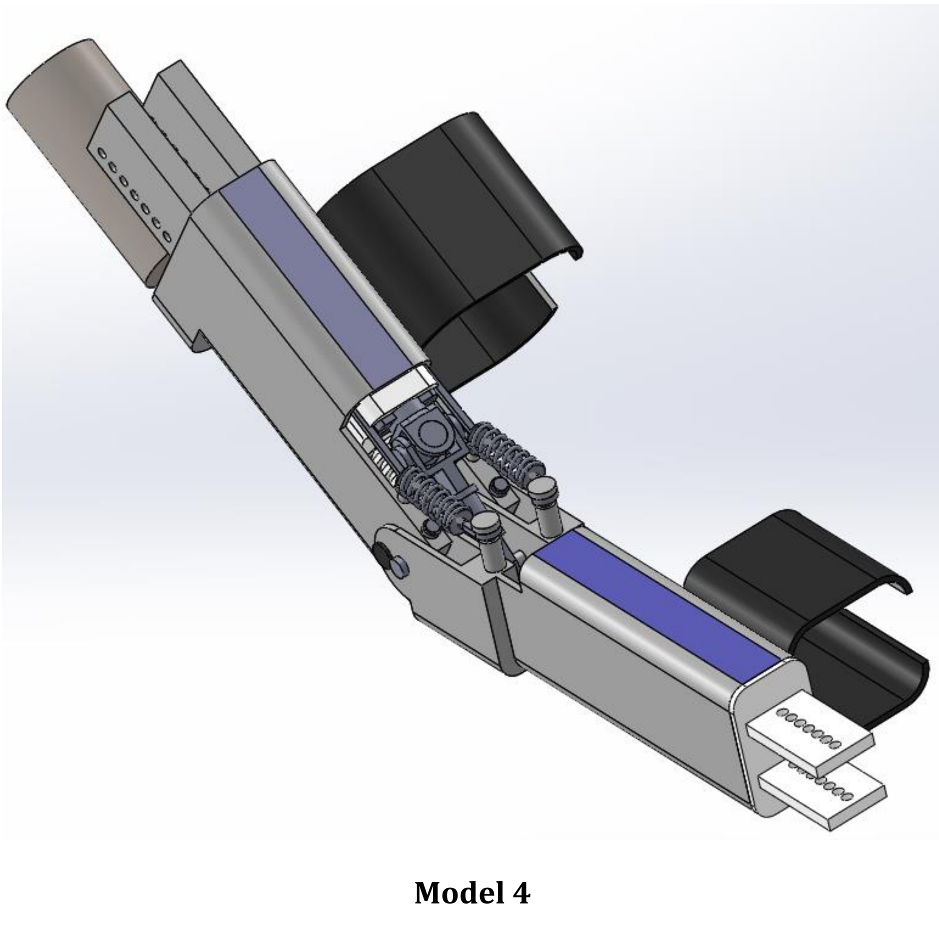
Model 1



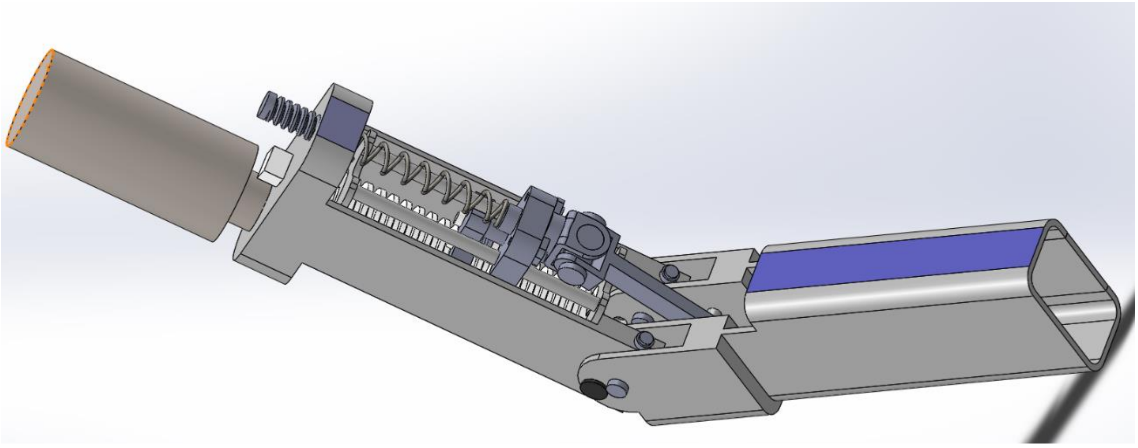
Model 2



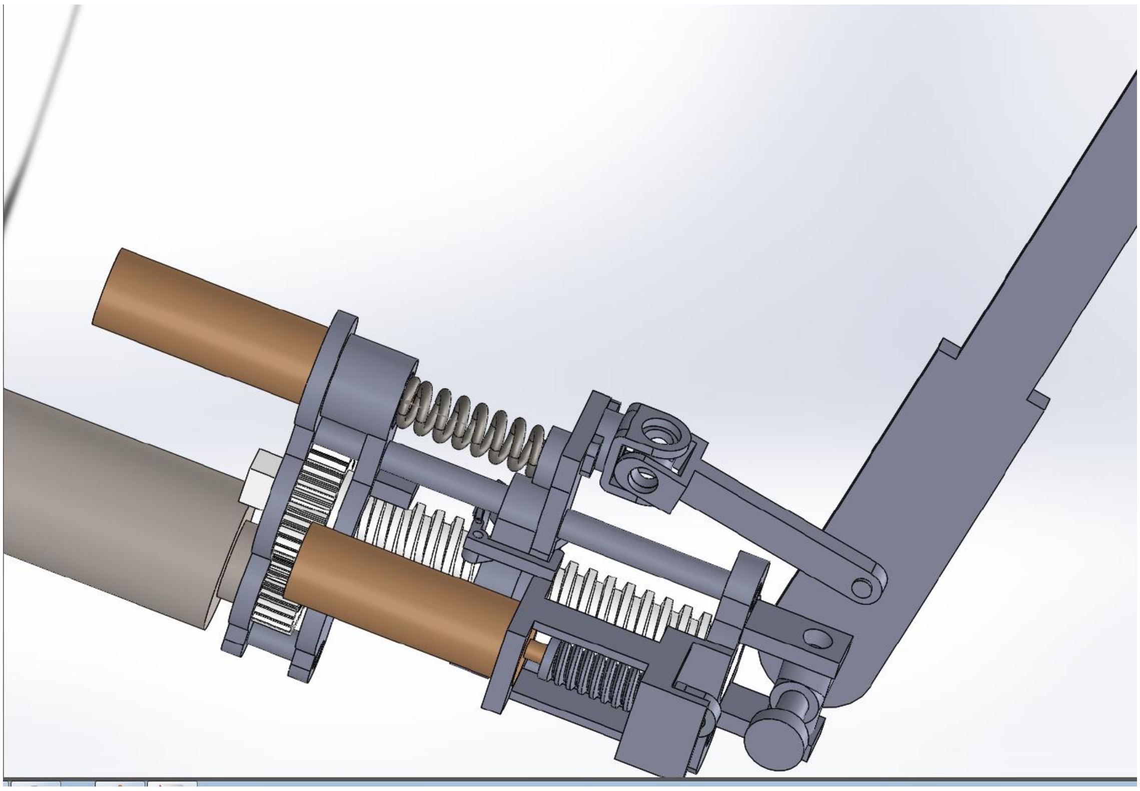
Model 3



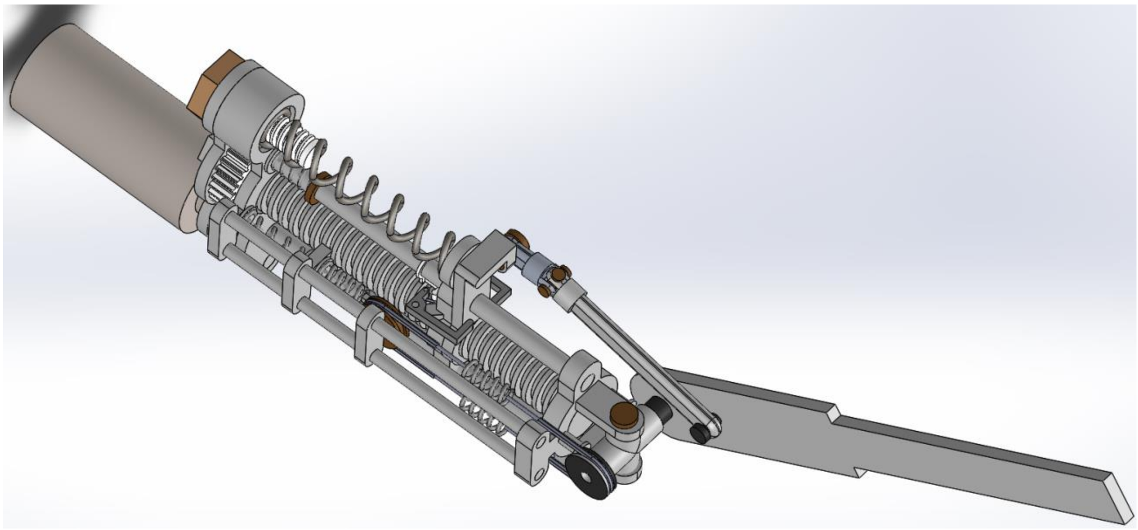
Model 4



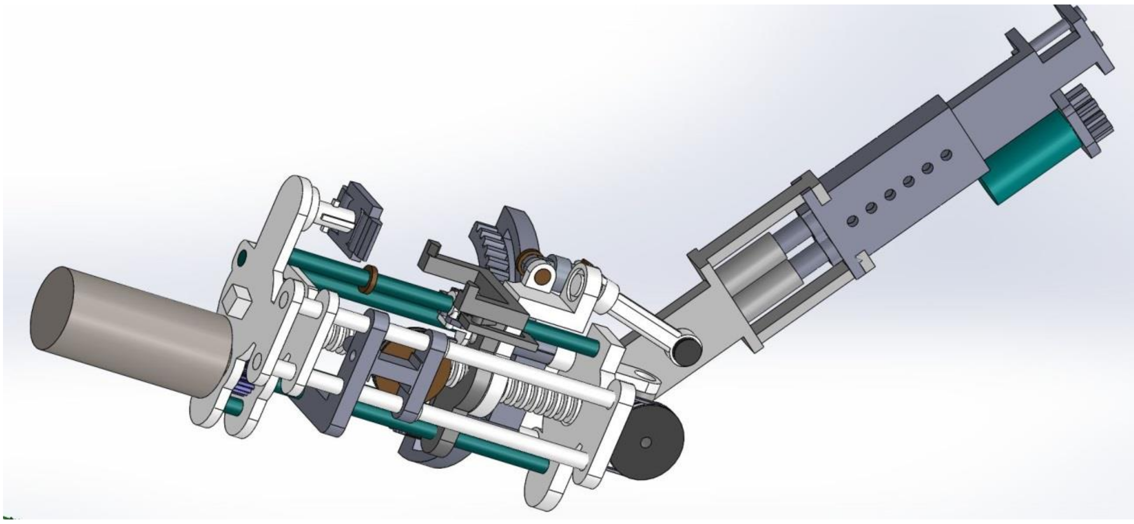
Model 5



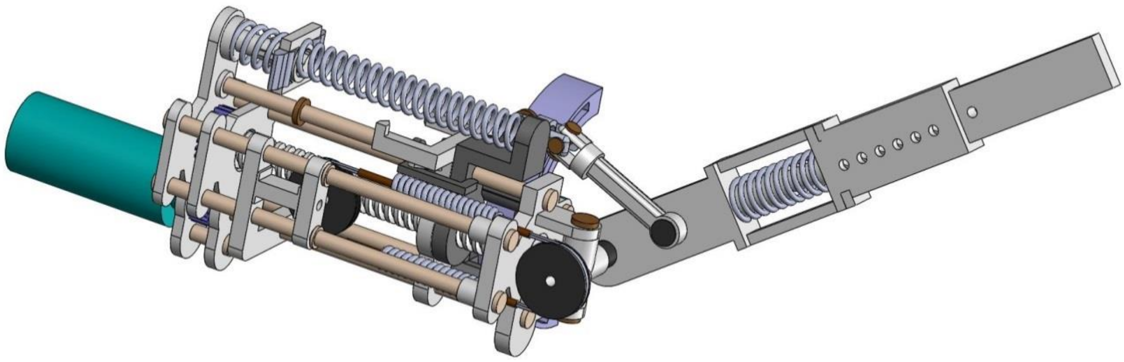
Model 6



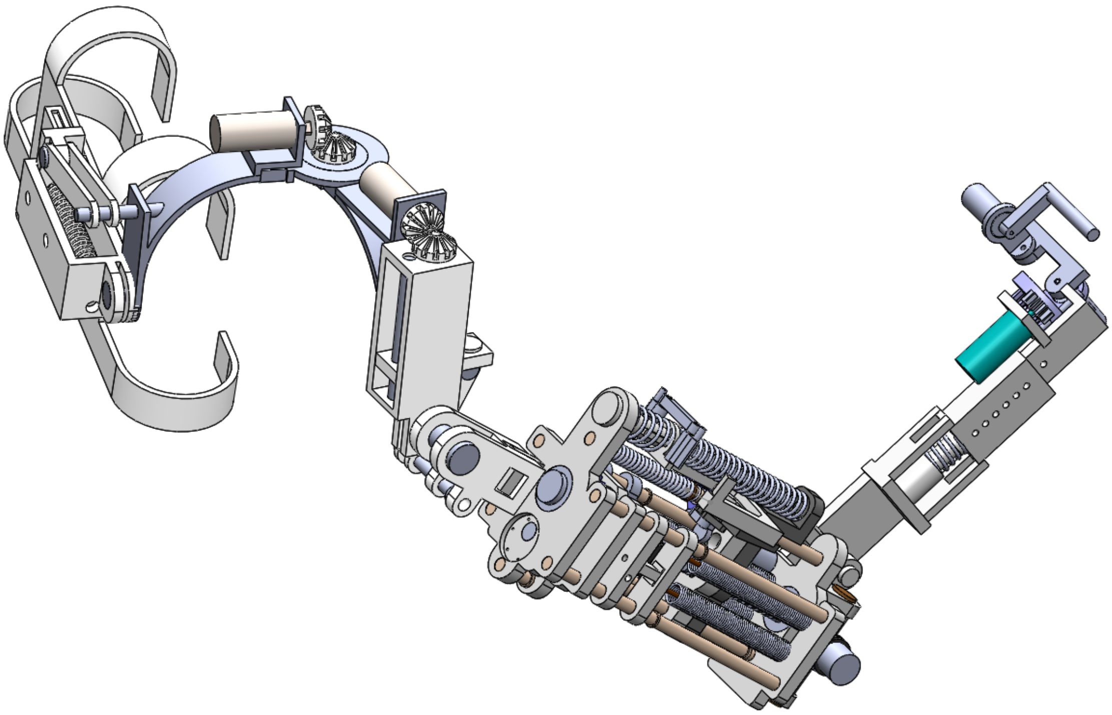
Model 7



Model 8



Model 9



Proposed full arm exoskeleton model

Appendix III : Datasheets

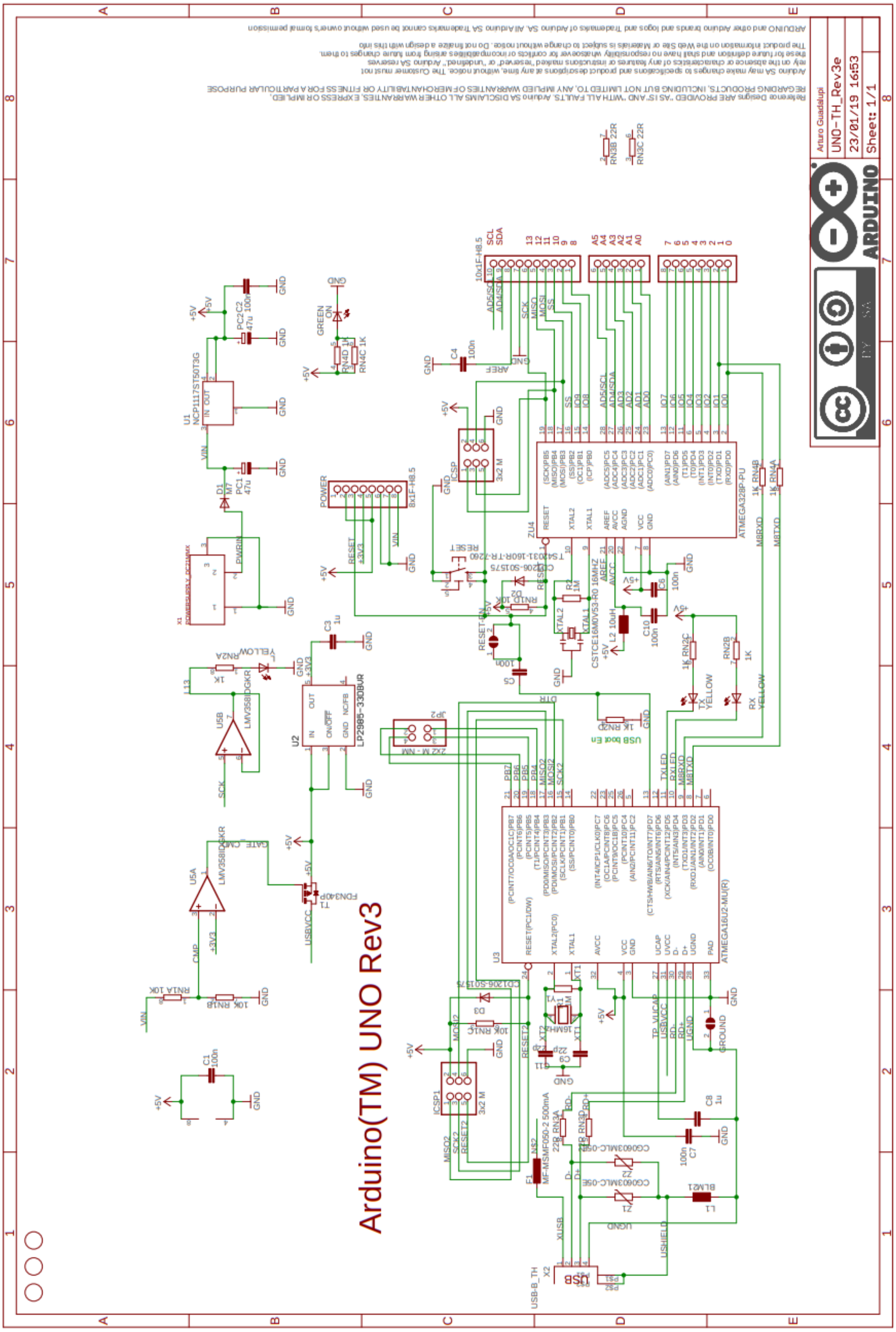
1. Arduino board

- **Technical Specification**

OVERVIEW TECH SPECS DOCUMENTATION

Microcontroller	ATmega328P
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limit)	6-20V
Digital I/O Pins	14 (of which 6 provide PWM output)
PWM Digital I/O Pins	6
Analog Input Pins	6
DC Current per I/O Pin	20 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32 KB (ATmega328P) of which 0.5 KB used by bootloader
SRAM	2 KB (ATmega328P)
EEPROM	1 KB (ATmega328P)
Clock Speed	16 MHz
LED_BUILTIN	13
Length	68.6 mm
Width	53.4 mm
Weight	25 g

- **Schematic diagram**



2. Microcontroller (Atmega328P)

- **Technical Specification**

MICROCHIP

ATmega48A/PA/88A/PA/168A/PA/328/P

megaAVR® Data Sheet

Introduction

The ATmega48A/PA/88A/PA/168A/PA/328/P is a low power, CMOS 8-bit microcontrollers based on the AVR® enhanced RISC architecture. By executing instructions in a single clock cycle, the devices achieve CPU throughput approaching one million instructions per second (MIPS) per megahertz, allowing the system designer to optimize power consumption versus processing speed.

Features

- High Performance, Low Power AVR® 8-Bit Microcontroller Family
- Advanced RISC Architecture
  - 131 Powerful Instructions – Most Single Clock Cycle Execution
  - 32 x 8 General Purpose Working Registers
  - Fully Static Operation
  - Up to 20 MIPS Throughput at 20MHz
  - On-chip 2-cycle Multiplier
- High Endurance Non-volatile Memory Segments
  - 4/8/16/32KBytes of In-System Self-Programmable Flash program memory
  - 256/512/512/1KBytes EEPROM
  - 512/1K/1K/2KBytes Internal SRAM
  - Write/Erase Cycles: 10,000 Flash/100,000 EEPROM
  - Data retention: 20 years at 85°C/100 years at 25°C[1]
  - Optional Boot Code Section with Independent Lock Bits
    - In-System Programming by On-chip Boot Program
    - True Read-While-Write Operation
  - Programming Lock for Software Security
- QTouch® library support
  - Capacitive touch buttons, sliders and wheels
  - QTouch and QMatrix™ acquisition
  - Up to 64 sense channels
- Peripheral Features
  - Two 8-bit Timer/Counters with Separate Prescaler and Compare Mode
  - One 16-bit Timer/Counter with Separate Prescaler, Compare Mode, and Capture Mode

 Data Sheet Complete DS40002061A-page 1

- Real Time Counter with Separate Oscillator
- Six PWM Channels
- 8-channel 10-bit ADC in TQFP and QFN/MLF package
  - Temperature Measurement
- 6-channel 10-bit ADC in PDIP Package
  - Temperature Measurement
- Programmable Serial USART
- Master/Slave SPI Serial Interface
- Byte-oriented 2-wire Serial Interface (Philips I^2C compatible)
- Programmable Watchdog Timer with Separate On-chip Oscillator
- On-chip Analog Comparator
- Interrupt and Wake-up on Pin Change

- Special Microcontroller Features
  - Power-on Reset and Programmable Brown-out Detection
  - Internal Calibrated Oscillator
  - External and Internal Interrupt Sources
  - Six Sleep Modes: Idle, ADC Noise Reduction, Power-save, Power-down, Standby, and Extended Standby
- I/O and Packages
  - 23 Programmable I/O Lines
  - 28-pin PDIP, 32-lead TQFP, 28-pad QFN/MLF and 32-pad QFN/MLF
- Operating Voltage:
  - 1.8 - 5.5V
- Temperature Range:
  - -40°C to 85°C
- Speed Grade:
  - 0 - 4MHz@1.8 - 5.5V, 0 - 10MHz@2.7 - 5.5.V, 0 - 20MHz @ 4.5 - 5.5V
- Power Consumption at 1MHz, 1.8V, 25°C
  - Active Mode: 0.2mA
  - Power-down Mode: 0.1μA
    - Power-save Mode: 0.75μA (Including 32kHz RTC)

1. Pin Configurations

Figure 1-1. Pinout ATmega48A/PA/88A/PA/168A/PA/328/P

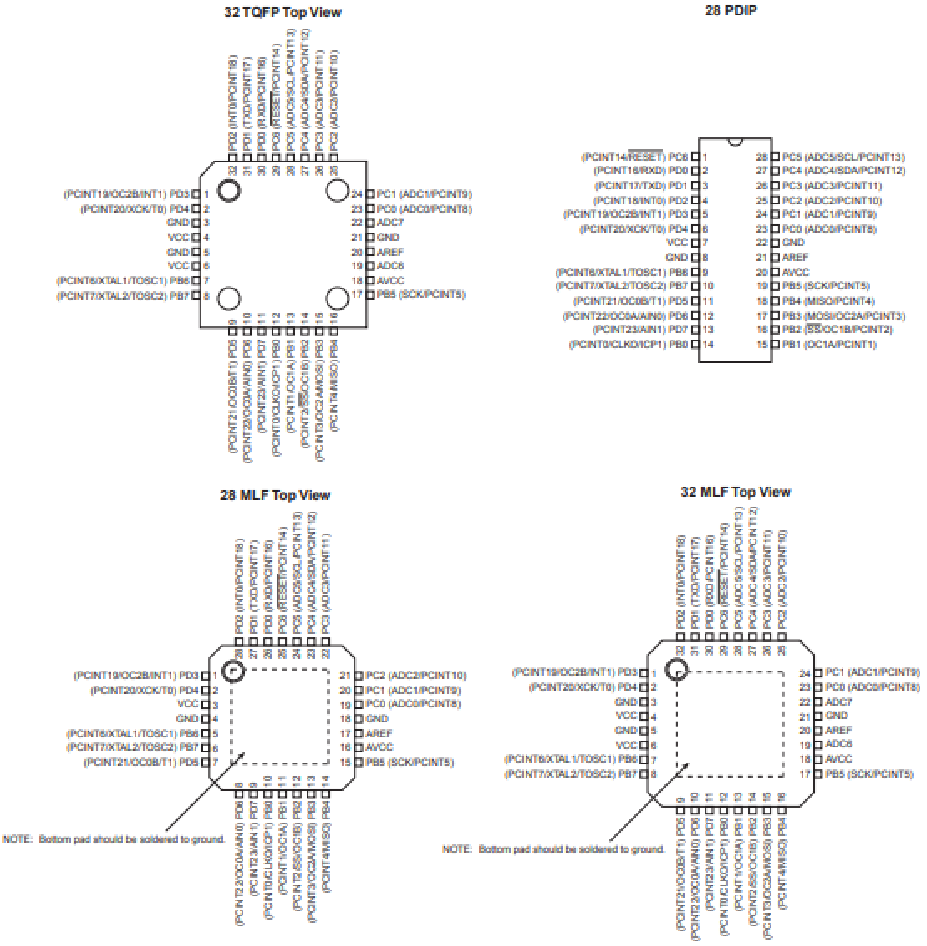


Table 1-1. 32UFBGA - Pinout ATmega48A/48PA/88A/88PA/168A/168PA

	1	2	3	4	5	6
A	PD2	PD1	PC6	PC4	PC2	PC1
B	PD3	PD4	PD0	PC5	PC3	PC0
C	GND	GND			ADC7	GND
D	VDD	VDD			AREF	ADC6
E	PB6	PD6	PB0	PB2	AVDD	PB5
F	PB7	PD5	PD7	PB1	PB3	PB4

3. DC motor (ZYTD520)

- **Technical Specification**

Metal DC Geared Motor - 12V 50RPM 50kg.cm

SKU:FIT0492-A Brand:Other

Tags: FIT0492 | FIT0492-A | gear motor | DC motor | Geared motor

Related Categories: All Products | Motors & Actuators & Drivers | DC Motors | Modules

ADD TO WISHLIST

Frequently Bought Together

Metal DC Geared Motor - 12V 50.....

MDV 2x2A DC Motor Controller (.....

2x2A DC Motor Shield for Ardui.....

DFRduino UNO R3 - Arduino Comp.....

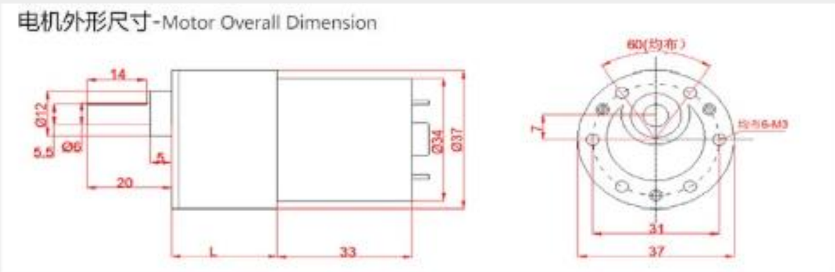
You have choosen:1

Total amount:$11.9

BUY NOW

INTRODUCTION

This is a metal DC geared motor, 100% pure copper coils, high-density molecular layer, 100:1 metal reducer, small size, large torque. The maximum torque could arrive 50 kg.cm, stable and durable!



SPECIFICATION

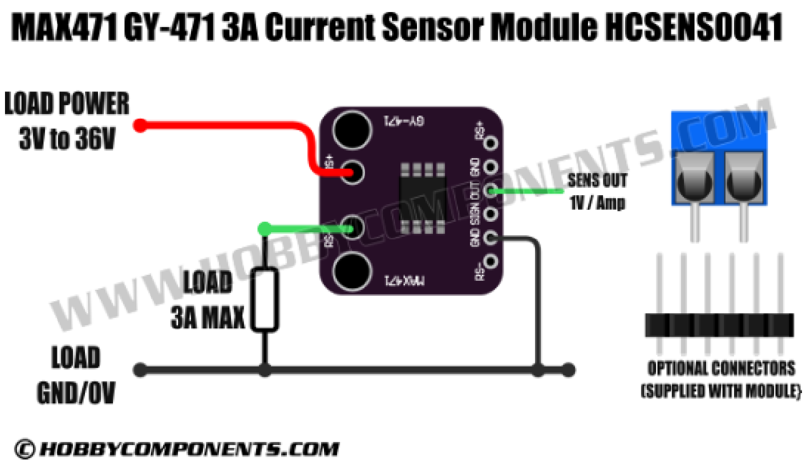
- Rated voltage: 12 V
- Gear reduction ratio: 100:1
- D output shaft diameter: 6 mm
- No-load speed: 50 RPM @ 12 v
- No-load current: 0.17 A
- Rated speed: 45 RPM @ 12 v
- Current rating: 0.68 A
- Rated torque: 9 kg.cm
- Locked-rotor torque: 50 kg.cm
- Locked-rotor current: 2.19 A
- Power: 5W
- Weight: 210 g

4. Current sensor (GY -471)

- ### Technical Specification

The MAX471 module (HCSENS0041) is a complete, bidirectional, highside current-sense amplifier for portable PCs, telephones, and other systems where battery/DC power-line monitoring is critical. High-side power-line monitoring is especially useful in battery-powered systems, since it does not interfere with the ground paths of the battery chargers or monitors often found in "smart" batteries. The MAX471 has an internal 35mΩ current-sense resistor and measures battery currents up to ±3A. The module has a built-in 2K Ohm sens resitor giving the module a full sensor range of +/- 3A. An open-collector SIGN output indicates current-flow direction, so the user can monitor whether a battery is being charged or discharged. Operation is from 3V to 36V, and draws less than 100µA over temperature

The module is also supplied with optional 2 way screw terminal and 0.1" pitch header (requires soldering).



Specification:

Product code: HCSENS0041
Current sens max: +/- 3A
Current sens voltage: 3 to 36V
Sensor output: 1V / Amp
Dimensions: 20mm x 19.5mm

Pinout

Sensor
RS+.........Load positive supply (3 to 36V)
RS-.........Connect to load or charger

Interface:
RS+.........Alternative load positive supply (3 to 36V)
GND.........Connect to loads 0V/GND supply
OUT.........Current sensor output (1V / Amp, 3V max)
SIGN........Current flow direction. An open-collector logic output (low = current flow from RS+ to RS-).
GND.........Alternative GND (Connect to loads 0V/GND supply)
RS-..........Alternative load/charger connection.

5. Potentiometer (4.7 KΩ)

- **Technical Specification**

PO6M+S-LIN 4,7K :: Rotary potentiometer + switch, linear, 6 mm, mono, 4.7 kOhm

Item-No.: PO6M+S-LIN 4,7K

Resistor: 4.7 KOhm

£2,53

incl. VAT. excl. shipping costs

in stock, delivery time: 3-4 business days

Quantity:

add to cart

Category of goods: 1 = discountable

Payment methods

more

Secure shopping

more

(Item 8 of 18)

Mark to compare

Compare items
Print item
Price infomail

FAQ (German)
Price trend
Deeplink item
Deeplink group
Report error with product

omeg Potentiometers and Switches

Product Description | Technical Details | Datasheets & Downloads

PO6M+S-LIN 4,7K

Product Description

Rotary potentiometer with switch, mono, linear, 4.7 kOhm

Technical information

General	
Type	Rotary potentiometer
Design	Mono
Assembly	Linear
Technology	With switch
Material	Plastic shaft
Electrical values	
Resistor	4.7 KOhm
Nominal load	0.25 W
Measures	
Spindle	6.0 mm

Manufacturer : OMEG
Factory number : PC20BU/PC1S 4K7A

Package weight : 0.01 kg

6. Optical sensor (GP2Y0A41SK0F)

- **Technical Specification**

SHARP GP2Y0A41SK0F

GP2Y0A41SK0F

Distance Measuring Sensor Unit
Measuring distance : 4 to 30 cm
Analog output type

■Description

GP2Y0A41SK0F is a distance measuring sensor unit, composed of an integrated combination of PSD (position sensitive detector) , IR-LED (infrared emitting diode) and signal processing circuit.
The variety of the reflectivity of the object, the environmental temperature and the operating duration are not influenced easily to the distance detection because of adopting the triangulation method.
This device outputs the voltage corresponding to the detection distance. So this sensor can also be used as a proximity sensor.

■Agency approvals/Compliance

1. Compliant with RoHS directive (2002/95/EC)

■Applications

1. Cleaning robot
2. Personal robot
3. Sanitary

■Features

1. Distance measuring sensor is united with PSD, infrared LED and signal processing circuit
2. Short measuring cycle (16.5ms)
3. Distance measuring range : 4 to 30 cm
4. Package size (29.5 × 13.0 × 13.5mm)
5. Analog output type

■Absolute maximum ratings

(Ta=25°C, Vcc=5V)

Parameter	Symbol	Ratings	Unit	Remark
Supply voltage	Vcc	-0.3 to +7	V	-
Output terminal voltage	Vo	-0.3 to Vcc+0.3	V	-
Operating temperature	Topr	-10 to +60	°C	-
Storage temperature	Tstg	-40 to +70	°C	-

■Operating supply voltage

Symbol	Rating	Unit	Remark
Vcc	4.5 to 5.5	V	-

■Electro-optical Characteristics

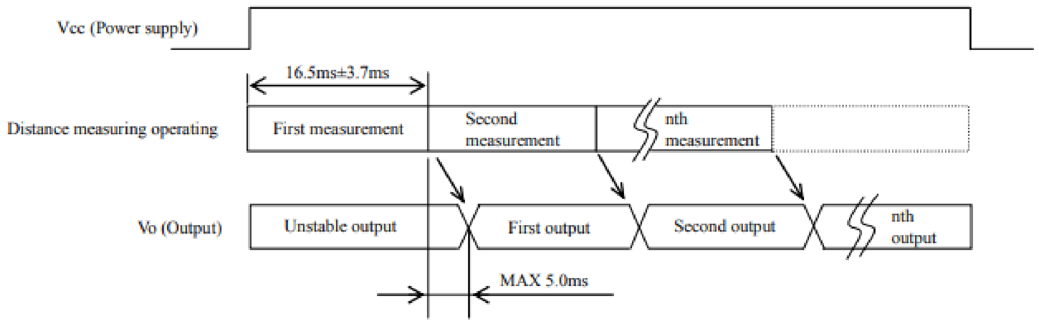
Parameter	Symbol	Conditions	MIN.	TYP.	MAX.	Unit
Measuring distance range	ΔL	(Note 1)	4	-	30	Cm
Output terminal voltage	Vo	L=30cm (Note 1)	0.25	0.4	0.55	V
Output voltage difference	ΔVo	Output change at L change (30cm → 4cm) (Note 1)	1.95	2.25	2.55	V
Average supply current	Icc	L=30cm (Note 1)	-	12	22	mA

※L : Distance to reflective object

(Note 1) Using reflective object : White paper

(Made by Kodak Co., Ltd. gray cards R-27・white face, reflective ratio ; 90%)

■Timing Chart



7. Motor driver (DFR0225:V2)

- **Technical Specification**

Romeo V2-All in one Controller (R3) (SKU:DFR0225)

Contents

Introduction

RoMeo V2[R3]is an All-in-One Arduino compatible microcontroller especially designed for robotics applications from DFRobot. The Romeo benefits from the Arduino open source platform, it is supported by thousands of open source codes, and can easily be expanded with Arduino Shields. The integrated 2 way DC motor driver and Xbee socket allows you to start your project immediatly without the need for an additional motor driver or wirless shield.

> The **analog sensor port pin mapping** on RoMeo v2 is different from the version before. Be careful to wire your sensor or other devices correctly or the wrong power connection would destroy your device.

Please **Turn OFF the Motor Power Switch** when debugging Romeo through USB cable. Or the external power supply(>12V) will destroy your Romeo.

NOTE:

- Please select **Leonardo** board when uploading a sketch by Arduino IDE.
- **Serial port** 0 or 1 Read more from Arduino.cc: Please use Serial**1**.***() instead of Serial.***() in code to communicate with devices connected to serial interface, i.e. Pin 0/1. e.g. Bluetooth, WiFi module, Xbee etc. Serial.***() is for USB debugging on pc serial monitor.
- **Analog 0**: If you are going to use the Analog port 0, you have to pay attention to the **switch(s1-s5)**, **turn it OFF** please. There are five buttons connected to A0, if you turn ON the button switch,then the A0 read value would be not the one you want.

Specification

Basic	Feature	Improvement compared with Romeo v1.1
DC Supply:USB Powered or External 6V~23V DC DC Output:5V(200mA) / 3.3V(100mA) Motor driver Continuous Output Current:2A Microcontroller:ATmega32u4 Bootloader: Arduino Leonardo Serial Interface TTL Level(Serial1.***();) USB(Serial.***()) Size:89x84x14mm	Compatible with the Arduino R3 pin mapping Analog Inputs: A0-A5, A6 - A11 (on digital pins 4, 6, 8, 9, 10, and 12) PWM: 3, 5, 6, 9, 10, 11, and 13. Provide 8-bit PWM output 5 key inputs for testing Auto sensing/switching external power input Support Male and Female Pin Header Built-in Xbee socket Integrated sockets for APC220 RF Module and DF-Bluetooth Module Three I2C/TWI Interface Pin Sets(two 90°pin headers) Two way Motor Driver with 2A maximum current	Wide operating input voltage Directly support Xbee and XBee form factor wifi,bluetooth and RF modules ON/OFF switch to control the system power from extermal motor power 3 Digital I/O extension(D14-D16) S1-S5 switch replace jump cap Micro USB instead of A-B USB connector Analog sensor extension port: Orange for Signal,Red for Vcc,Black for GND

RoMeo V2 Pinout

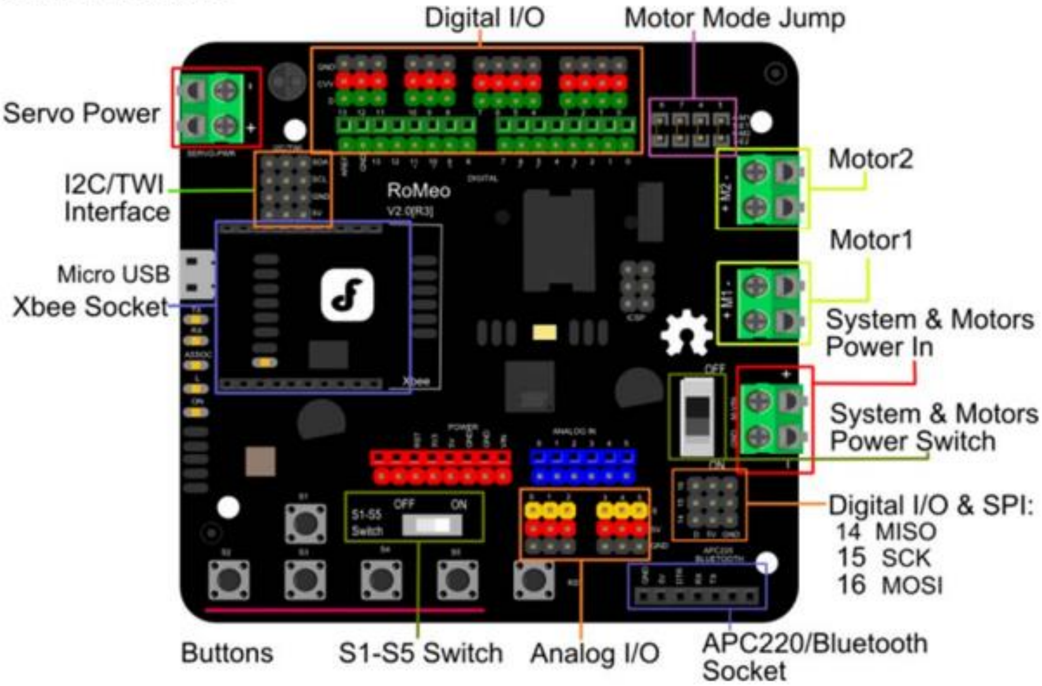


Fig1: Romeo V2 Pin Out

Power solution design

This motor controller power solution is specially designed for the robotics application.
Servo Power terminal

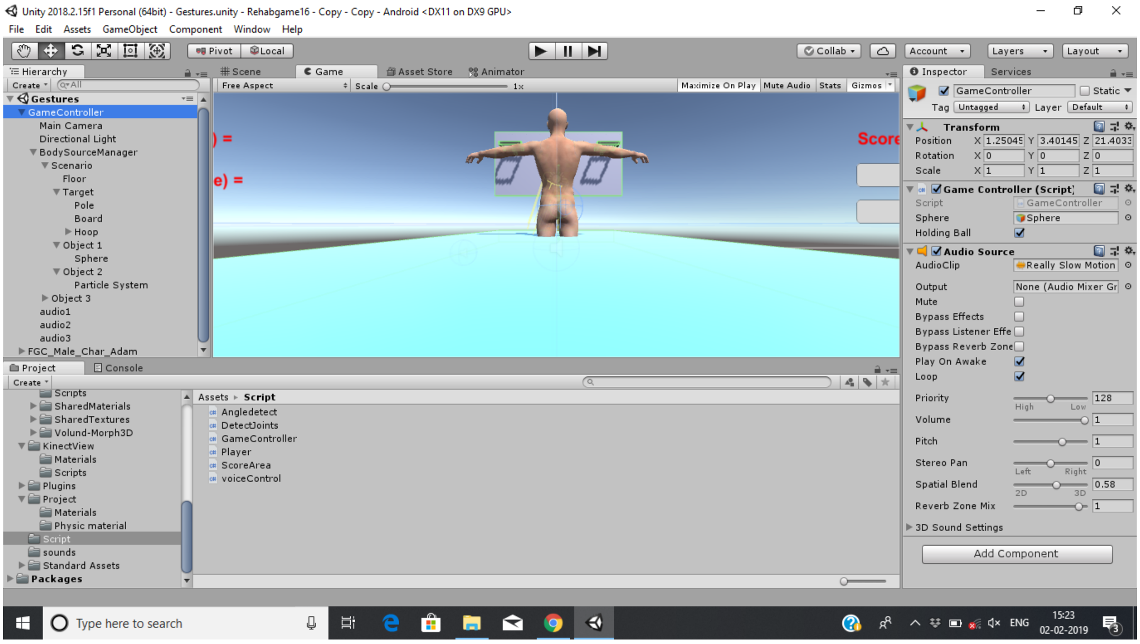
- It integrated an external servo power terminal. The range of this power input is about 5~12v. We recommend you to use 5v. So the servo power supply extension won't break the digital sensors connected to the 3p digital sensor interface. However,for driving 6~12v servos with the voltage input higher than 5v, it's not available to extend 5v sensor on all the digital sensor interface anymore.
- The servo power terminal won't supply system working voltage.

Motor Power terminal
The setting for the system & motor power switch:

- On: supply power to the motor driver and system power regulator. The input range is from 5~23 volts. It's suitable for most of robot platform.
- Off: Isolate the system power supply from the motor power. In this case, it requires to supply system voltage from Micro USB port,5v power source to 5v & GND pins directly or 5~23v power source to VIN & GND pins.

Appendix IV : Programs

1. Unity game engine platform



C# programs

- **Program for audio-visual feedback**

Angledetect.cs

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using Windows.Kinect;
using UnityEngine.UI;

public class Angledetect : MonoBehaviour {

        public GameObject BodySrcManager;
        public BodySourceManager bodyManager;
        private Body[] bodies;
        public float multiplier=10f;
        public Text myText;
        public Text myText2;
        public float degree=0.0f;


        public UnityEngine.AudioSource audio1;
        public UnityEngine.AudioSource audio2;
        public UnityEngine.AudioSource audio3;


        // Use this for initialization
        void Start () {
                if (BodySrcManager == null) {
                        Debug.Log ("Assisgn Game Objct with Body Source Manager");
```

```
		}
		else {
			bodyManager = BodySrcManager.GetComponent<BodySourceManager> ();
		}

	}

	// Update is called once per frame
	void Update () {
		if (bodyManager == null) {
			return;
		}
		bodies = bodyManager.GetData ();
		if (bodies == null) {
			return;
		}
		foreach (var body in bodies) {
			if (body == null) {
				continue;
			}
			if (body.IsTracked) {
				Vector3 shouldertoelbow = new Vector3 (body.Joints
[JointType.ElbowRight].Position.X - body.Joints [JointType.ShoulderRight].Position.X, body.Joints
[JointType.ElbowRight].Position.Y - body.Joints [JointType.ShoulderRight].Position.Y, body.Joints
[JointType.ElbowRight].Position.Z - body.Joints [JointType.ShoulderRight].Position.Z);
				Vector3 elbowtowrist = new Vector3 (body.Joints
[JointType.ElbowRight].Position.X - body.Joints [JointType.WristRight].Position.X, body.Joints
[JointType.ElbowRight].Position.Y - body.Joints [JointType.WristRight].Position.Y, body.Joints
[JointType.ElbowRight].Position.Z - body.Joints [JointType.WristRight].Position.Z);
				shouldertoelbow.Normalize ();
				elbowtowrist.Normalize ();

				Vector3 crossProduct = Vector3.Cross (shouldertoelbow,
elbowtowrist);
				float crossProductLength = crossProduct.z;
				float dotProduct = Vector3.Dot (shouldertoelbow, elbowtowrist);
				float segmenAngle = Mathf.Atan2 (crossProductLength, dotProduct);
				float segmentAngle = Mathf.Abs (segmenAngle);

				float degree = segmentAngle * (180 / Mathf.PI);


				myText.text = degree.ToString ();





				if (degree >= 100) {
					audio1.mute = false;
					audio2.mute = true;
					audio3.mute = true;
					if (!audio1.playOnAwake) {
						audio1.playOnAwake = true;
						audio1.Play();
						audio1.loop = true;

						audio2.mute = true;
						audio3.mute = true;
					}
					myText2.text = ("Come on! you can do it");
				}
```

```
else if (degree >=70 && degree < 100) {

        audio1.mute = true;
        audio2.mute = false;
        audio3.mute = true;
        if (!audio2.playOnAwake) {
                audio2.playOnAwake = true;
                audio2.Play ();
                audio2.loop = true;


                audio1.mute = true;
                audio3.mute = true;
        }
        myText2.text = ("Almost reached");

}

else {
        audio1.mute = true;
        audio2.mute = true;
        audio3.mute = false;
        if (!audio3.playOnAwake) {
                audio3.playOnAwake = true;
                audio3.Play ();
                audio3.loop = true;



                audio1.mute = true;
                audio2.mute = true;
                }
                myText2.text = ("you have done it");


}

                        }
                }
        }
}
```

- **Program for synchronizing right hand movement with ball**

DetectJoints.cs

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using Windows.Kinect;
using System.IO;

public class DetectJoints : MonoBehaviour {


        public GameObject BodySrcManager;
        //public JointType TrackedJoint;
        public BodySourceManager bodyManager;
        private Body[] bodies;
```

```
        public float multiplier=10f;
        // Use this for initialization
        void Start () {
                if (BodySrcManager == null) {
                        Debug.Log ("Assisgn Game Objct with Body Source Manager");
                }
                else {
                        bodyManager = BodySrcManager.GetComponent<BodySourceManager> ();
                }
        }

        // Update is called once per frame
        void Update () {
                if (bodyManager == null) {
                        return;
                }
                bodies = bodyManager.GetData ();
                if (bodies == null) {
                        return;
                }
                List<double> xList = new List<double> ();
                List<double> yList = new List<double> ();
                List<double> zList = new List<double> ();
                foreach (var body in bodies) {
                        if (body == null) {
                                continue;
                        }
                        if (body.IsTracked) {
                                var pos = body.Joints[JointType.HandRight].Position;
                                float x = pos.X * multiplier;
                                float y = pos.Y * multiplier;
                                float z = pos.Z * multiplier;
                                gameObject.transform.position = new Vector3 (x, y, z);

                        }

                }

        }
}
```

- **Program for resetting new scene in game platform**

GameController.cs

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using UnityEngine.SceneManagement;

public class GameController : MonoBehaviour {

        private Scene scene;
        public GameObject Sphere;
        public bool holdingBall = true;
        //public float resetTimer = 5f;
        // Use this for initialization
        void Start () {
                scene = SceneManager.GetActiveScene ();
        }
```

```
	// Update is called once per frame
	void Update () {

		if (holdingBall == false) {
			SceneManager.LoadScene ("Gestures");
			}

		}

}
```

- **Program for showing particle system after scoring**

ScoreArea.cs

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using UnityEngine.UI;

public class ScoreArea : MonoBehaviour {

	public GameObject effectObject;
	public Text myText1;


	void Start(){
		effectObject.SetActive (false);
	}
	// Use this for initialization
	void OnTriggerEnter (Collider otherCollider){
		if (otherCollider.GetComponent<SphereCollider> () != null) {
			effectObject.SetActive (true);
			myText1.text = ("Hurray! You have scored");
		}
	}
}
```

- **Program for calculating joint angle from joint vectors**

voiceControl.cs

```
using System.Collections;
using System.Collections.Generic;
using System;
using System.Linq;
using UnityEngine;
using UnityEngine.Windows.Speech;
using Windows.Kinect;
using UnityEngine.UI;
using System.IO;

public class voiceControl : MonoBehaviour {


	//public UnityEngine.AudioSource _audio;
```

```
private Dictionary<string, Action> keywordActions = new Dictionary<string, Action> ();
private KeywordRecognizer keywordRecognizer;
public GameObject BodySrcManager;
public BodySourceManager bodyManager;
private Body[] bodies;
public float multiplier=10f;
public float degree=0.0f;
public GameObject Sphere;
//public float ballThrowingForce = 5f;
public bool holdingBall = true;
public Text myText7;
public Text myText13;

//public Text myText2;

// Use this for initialization
void Start () {

        //_audio = gameObject.GetComponent<UnityEngine.AudioSource> ();

        keywordActions.Add("Drop", Drop);
        keywordRecognizer = new KeywordRecognizer (keywordActions.Keys.ToArray ());
        keywordRecognizer.OnPhraseRecognized += OnKeywordsRecognized;
        keywordRecognizer.Start ();

        Sphere.GetComponent<Rigidbody> ().useGravity = false;
        if (BodySrcManager == null) {
                Debug.Log ("Assisgn Game Objct with Body Source Manager");
        }
        else {
                bodyManager = BodySrcManager.GetComponent<BodySourceManager> ();
        }
}

private void Drop()
{
        holdingBall = false;
        Sphere.GetComponent<Rigidbody> ().useGravity = true;
}

private void OnKeywordsRecognized(PhraseRecognizedEventArgs args){
        Debug.Log ("Keyword: " + args.text);
        keywordActions [args.text].Invoke ();
                }
// Update is called once per frame
void Update () {
        if (bodyManager == null) {
                return;
        }
        bodies = bodyManager.GetData ();
        if (bodies == null) {
                return;
        }

        foreach (var body in bodies) {
                if (body == null) {
                        continue;
                }
                if (body.IsTracked) {
                        var pos2 = body.Joints [JointType.Neck].Position;
                        var pos1 = body.Joints [JointType.ShoulderRight].Position;
                        var pos0 = body.Joints [JointType.ElbowRight].Position;
```

```
                                        var pos = body.Joints [JointType.HandRight].Position;

                                        float x2 = pos2.X * multiplier;
                                        float y2 = pos2.Y * multiplier;
                                        float z2 = pos2.Z * multiplier;

                                        float x1 = pos1.X * multiplier;
                                        float y1 = pos1.Y * multiplier;
                                        float z1 = pos1.Z * multiplier;

                                        float x0 = pos0.X * multiplier;
                                        float y0 = pos0.Y * multiplier;
                                        float z0 = pos0.Z * multiplier;

                                        float x = pos.X * multiplier;
                                        float y = pos.Y * multiplier;
                                        float z = pos.Z * multiplier;

            float mag1;
            float mag2;


    //double length = Mathf.Sqrt (Mathf.Pow ());

    gameObject.transform.position = new Vector3 (x, y, z);

            //myText4.text = x.ToString ();
            //myText5.text = y.ToString ();
            //myText6.text = z.ToString ();


                                        Vector3 shouldertoelbow = new Vector3 (body.Joints
[JointType.ElbowRight].Position.X - body.Joints [JointType.ShoulderRight].Position.X, body.Joints
[JointType.ElbowRight].Position.Y - body.Joints [JointType.ShoulderRight].Position.Y, body.Joints
[JointType.ElbowRight].Position.Z - body.Joints [JointType.ShoulderRight].Position.Z);
                                        Vector3 elbowtowrist = new Vector3 (body.Joints
[JointType.ElbowRight].Position.X - body.Joints [JointType.WristRight].Position.X, body.Joints
[JointType.ElbowRight].Position.Y - body.Joints [JointType.WristRight].Position.Y, body.Joints
[JointType.ElbowRight].Position.Z - body.Joints [JointType.WristRight].Position.Z);
            mag1 = shouldertoelbow.magnitude;
            mag2 = elbowtowrist.magnitude;
            shouldertoelbow.Normalize ();
                                        elbowtowrist.Normalize ();

                                        Vector3 crossProduct = Vector3.Cross (shouldertoelbow,
elbowtowrist);
                                        float crossProductLength = crossProduct.z;
                                        float dotProduct = Vector3.Dot (shouldertoelbow, elbowtowrist);
                                        float segmenAngle = Mathf.Atan2(crossProductLength, dotProduct);
                                        float segmentAngle = Mathf.Abs (segmenAngle);


                                        float degree = segmentAngle * (180 / Mathf.PI);

                                        float rad = degree * Mathf.Deg2Rad;

                                        double torque = 1 * 9.81 * 0.1*(Mathf.Cos(rad));

                                        float rad1 = 180 - degree;

                                        int point = (int)rad1*100/140;
```

```
					Vector3 necktoshoulder = new Vector3 (body.Joints
[JointType.ShoulderRight].Position.X - body.Joints [JointType.Neck].Position.X, body.Joints
[JointType.ShoulderRight].Position.Y - body.Joints [JointType.Neck].Position.Y, body.Joints
[JointType.ShoulderRight].Position.Z - body.Joints [JointType.Neck].Position.Z);
					Vector3 elbowtoshoulder = new Vector3 (body.Joints
[JointType.ShoulderRight].Position.X - body.Joints [JointType.ElbowRight].Position.X, body.Joints
[JointType.ShoulderRight].Position.Y - body.Joints [JointType.ElbowRight].Position.Y, body.Joints
[JointType.ShoulderRight].Position.Z - body.Joints [JointType.ElbowRight].Position.Z);
					necktoshoulder.Normalize ();
					elbowtoshoulder.Normalize ();

					Vector3 crossProduct1 = Vector3.Cross (necktoshoulder,
elbowtoshoulder);
					float crossProductLength1 = crossProduct1.z;
					float dotProduct1 = Vector3.Dot (necktoshoulder, elbowtoshoulder);
					float segmenAngle1 = Mathf.Atan2 (crossProductLength1,
dotProduct1);
					float segmentAngle1 = Mathf.Abs (segmenAngle1);

					float degree1 = segmentAngle1 * (180 / Mathf.PI);

					myText13.text = degree1.ToString ();
					//float torque = Convert.ToSingle (tor);

					myText7.text = point.ToString ();

					DateTime baseDate = new DateTime(1970, 1, 1);
					TimeSpan span = DateTime.Now - baseDate;


						using (StreamWriter w = File.AppendText("D://test.csv"))
					{
						w.WriteLine (span.TotalMilliseconds + "," + x + "," + y + "," +
z + "," + x0 + "," + y0 + "," + z0 +"," + x1 + "," + y1 + "," + z1 +"," + x2 + "," + y2 + "," + z2 +',' + degree1 + ',' +
degree + ','+ mag1 + ',' + mag2);
					}
					/*StartCoroutine (DownloadTheAudio ());

					if (degree >= 0) {
						myText2.text = ("Come on! you can do it");
					}

					if (degree >= 90) {
						myText2.text = ("Almost reached");

					}

					if (degree >= 130) {
						myText2.text = ("you have done it");


					}*/

				}
			}
		}

		/*IEnumerator DownloadTheAudio ()
		{
			string url="http://translate.google.com/translate_tts?ie=UTF-
8&total=1&idx=0&textlen=32&client=tw-ob&q="+myText2.text+"&tl=En-gb";
```

```
            WWW www = new WWW (url);
            yield return www;

            _audio.clip = www.GetAudioClip (false, true, AudioType.MPEG);
            _audio.Play ();
        }*/

}
```

2. Matlab program for calculating joint parameters from excel file

```matlab
f1 ='testfile.xlsx';

xx=xlsread(f1,'A:A');
x=xlsread(f1,'B:B');
y=xlsread(f1,'C:C');
z=xlsread(f1,'D:D');

x0=xlsread(f1,'E:E');
y0=xlsread(f1,'F:F');
z0=xlsread(f1,'G:G');

x1=xlsread(f1,'H:H');
y1=xlsread(f1,'I:I');
z1=xlsread(f1,'J:J');

x2=xlsread(f1,'K:K');
y2=xlsread(f1,'L:L');
z2=xlsread(f1,'M:M');


degree1 = xlsread(f1,'N:N');
degree2 = xlsread(f1,'O:O');
%tor = xlsread(f1,'P:P');

reatime = (xx(size(xx,1),1)-xx(1,1))/1000;

xxdis = zeros(size(xx,1),1);
vell1 = zeros(size(xx,1)-1,1);
vell2 = zeros(size(xx,1)-1,1);
acce11 = zeros(size(xx,1)-1,1);
acce22 = zeros(size(xx,1)-1,1);
theta1= 180-degree1;
theta2= 180-degree2;
alpha1 = theta1*0.0174533;
alpha2 = theta2*0.0174533;

i = 1;

for a = 1:1:size(xx,1)

  xxdis(i,1) = (xx(i,1)-xx(1,1))/1000;
  i=i+1;
```

```
end

for a = 1:1:size(xx,1)-1

   vell1(a,1)= (theta1(a+1,1)-theta1(a,1))./(xxdis(a+1,1)-xxdis(a,1));
   vell2(a,1)= (theta2(a+1,1)-theta2(a,1))./(xxdis(a+1,1)-xxdis(a,1));

end
vell1a=vell1';
vell1b=[zeros(1,1),vell1a];
vell1c=vell1b';
vel1=smooth(vell1c,'moving',10);

vell2a=vell2';
vell2b=[zeros(1,1),vell2a];
vell2c=vell2b';
vel2=smooth(vell2c,'moving',10);


for a = 1:1:size(xx,1)-1

   acce11(a,1)= (vel1(a+1,1)-vel1(a,1))./(xxdis(a+1,1)-xxdis(a,1));
   acce22(a,1)= (vel2(a+1,1)-vel2(a,1))./(xxdis(a+1,1)-xxdis(a,1));

end



acce11a=acce11';
acce11b=[zeros(1,1),acce11a];
acce11c=acce11b';
a1=smooth(acce11c,'moving',10);



acce22a=acce22';
acce22b=[zeros(1,1),acce22a];
acce22c=acce22b';
a2=smooth(acce22c,'moving',10);

torque1 =
(m1.*l1.^2+I1+m2.*(L1.^2+l2.^2+2.*L1.*l2.*cosd(alpha2))+I2).*a1+(m2.*(l2.^2+L1.*l2.*cosd(alpha
2))+I2).*a2-
(m2.*L1.*l2.*sind(alpha2).*(2.*vel1.*vel2+vel2.^2))+(m1.*g.*l1.*cosd(alpha1))+(m2.*g.*(L1.*cosd(
alpha1)+l2.*cosd(alpha1+alpha2)));
torque2 =
(m2.*(l2.^2+L1.*l2.*cosd(alpha2))+I2).*a1+(m2.*l2.^2+I2).*a2+(m2.*L1.*l2.*sind(alpha2).*vel1.^2
)+(m2.*g.*l2.*cosd(alpha1+alpha2));

figure(1);
plot3(x,z,y,'*');
hold on
plot3(x0,z0,y0,'*');
hold on
line ([x x0],[z z0],[y y0]);
hold on
line ([x1 x0],[z1 z0],[y1 y0]);
hold on
```

```
line ([x1 x2],[z1 z2],[y1 y2]);
hold on
for a=1:1:size(xx)
L1=line([x0(a,1) x(a,1)],[z0(a,1) z(a,1)],[y0(a,1) y(a,1)]);
hold on
L2=line([x0(a,1) x1(a,1)],[z0(a,1) z1(a,1)],[y0(a,1) y1(a,1)]);
hold on
L3=line([x2(a,1) x1(a,1)],[z2(a,1) z1(a,1)],[y2(a,1) y1(a,1)]);
hold on

set(L1,'color','r')
set(L2,'color','b')
set(L2,'color','b')
hold on
end
xlabel('X position');
ylabel('Y position');
zlabel('Z position');
grid on;


figure(2);
ss1=plot(xxdis,degree1);
la1='Shoulder joint';
hold on
ss2=plot(time,degree2);
la2='Elbow joint';
xlabel('Time (sec)');
ylabel('Joint angle (degree)');
legend([ss1;ss2], la1, la2);
grid on;


figure(3);
ss3=plot(xxdis,vel1);
la3='Shoulder joint';
hold on
ss4=plot(time,vel2);
xlabel('Time (sec)');
la4='Elbow joint';
ylabel('Joint velocity (rad/sec)');
legend([ss3;ss4], la3, la4);
grid on;

figure(4);
ss5=plot(xxdis,a1);
la5='Shoulder joint';
hold on
ss6=plot(xxdis,a2);
xlabel('Time (sec)');
la6='Elbow joint';
ylabel('Joint acceleration (rad/sec^2)');
legend([ss5;ss6], la5, la6);
grid on;

figure(5);
ss7=plot(xxdis,torque1);
```

```
la7='Shoulder joint';
hold on
ss8=plot(xxdis,torque2);
la8='Elbow joint';
xlabel('Time (sec)');
ylabel('Joint torque (Nm)');
legend([ss7;ss8], la7, la8);
grid on;
```

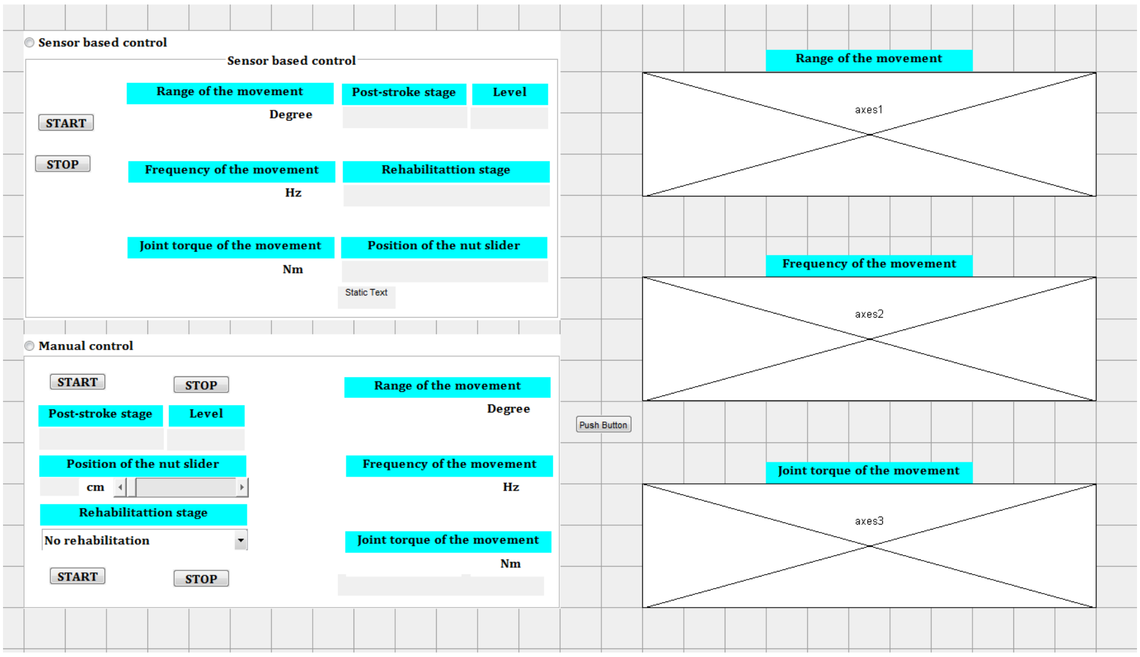
3. Arduino program for communicating between Arduino board and GUI

```
int E1 = 5;
int M1 = 4;
int E2 = 6;
int M2 = 7;
//int recb=0;
int value=200;
#define kPin_Photocell A0
#define kPin_Photocell1 A1
#define kPin_Photocell2 A2

void setup()
{
pinMode(M1, OUTPUT);
pinMode(M2, OUTPUT);
Serial.begin(9600);
}

void loop()
{
int value = analogRead(kPin_Photocell);
int value1 = analogRead(kPin_Photocell1);
int value2 = analogRead(kPin_Photocell2);
Serial.print(value);
Serial.print(',');
Serial.print(value1);
Serial.print(',');
```

```
Serial.println(value2);
if (Serial.available())
 {
   char recb = Serial.read();
if (recb=='a')
   {
      digitalWrite(M1,HIGH);
   digitalWrite(M2, HIGH);
   analogWrite(E1, value);
   analogWrite(E2, value);
   //delay(30);

   }
   else if(recb=='b')
   {
   digitalWrite(M1,LOW);
   digitalWrite(M2,LOW);
   analogWrite(E1, value);
   analogWrite(E2, value);
   }
   else if (recb=='N')
   {
     digitalWrite(M1,HIGH);
     analogWrite(E1, LOW);
     }
   }
}
```

4. Matlab program for GUI

- **GUIDE for GUI**




```
function varargout = GUIsensor(varargin)
% GUISENSOR MATLAB code for GUIsensor.fig
%      GUISENSOR, by itself, creates a new GUISENSOR or raises the existing
%      singleton*.
%
%      H = GUISENSOR returns the handle to a new GUISENSOR or the handle to
%      the existing singleton*.
%
%      GUISENSOR('CALLBACK',hObject,eventData,handles,...) calls the local
%      function named CALLBACK in GUISENSOR.M with the given input arguments.
%
%      GUISENSOR('Property','Value',...) creates a new GUISENSOR or raises the
%      existing singleton*.  Starting from the left, property value pairs are
%      applied to the GUI before GUIsensor_OpeningFcn gets called.  An
%      unrecognized property name or invalid value makes property application
%      stop.  All inputs are passed to GUIsensor_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help GUIsensor

% Last Modified by GUIDE v2.5 12-Feb-2018 19:26:53

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @GUIsensor_OpeningFcn, ...
                   'gui_OutputFcn',  @GUIsensor_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
```

```
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin(Manna and Dubey));
else
    gui_mainfcn(gui_State, varargin(Manna and Dubey));
end


% End initialization code - DO NOT EDIT


% --- Executes just before GUIsensor is made visible.
function GUIsensor_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to GUIsensor (see VARARGIN)

% Choose default command line output for GUIsensor
handles.output = hObject;

% Update handles structure
guidata(hObject, handles);



% UIWAIT makes GUIsensor wait for user response (see UIRESUME)
% uiwait(handles.figure1);


% --- Outputs from this function are returned to the command line.
function varargout = GUIsensor_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;


% --- Executes on button press in pushbutton1.
function pushbutton1_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
global s flag1 g q g1 q1 x;
flag1=1;
char c;
s=serial('COM4','BaudRate',9600);
fopen(s);
filtvalue=0.5;
tr=10;
```

```
x=0;
g=zeros(x,3);
q=zeros(1,3);
aa0=zeros(50,1);
 aa1=zeros(50,1);
 aa2=zeros(50,1);

 g1=zeros(x,1);
 q1=zeros(1,1);


 newv=0;
 newv1=0;
 newv2=0;

 i=0;
 while tr>5
    if flag1==1
       x=x+1;
     tmp =fscanf(s,'%d,%d,%d');

    bb=tmp(1);
    bb1=tmp(2);
    bb2=tmp(3);
    cc1=(bb-62)/3.52;


    newv=(1-filtvalue)*newv+filtvalue*cc1;
    newv1=(1-filtvalue)*newv1+filtvalue*bb1;
    newv2=(1-filtvalue)*newv2+filtvalue*bb2;


    aa0=[aa0(2:end);newv];
    aa1=[aa1(2:end);newv1];
    aa2=[aa2(2:end);newv2];


axes(handles.axes1);
set(handles.text12,'string',cc1);
plot(aa0,'r');ylim([0 1000]);

axes(handles.axes2);
set(handles.text14,'string',tmp(2));
plot(aa1,'r');ylim([200 400]);


axes(handles.axes3);
set(handles.text16,'string',tmp(3));
plot(aa2,'r');ylim([0 1000]);


q=tmp(1:3)';
g(x,:)=q;
```

```
q1=cc1';
g1(x,:)=q1;
drawnow;
c = (bb2/40);
set(handles.text22,'string',c);
%set(handles.text42,'string',tmp(3));
if (c >= 0 && c <= 18)
   i=0;
if (tmp(1)>0 && i==0)

    set(handles.text18,'string','Acute');
    set(handles.text20,'string','Passive');
    set(handles.text19,'string','Level 1');
    fwrite(s,'a');
    i=i+1;
end
if (tmp(1)>200 && i==1)

   set(handles.text19,'string','Level 2');
   i=i+1;
end

if (tmp(1)>400 && i==2)

   set(handles.text19,'string','Level 3');
   i=i+1;
end

if (tmp(1)>600 && i==3)

   set(handles.text19,'string','Level 4');
   i=i+1;
end

if (tmp(1)>800 && i==4)

   set(handles.text19,'string','Level 5');
   i=i+1;
end
end

if (c > 18 && c <= 22)
   i=0;
if (tmp(1)>0 && i==0)

   set(handles.text18,'string','Mid-level');
   set(handles.text19,'string','Level 1');
   set(handles.text20,'string','Assistive active');
   fwrite(s,'b');
    i=i+1;
end
if (tmp(1)>200 && i==1)

   set(handles.text19,'string','Level 2');
   i=i+1;
end
```

```
if (tmp(1)>400 && i==2)

   set(handles.text19,'string','Level 3');
   i=i+1;
end

if (tmp(1)>600 && i==3)

   set(handles.text19,'string','Level 4');
   i=i+1;
end

if (tmp(1)>800 && i==4)

   set(handles.text19,'string','Level 5');
   i=i+1;
end
end


if (c > 22 && c <= 25)
 i=0;
if (tmp(1)>0 && i==0)

   set(handles.text18,'string','Cronic');
   set(handles.text19,'string','Level 1');
   set(handles.text20,'string','Resisitive active');
   fwrite(s,'c');
    i=i+1;
end
if (tmp(1)>200 && i==1)

   set(handles.text19,'string','Level 2');
   i=i+1;
end

if (tmp(1)>400 && i==2)

   set(handles.text19,'string','Level 3');
   i=i+1;
end

if (tmp(1)>600 && i==3)

   set(handles.text19,'string','Level 4');
   i=i+1;
end

if (tmp(1)>800 && i==4)

   set(handles.text19,'string','Level 5');
   i=i+1;
end
end
```

```
set(handles.text41,'string',i);


    else
       break;
   end
 end




% --- Executes on button press in pushbutton2.
function pushbutton2_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
global s flag1
flag1=0;
fwrite(s,'c');
fclose(s);



% --- Executes on button press in pushbutton4.
function pushbutton4_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton4 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
global s flag1
flag1=0;
fwrite(s,'c');
fclose(s);

% --- Executes on button press in pushbutton3.
function pushbutton3_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
global s flag1;
flag1=1;

s=serial('COM4','BaudRate',9600);
fopen(s);
filtvalue=0.5;
tr=10;
aa0=zeros(50,1);
 aa1=zeros(50,1);
 aa2=zeros(50,1);

 newv=0;
 newv1=0;
 newv2=0;

 while tr>5
    if flag1==1
     tmp =fscanf(s,'%d,%d,%d');
```

```
    bb=tmp(1);
    bb1=tmp(2);
    bb2=tmp(3);


    newv=(1-filtvalue)*newv+filtvalue*bb;
    newv1=(1-filtvalue)*newv1+filtvalue*bb1;
    newv2=(1-filtvalue)*newv2+filtvalue*bb2;


    aa0=[aa0(2:end);newv];
    aa1=[aa1(2:end);newv1];
    aa2=[aa2(2:end);newv2];


axes(handles.axes1);
set(handles.text30,'string',tmp(1));
plot(aa0,'r');ylim([0 1000]);

axes(handles.axes2);
set(handles.text32,'string',tmp(2));
plot(aa1,'r');ylim([0 1000]);


axes(handles.axes3);
set(handles.text34,'string',tmp(3));
plot(aa2,'r');ylim([0 1000]);

drawnow;

    else
       break;
   end
 end





% --- Executes on slider movement.
function slider1_Callback(hObject, eventdata, handles)
% hObject    handle to slider1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'Value') returns position of slider
%        get(hObject,'Min') and get(hObject,'Max') to determine range of slider


% --- Executes during object creation, after setting all properties.
function slider1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to slider1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called
```

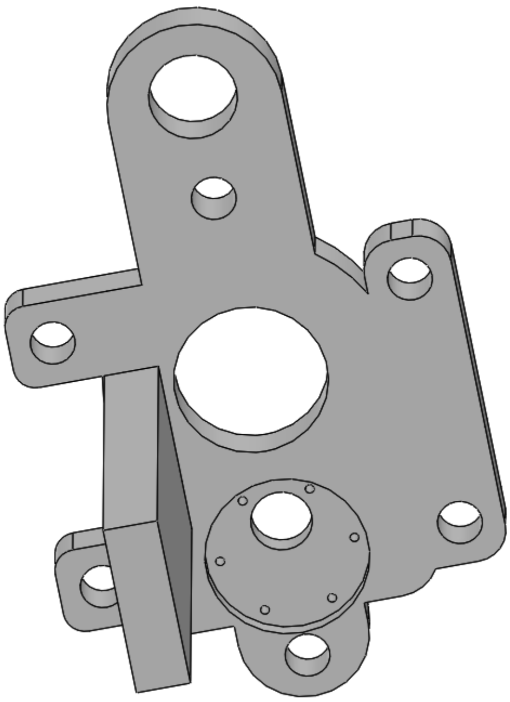
```
% Hint: slider controls usually have a light gray background.
if isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
   set(hObject,'BackgroundColor',[.9 .9 .9]);
end


% --- Executes on selection change in popupmenu1.
function popupmenu1_Callback(hObject, eventdata, handles)
% hObject    handle to popupmenu1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: contents = cellstr(get(hObject,'String')) returns popupmenu1 contents as cell array
%        contents{get(hObject,'Value')} returns selected item from popupmenu1


% --- Executes during object creation, after setting all properties.
function popupmenu1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to popupmenu1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: popupmenu controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
   set(hObject,'BackgroundColor','white');
end


% --- Executes on button press in radiobutton2.
function radiobutton2_Callback(hObject, eventdata, handles)
% hObject    handle to radiobutton2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of radiobutton2
set(handles.uipanel1,'visible','off');
set(handles.uipanel2,'visible','on');


% --- Executes on button press in radiobutton1.
function radiobutton1_Callback(hObject, eventdata, handles)
% hObject    handle to radiobutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of radiobutton1

set(handles.uipanel2,'visible','off');
set(handles.uipanel1,'visible','on');


 function str = getCurrentPopupString(hh)
%# getCurrentPopupString returns the currently selected string in the popupmenu with handle hh
```

```
%# could test input here
if ~ishandle(hh) || strcmp(get(hh,'Type'),'popupmenu')
error('getCurrentPopupString needs a handle to a popupmenu as input')
end

%# get the string - do it the readable way
list = get(hh,'String');
val = get(hh,'Value');
if iscell(list)
  str = list{val};
else
  str = list(val,:);
end



% --- Executes on button press in pushbutton6.
function pushbutton6_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton6 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)



% --- Executes on button press in pushbutton7.
function pushbutton7_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton7 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
global s flag1
flag1=0;
fwrite(s,'c');
fclose(s);



% --- Executes on button press in pushbutton8.
function pushbutton8_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton8 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
global s flag1;
flag1=1;

str = getCurrentPopupString(handles.popupmenu1);
if str == 'Passive'
    set(handles.text36,'string','Acute');
   fwrite(s,'x');
end
if str == 'Assistive Active'
   set(handles.text36,'string','Mid-level');
   fwrite(s,'y');
end
  if str == 'Resistive Active'
     set(handles.text36,'string','Cronic');
     fwrite(s,'z');

  end
```

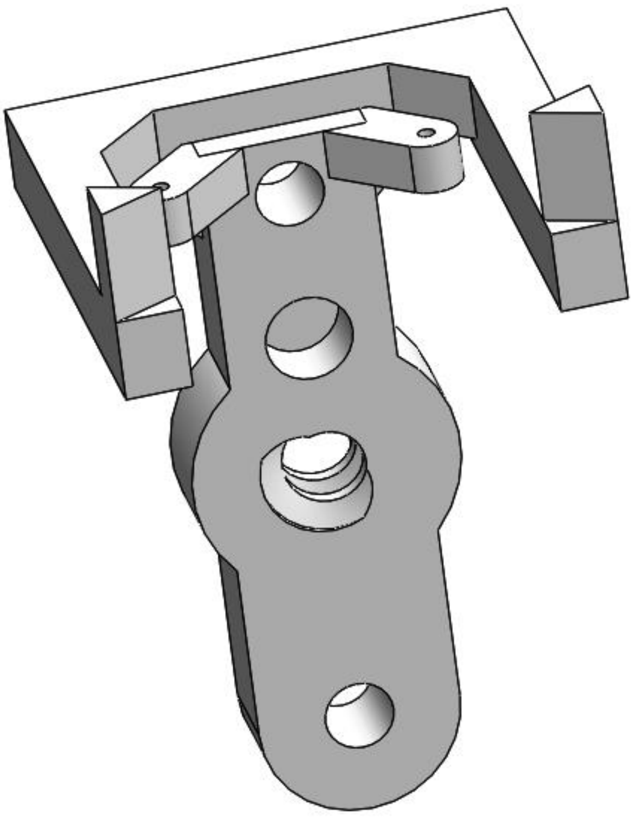
```matlab
% --- Executes on button press in pushbutton9.
function pushbutton9_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton9 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
global g g1;

% [filename1, path]=uiputfile('.xlsx','Save the sensor value as');

xlswrite('filename1',g,1);
xlswrite('filename1',g1,1,'D1');
```

Appendix V : Solidwoks components

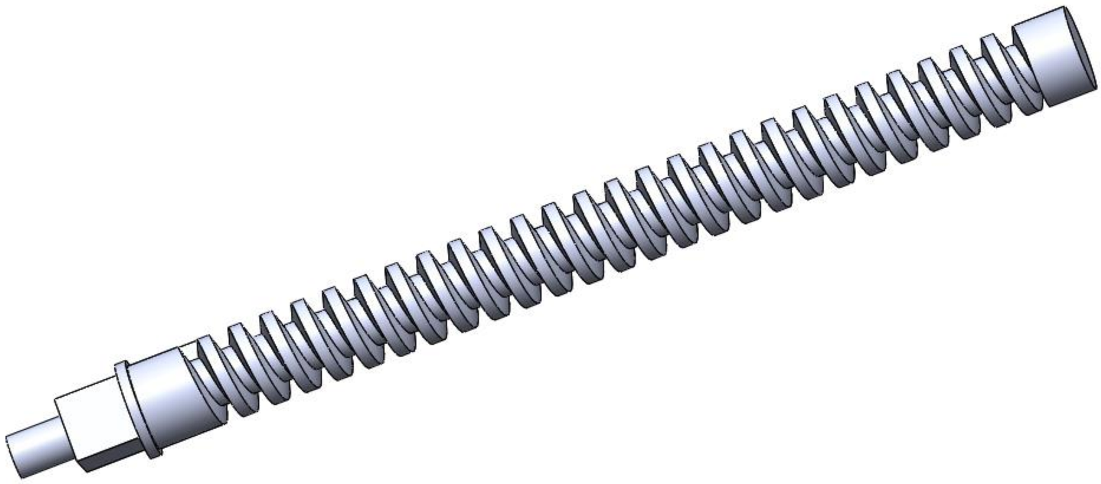
Base structure



Nut slider



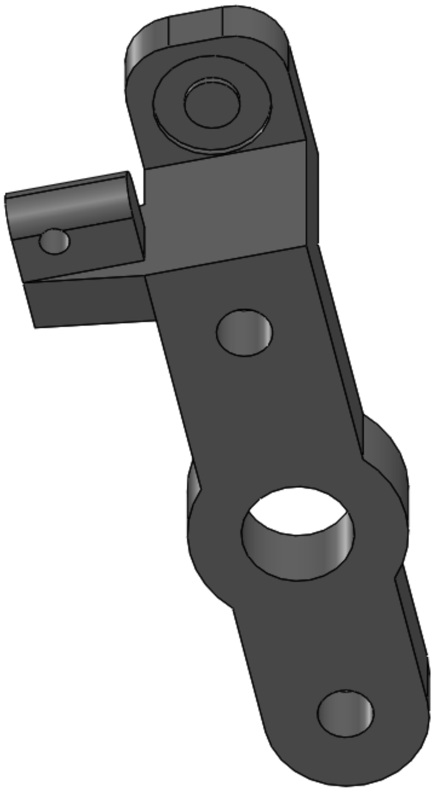
Leadscrew



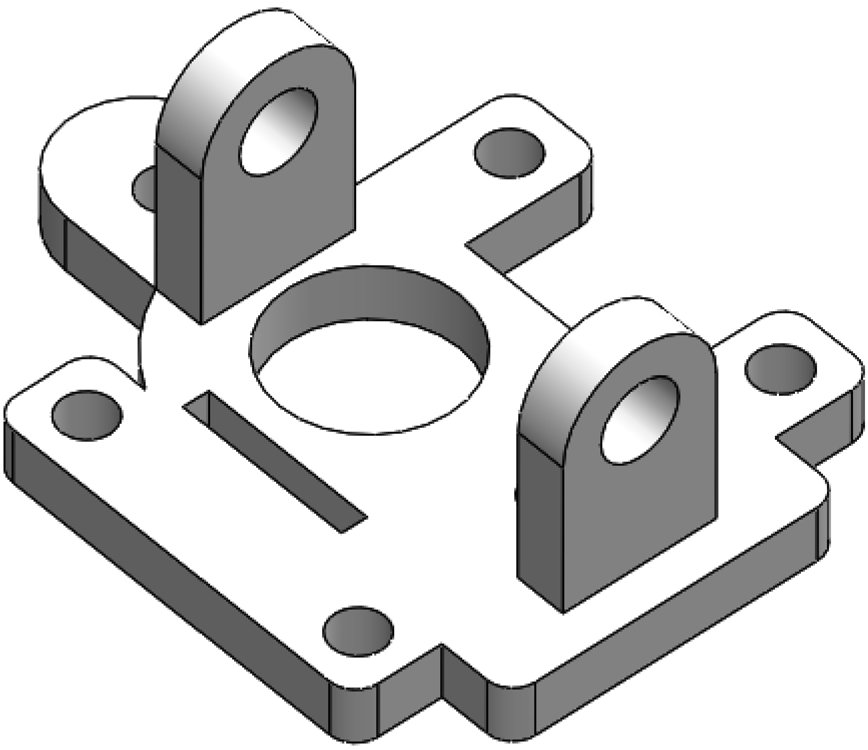
Solid rod

Supporting rod

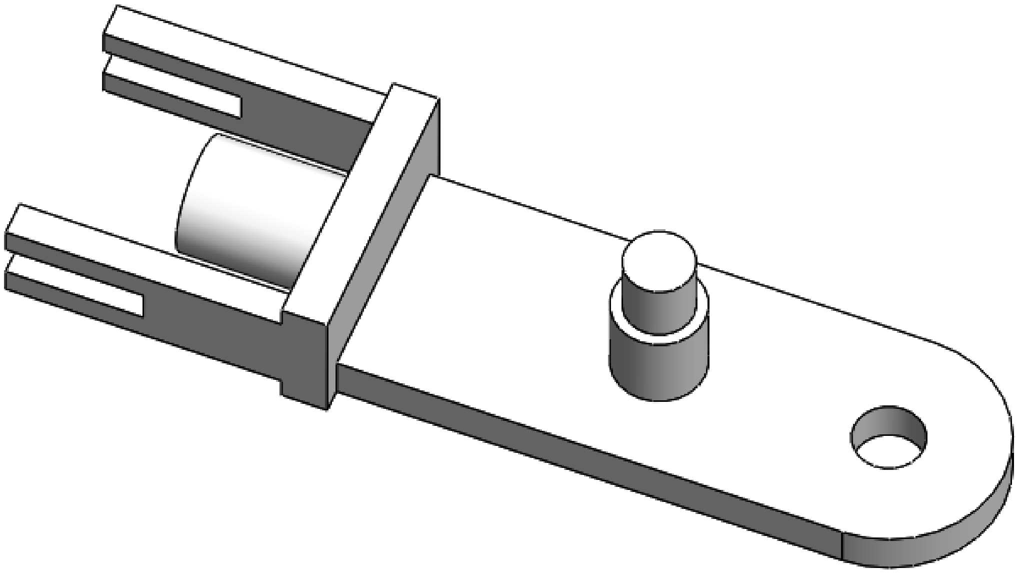
Concentric slider



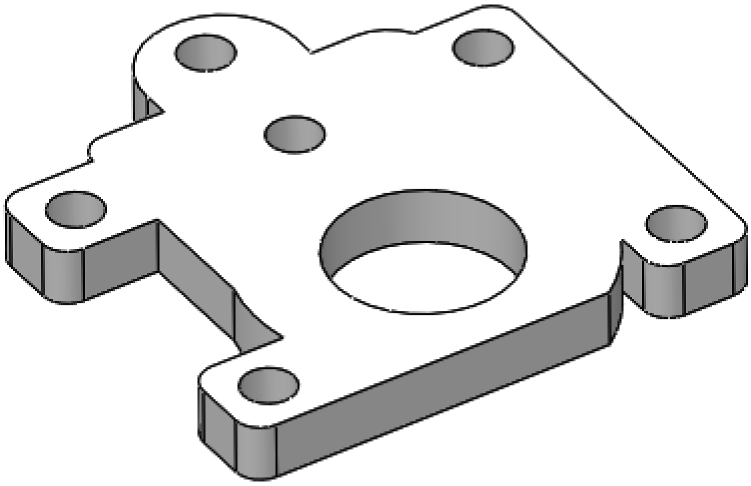
Structure of elbow joint



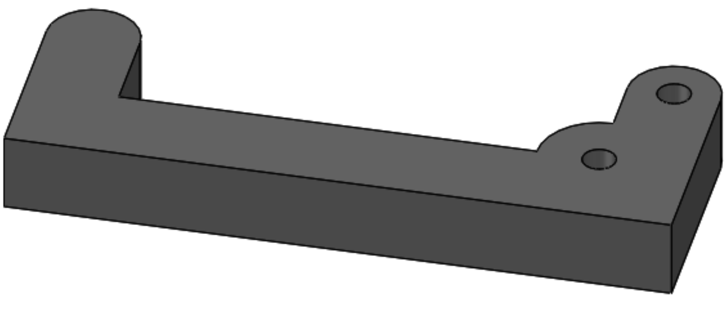
Forearm supporting link



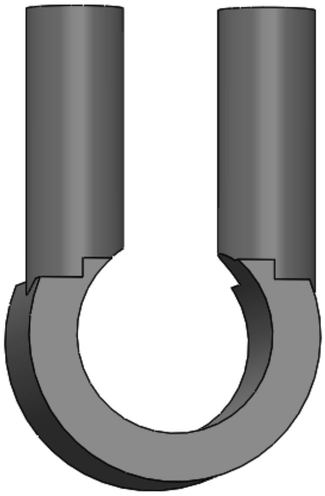
Second part of base structure



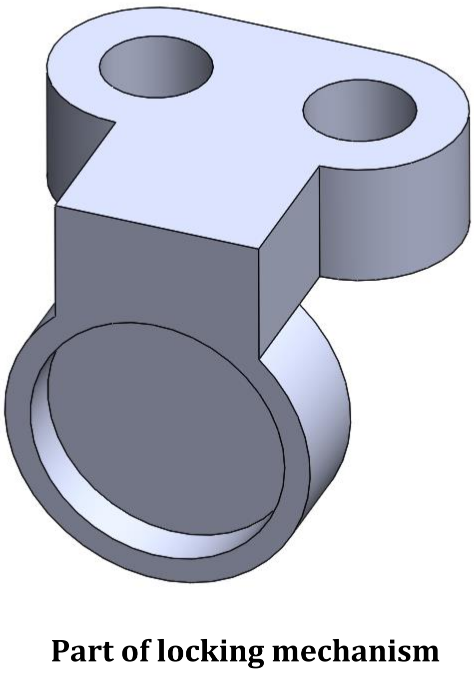
Claw type jaws of locking mechanism



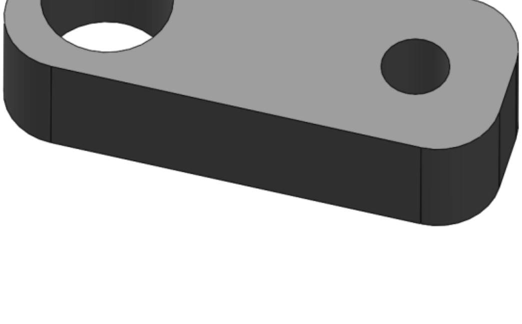
Part of locking mechanism



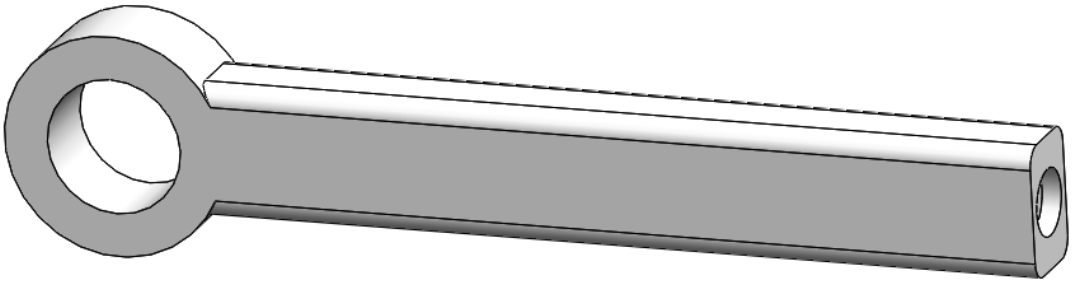
Part of locking mechanism



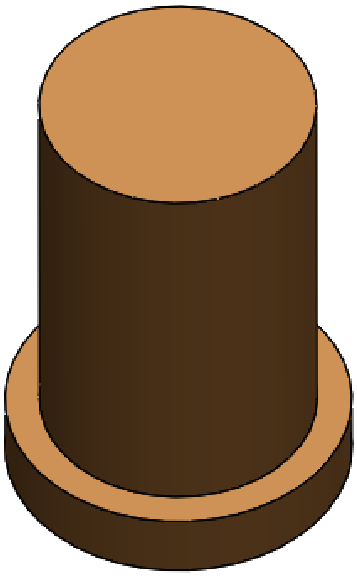
Part of locking mechanism



Connecting link

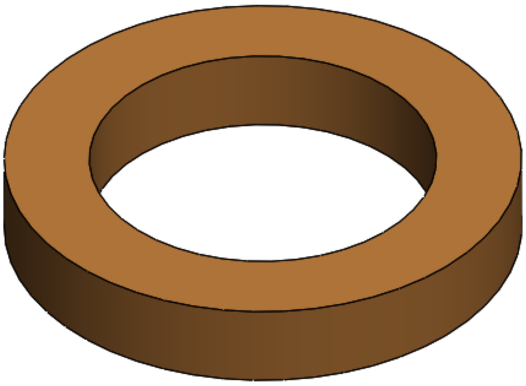


Part of elbow joint

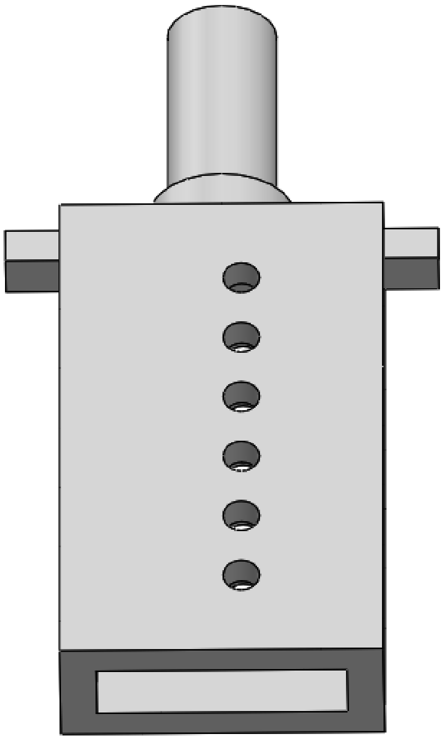


Pulley connected at elbow joint

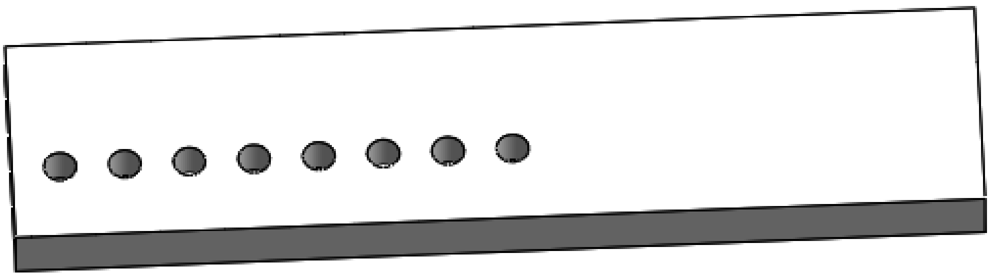
Concentric ring at the junction between S_5 and S_6



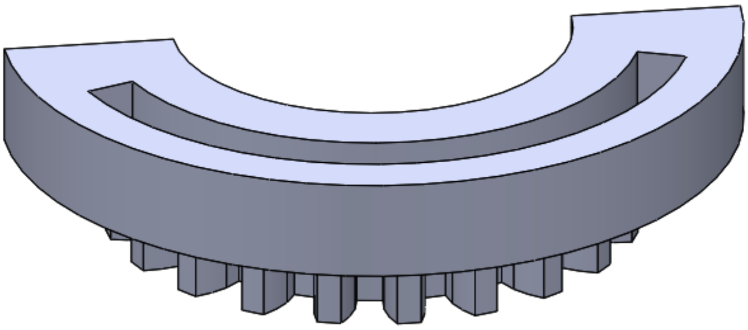
Part of forearm supporting structure



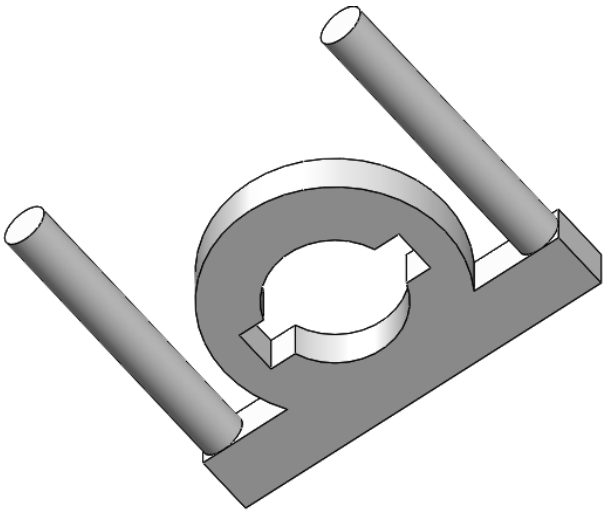
Part of forearm supporting structure



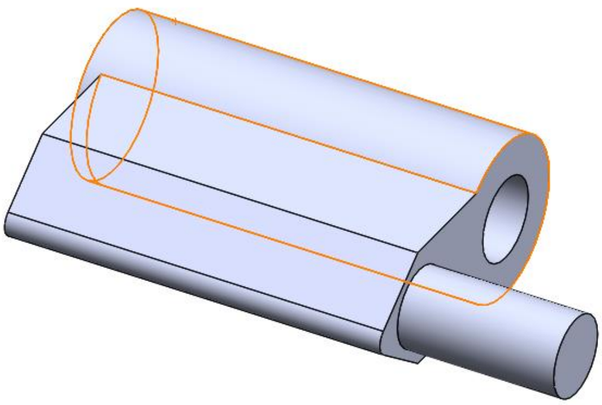
Half circular gear for forearm twisting motion



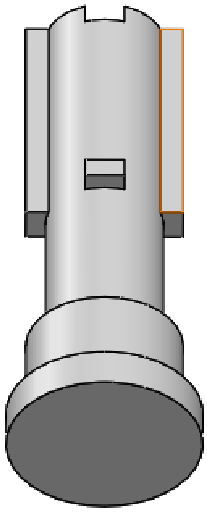
Part of switching mechanism between motor control and assistive mode



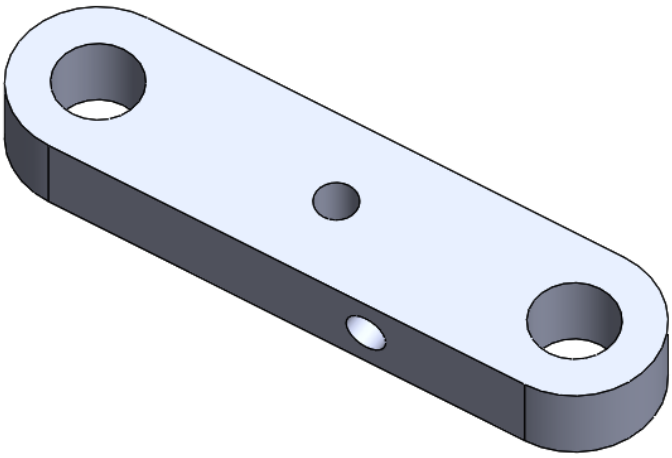
Part of switching mechanism between motor control and assistive mode



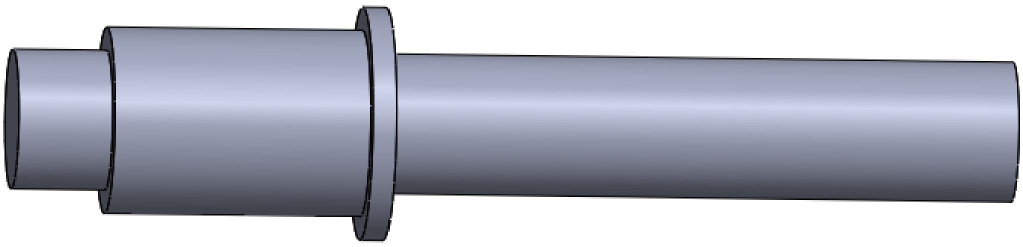
Part of switching mechanism between motor control and assistive mode



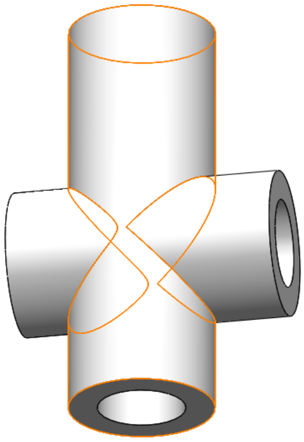
Slider for changing variable joint stiffness



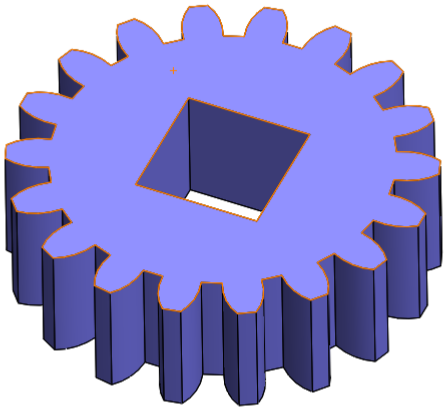
Spindle of elbow joint



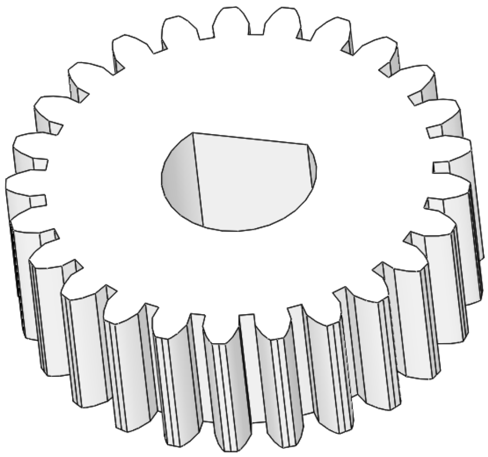
Universal joint at elbow joint



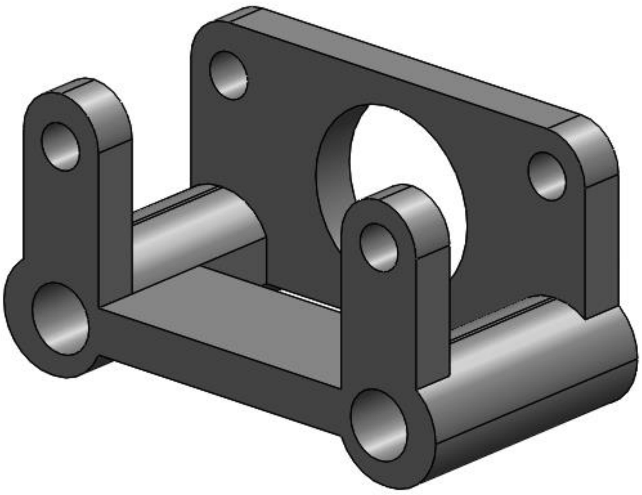
Gear between motor and leadscrew



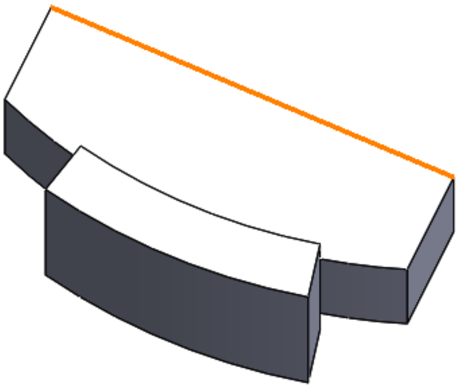
Gear between motor and leadscrew



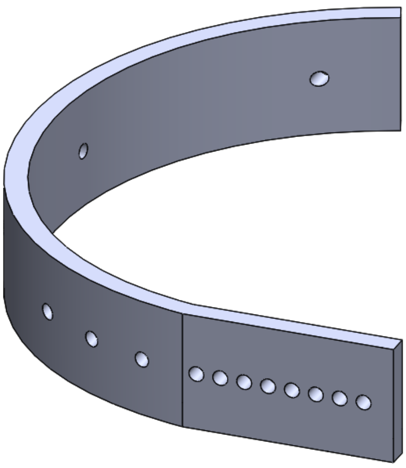
Supporting structure for forearm twisting motion



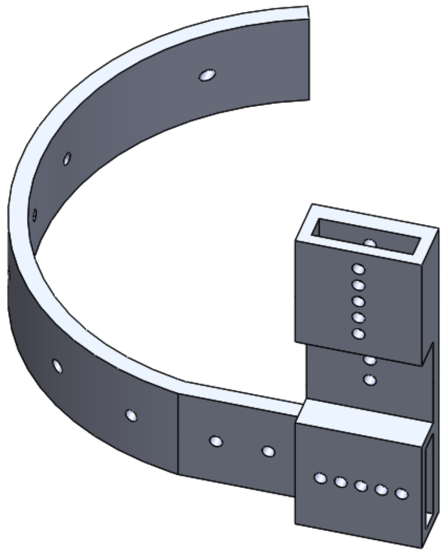
Slider for forearm twisting motion



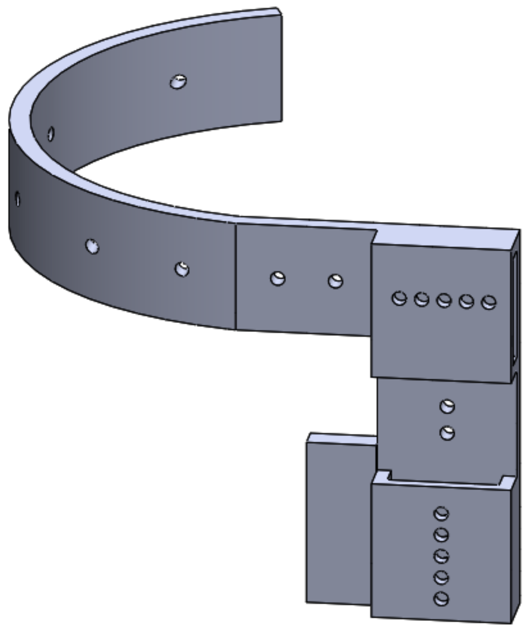
Part of shoulder supporting structure



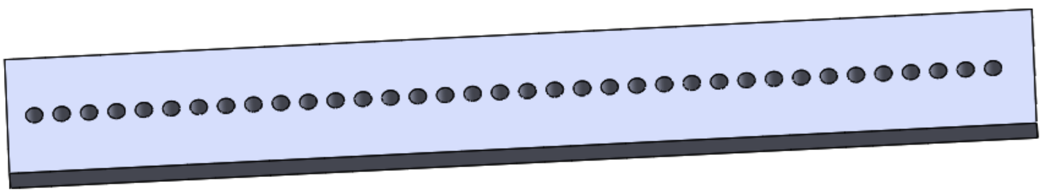
Part of shoulder supporting structure



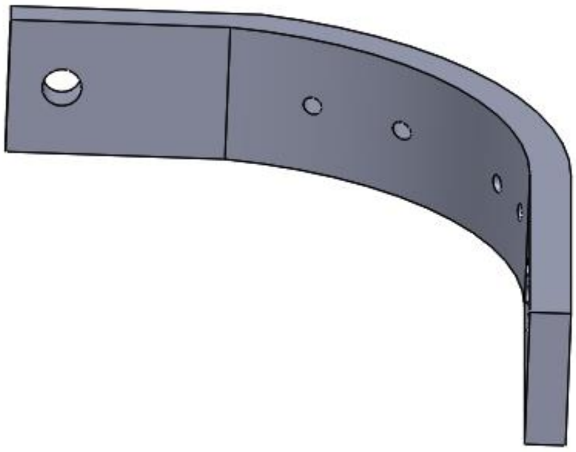
Part of shoulder supporting structure



Part of shoulder supporting structure



Holder between shoulder supporting structure and exoskeleton



Holder for distal end of exoskeleton