Design, Development and Evaluation of Transfer Assistive Device Using Biomechanics in Human-Machine Environment

Thesis submitted in partial fulfilment of the requirements for the award of the degree of

Doctor of Philosophy

in

Design

by

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Certificate

This is to certify that this thesis entitled good ***Design, Development and Evaluation of Transfer Assistive Device Using Biomechanics in Human-Machine Environment,*** submitted by "Mr. Kelifa Seid Mahammed, in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy, to the Indian Institute of Technology Guwahati, Assam, India, is a record of the bonafide research work carried out by him under my guidance and supervision at the Department of Design, Indian Institute of Technology Guwahati, Assam, India". To the best of my knowledge, no part of the work reported in this thesis has been presented for the award of any degree at any other institution.

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ABSTRACT

This study aims to design a simple, inexpensive, and safe transfer assistive device with a focus on introducing a new research direction in the field of assistive technology devices through a context-driven research approach during concept selection, evaluation and development process. The preliminary research involved a pilot survey in the health care system, including stakeholders' viewpoints, to determine the design characteristics and gaps of the existing transfer assistive device and examine the relationship between the needs of the assistive device users, caregivers, and therapists. In this thesis, an effort was made to design a simple transfer assistive device that meets the complex needs of temporary and permanent wheelchair users based on the existing gaps observed in healthcare centres and from the previously reviewed research studies. An alternative design methodology was executed and adopted to explore the interaction between the user and the current device and generate integrated human-machine design conceptualization and evaluation strategies. An appropriate design selection was made through a rigorous concept evaluation process based on biomechanics, anthropometry, and human dynamics in a Human-Machine environment to achieve design simplicity and optimum component selection, thereby reducing the proposed device's overall design cost. Custom biomechanical assessment methods for human-machine interaction were synthesized to evaluate the device's safety and usability. A working prototype was developed, and an EMG-based experimental validation was conducted on the selected potential participants to examine the functionality of the developed transfer assistive device. The collected data were statistically analyzed, and the results were discussed and interpreted, followed by a conclusion. The study's main contributions are: an alternative biomechanical loading prediction equation was formulated to determine the compressive loads at the L5/S1 lumbar spine for any load and handle orientations, which would be helpful in the early estimation of musculoskeletal disorders in a similar product. A simple alternative methodology for identifying an optimum handle design and orientation was presented using a human-machine approach based on the EMG data recorded during the experiment, and a new technique was also presented for the effective selection of an optimum actuator load and its location in the context of human-machine design. A transfer assistive device employing a precisely selected component was developed to transfer users in a biomechanically accepted posture.

Keywords – Biomechanics; Human-Machine Environment; Transfer Assistive Device.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

List of Abbreviations

CHAPTER ONE

1. Introduction

1.1 Background

Assistive technology devices are those whose primary goal is to maintain or improve a disabled person's functionality and independence in order to facilitate daily living activities and increase overall well-being. According to the classification of the International Organization for Standardization (ISO 9999:2016), all assistive products under this classification are primarily intended for use outside of healthcare settings; however, some of the products can be used in facilities such as rehabilitation centres to teach clients how to use these products [1]. The World Health Organization (WHO) and its global initiative, Global Cooperation on Assistive Technology (GATE), defines assistive technology systems as the development and application of organized knowledge, skills, procedures, and policies relevant to providing, using, and assessing assistive products. An assistive product is any product (including devices, equipment, instruments, and software), either specially designed and produced or generally available. Its primary purpose is to maintain or improve an individual's functioning and independence, thereby promoting well-being [2].

Transfer assistive device (TAD), as one category of assistive technology devices, not only helps in transferring or shifting users from wheelchairs to bed or other surfaces but also helps to prevent the occurrence of secondary impairments. The majority of present devices for disabled persons, whether they are used in hospitals or at home, lack a mechanism to provide an autonomous and regular way of transferring the users. People with lower limb disability and knee or hip replacement patients have traits that make them entirely or partially dependent on caretakers for mobility and activity of daily living. Most disabled individuals in developing countries have no access to transfer devices due to unaffordability and suitability issues; thus, they struggle to complete their daily activities independently or with a caregiver. For people with disabilities, however, completing every activity without caregivers gives them a sense of self-worth. As a result, developing appropriate transfer assistive devices that can be used independently with little to no support from the caregiver is critical for self-sufficiency.

Designing a product for disabled individuals requires knowing the perfect interaction between the device and the users; generating 3D biomechanical models with computer models, such as digital human models, is one of the convenient methods in today's advanced 3D computer technology for evaluating the human-machine interaction that starts in the early concept selection process, and it reduces the number of unnecessary tryouts. Several existing assistive transfer devices provide limited service for the users; most of the reasons are due to a lack of proper integration of users with the device during the early design process. Previous studies [3,4] in patient handling and transfer devices stated that the present transfer assistive devices might need additional

improvements. Another similar research study concluded that their actual application had not been adequately studied despite the importance of using transfer devices in improving caregiver safety when repositioning patients in bed [5,6].

Before subscribing to assistive products, such characteristics as a concise explanation of the typical cause of injury for the user, the patient's range of motion, how the patient feels discomfort, and the injuries they might be vulnerable to should be established. Similarly, a significant element in deciding the amount of assistance provided by caregivers or home nurses for the user must be identified through a preliminary patient transfer algorithm.

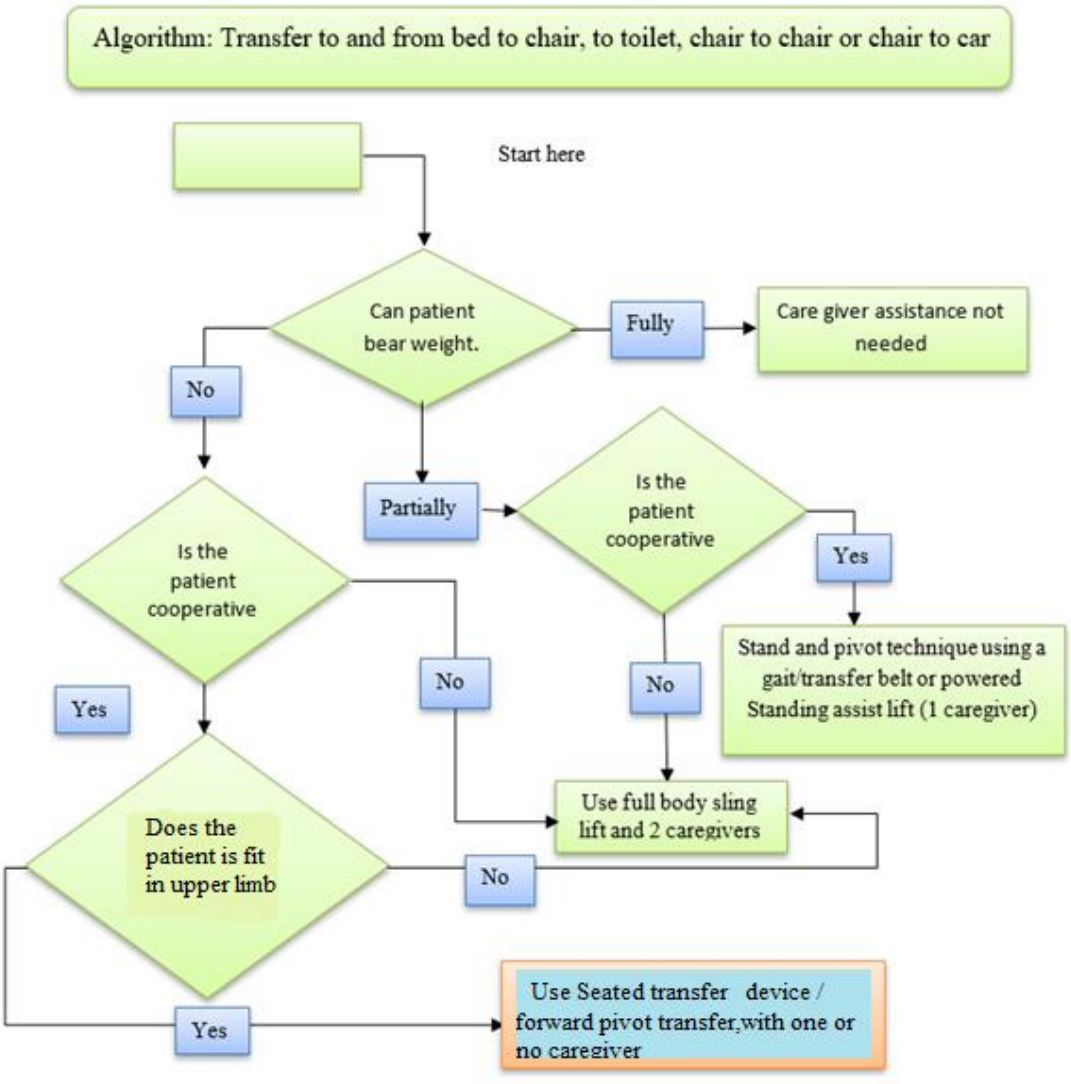


Figure 1-1 Algorithm for deciding suitable types of patient transfer assistive devices

Figure 1.1 above shows one of such algorithms for deciding suitable types of patient transfer assistive devices; this algorithm is generally a necessary decision-making tool to decide the appropriate type of transfer device for disabled individuals. The technique can be identified based on whether the patients bear their weight, have upper body strength, and cooperate with the caregivers. Generally, the present research focuses on an alternative method to help design a simple and affordable transfer assistive device by minimizing the complexity of unnecessary and overdesigned components. To come up with creative ideas for developing a transfer device that could remove the barriers faced by the majority of lower limb impaired individuals, especially those living in low-income developing countries, and to increase the affordability of the device and close the gaps for inadequate access of the transfer device, it was planned to adopt a user-centred design approach using human biomechanics in a human-machine environment. Thus, this study will investigate the processes and methods employed in designing simple, affordable, and safe transfer-assistive devices. Applying design tools and utilizing the biomechanical evaluation method in the early concept selection and evaluation phases.

1.2 Problem Statement

Currently, the number of nurses or caregivers leaving their jobs is increasing due to health conditions or burdens associated with the manual transfer of individuals with a lower limb disability. Most of the existing transfer devices are complex in design, increasing their costs, making them unaffordable for developing countries and unsuitable for the forward pivot transfer technique. Also, some of these devices are not in line with the comfort and safety zone of the users, which highlights the need for biomechanical and ergonomic assessment of such devices from users' perspective during concept and product evaluation. Hence, an attempt was made to develop a simple and safe transfer device by exploring an alternative research direction in the field of transfer assistive technology devices.

1.3 Research Aims and Objectives

Aim: The aim of this study is –

Design, development, and evaluation of a simple and affordable transfer assistive device by integrating biomechanics principles in a human-machine environment and introducing an alternative design approach for predicting a biomechanically accepted transfer posture.

Objectives: To achieve the above aims, the specific objectives of this research are:

- **a)** To conduct a field study with selected healthcare stakeholders to gain insight into the existing transfer/mobility devices and techniques and understand their requirements for future devices.
- **b)** To generate and apply a context-driven design approach in a human-machine environment using digital human modelling software
- **c)** To explore an alternative approach for graphical-based biomechanical loading analysis
- **d)** To analyze and investigate an optimum handle design selection for the proposed concepts.
- **e)** To design and investigate the novel under-arm support through EMG-based experiments using a real subject-device interaction
- **f)** To design and develop an appropriate transfer assistive device based on the current gaps

g) To prepare documentation of the manufacturing drawings for further production.
h) To fabricate the prototype and perform subjective/objective evaluations

1.4 Research Question

RQ1: How can the level of compressive load at L5/S1 be predicted concerning patient transfer posture and the load imposed by the transfer device?
RQ2: Does integrating the biomechanics principle in a human-machine context help to predict a biomechanically accepted transfer posture and investigate design simplicity and an appropriate interfacing mechanism of a device?

1.5 Research Hypothesis

H1: The level of the induced compressive load at L5/S1 during a patient transfer activity could be predicted by investigating the biomechanics of the existing transfer posture and from the induced load of the transfer assistive device.
H2: If a development process is assisted using the biomechanics principle, the biomechanically accepted transfer posture and a simple transfer device with a suitable interface mechanism could be simply obtained.

1.6 Methodology

The systematic methods for developing a transfer assistive device in a human-machine setting using an integrated framework of biomechanics and product design start with collecting and reviewing two data sets: primary data and secondary data. The primary data was collected from nearby healthcare institutes in the form of an interview, questionnaire and focus group discussion, and secondary data was collected from published papers, books and internet sources which are relevant to the present research. The present thesis comprises a design-based activity and research-aided product development process; therefore, the application of context-specific concept ideation and development processes and validation of the prototype were taken as the main parts of the thesis. In order to fulfil these tasks, first, the preliminary concepts related to the transfer motion algorithms have been decided, considering the seating forward transfer method as one of the chosen transfer techniques among the existing reviewed devices. Based on this option, the concept design of a motion algorithm comprising a human manikin-device interaction was virtually created using Catia v5 software in a human modelling environment; thus, by exporting the assembly model into an advanced sketcher workbench, the precise dimensions of the supporting mechanisms were digitized in the given posture. Each digitized coordinate is then exported to linkage software to perform a graphical mechanism synthesis; due to space limitation and motion requirements, only two candidate mechanism categories were selected and found suitable to perform the forward seating transfer in the prescribed reach envelope of the manikin (modelled using an Indian anthropometric database). Various mechanism syntheses of these categories were generated to select the best mechanism as per the criteria, such as having a lower complexity, ease of actuation and lower degree of freedom; based on these criteria, one of the candidate mechanisms has been selected. The 3D model was created for the selected mechanism; this mechanism was again

decomposed into three concepts based on the design and orientation of the handle. In order to choose the best concepts, a lifting platform equipped with prefabricated three handle frames comprising similar components to each of the decomposed concepts was used. Thus, the biomechanical loading assessments using EMG experiments were conducted on selected participants recruited from the "Indian Institute of Technology Guwahati". Statistical analysis was carried out to predict the effect of handle location and posture.

Additionally, custom-derived predictive equations for biomechanical loading assessment were used to determine the compressive loads on the low back L5/S1 join on the same subjects in the above experiment. The results were also compared using commercial software. Anthropometric data, along with the necessary biomechanical inertial parameters, were calculated to determine the critical components of the transfer device, such as the actuator load and its locations. The preliminary proof of concept experiments were also done at a laboratory level with a potential subject to identify the effect of heart rate and the rate of perceived exertion and the impact of the under-arm support on biomechanical loading. Generally, this report adopted a graphical and analytical method of determining the design parameters in a human-machine context. Based on the extracted design parameters, the development of the transfer assistive device was decided, followed by an experiment for subjective and objective evaluation of the device. Below is a summary of the methodological flow chart and an overall thesis framework.

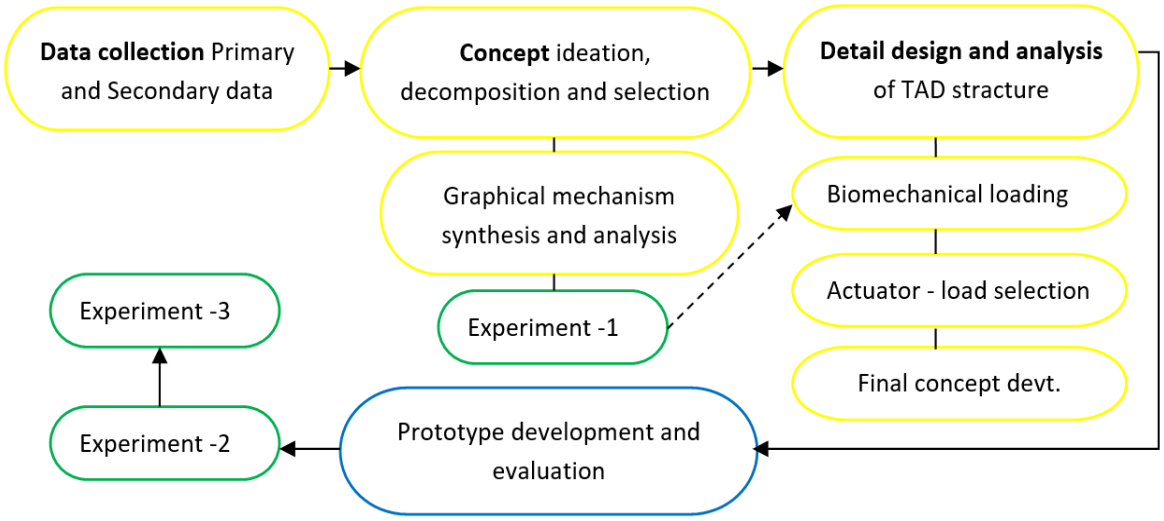
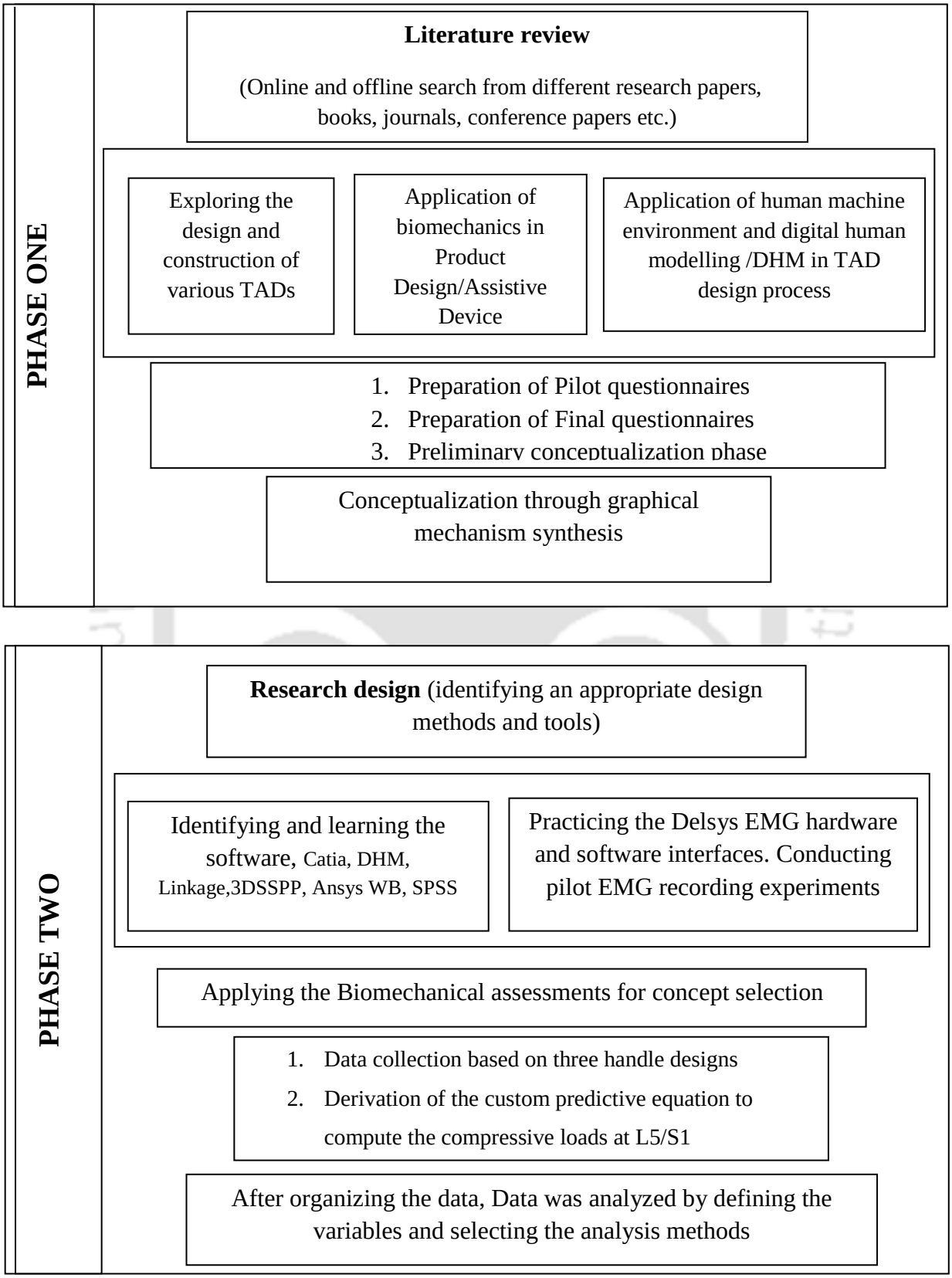
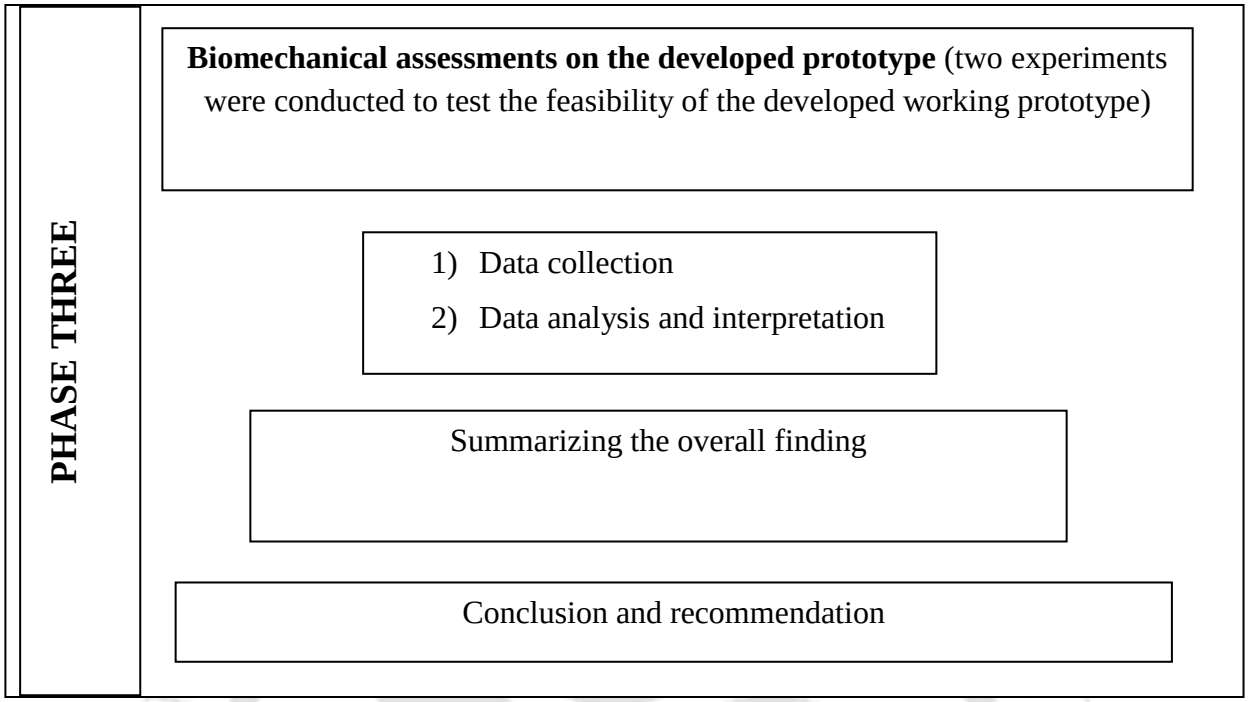


Figure 1-2 Flow chart of the Methodology

Table 1-1 Overall thesis framework





1.7 Thesis Outline

Generally, this report is divided into seven chapters, and various topics covered under each chapter are as follows:

Chapter 1 is an introduction chapter highlighting the overall view of assistive devices and disability as per the WHO data. It also includes the Proposed algorithm for deciding the type of assistive devices, Problem statement, Research question, Research hypothesis, Aim and Objectives and the adopted Research Methodology. **Chapter 2** is an overview of related studies and covers various aspects of disability and accessibility of transfer assistive devices and their techniques, highlighting the role of biomechanics and DHM in the product design and evaluation process. It also summarizes the literature review with an identified research gap. **Chapter 3** covers Questionnaire design, Questionnaire procedure, Analysis of questionnaires and Summary of Questionnaire; it also covers Preliminary Concept Development, Overview of the Initial Concept, Virtual Motion Planning and Mechanism Synthesis, Graphical Mechanism Simulation and Selection and Concept decomposition of the selected candidate mechanism-1. **Chapter 4** Describes the Biomechanical assessment of the upper and Lower Arm Muscles During a Forward Transfer Activity. It also includes the Procedures for Evaluating the Handle Orientations Based on the Recorded Muscle EMG Excitations, Statistical analysis results of the recorded EMG Data, Estimation of the Biomechanical loadings at L5/S1 joint in the context of the proposed concepts, Procedure for estimating the biomechanical loadings on the selected joints and Comparison of the Estimated Compressive Loads by Commercial Software.

Chapter 5 presents the Design and Analysis of the Transfer Mechanism Based on Biomechanics and Anthropometrics Data, the Computation of the "Center of Mass" in the Context of a Human-Machine Environment, the Computation of the moment of inertia of the body segment and the Transfer device in the Context of a Human-Machine Environment, Design and Selection of Actuators for the Transfer device, Evaluation and comparison of the effective position of the actuator on the frame, Design of the lower rotating mechanism, Finite Element Analysis for the selected structural part of the proposed device and Summary of the concept selection process. **Chapter 6** Presents the Prototype Development and Testing, Prototype evaluation, Data Collection, Data Analysis and interpretation, Estimating the Physical Strain Level During Transfer Activities, Experiment conducted with a paraplegic individual, experiment conducted with a person having difficulty in STS, Statistical Analysis on the Effect of Transferring with and without the Under-Arm Support, Data collection and presentation, and in **Chapter 7** is the last chapter, where the overall methods and results are discussed in relation to the research questions followed by Conclusion, limitations and contributions of the present study as well as highlights about the future research study. A list of References and Appendices is provided at the end of the thesis, containing the manufacturing drawings and sample questionnaire lists.

CHAPTER TWO

2. Literature Review

2.1 Introduction

This section will review existing literature or prior arts from relevant organizations, product developers, and research works studied by various researchers related to the current topic. Depending on the multidisciplinary nature of the topic (Assistive Technology) under consideration, the outline of the review is structured based on three broad categories: (1) Overview of Disability and Accessibility of Assistive Technology Devices, (2) Review of Transfer Assistive Devices and Transfer Techniques and (3) Role of Biomechanics and DHM in the product design and evaluation process. Their particular contributions towards patient handling and transferring devices will be discussed briefly through a systematic approach. Finally, the comprehensive summaries on the relevant topic of the literature review and its corresponding research gap will be presented at the end of this chapter.

2.2 Overview of Disability and Accessibility of Assistive Technology

The comprehensive pieces of literature and the majority of research on global reports for estimating disability and the need and access to assistive technology devices were conducted by the World Health Organization (WHO) in the last few decades; on the other hand, researchers have contributed relatively few reports as compared to the WHO. The fundamental need for estimating disabled individuals in a given population is considered one of the commonly adopted methods that help an organization like WHO determine the balance between supply, need and demand of assistive technology devices. It can also be used as a proxy for estimating the market size of assistive technology products required to satisfy the needs of disabled populations. Based on this method, in 2010, the World report on disability estimated that more than one billion adults and children worldwide (15% of the global population) were living with some form of disability, a substantial increase from the previous estimate of about 10% in the 1970s [7]. Similarly, the population data from 2010 showed that of individuals aged 15 years and older living with a disability, an estimated 2.2–3.8% had significant difficulties in functioning [7].

According to the estimations made by WHO, there are over one billion people, the majority of whom are people with disabilities and older people, who need one or more assistive devices [8]. The studies on the need for assistive devices also found that the number in need of assistive devices was projected to increase to surpass two billion by 2050 due to rises in non-communicable diseases and the ageing global population [9]. However, evidence indicates that an estimated 90% of people who would benefit from assistive technologies do not have access to them, and it was also reported that there is a vast unmet need for such devices [10,11]. Additionally, research was carried out on the accessibility of basic assistive devices such as a wheelchair in low- and middle-income countries, and their findings showed that 70 million people need a wheelchair, but only 5–15% have access to one, and production of hearing aids meets only 10% of global need and 3% of the

need in low- and middle-income countries. Moreover, the same study has reported that 200 million people with low vision cannot access spectacles or other low-vision devices [12]. The prevalence of disability by World Health Organization region was reported based on the Global Burden of Disease (GBD) data from 2004, and they found that the WHO South-East Asia Region was reported to have the second highest prevalence of moderate disability (16%) and the third highest prevalence of severe disability (2.9%) [7].

Similarly, research was conducted in East African regions such as Ethiopia and showed that there are an estimated 15 million children, adults and elderly persons with disabilities, signifying 17.6 per cent of the population. The alarming rate is increasing due to one of the reasons why the majority of people with disabilities live in rural areas, and this has an impact on the limitation or not getting access to basic healthcare services. According to the country's profile study on persons with a disability, a little consideration will show that the lower limb disability is considered to share the highest percentage of disability types associated with the individuals, as depicted in figure 1.1 below [13]. This finding helps to identify and balance the accessibility of assistive technology devices based on the estimated type of disabilities in a given region or population. This information demonstrates the higher prevalence of impairment and the need for assistive devices among lower limb-impaired people living in developing countries. These types of patients require caregivers or nurses in their daily activities. However, since the number of caregivers and patients is not proportional in low-income developing countries, increasing the accessibility of adequate assistive devices is required for this group of patients.

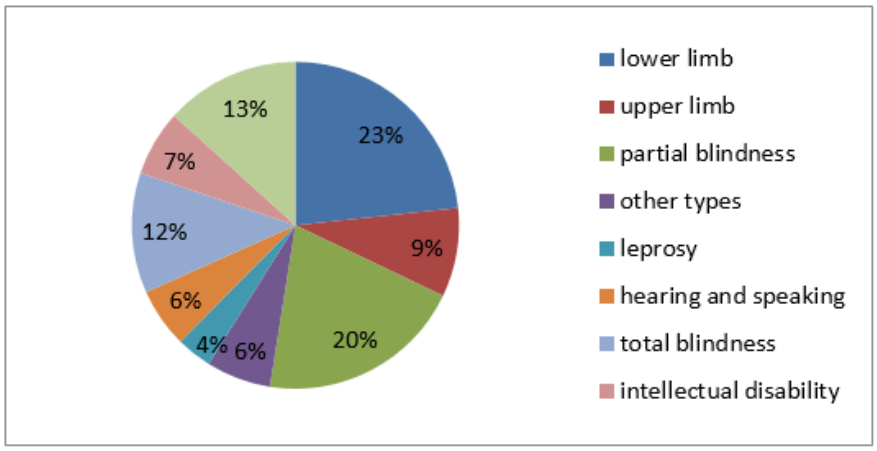


Figure 2-1 "Country Profile Study on People with Disabilities"

Recently, some studies have highlighted that the increasing rate of disabilities is not the only factor that affects the accessibility of assistive technology devices. This study stated that inequalities in access to assistive devices and services had been found among people living in different countries or regions of a country, under different economic conditions, among people with different impairments, genders, ages, languages, and cultures [14]. Similarly, in another study, they found that men are often more likely than women to have assistive technologies, adults are generally

more likely to have them than children, and in some countries, people with a specific type of impairment more frequently have assistive technologies than people with other impairments do [15]. Conversely, a group of researchers found additional factors that affect the accessibility of assistive technology; according to their findings, lack of access to assistive devices was due to high costs, limited availability, and lack of governance and inadequate financing in many settings, as well as a widespread lack of awareness and suitably trained personnel [16,17].

According to the recent reports of the World Health Organization, various challenges for improving the accessibility of AT devices were investigated; the report found that some existing assistive products are produced only at international standards, and they are more specific to high-income settings, which was not appropriate for diverse settings, especially rural environments. Similarly, there is also a lack of context-appropriate product design because most AT products are often manufactured using parts that are not replaceable locally, which contributes to high abandonment rates. Another challenge was that most disabled individuals from low and middle-income countries are forced to rely on donations or charitable services; such services are usually of low-quality or used products that are inappropriate for the user or the setting and are not maintainable, repairable, or replaceable locally [12].

Another reason for limited access to AT products is the lack of research and development activities in most low- and middle-income countries in the field of assistive technology. For instance, the high-income countries' research and development centres focus on high-tech solutions, such as developing an assistive technology device, which may not be appropriate for low- and middle-income countries. According to recent reports, the majority of research and development in high-income countries has concentrated on high-income contexts, with a trend toward high-tech solutions with optimal functionality, and little research and innovation has concentrated on developing robust, affordable but high-quality assistive products which can be easily accessed by the low- and middle-income countries [9].

Achieving affordable access to assistive technology equipment, on the other hand, has been discovered to rely on government support to compensate for extra costs such as maintenance and travel costs, particularly to encourage local producers. According to research reports, a lack of state funding, user-centred research and development, procurement systems, quality and safety standards, and context-appropriate product design are all negative factors. Similarly, they have emphasized that many local manufacturers in low- and middle-income countries do not produce assistive products or have small-scale production in terms of both quantity and variety of products. Lack of access to necessary materials and equipment and accompanying high tariffs and import taxes have been identified as constraints to local production [18]. Furthermore, this study discovered that the significant obstacles to accessing an effective assistive technology device include the initial cost and the requirement for equipment maintenance and replacement, explicit education and practice on its usage, and associated services and travel expenditures [18]. The high cost of assistive technology devices arising from the unaffordability of imported products is also

found to be the barrier to improving the accessibility of such devices; research studies in this regard have highlighted that the cost of assistive devices can be prohibitive in low-income contexts and lack of economic means has been identified as a primary barrier to access assistive technologies [15]. Similarly, other studies have stated that prohibitive costs also arise from the costs of maintaining and repairing assistive devices and those involved in travelling and accessing associated services [14,19].

Several challenges affecting the accessibility of assistive technology services or products have been mentioned in the above reports; for instance, utilizing imported AT products was found to have a negative impact due to its high cost and on user preference since such devices are designed based on the Anthropometric data of a different country; hence, it lacks a proper fit. Adopting the principle of matching the person with technology (MPT) in the field of assistive technology will have more advantages than other ordinary product development processes. One of the reasons for the inadequate accessibility of assistive technology products, as seen from previous studies, is due to the problem of a mismatch between the user and the device.

Various studies have highlighted the need and impact of MPT; for instance, one study stated that distributing a "one-size fits all" assistive product may result in limited usage and poor technology adoption [20]. Moreover, a poor person and technology-matching device might not only result in non-use. However, they can harm the user or other people in the user's environment and lead to reluctance to try other or additional products. Another study has denoted that matching assistive technology products must include a needs assessment process with appropriate assessment instruments and personnel who are trained to work with people with disabilities and their families to perform these assessments [21]. It was also stated that assistive technology devices imported from high-resource settings are developed without taking into consideration the true environmental, social and resource factors that impede the adoption of technology in low-resource settings [22]

Improving the awareness of the usage of assistive technology devices for its users and their caregivers has a positive impact on enhancing the accessibility of AT devices; it also provides a ground for receiving feedback on how to improve the existing product in the future. In order to improve awareness of the usage of assistive technology devices, for instance, [23] suggested that people with disabilities should have a full range of access to their devices, such as to involve them in assessment, fitting, training and follow-up, this will help to address issues such as abandonment of devices. Similarly, [24] highlighted that, in order to improve awareness of AT devices, in most high-resource settings, there is a strong clinic-patient relationship that exists beyond fitting or initial prescription, which helps to improve the awareness among users and their families, thereby facilitate easy access of the AT product which is not the case in low resource settings.

The World Health Organization have introduced the Priority Assistive Products List [25]. This list comprises 50 priority assistive items to increase access to high-quality, affordable assistive products in all nations. It aimed to provide member states with a model to develop a national

priority assistive products list according to national needs and available resources. However, most of the assistive products in this list are not related to mobility and transfer assistive devices; only a few are used as standing and walking frames, but none are used as transfer assistive devices.

Today, most patients in nursing homes or healthcare centres might face an injurious fall while trying to transfer manually from one surface to another, resulting in temporary or permanent disability. Similarly, there might be a chance of getting a secondary impairment for those already listed as disabled; this fall is due to the unavailability of suitable assistive transfer devices.

It is well recognized that improving the accessibility of assistive technology devices can enhance the quality, privacy, and independence of people with disabilities. Despite these benefits, the use of assistive technology for preventing secondary impairments is low in developing countries; this negatively impacts the accessibility of assistive technology devices in low- and middle-income countries. The research was conducted to highlight this issue in six low- and middle-income countries: Brazil, Cambodia, Egypt, India, Turkey, and Zimbabwe. They found that, although this country had some assistive technologies designed for older adults with existing disabilities, they had limited assistive technologies designed for preventing secondary impairment [26].

2.3 Review of Transfer Assistive Devices and Transfer Techniques

Patient transfer assistive technology devices are generally used to transfer lower limb disabled individuals or patients with spinal cord injuries, severe burn injuries, or other serious injuries, particularly between wheelchair to bed or operating tables and hospital beds and vice versa. Its objective is to transfer patients safely and painlessly to prevent secondary impairments and lessen the workload of nursing personnel and the risk of infection. Individuals with spinal cord injury (SCI) living in developing countries face problems due to unavailability or inadequate access to transfer aids; hence, a manual transfer such as sitting-pivot transfer (SPT) is the most common type of task in their activity of daily living (ADLs). It is evident that many people who suffer a spinal cord injury would need to use a wheelchair for the rest of their lives [27,28]. On the other hand, individuals who are fit in their upper limbs may do sitting pivot transfers on their own, which increases the risk of falling. Furthermore, such activities will cause the shoulders to flex and horizontally adduct, resulting in high biomechanical loading in the upper limbs. According to the study conducted by the “Occupational Safety and Health Administration (OSHA)” [29], They discovered that using transfer devices or lifting equipment in healthcare institutions and at home can reduce manual lifting accidents by up to 95%. Furthermore, according to the same survey, healthy patient handling services were found to reduce the risk of injury for both healthcare professionals and patients while improving patient care quality.

In the last few decades, the need for TADs has become high due to the increasing rate of disability, ageing, amputee from landmines and disease. Most researchers tried to address the need for TADs, and many TADs were invented by product developers and organizations, but few of them became

available commercially in the market. In this report, only relevant TADs which are found at a physical prototype level or finalized product and thus published in scientific papers will be reviewed. Additionally, this review will include relevant TADs available on the market and routinely used by patients in healthcare facilities or nursing homes. In order to study the characteristic features of transfer devices and their transfer technique, various researchers have classified Transfer assistive devices (TADs) based on different perspectives; for instance, from a technological point of view, TADs were classified as low-tech devices, mechanical lifts, and powered or robotic systems [30]. Low-tech Transfer assistive devices include transfer boards, slides, and slings, which are predominately used for lateral transfers. Mechanical lift systems include hydraulic floor-based systems which use a hand crank to operate the lift and placement of a person. Powered lift systems use electronic actuators to replace the hand crank in floor-based systems. Similarly, according to the lifting types, TAD was also divided into two categories, such as hoisting (using a bracket attached to a ceiling) and lifting (using a supporting plate) Transfer assistive devices [31]. Additionally, based on the way of transferring patients, TAD was mainly divided into two types: lift-sliding type and horizontal moving type [32]. The lift-sliding type TAD is used to lift a patient (who lies on the hospital bed) vertically through the rising of the carrying arm and transferring the patient to the top of the transferring bed. Whereas the horizontal moving type TAD adopts horizontal movement in the process of transferring patients from a hospital bed to a transferring bed.

In this thesis, a general review of patient transfer assistive devices was presented by systematically grouping them into four broad categories based on their functionality and on the method of lifting techniques / transferring posture; it has been classified as follows: *Sitting transfer, Supine* or *laying transfer, Forward pivot transfer* and *Sit to standing transfer*. Based on this classification, the review was presented as follows:

Sitting transfer*:* these categories of TADs are generally recommended for patients who can transfer in a sitting posture; various TADs are developed to help users of such categories. For instance, The Gantry lift mobile [33] was designed for lifting and transferring very obese and bariatric patients, and it is especially useful when there is no ceiling lift available to move and lift these patients. It has two vertical side supports, and a horizontal support bar that extends between the two side supports, as shown in Figure 2.2A, and its lift motor assists in traversing across the horizontal bar. The gantry lift is placed over a patient's bed and works similarly to a ceiling lift. The disadvantage of this device is that it is not used to transport a patient from one patient room to another. Adjusting such devices over the patient's bed and arranging the slings adds to the nurses' workload. Because of its high cost, it is generally only suitable for high-income countries.

The Vertical Patient Lift [34], with a lifting capacity of 500lb, is one of the patient transfer devices currently available in the market; as shown in Figure 2.2B, it was designed to feature a fixed suspension column and vertical lifting pattern that keeps the user equally far away from the lift column during the entire lifting motion, and it can easily fit under most beds, chairs, and wheelchairs. This patient transfer device provides stability and comfort for users weighing up to

562 pounds. The lifting pattern keeps patients from swinging too closely to the suspension column. The drawback of this device is that it is not as easy to move larger patients over the carpet as it is over smooth flooring, and it uses six suspension points for positioning flexibility rather than the existing 4-point suspension points. Due to the metallic and hoisting structure, such devices are expensive, bulky, time-consuming, and often involve complicated steps requiring training.

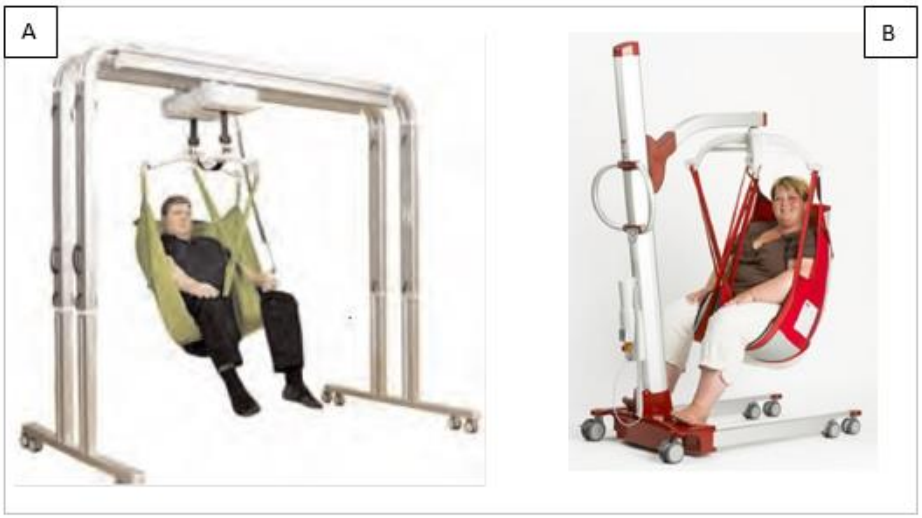


Figure 2-2 The Gantry lift mobile (A) and the Vertical Patient Lift (B)

Handicare Multi-Room Ceiling Lift [35], as shown in Figure 2.3A, is also another type of patient TAD which provides horizontal and vertical movements. It can also raise, lower and move the patient from right to left directions by the caregiver either manually using a non-motorized track or with a hand-held remote. It has a constant charge feature, which continuously charges the lift. The overall movement of this ceiling lift requires a traverse track design which could extend through the living room, hallway, bathroom, and bedroom. The drawback of this device is that the traverse track design affects the use of privacy curtains; hence, room design specifications must incorporate solutions that ensure patient privacy. Also, the structural deficiencies in existing buildings may prevent the installation of a traverse track motor. Additionally, adjustment of slings and lifting setups is time-consuming; also, due to its high cost ($4500), its usage is limited by high-income countries. Recently, the trends of combining lifting devices and mobility devices, such as mounting the TAD on a wheelchair, are getting more focus in the field of transfer assistive technology devices. Strong Arm [36] is a highly automated transfer robot where the robotic arm is mounted on the lateral side of the electric power wheelchair's armrest. It is a five degrees of freedom (DOF) robotic arm with a three-axis load sensor that can help the patient move from bed to wheelchair. This robot is powered electromechanically by a combination of planetary gear motors and linear actuators. The carriage is moved around the track using a planetary gear motor,

which is connected to spur gear that propels it along a rack machined in the centre of the face of the track, as shown in Figure 2.3B. Like the previous patient lifting devices, the hoisting system should be attached to the robotic arm using the slings to lift the patients from the wheelchair to the bed. The drawback of this device is that the patients are entirely passive during the transfer manoeuvre, which is not in line with the rehabilitation settings or requirements. Similarly, the weight of the patient being lifted is concentrated on one side of the wheelchair's armrest; hence, the system's stability could be at risk of tipping over; therefore, ensuring safety has become a difficult job. Furthermore, comprehensive caregiver assistance is required to assist the patient in shifting from the wheelchair to another position.

Figure 2-3 The Ceiling Lift (A) and the Strong Arm (B)

A novel lateral transfer assist robot (LTAR) [37] was developed for transferring patients laterally in a sitting posture between surfaces without any height differences, gaps, or obstacles and without using the flip-up armrest and transfer board. LTAR was designed to facilitate independent transfers and decrease the need for transfer assistance in poststroke hemiparesis patients. It has 360^0 manoeuvrability for facilitating easy movement close to the transfer surface because of the mecanum wheels, which have free rollers with axes tilted at 45^0 from the wheel plane to the outer circumference of each wheel, has a joystick which is placed in the armrest on the left or right side depending on the user's preference as shown in figure 2.4A. Before the transfer, the height of the seat and armrest increase or decrease until it is at the same height as the transfer surfaces; at the same time, the footrest moves down to lie flat at the floor level. The drawback of this device is that a substantial effort from caregivers is still required during both loading and unloading the

users; in either case, the users should be displaced from their seat surface to the new destination, and again positioning the users in a supine posture will be an extra task in case of shifting to the bed.

Home Lift, Position, and Rehabilitation (HLPR) chair [38], designed at the National Institute of Standards and Technology, aims to be able to lift wheelchair users, rotate them, and place them on a toilet, chair, or bed. Additionally, it can also be used as a locomotion and rehabilitation facility. Figure 2.4B shows the HLPR chair's dynamic architecture, which is based on a "forklift" theory. Although the design of HLPR has many advantages, it lacks an ergonomic design due to its bulky and double-frame metallic structure. Generally, this device has seven drivers, one for lift control and two each for steering and riding seat and footrest actuation and torso lift operations, which makes the unit more expensive, and its size is incompatible with standard room and door sizes. Moreover, the users become passive as they are in a sitting posture during the whole process.

Figure 2-4 The LTAR (A) and the HLPR (B)

Supine* or *laying transfer: this type of transfer technique is commonly used for transferring or lifting patients who are bedridden or completely unable to be lifted up in a sitting posture. Lateral transfer devices aid with moving or repositioning patients horizontally (in supine or laying posture) from one flat surface to another, such as transfers to/from bed to stretcher to exam or treatment table. A novel person transfer assist system, E-Pat (Easy-Patient Transfer), which can meet the transfer needs of the patient between beds, has been introduced [39]. It has a double-layer flat belt structure as its core mechanism for transferring the users, effectively reducing the friction between humans and machines during the transfer process. The E-Pat also contains a bevel arm that diminishes the insertion angle when transferring the users, making it easier for the human body to be transferred to the device. An electric stretcher is used as an auxiliary drive to move the patient who is already placed on the E-Pat, as shown in Figure 2.5A. The Careful Patient Mover or C-Pam

[40] developed by DAIHEN is also another lateral–laying transfer device that can transfer the patient between beds and bed to stretcher; it has an electrically driven chassis, and a transfer module board with an annular belt as shown in figure 2.5B below. The complete transfer of the patient is performed due to the combined mechanism of plate expansion and belt rotation. When moving a patient from a bed to a stretcher, the equipment rolls across the bed from the stretcher and carefully slides under the person resting on the bed. The apparatus then lifts the patient slightly and pulls him or her back to the stretcher. The advantages listed in both cases of the E-Pat and C-Pam would greatly help the caregivers transfer their clients. Despite the benefits of transferring the patients without significantly changing their posture, friction and slight skin deformation between the device and users still exist, which may not be suitable for patients in serious medical cases. Additionally, the need for an extra auxiliary platform, which is used for shifting the patients from one room to another, may increase the initial cost of such devices; hence, it may not be affordable for most users who are living in a low-income context.

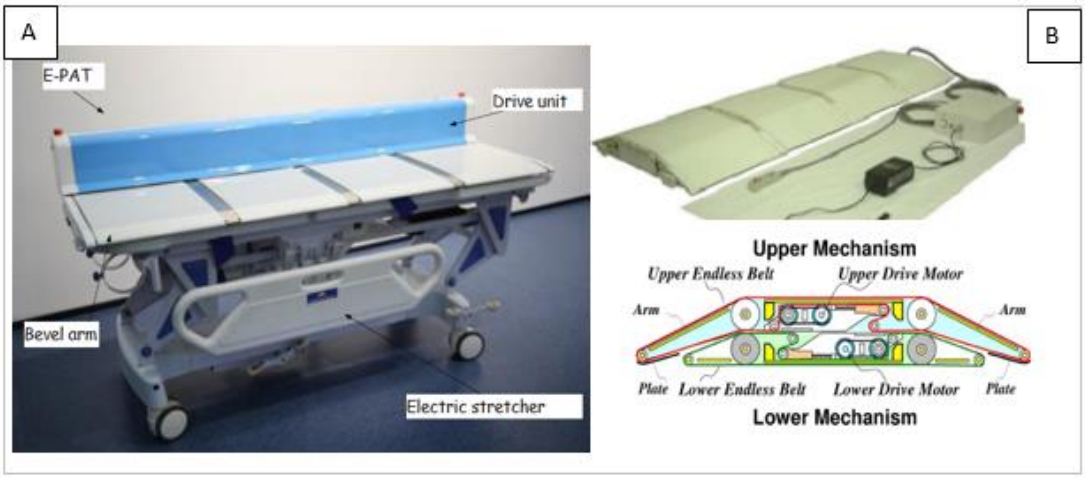


Figure 2-5 The E-Pat (A) and the C-Pam (B)

A new prototype named RIBA (Robot for Interactive Body Assistance), shown below in Figure 2.6, has been developed [41] by adopting a new human-robot interface tactile guidance based on tactile sensors. The developed prototype has an overall size of 1200 width, 850 depth and a height of 1400 mm. It has 12 d.o.f, employing an omnidirectional wheel driven by DC motors. Its primary usage is for transferring a patient between a bed and a wheelchair, using human-type arms. These arms allow RIBA to adapt its lifting motion to different situations, including lifting to and from a wheelchair without a reclining function. Its disadvantages include the increased cost and probability of malfunction caused by the complexity of the arm structure and the danger of

dropping the lifted patient. Also, its maximum lifting payload is limited to 63kg, which may not be suitable for many users.

Figure 2-6 The RIBA (Robot for Interactive Body Assistance)

Forward pivot transfer: this type of transfer technique is used to transfer users from wheelchair to bed or other surfaces either manually or with the help of transfer devices. Individuals in this category are generally weak or paralyzed in their lower limbs; there might also be long-term patients who are waiting to recover after hip/knee replacement surgery. This technique requires three steps to completely transfer the patient from the wheelchair/bed to other seating surfaces; firstly, the patient should be in a seated posture with slightly leaning forward after ensuring that the patient's chest or upper abdomen has made good contact with the supporting platform or saddle, at this point the forward lifting (rotation about the vertical axis) will be completed. Secondly, the patient should be moved/rotated to the direction of the destination seat/bed; this can be accomplished (rotation about the horizontal axis) either manually or using a powered system. Finally, the patient will be seated in the destination seat by following step one reversely.

Very few researches have been conducted on this type of transfer assistive device, and few devices in this category have been developed in the last two decades. For instance, the development of a simple self-transfer aid robotic system [42], which was inspired by the improvements made on the manual transfer system of "Komawari-San", which needs a caretaker for transferring the patient as shown in figure 2.7A, similarly, figure 2.7B shows the enhanced rig, which comprises a robotic arm with a saddle on top, hinged over a horizontally moving frame of Omni-directional wheels, this device employs three working steps such as standing, turning and sitting while transferring the user to the seat surfaces. It has a two-degree-of-freedom robotic arm with a motor drive and a wire-driven mechanism, which is used for lifting the user; the wire is wound up by a pulley, which is rotated by a geared motor. The drawback of this device is that it is only designed for those who can stand with the help of standing assistance or a walker, so the user should keep the stability of

the device partially in standing mode. Thus, individuals unable to stand with their legs are excluded from using this device.

Similarly, using a wire-driven mechanism (pully and geared motor) and omnidirectional wheels increased the complexity of the device. An omnidirectional wheel is unsuitable for transferring passive patients as it leads to undesirable motion or slips, which may cause danger to the user. Generally, this device employs four motors for the omnidirectional wheel mechanism and one motor for the arm, making the system costlier. While evaluating the suitability of the Omni-directional wheels, they found that the speed and acceleration of the Omni wheel are not within the limit.

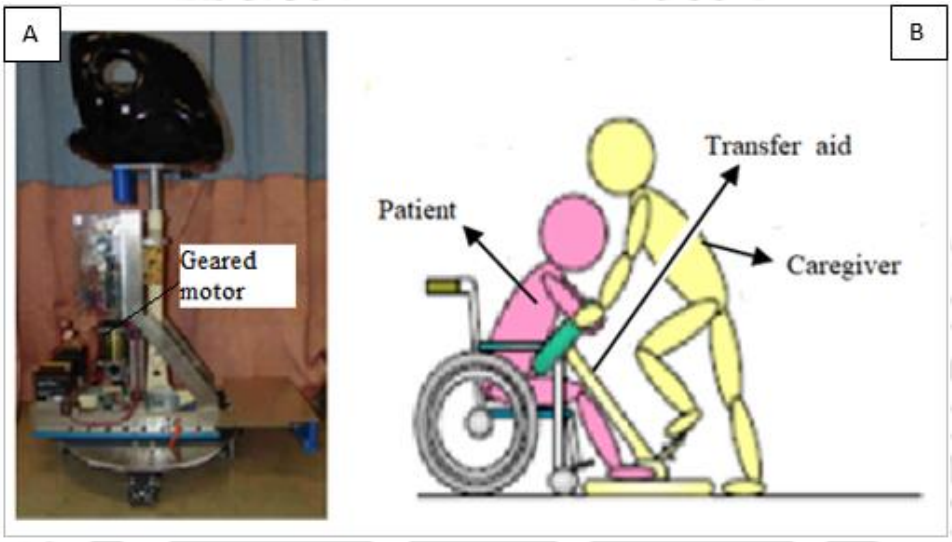


Figure 2-7 The self-transfer aid robotic system (A) and the Komawari-San (B).

The Easy Pivot Mechanism [43] is also among the forward pivot transfer devices currently available in the market. This device has the capacity to lift patients from a wheelchair to a bed or other surfaces; once the patient is ready to shift from a wheelchair, part of the straps will be wrapped around his/her buttock and towards the L-shaped fulcrum or lifting handle, similarly his/her shank will also be attached to the lower part of the device using another piece of the strap. The caregiver will manually turn the lifting handle to transfer the patient from sitting to a forward bending posture, as shown in Figure 2.8A. Once the patient is fully lifted up, as shown in Figure 2.8A, he/she should be manually moved to his/ their last destination using the pulling and rotating action. The limitation of this device is that the caregivers should apply a substantial amount of pulling force at the handle in order to lift the user, and it should keep the stability of the device while releasing the handle to the seated position. The caregivers also apply extra effort while manoeuvring the loaded device in a lifted-up condition. Similarly, the patient's knee is kept attached to the device, acting as a turning pivot throughout the transferring phases. This condition creates discomfort for the users, and it leads to fatigue, knee dislocation and skin deformation. The safety of the patients is also at risk because once the patient is in a lifted phase, there might be a

chance of a sudden fall or return if the caregiver unconsciously releases the lifting handle. The difficulty of attaching the straps and the time taken for adjusting, loading, and unloading are also other drawbacks observed in this device.

Figure 2-8 The Easy Pivot Mechanism, during lifting(A) and lifted up phase (B)

Researchers have developed the self-transfer system [44], which can be attached to a wheelchair in order to facilitate easy manoeuvrability. It was designed to transfer a patient in a forward pivot transfer technique who is not able to transfer alone without the caregiver. It works based on a three-degree-of-freedom robotic arm and turntable attached to the base, and the arm is actuated using a gas-spring cylinder. The turntable is rotated using the epicyclic gear mechanism. Generally, it has three steps for transferring a patient from a wheelchair to a bed or other surface. First, the patient should lay on the saddle with the upper abdomen and firmly hold the hand; once lifted up, the robotic arm rotates by 180 degrees, facing the destination's direction. Finally, the patient will be placed to the last destination by lowering the robotic arm. Figure 2.9 below shows the test subject while using the device. The drawback of this mechanism is that the users' full weight is only supported by the saddle, and no more provision was included to distribute the pressure evenly towards other body parts; it lacks the design of the under-arm support to minimize the contact pressure between the saddle and the subject's abdominal region. Additionally, this device was made to transfer the patient to a destination which is located only 180 degrees from the initial seat and was never used for transferring users to a seat located 90 degrees from the initial position. Similarly, the arm that works by a gas spring has a limited angular tilt, which the manufacturer usually recommends as less than 60 degrees from the vertical to avoid failure; hence, it is intended for limited motion.

Figure 2-9 The self-transfer robotic system

The manual transfer device named Senior Transfer Lift is also another type of transfer device which is currently available in the market [45], as shown in figure 2.10. It adopts a similar technique with some of the above devices [43,44] and is used to transfer a person who is not able to transfer alone from a wheelchair to a bed or commode and vice versa by employing a forward pivot transfer technique. Generally, this device was built with metallic frames comprising a saddle for supporting the user in a forward-bending posture and two handles employing a crank mechanism. One of the handles is used for lifting the patient and steering or manoeuvring the device with the help of the four caster wheels mounted at the lower part of the chassis. The second handle was designed in such a way that the first handle governs its motion; when the caregiver applies a pulling or pushing effort to lift or lower the user, the user will keep on holding the second handle throughout the transfer process to overcome the backward movement. This device was also equipped with a strap to hold a user's torso during both lifting-up and lowering conditions.

The drawback observed in this device is that, from the caregiver's point of view, the caregiver's burden is not relieved as the entire lifting and manoeuvring process is accomplished manually by the caregiver. Besides applying a high pull-push exertion at the handle by the caregiver, the patient should also apply considerable effort at the handle to overcome the backward sliding action while lifting up and avoid a sudden fall while lowering. This type of fall is known as the main cause of secondary impairments in most disabled individuals. The only support made on this device is the belt strap passing through the upper torso of the user, which helps for vertical support instead of keeping the user from slipping horizontally back to the initial position; hence, it puts the safety of the users at high risk. Similarly, there is a lack of safety issues in the user's lumbar posture, and it is shown as being over-flexed, which is beyond the biomechanical limit of the human torso, and applying a pulling force at this posture (both posture and orientation of hand-wrist and torso) is not recommended from ergonomics point of view as it increases the chance of lower back pain.

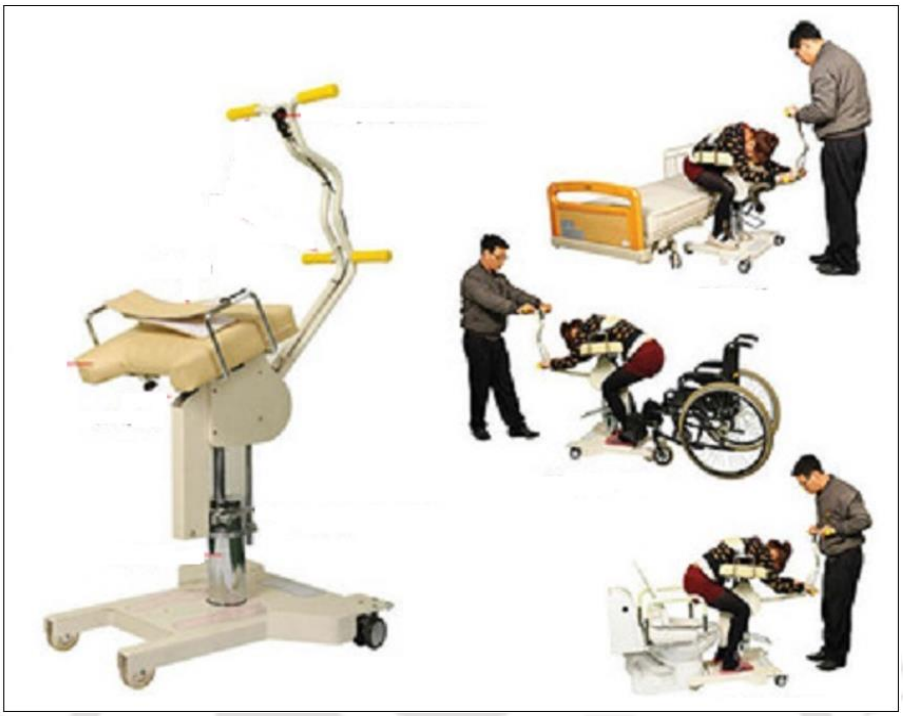


Figure 2-10 The Senior transfer lift.

Sit-to-standing transfer: This type of transfer technique is considered the simplest type of transfer technique for users with sit-to-stand (STS) problems. Generally, it has two steps: first, the person should be in a sitting posture, and make him/her ready for the transfer by giving instructions such as to grip the handle and keeping the slings in place. Secondly, to lift up the person from a sitting to a standing posture. A sit-to-stand transfer device is intended for persons with limited mobility who require assistance getting up from one seat and transferring to another, and it is also used for ambulation. A patient must be able to actively participate in the transfer procedure to safely use a stand-up lift. The patient must first be able to sit forward in a chair or sit unassisted on a bed while a caregiver is placing the sling. Similarly, the patient must have sufficient upper body strength to grasp onto the grip handles and bear weight while transferring and while keeping both feet flat on the footplate.

Several kinds of research have been conducted in the area of sit-to-stand devices, and most of such devices have been developed, and some of them are currently available in the market. Due to the similarities of this category of devices, only the design of selected devices will be reviewed in this section. Subsequent research was conducted [46-49] to develop a robotic walker system with standing and walking assistance functions, consisting of a support pad with three degrees of freedom and an active walker system, as shown in Figure 2.11A. The assistance manipulator mechanism actuates the support pad with four parallel linkages. The patient leans on this pad during standing assistance. Similarly, the active walker is actuated by two brushless motors on each front wheel. This walker can assist both operations continuously. A novel control scheme was also included in this device, which works according to the patient's condition during standing up.

Despite the advantage of integrating both standing and walking assistance simultaneously in this device, the architecture of the prototype needs more improvement in terms of safety, space utilization and aesthetic aspects. The reach envelops, or the working space partly occupied by the control box, limit the free movement of the patient while standing and moving; hence, the location of the control box should be shifted to the front side and in the middle of the front wheels. The design of parallel linkages and their arrangement may also increase the complexity of the device and, at the same time, it may raise the safety issue. Patients who are weak in their upper extremities may not be able to use this device as there are no extra supports from the back side of the user.
The Sara Steady Patient Transfer Aid is another type of sit-to-standing transfer device which is currently available in the market [50]. This device can accommodate patients up to 400 pounds, and it has two twist-away ergonomically curved seat panels that both swing out of the way to allow the patient to climb on and off the standing platform, as shown in Figure 2.11B. Once the patient is in a standing posture, the caregiver may easily hold the panels to restore the seat panels to their original position, allowing the patient to sit at an angle. The patient can use the handy crossbar to self-raise or descend from sitting or standing. The versatility of this manual patient lift lies in its ability to serve patients with varying degrees of mobility, ability, and strength. In addition to being a patient transfer device, it can be used for therapeutic exercises. The drawback of this device is that the user must have the strength to grab the crossbars and bear weight. The caregiver requires significant effort to manipulate the device with the patient in the raising-up position. Generally, this device is not suitable for patients who are not able to stand even with the help of assistance and who are weak in their upper extremities.

Standing Hoist Mechanism [51] is one of the commercially available lift transfer devices which is designed for users who lack lower body strength but have enough upper body strength to pull themselves up by grab bars during the lifting process. It can accommodate users up to 400 pounds for transfers between the bed, chair, tub, commode, or wheelchair; this sit-to-stand lift is also useful for assisting patients with getting dressed. It has adjustable knee pads and an optional rear strap for additional support, as shown in Figure 2. 12A.The drawback of this device is that it can only work well for patients who can support most of their weight and have the capability to grip the handles during the lifting process; hence, it is not suitable for patients who are not able to stand even with the help of assistance. The selected posture of the user under consideration is not suitable for paraplegic patients having serious shoulder pain. Similarly, the use of this device depends on the strength of the users; if their strength diminishes in the long run, they cannot use this lift anymore. Additionally, the need for two caregivers and the high cost of the device reduces its accessibility for low-income individuals.

The TEK Robotic Mobilization System (TEK RMD) [52] is another type of stand-standing transfer device, and it is also one of the commercially available manoeuvrability systems for wheelchair users. TEK RMD comprises a rotating frame with a swivelling arm connected to it, as shown in Figure 2.12B. The pelvis brace is carried by the device's swivelling arm and is intended to connect well with the user's lower abdomen or anterior pelvis on its extreme portion.

Figure 2-11 The Robotic walker with standing assistance (A), Sara steady patient transfer aid (B)

Figure 2-12 The Standing Hoist Mechanism (A) and the TEK RMD (B)

This device is only intended for those who can stand with support but not for those who are weak in their lower limb or unable to balance themselves with their feet on the footrest. This device is also not used for those having deformities in their legs or unbalanced leg sizes like the one who is affected by polio, which is one of the main causes of lower limb disability in developing countries. Another drawback that has been viewed on this device is that it uses a complex fixing belt or harnesses to tie the user to the machine, making it more difficult to remove. Moreover, the

suspension system containing gas springs counterbalances the weight of the user; therefore, users should apply a substantial amount of pull in order to initiate the lifting process. All of the above devices can be categorized structurally either as being made for users who are able to walk with minimum support after being lifted up using the transfer device or as a device made for whole-body transfer in a forward seating posture. The later devices are somehow trying to solve the presently existing limitations of patient transfer in most healthcare centres. But still, they are not relieving the burden of caregivers and no research works were found that evaluate the device's usability from the user's perspective; hence, the design and development of suitable transfer devices are still left as a question for researchers in this field.

2.4 Role of Biomechanics and DHM in Product Design and Evaluation Process.

Product manufacturers and occupational therapists use biomechanics to design job tasks and assistive devices to avoid overuse accidents associated with particular occupations. Generally, biomechanics is commonly applied in product design and development to identify the human or the user's limitations under which they can work and use products in their preferred ways [53]. A typical ergonomic product development process includes needs assessment, which primarily involves the subjective methods of observations, questionnaires, interviews, checklists, and expert appraisals to determine what users want. However, biomechanics is most often used in user trials, which are considered the most insightful and interesting method as an objective evaluation rather than the subjective methods mentioned in the needs assessment [54]. Many careers are involved in using biomechanical analysis to change human locomotion. For example, a person who makes prosthetics (artificial limbs) will use biomechanics to understand how joints usually work, the loads that the prosthetic must withstand, and how the prosthetic can be securely applied to the user. Product designers and human factors experts incorporate research evidence on a person's physical capacities into structures and equipment development strategies. Unlike robots, human physical features cannot be engineered. However, failing to consider a person's physical requirements when designing systems or equipment will result in excessive requests and user staffing constraints.

Adopting the anthropometric measurement with biomechanics assessments is helpful as it solves the mismatch between the human body and the product to be manufactured; for instance, if an injury results in amputation, prosthetics or artificial limbs may be constructed to match the mechanical properties of the phantom limb [55]. The science behind Biomechanics is also used to help physiotherapists decide on how to prescribe rehabilitative activities as well as assistive devices/orthotics [56]. Anthropometric measurements are one of the first steps to be considered while designing an assistive device, including prosthetic and orthotic devices, and many anthropometric measurements are often taken on individuals by developers to tailor the device to the person. For example, design engineers and product designers use these dimensions to build tools and workspaces that suit most people while minimizing the possibility of overuse injuries. Analogously, Biomechanists use most of these mean body parameters to accurately calculate kinetic or centre-of-gravity values. Slower movements are preferred in the analysis of patient transfer; as a result, many biomechanics experiments often employ static or quasi-static analyses

in order to investigate slow movement patterns with minimal accelerations. The theory of moving or transferring a patient utilizing any transfer device emphasizes the equilibrium of the user's and the device's mutual gravity field. According to this source [56], the horizontal range between the border of the base of support and the centroid or line of action of gravity defines how much the mass must be moved to destabilize an individual. This idea is depicted in Figure 2.13, which shows that positioning the gravity line outside the base of support can facilitate the body's rotation by the force of gravity. This technique is important for designing a transfer assistive device and normally specifies how far the weight of a person must be moved for gravity to appear to overthrow the body or how much gravitational momentum is required to produce the required motion [56]. Developing a product in the context of the human needs the analysis of inertial data, such as the centre of mass, for identifying an optimum human-machine interaction. Research studies investigated that knowing exactly where the gravitational pull takes place in different human body postures helps biomechanists investigate the kinetics and stability of these body postures. The detailed study of biomechanical factors is found important to understand the exact stability during any movements. Some of the considerations are the location and motion of the centre of gravity relative to the "base of support", which changes to modify stability/mobility during movement activities. Even though gravitational pull is the predominant opposing factor that our bodies use to drive toward the horizontal and vertical configurations of the "centre of gravity" relative to the base of support, it is found as one of the critical parameters that would help in deciding the stability/mobility of that particular posture [57].

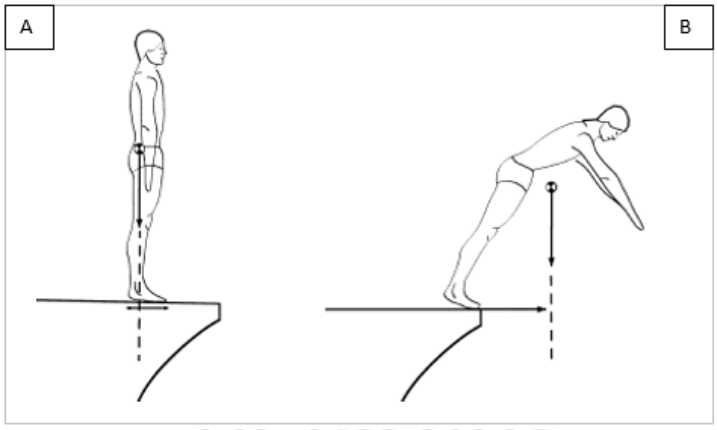


Figure 2-13 The effect of the "line of gravity" relative to the limits of the "base of support"

Most patient handling and transfer devices are currently not in line with human biomechanics requirements; thus, they are the primary sources of low back pain in most nursing assistants. Application of biomechanics during product conception and development of products, such as developing the transfer assistive device, provides an integrated approach by proactively assessing the suitability of the device and the prevalence of the musculoskeletal disorder. The

biomechanical evaluation of floor and overhead-based patient transfers utilizing one or two clinicians was analyzed, and this research examined the discrepancies in maximum external hand pressures and external moments produced at the "L5/S1 lumbosacral joint" and they discovered that the use of overhead lifts resulted in considerably lower back loads than floor lifts [58]. Adopting Biomechanical evaluation strategies is crucial during product conceptualization and product testing. It significantly impacts developing a suitable device that minimizes the biomechanical loadings that might occur with improper human interaction. The research was conducted related to biomechanical modelling of the lower part of the body to estimate the force exerted on the bedside by a nurse during different patient handling tasks and to investigate its contribution to the moment at the spine joint. According to their findings, the bedside reaction moment significantly contributes to the total moment and could result in significant overestimation if not appropriately included in the calculations [59]. The biomechanical evaluation of Transfer equipment for moving patients was investigated with the aim of examining the impact of the transfer process and patient weight on the biomechanical pressure experienced by nursing assistants when conducting the transfer mission. Also, to discover resident-transfer strategies that could lessen the biomechanical strain on the nursing staff [60].

The above study compared the biomechanical performance of nine battery-powered lifts, a sliding board, and a walking belt to a manual technique for moving nursing home patients from a bed to a chair. The results indicated that the transfer procedure and occupant weight affected the nursing assistant's low back-loading. Also, the mean back compressive forces during patient hoisting, rolling, and rotating tasks when using a floor-based basket-sling lift or an overhead lift were less than those forces when using manual lifting methods and the result was found under the National Institute for Occupational Safety and Health (NIOSH) recommended disc compression force limit [60]. Furthermore, the biomechanical examination of muscle activity patterns in manual and lift-assisted patient transfers performed by skilled and novice patient handlers was investigated. Surface EMG was employed to monitor muscle activation when performing bed-to-wheelchair and wheel-chair-to-bed patient handling activities. They observed very little change in EMG measures between the two transfer tasks in this investigation; however, muscular activity was lowest while utilizing the ceiling lift, increased when using the floor lift, and maximum when using the manual lift [61]. Similarly, the biomechanical loading differences between ceiling-based and floor-based patient transfer systems were investigated. They studied the stresses on the lumbar spine in ten volunteers doing various patient-handling duties while utilizing both ceiling- and floor-based devices. Floor conditions, wheel layout in floor-based devices, and patient weights were also investigated in the experimental environment. Compared to the floor-based system, the ceiling-based system provided considerably lower spine stresses for the patient-handling activities evaluated [62]. A similar research examined the differences in hand forces between floor-based and ceiling-based patient transfer platforms. Two floor-based systems and one overhead system were evaluated for pushing, pulling, and rotating patients. The hand forces necessary for floor-based lifts were found to be roughly ten times more than the force required for an overhead-mounted lift. This study suggested the need for biomechanical studies to determine whether the

compression force level created by these required forces surpasses the spine's acceptable load tolerance limits (i.e., 3400 N) [63]. Another group of researchers reported somewhat contradictory results in biomechanical analysis of spinal loads during simulated patient-handling activities, indicating that while the use of assistive devices such as mechanical lifts reduced peak spinal loads below the NIOSH recommended criterion limits, the variation in techniques used and the elevated time involved with mechanical devices resulted in increases in cumulative spinal loading [64].

Several existing studies in the area of patient transfer devices used the biomechanics approaches typically at the evaluation phase of the final product rather than during concept selection and concept evaluation phases. Similarly, it has been stated that most of the focus of existing research concerning patient handling has been on the actual transfer process [65]. There has been little research was carried out on the assessments of biomechanical pressures encountered during the sling application and removal process. These sling installation and removal tasks require significant physical manipulation of the patient, such as rolling, pushing, and tugging on the bed. One study was carried out to assess the biomechanical loadings during the sling application and removal process. They have used a human simulation approach in this study to acquire body postures with measured hand force data to estimate spinal forces using the University of Michigan 3D Static Strength Prediction Program (3DSSPP) model. They looked at the spine loading caused by installing and removing slings during patient transfer. Peak compression and anterior shear forces surpassed the established thresholds when putting slings beneath heavier patients. They also claim that elevating the bed to at least a knuckle level helps to reduce these spinal strains. [65]. From the above studies, it is clear that almost all of the researchers have focused on evaluating the effectiveness of the existing transfer devices, especially the ceiling and floor-based devices; however, none of the studies has made evaluations on specific components of the transfer devices such as on the suitability of the handle design, supporting parts and on the manoeuvrability of the device. Furthermore, the entire evaluation focuses on the safety of caregivers, such as minimizing lower back pain, without including the safety of the patients, which violates the proper rehabilitation settings.

Some researchers have studied the effects of lifting angles on biomechanical pressures and the lower back. The distinctions between dragging a load at an angle and then raising the same load upward were compared. According to this study, raising at an angle reduced the moment at the elbow, back, L5/S1 disc, and hips while increasing the moment at the knees and ankles. The angle of draw of the muscle shown in Figure 2.14, which defines the intensity of the members of the muscular strength, is said to be affected by shoulder and elbow alignment [66]. Biomechanical problems created by the component due to a shortage of capability to execute the functions should be identified to establish prevention steps in injury-prone circumstances. Experts have suggested relationships between seat stress circulation and the customer's comfort zone, taking stress appropriation as a desired measure of dissatisfaction. Biomechanics knowledge related to factors related to muscular strength may help product designers understand human physical capabilities. The maximum effort needed to apply on an object (control or support handle) is determined by a

variety of variables, including the sort of system, the physical member used to manipulate it, the location of this body component throughout control operations, the overall body posture, and whether or not backrests are used for a “seating case” to provide support [67].

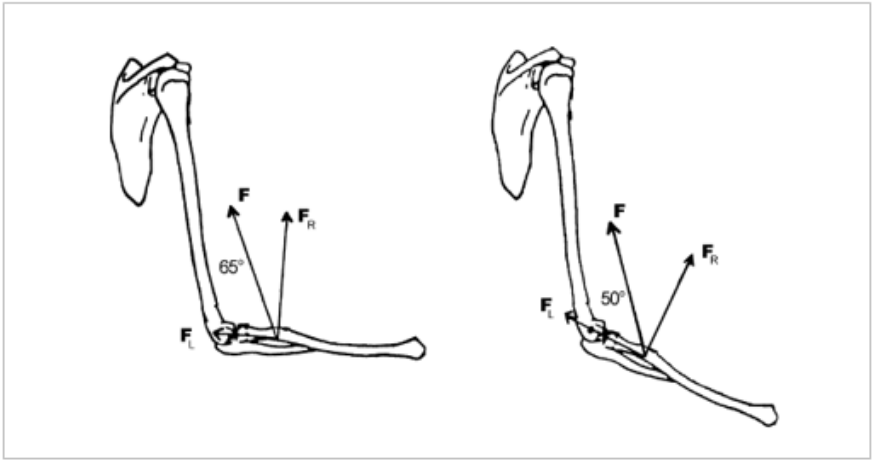


Figure 2-14 Typical angles of the pull of the biceps brachii muscle in an arm curl.

Biomechanical measurement and computer modelling have offered more precise techniques for gathering the data required to guide intervention planning to avoid upper extremity joint deterioration and preserve function in people with SCI. Identifying stressful sub-components during transfers will allow intervention clinicians and engineers to create and alter assistive and adaptive technologies to better serve patients with SCI. [68]

Digital human modelling software (DHM) has been extensively and frequently used throughout the platform conceptualization and creation process, from its early stages to product assessment. Some examples of these programs include Jack (Siemens PLM), Human Builder (Dassault Systems), and RAMSIS (Human Solutions), with RAMSIS also including features and functionality for seat and belt assessments [69]. Additionally, software packages such as Anybody and Opensim are mainly used for biomechanics aspects, which incorporate the skeleton and muscle arrangements. The digital human model, a simulated humanoid in 3D space that can be shifted and modified to mimic actual and realistic motions of humans, can be used to create a concise interaction between virtual humans and machines. DHM has potentially spared person-hours and resources and trimmed numerous months off the idea of project schedule development timelines. DHM software application is widely used in various industries, including automobile, aviation, defence, garment, helmet design and industrial equipment. [70,71]. It has been affirmed that the usage of DHM tools for biomechanical analyses of patient relocating tasks can aid in the investigation of MSD exposures; however, researchers must understand the purpose of each DHM modelling approach as well as the underlying assumptions of digital human models that may affect kinematic and kinetic outputs used to quantify the exposure to MSDs. Similarly, this study stated that there is a clear need to validate the utility of DHM for use in healthcare because of the very

few studies that have explored the validity of simulating complex healthcare tasks such as patient repositioning [72]. Due to the high manufacturing and design costs that exist in the traditional product development process with physical mock-up creation, most of the research studies have used DHM to conduct predictive simulations, such as for improving the manual material handling tasks as well as for testing the human-machine interaction, they have also generated multiple simulations of a manual loading operation across females in the 5^{th} and 50^{th} percentiles and males in the 50^{th} and 95^{th} percentiles to predict the reachability of different workers in order to optimize the height of a loading platform [73,74].

The Finite element (FE) model is one of the most widely applied research tools for analyzing the interaction between the human body and its surroundings. Numerous experiments have been performed using these methodologies; for example, the human buttock FE models are used to quantify the stress dispersion between the individual and seating area using the FE method with a precise and practical geometric representation [75]. The variety of cushion materials used, as well as the cushion thickness, have a substantial impact on the real pressure distribution; the findings from the above researcher's parametric analysis show that pressure distribution at the "human-seat interface" is highly influenced by differences in human tissue and seat cushion characteristics. In a related analysis, the interaction issues among two homogeneous and isotropic soft bodies were studied analytically; in consequence, the Poisson's ratio of the seat cushion was permitted to be negative when modelling the relationship of human buttocks and seat cushions to achieve a converged result [76].

2.5 Summary of Literature Review and Research Gaps

The survey presented in this chapter reviewed the state of the art in assistive technology in general, the ***disability and accessibility of assistive technology, transfer device and transfer technique***, and the ***role of biomechanics and DHM in the product development and evaluation process*** in particular. The reviews under ***disability and accessibility of assistive technology*** have explored the current aspects of disability and the need for assistive technology devices. Furthermore, the main barriers to assistive technology provisions and the reasons for inadequate accessibility of AT products and services, predominantly in low-income countries, have been reviewed in detail by referring to the WHO and other stakeholders' sources. According to this review, the lack of access to assistive devices and services was partly due to high costs, limited availability, lack of state funding, and lack of governance and inadequate financing. There is also a lack of user-centred research and development, a lack of adopting the principle of matching the person with technology (MPT) and a lack of context-appropriate product design; most of the existing AT products are often manufactured using parts that are not replaceable locally, which contributes to high abandonment rates. The World Health Organization report also found that some existing assistive products are produced only to international standards, which may not be suitable for individuals in developing countries.Even though the main reasons for the lack of access to AT products listed above were a lack of context-appropriate product design and MPT, in addition to high costs, limited availability, lack of governance and inadequate financing, these barriers can be overcome

if one of the most influential barriers that can be considered as a solution for others is clearly identified, which means identifying one of the obstacles whose improvement affects the progress of others. In this thesis, the author would like to conclude that the existing barriers of inadequate accessibility of AT products could be improved by adopting cost-effective product design approaches such as using locally available materials, adopting proper MPT principles, applying innovative concepts, and context-appropriate product design to minimize design costs, thereby improving affordability and accessibility of AT devices. Furthermore, one of the critical barriers that indirectly affects the accessibility of AT devices is the unavailability of suitable preventive AT devices, and they were not included in the list of 50 priority AT devices that WHO approved.

Since most secondary impairments occur because of falls in existing patients during their daily activities, such as transferring from bed to wheelchair, the unavailability of such devices will significantly impact the accessibility of AT devices. Thus, in this thesis, this has been considered as one of the gaps that should be considered. Hence, focusing on the design and development of appropriate transfer assistive devices that could prevent temporary or permanent secondary impairments could increase the contribution towards the current state of the art in the field of AT devices, and it could help as a key solution for the existing activities on improving the accessibility of AT devices.

The reviews under ***transfer assistive devices and transfer techniques*** have explored the prior arts of transfer devices and their corresponding transfer techniques. In order to study the characteristic features of various transfer devices, researchers have used various classifications [30-32]. In this thesis, this review was presented by systematically grouping various types of TADs into four broad categories, which was done based on their functionality and on the method of lifting techniques / transferring posture; thus, it has been classified as follows: *Sitting transfer, Supine* or *laying transfer, Forward pivot transfer* and *Sit to standing transfer*. In the last few decades, many TADs have been invented by product developers and organizations, but few have become available commercially. This report reviewed only relevant TADs found at a physical prototype level or finalized product and thus published in scientific papers. Additionally, this review included relevant TADs available on the market and routinely used by patients in healthcare facilities or nursing homes.

The general review of TADs employing a *Sitting transfer* technique was examined by considering various transfer devices from this category. The most relevant TADs that were selected under the first category of *Sitting transfer* technique were the Gantry lift mobile, Vertical Patient Lift, Handicare Multi-Room Ceiling Lift, Strong Arm, lateral transfer assist robot and the HLPR chair [33-38]. These categories of TADs are generally recommended for patients who can transfer in a sitting posture. Generally, they are proven to play an important role by reducing the burden of patient handling and transferring activities. However, these technologies still have flaws that need to be addressed. Based on the reviews made on the first category of TADs, the following limitations or gaps were found: A) None of the above devices are designed to completely avoid the assistance of caregivers, such as to avoid the need for mounting / unmounting the slings of the

hoist and manually manoeuvring the loaded device. B) Limited to transfer patients only in a sitting posture, thus forcing the users to change their posture without considering their preferred posture. C) Reduces the rehabilitation outcome because patients are completely passive throughout the transfer movement. D) The structure's design is bulky; thus, the giant steel frame makes storage problematic, and the transfer method is relatively complicated, limiting its use in underdeveloped nations. E) High design complexity and the use of more actuators, leading to more expensive, time-consuming, and sophisticated stages that need training. F) Ceiling tracks, slings, and automatic lifting mechanisms used in lift systems are developed exclusively for the house.

The review under the second category of TADs employing a *Supine* or *laying transfer* technique was also examined; this type of transfer technique is commonly used for transferring or lifting patients who are bedridden or unable to be lifted in a sitting posture. Due to the similarity of the existing devices in this category, only recent devices were chosen for the review. The relevant devices which were selected under this category are the E-Pat (Easy-Patient Transfer), C-Pam (Careful Patient Mover) and RIBA (Robot for Interactive Body Assistance). Based on the reviews made on the second category of TADs, the following limitations or gaps were found: A) The chosen transfer techniques may not be suitable for patients in some medical cases, as it is impossible to prevent friction between users' skin and the device. B) Need an extra auxiliary platform for shifting the patients from one room to another. C) Do not relieve the burden of caregivers because a horizontal movement of the patient will be conducted manually by the caregiver; hence, the physical burden is still a severe issue. D) The design of the automation system is too complex, leading to high costs, which become unaffordable for low-income individuals.

Similarly, the review under the third category of TADs employing a *Forward pivot transfer* technique was also examined; this type of transfer technique is used for transferring an individual who cannot transfer from a wheelchair to a bed or other surfaces without the assistance of a caregiver. Individuals of this category are generally weak or paralyzed in their lower limbs or have a history of SCI; long-term patients might be waiting to recover after hip/knee replacement surgery. This technique requires three steps to completely transfer the patient from the wheelchair/bed to other seating surfaces. Firstly, the patient should be in a sitting posture with their upper half slightly leaning forward. After ensuring that the patient's chest or upper abdomen has made good contact with the supporting platform or saddle, at this point, the forward lifting (rotation about the vertical axis) will be completed; secondly, the patient should be moved/rotated toward the destination seat/bed. These steps can be accomplished (rotation about the horizontal axis) either manually or using a powered system. Finally, the patient will be seated in the destination seat by following step one reversely. Very few researches have been conducted on this type of transfer assistive devices. Thus, the relevant devices which are currently available in the market, as well as those developed by researchers, were included for the review; the selected devices under this category are the self-transfer aid robotic system [42], Easy Pivot Mechanism [43], Self-transfer robotic system [44] and Senior transfer lift [45].

Based on the reviews made on the third category of TADs, the following limitations or gaps were found: A) The reviewed devices do not have an under-arm support mechanism, which is the essential part in developing a suitable TAD, the design of under-arm supports are generally used to facilitate easy transfer by reducing the force required to lift the users either manually by the caregiver or with the help of electric actuators. Similarly, it is also used to avoid a sudden fall due to sliding or returning backwards. B) None of the reviewed devices have shown to include a suitable design of the handle; the observed handle mechanisms are not designed from a biomechanics point of view; similarly, the position and orientation of the handles are not located ergonomically with the proper function of the human hand/ wrist posture. C) None of the reviewed devices have been shown to include the ability to transfer users automatically from a wheelchair to a seat located at 90^0 c.w or c.c.w. Adding this type of transfer technique minimizes the transfer time, reduces the amount of strain due to contact between the user's body and the saddle, reduces the amount of energy needed during transfer, and allows the device to work in a compact space. D) The reviewed devices do not have a safety wheel mechanism. Since the nature of the transfer techniques under this category is more susceptible to accidents resulting from stability issues, it is necessary to incorporate a safety wheel mechanism to guarantee the safety of users. E) None of the reviewed devices have been found to include a simple rotating mechanism; the above devices are observed employing an epicyclic gear mechanism [44] and an omnidirectional wheel mechanism [42] combined with controllers and geared motors. This type of mechanism increases the complexity of the device, thus increasing the overall cost of the device, and this is one of the barriers that limit the affordability of such devices for low-income countries. In the case of [43] and [45], they are employing a manual mechanism both during the lifting and rotating phases; thus, the caregivers must apply a substantial amount of force at the handle of the device in order to perform the above tasks, similarly, in this type of manual transfers, where the overall safety and control are under the hands of the caregivers, the comfort and safety of the users was not getting more focus.

Finally, the review under the fourth category of TADs employing a *Sit-to-standing transfer* technique was also examined. A sit-to-stand transfer device is intended for persons with limited mobility who require assistance getting up from one seat and transferring to another or for patients who can put weight on their feet, and it is also used for ambulation. A patient must be able to actively participate in the transfer procedure to use a stand-up lift safely. Several kinds of research have been conducted in the area of sit-to-stand devices, and most of such devices have been developed, and some of them are currently available in the market. Due to the similarities of this category of devices, only the design of selected devices was considered for the review. Thus, the relevant devices which are currently available in the market, as well as those developed by researchers, were included for the review; the selected devices under this category are the Robotic walker with standing assistance [49], Sara steady patient transfer aid [50], Standing Hoist Mechanism [51] and the TEK RMD [52]. Based on the reviews on the fourth category of TADs, the following limitations or gaps were found: A) None of the reviewed devices were designed to lift individuals with lower limb amputees. These devices require users to balance while lifting with

their feet. Therefore, it may not be suitable for users with totally weak legs due to injury and polio (one of the leading causes of lower limb disability in developing countries) or with lower limb amputees. B) The selected posture of the transfer technique and the orientation of handles might force the users to over-extend their upper limbs beyond the range of motion. The users of this category should have ample strength to grip the handle while doing a sit-to-standing task; thus, paraplegic patients with serious shoulder pain and users with weaker upper limbs are limited from using such devices. C) A significant amount of effort is required by the caregiver except for (TEK RMD). Two or more caregivers are required to manipulate the device with the patient in the raising up position; in the case of [51] and [52], considerable effort is also needed to fix and adjust the slings.

The reviews under the ***Role of Biomechanics and DHM in the Product Design and Evaluation Process*** were also included in the last section; the survey has explored the current aspects of biomechanics and DHM and its applications in the field of assistive technology devices. Furthermore, this review has identified the work of researchers who have used biomechanics approaches for evaluating the state of caregivers while using different types of TADs. Generally, biomechanics is commonly applied in product design and development to identify the human or the user's limitations under which they can work and use products in their preferred ways [53]. It was also highlighted that biomechanics was most often used in user trials, which are considered the most insightful and interesting method as an objective evaluation rather than the subjective methods performed during the need assessment [54]. The adoption of anthropometric measurement with biomechanics assessments was also discussed in the review, and it was stated that this method is helpful as it solves the mismatch between the human body and the product to be manufactured, for instance, if an injury results in amputation, prosthetics or artificial limbs may be constructed to match the mechanical properties of the phantom limb [55]. The application of DHM in the product development process was also reviewed. It was stated that due to the high manufacturing and design costs that exist in the traditional product development process with physical mock-up creation, most of the research studies have used DHM to conduct predictive simulations to improve the manual material handling tasks as well as for testing the human-machine interaction [73,74]. It was also affirmed that the usage of DHM tools for biomechanical analyses of patient relocating tasks has the possibility to aid in the investigation of MSD exposures; however, researchers need to understand the purpose of each DHM modelling approach as well as the underlying assumptions of digital human models that may affect kinematic and kinetic outputs used to quantify the exposure to MSD [72]. Despite the advantages of applying the biomechanical evaluation approaches in the process of testing the usability of the existing TADs, almost all evaluations were focused on comparing the effect of using the ceiling lift and floor-based lifts on caregiver's low back pain, the use of EMG was also shown as one of the biomechanical tools for measuring the muscle activities. The recorded EMG results showed that the muscular activity of the caregivers while lifting the patients was found to be lowest while utilizing the ceiling lift and increased when using the floor lift [61]. Similarly, all other results also showed that ceiling lifts are better than floor-based lifts because it has been shown in all experiments to reduce lower back

pain as compared to floor-based lifts. Only one study was carried out to assess the biomechanical loadings during the sling application and removal process. They have used the human simulation / DHM approach to acquire body postures with measured hand force data and to estimate spinal forces using the University of Michigan 3D Static Strength Prediction Program (3DSSPP) model [65]. Similarly, from previously reviewed devices only two research studies were conducted on the subjective evaluation of the user's experience [36,44], and one study was conducted on the usability of the robotic arm for reducing the users burden using EMG based experiment [42]

From the above studies, it is clear that almost all of the researchers have focused on evaluating the effectiveness of the existing transfer devices, especially the ceiling and floor-based devices; their main criteria for assessing the existing TADs were to measure the amount of low back pain developed by the respective caregivers instead of the users. However, none of the studies have made biomechanical evaluations on critical components of the transfer devices, such as the handle design, supporting mechanism and the device's maneuverability. The advantage of conducting a biomechanical evaluation on the selected critical components is that, it would help to identify wrongly designed components that lead to low back pain. At the same time, it becomes easy to modify a particular component with a minimum cost instead of discarding the entire device. Based on the reviews made under the *Role of Biomechanics and DHM in the Product Design and Evaluation Process*, the following limitations or gaps were found: A) Limited researchers were found to use the application of biomechanical evaluation approaches in the area of TADs, with a focus on ceiling and floor-based lifting devices. B) Limited researchers were found to use the application of DHM and Human-Machine design approaches in the area of transfer assistive devices. C) None of the research studies have used a biomechanical objective assessment for examining the effectiveness of TAD components and their supporting mechanism from the patient's point of view. D) Limited studies were conducted to evaluate the effectiveness of the existing TADs from the user's or patient's context. E) None of the reviewed studies have used the biomechanical evaluation approaches during the conceptual phase of the product (transfer assistive device) development process. Generally, the main purpose of this section was to carry out a comprehensive literature review on the selected topics and to find out the research gaps from the reviewed topics. Taking some of the reviewed points for improving the accessibility of AT devices, the transfer devices/techniques and the application of biomechanics and DHM into consideration, further research and development will be commenced once the decision is made on the type of transfer technique. Generally, the research activities in the field of AT devices are relatively poor, especially in areas of patient transfer devices. Also, there are no standardized design tools and methodologies specific for developing a TAD from the users' point of view. So, this limitation highly indicates the need for introducing standardized design tools and methodologies.

CHAPTER THREE

3. User-Centered Concept Selection and Design Synthesis

3.1 Background

This chapter presents the questionnaire design, concept selection process, design synthesis, and its outcomes. The research gaps which were identified in the previous chapter are taken as a reference to establish the concept generation and selection process. The sitting forward pivot transfer technique is a well-known manual method of patient transfer that is used by wheelchair users and their caregivers, particularly in developing countries. Few transfer devices were developed in the last decades to overcome these types of manual transfer methods; however, none of these devices were designed to overcome the caregivers' burden or to transfer the users in a biomechanically accepted posture. In this thesis, only the first phase of this technique was adopted for the purpose of exploring a new design approach that helps in predicting a biomechanically accepted transfer posture. The justifications for choosing a sitting forward pivot transfer technique were stated as follows: - A) Due to its resemblance with the manual transfer technique, which is the common type of transfer technique of wheelchair users in developing countries. This feature also helps wheelchair users to be familiar with the transfer technique and easily adopt the proposed device. B) Only a few researches were conducted on this type of transfer technique compared to others, and no further attempts were made to enhance the existing research boundaries with new research opportunities. C) There are high possibilities for designing a TAD with new features, such as making it compact, simple, comfortable, and affordable by applying novel design approaches and introducing a novel component. The chosen concept ideation and selection approaches are expected to address the existing research gaps by opening a new window for research activities in the field of AT devices, especially in the state of the art of new TAD development and evaluation methods.

Three phases of the concept selection and development process were generally taken into consideration; in the first phase, only the platform's structural layout and the corresponding transfer technique were chosen, considering the limitations of the transfer techniques that had been reviewed as recommendations. After the selection process of the structural layout and the corresponding transfer technique was completed, the 3D model of the transfer technique was generated in the digital human modelling environment. This 3D model of the proposed transfer technique combined with a wheelchair and the virtual human was included in the questionnaire list. By demonstrating the transfer technique in a tangible and illustrative manner, stakeholders can gain a better understanding of how it functions in practice. This strategic approach was selected intentionally to gain early feedback from these stakeholders, as their insights would be crucial to the development of the concept in the subsequent phases. The mechanism selection was accomplished in the second phase of the concept selection process; details are found in sub-section 3.7.1. Generally, after conducting a graphical simulation of many iterations, only two types of mechanisms (Four Bar Slider Mechanism and Modified Scissor Mechanism) were found to satisfy

the requirements of the given task based on the set criteria. Due to the simplicity of the chosen mechanism, only graphical methods of mechanism synthesis were implemented using commercially available software. The proposed TAD was again decomposed into three more concepts with different handle mechanism orientations in the third and last phases of the concept selection process. EMG-based biomechanical evaluation approaches were also used to select the best handle orientation.

One of the primary requirements for adopting an effective user-centred concept generation technique relies on including all the stakeholders' views in the concerned area. The selected stakeholders might have direct or indirect contact with the related product or services. Users of a particular product might be the end-users or the individuals helping others with the same device. The importance of considering the stakeholder's view in the conceptual phase of a given product design will significantly help understand the current state of the target product's art; it also provides an insight into the problem areas of the existing product that need to be modified or redesigned. Similarly, knowing the general information about the facilities in the health care centres related to the availability and type of existing devices or products and how their client uses them impacts the concept selection's final decision. This intern helps to identify the requirements for the new design in the selected healthcare centre.

This chapter begins with the techniques of the questionnaire-based field surveys at a selected hospital, followed by design ideation and synthesis of the concepts that could be used as input for strengthening the development of the proposed transfer device. In this report, healthcare providers and their clients are taken as the stakeholders for providing the necessary pieces of information related to the types of existing patient mobility and transfer assistive devices. Moreover, a focus group session was also implemented to obtain feedback on the existing transfer method and the usage of the mobility or transfer devices. To have a piece of practical knowledge about the present transfer process and system, as well as to choose a better alternative device than the one currently in use, conducting a field study at the selected health care centre was found to be an important decision; therefore, it is necessary to prepare a pilot questionnaire with a list of questions as it also helps to reframe the overall concept generation and development phases.

3.2 Questionnaire Design

The primary goal of this survey is to look at the interaction between the users of mobility or transfer assistive devices, caregivers/nurses, rehabilitation engineers, and therapists, as well as product considerations from a biomechanics and ergonomics standpoint. To better explain product enhancements on the proposed transfer system, part of this goal entails addressing stakeholders' perspectives on design aspects or differences in current patient handling or transfer devices. This survey intends to understand the selected stakeholders' picture when comparing various transfer assistive devices/methods based on defined design characteristics and their familiarity with a current transfer assistive device/method. The therapists, who are responsible for providing professional guidance and, in some cases, managing the assistive device program, are considered

central players in creating and prescribing mobility or transfer assistive devices, alongside manufacturers and recovery engineers. Figure 3.1 below shows the questionnaire design flow diagram for the pilot survey, which includes the selected stakeholders and their corresponding contributions towards the proposed TAD.

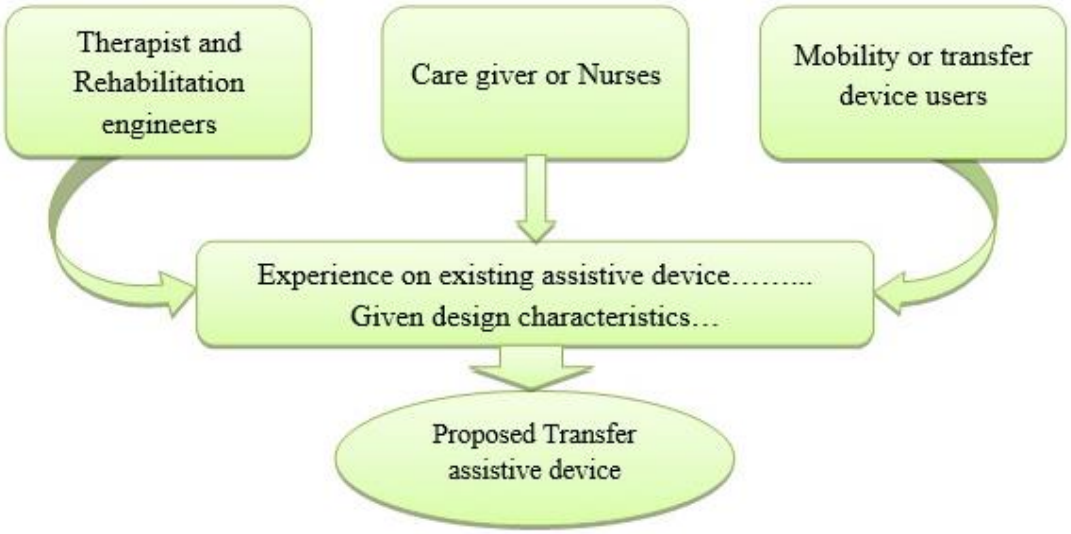


Figure 3-1 The questionnaire design flow diagram for the pilot survey of the proposed TAD

3.3 Questionnaire Procedure

The pilot survey was conducted in two stages. In the first stage, observations and discussions were made on the assistive device facilities provided by the selected centres with the medical practitioners and authorities of the specific healthcare centres. Additionally, a pilot questionnaire was forwarded for nearby therapists and nurses to thoroughly view the overall question and let them discuss each other. Finally, they are asked to give feedback or comments regarding the questionnaire.

After receiving approval to administer the questionnaire, the second stage includes developing a "complete version of the questionnaire" based on the previously offered input and suggestions, which is then delivered to the selected healthcare facilities. Initially, the aim was to conduct the questionnaires at three hospitals located in Guwahati city. Still, it was observed that in some wards, the therapists and nurses were in a complicated situation with their clients, so due to similar reasons, the present questionnaire is conducted only at one hospital, i.e. Guwahati Medical College and Hospital (GMCH).GMCH, a tertiary care government hospital with a bed strength of 2185, is well-known for providing the best healthcare facilities in India's North East region**.** Interviews and discussions were carried out with the authorities and medical practitioners of GMCH, assuming they have a good understanding of the suitable assistive devices and have experience in the use of various assistive devices.

Additionally, the pilot questionnaire was forwarded to medical practitioners such as physiotherapists and nurses as a stakeholder to thoroughly view the overall questions and to give feedback or comments regarding the questionnaire. The overall discussion and data collection process was done with actively participating therapists, caregivers/nurses and patients who are in one shift; part of the activities is shown in Figure 3.2 below. Before starting to fill out the questionnaire, orientation was given by one of the moderators (assigned by the author) based on the purpose of the present questionnaire, which is enclosed in a cover letter. The questionnaires also provided anonymity, which encouraged the candidate's response; free spaces were included in the questionnaire to allow respondents to comment.

Similarly, when two or more participants were expected to complete their questionnaire in the same room at the same time, participants were asked to participate in a conversation, specifically about design characteristics relative to which form of transfer assistive device sounds more appealing in their wards, whilst the moderator led the entire session. Three categories of questionnaires are prepared for the chosen stakeholders: a questionnaire for therapists and rehabilitation engineers, a questionnaire for caregivers or nurses and a questionnaire for transfer assistive device (TAD) users. Each questionnaire's central core focuses on three points, and they are listed as follows: -

a) Exploratory questions on the existing transfer device and method of transfer.
b) Exploratory questions on the importance of implementing the proposed transfer device
c) The design characteristics included to evaluate transfer device development.

Figure 3-2 Sample of participants taken during survey activities from the Health Care Center

3.4 Analysis of Questionnaires

The overall number of participants in one shift was estimated to be 56; thus, using a random sampling technique with a marginal error of 5% and confidence level of 95%, a sample size was randomly selected as 49 out of 56 population size. Initially, the questionnaire was distributed to the participants according to their categories, such as 18 questionnaires for the first category (therapists and rehabilitation engineers), 11 questionnaires for the second category (caregivers/nurses) and 20 questionnaires for the third category (patients/users of TAD). The content of questions in each category of questionnaires is slightly varied from one another, and generally, there are 12 questions on average. After receiving the responses to the questionnaire, four responses from the third category were found invalid due to improperly filled responses; thus, out of 45 replies, 18 responses were obtained from the first category, 11 responses from the second category and 16 responses from the third category. The responses given under the personal data related to the therapists' qualifications indicated that almost all of them belong to physiotherapy with a range of experience from assistants to senior physiotherapists. Two doctors belong to a neurology department and have worked in an assistive device prescription. The personal data of patients/users, such as age, gender, and the nature of the impairments considered necessary for the current study, are included in the questionnaire. Their responses are shown in Figure 3.3 below, together with the nature of the impairments they have encountered. Similarly, the dichotomous (yes/no) responses are used for questions related to impairments in their upper extremity and their current ability to transfer independently from bed to another surface. 56.3% of the nature of the impairments were found to correspond to a lower limb accident. Regarding impairment in their upper extremity, 75% responded (No), indicating that they are fit enough to use their upper half to transfer from bed to other surfaces if a suitable transfer mechanism is provided for them.

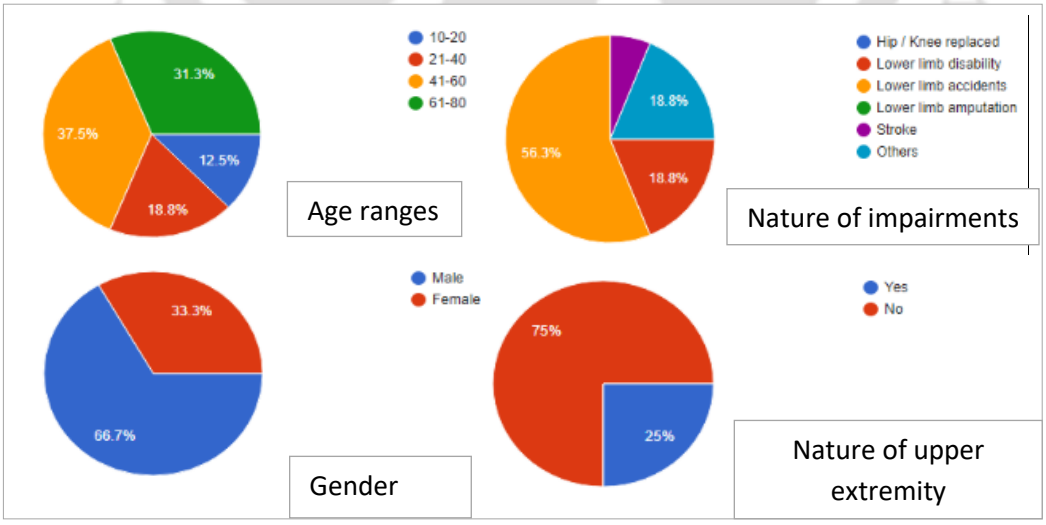


Figure 3-3 The personal data responses from the patients or users under consideration

When the therapists were asked whether they were taking part in the assistive device prescription or attending the assessment process, 94.4% of the therapists responded (Yes). Similarly, when the caregivers were asked whether they were following the assessment process, only 54.5% of the caregivers/nurses responded (Yes), which means they were attending the assessment process. Still, when asked if their abilities are considered, almost all responded (No); this shows that the sound of the direct actors, who are the caregivers, is usually not considered while modifying or designing a new device. These are the main reasons why most burdens are imposed on the caregivers/nurses, leading them to musculoskeletal disorders. Additionally, when therapists and caregivers were asked if they had ever contacted designers or manufacturers and tried to share their experience regarding the existing transfer assistive devices from their client's point of view, 61.1% of therapists responded (Yes). In contrast, none of the caregivers responded that they had contact with designers or manufacturers, as depicted below in Figure 3.4.

The responses related to the commonly used existing transfer devices or transfer methods showed that almost the three categories of all participants responded that the manual transfer method, either with one or two caregivers, was the most adopted means of transfer in the hospitals under consideration. Slide sheet is also considered a frequently adopted means of transfer next to manual transfer, as depicted below in Figure 3.5. These responses are crucial for the current study since they would help identify and compare the existing methods or transfer devices adopted in the healthcare centres concerning the proposed one. Thus, it also gives an insight into the need for a new transfer device that overcomes the existing means of transfer methods or devices.

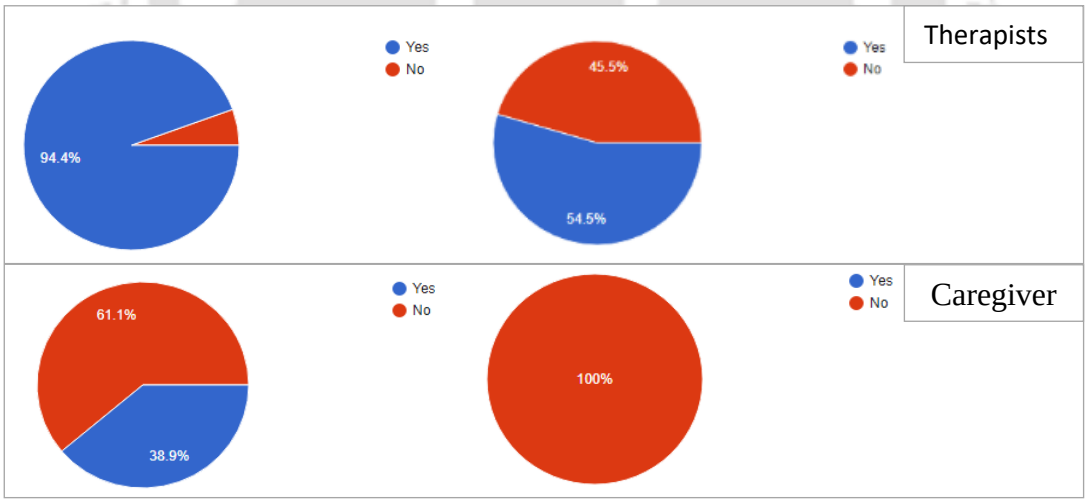


Figure 3-4 The responses related to activities in the assistive device prescription/assessment process

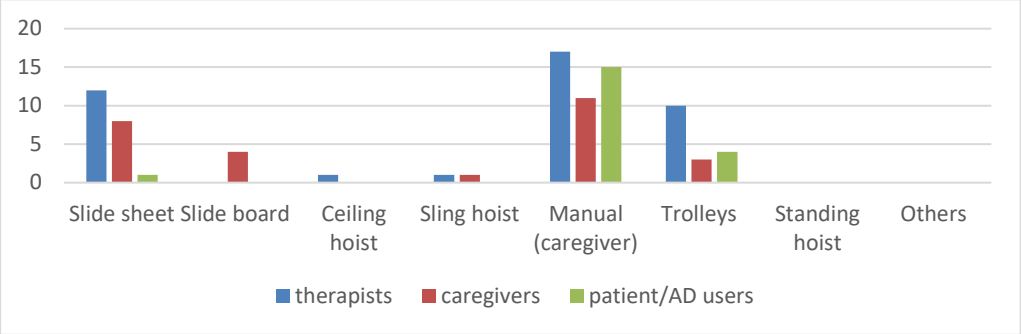


Figure 3-5. Responses for the commonly used existing Transfer devices or transfer methods

Similarly, the responses given related to the commonly used existing mobility devices. All three categories responded that a manual wheelchair was considered the most adopted means of mobility in the hospitals under consideration. This response indicates that caregivers are still engaged in transferring their clients manually from wheelchairs to other surfaces and vice versa. Hence, a suitable transfer device which is compact and easily fit with a wheelchair will be considered as one of the focuses in the present work.

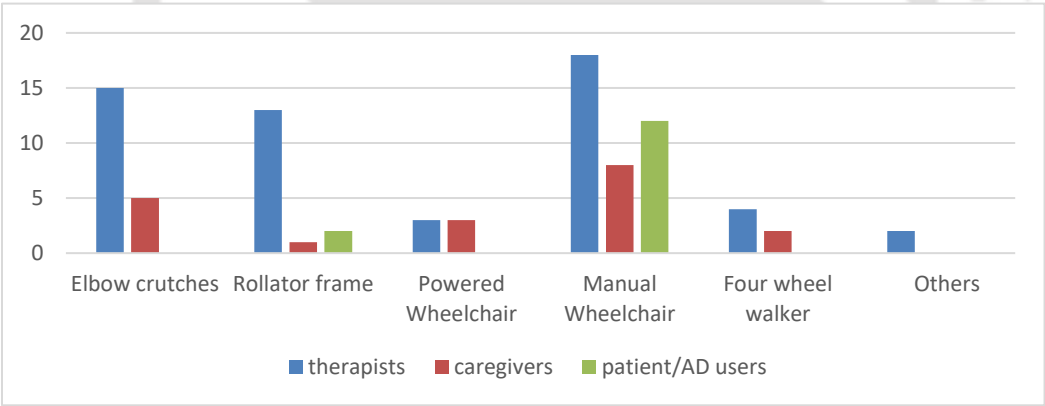


Figure 3-6 Responses for the commonly used existing Mobility assistive devices

Participants from therapists and caregivers are asked to rate their client's perceptions concerning the existing Transfer methods. Similarly, patients or device users are invited to rate their perception of the current Transfer methods or assistive devices application on a scale of one to five with "extremely not good, fair, average, important to extremely good". The ratings given by the respective respondents reveal that the degree of perceptions as viewed from the therapists' side may not equally reflect the perception of the patients or caregivers, and this indicates that the inclusion of the potential users or, thus, patients who are seeking the above services are the best sources to identify whether the existing devices need modification or replacing with a new device. Figure 3.7 represents the outcomes obtained from the above ratings.

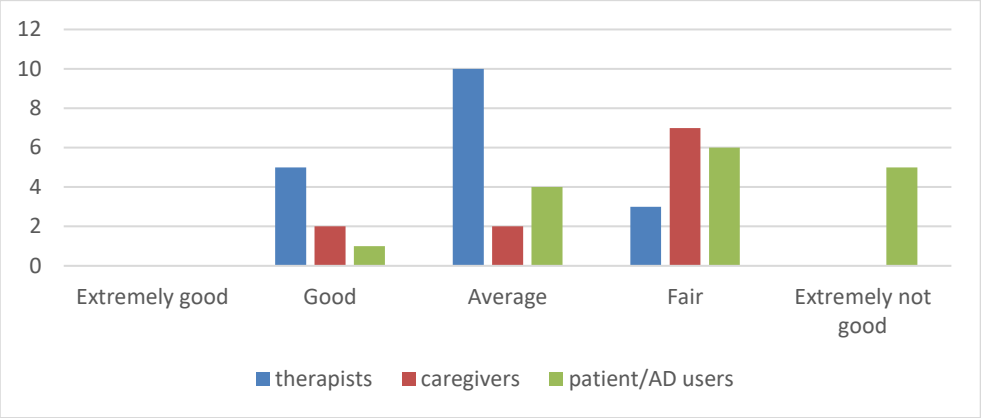


Figure 3-7 Responses from therapists and caregivers for their clients' perception and users' perception of the existing Transfer device

The two categories of participants, such as the caregivers and their clients, were instructed on how to give their answers from the corresponding human body figures; the probable pain or discomfort encountered to the body parts during a transfer activity is represented by a number as shown below. Participants are asked to select the numbers located on the body parts corresponding to the pain that might occur only during transfer tasks. The highest complaints given by the caregivers are coded as "15FB", which means 15 indicates the location of the body parts (knee), whereas F and B are for the frontal and back side of the knee. These results reveal that one of the leading causes of early knee joint degradation among the caregiver's community is prolonged activities of manual patient transfer. Similarly, the responses from the patient side were coded as "6FB shoulder pain,16FB shank and calf pain and 9FB triceps and biceps muscle pain", respectively.

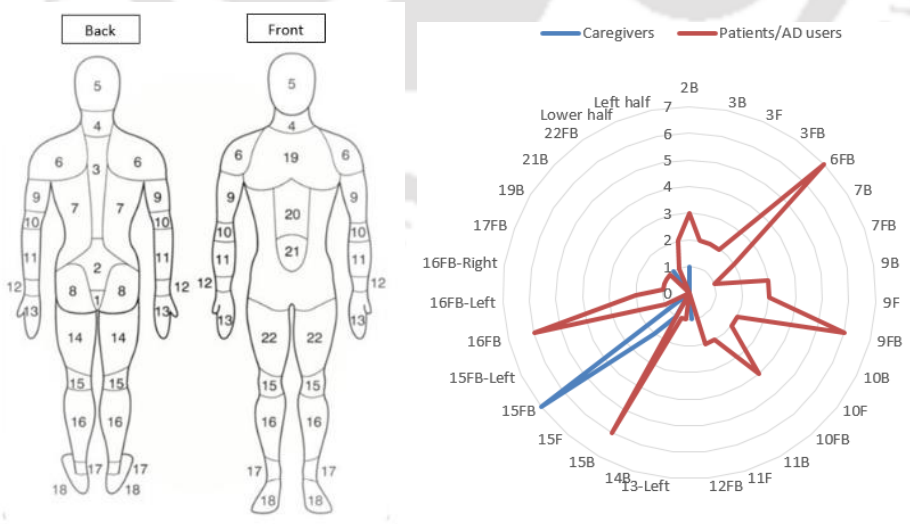


Figure 3-8 Responses related to the pain or discomfort during transfer activities

Participants of the three categories were also asked about the importance of implementing or introducing the new transfer assistive device that can transfer the users independently from wheelchair to other seats and asked to rate based on the five scales as shown in figure 3.9. According to their responses, one of the necessary solutions to improve the lives of users and caregivers was the introduction of a new transfer device.

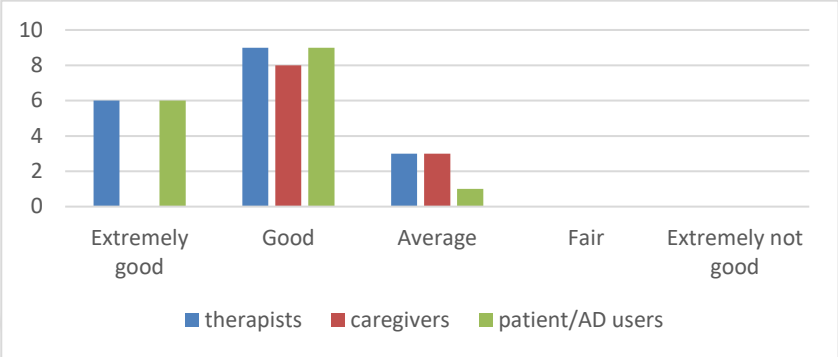


Figure 3-9 Responses related to the importance of introducing a new TAD

Based on the expected outcomes that might be obtained by introducing the combined transfer assistive device, participants were asked whether the privacy and independence of clients (or their privacy, for patients/AD users) can be enhanced while using a self-transfer assistive device. 81.3% of the users, 63.6% of caregivers and 72.2% of physiotherapists have responded positively, showing their agreement. On the other side, related to the design characteristics to be included in the development process of a new assistive transfer device, therapists and caregivers are given a brief explanation of the definition of design characteristics. Once they have gained a good understanding, they are asked to discuss each other and then choose from a list of general design attributes or characteristics that they might expect to be more suitable to be included in the design process. The responses from therapists and caregivers shown in Figure 3.10 indicated that safety, comfort, cost and reliability are the most recommended design characteristics. These design characteristics, which most participants chose compared to others, reveal that they are the most important design features that should be incorporated into the proposed transfer device. Generally, this result indicates the design requirements to be considered while developing a new device to overcome the physically demanding tasks of caregivers in the context of the current healthcare centre.

Figure 3-10 Responses related to design characteristics to be included in the new TAD design

In the above question, participants were asked to a list of design characteristics that should be included while developing a transfer device, whereas in the next and last question, similar but slightly different design characteristic features along with the 3D pre-concept model were provided for the three categories of the participants. This 3D pre-concept model is not a full or actual concept of the proposed concept; rather, it is a 3D layout that shows the phases of the new transfer technique. A series of digital human models while transferring from a wheelchair to another chair were also incorporated into the questionnaire to illustrate the previously proposed transfer techniques. The basis for the early introduction of the conceived layout of the 3D model and its sequence of transfer techniques has two advantages. Firstly, it is a highlight of the undergoing research direction; in this way, participants will have enough confidence to discuss and give their ratings according to the given design characteristics. Secondly, it helps provide critical insight for the respondents while evaluating the design features that should be included concerning the new transfer algorithms; also, it helps as a proactive design step for early design modification based on the respondents' feedback.

The expected working operation and overall architecture series are discussed with the participants before choosing the design features that they think are extremely good. Generally, participants are encouraged to visually inspect the 3D model and then to rate the appropriate design features if it is considered during the development process. Finally, they are asked to rate them on a five-point scale ranging from “extremely good to extremely not good”. The results are illustrated in Figure 3.11. Device compactness, sequence of transfer, safety and design simplicity were among the design features chosen by most of the respondents. Additional feedback was also taken to improve the current concept, especially to include an option for controlling the device by the caregivers instead of restricting only an independent transfer.

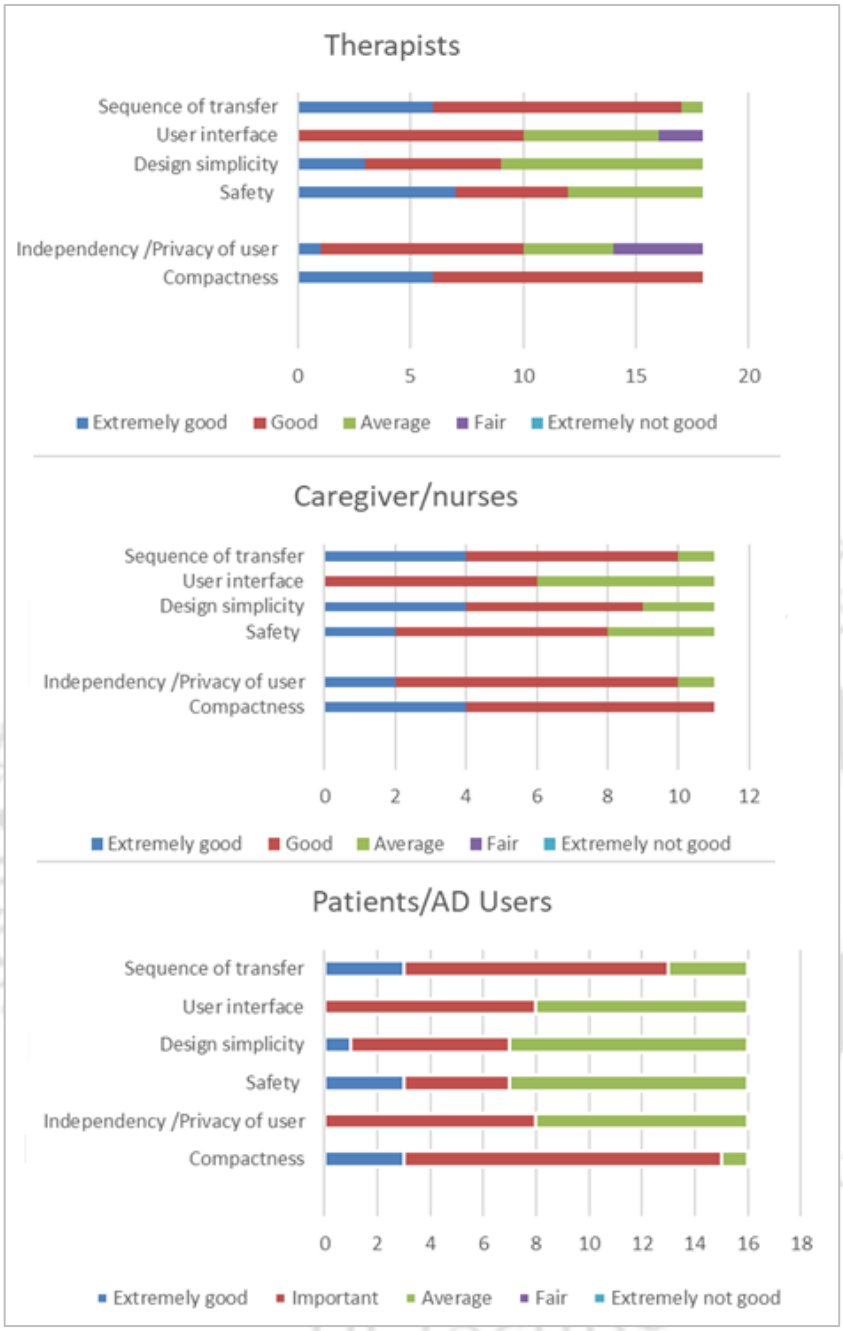


Figure 3-11 Responses related to the 3D conceptual model of transfer technique based on the design characteristics.

3.5 Summary of the Questionnaire

The patient transferring activities are known as one of the most physically demanding tasks, which exposes the respective caregivers and their clients to ergonomic stress. The severity of the ergonomic stress during such activities will be the worst in areas without appropriate means of transferring devices. In order to find a suitable transfer device in the proposed context, a design research approach was used. Based on this approach, a comprehensive review was carried out on the existing transfer devices once the general research gaps had been identified. It was planned to reframe the tasks from the contextual perspectives of the stakeholders in a selected healthcare centre. For this purpose, a questionnaire-based survey comprising three categories of participants was conducted at a selected hospital.

The survey was carried out in one shift and within a ward comprising therapists, caregivers and patients or disabled individuals. In order to assess the requirements of the new device, various relevant questions were included. For instance, the responses for the nature of impairments of the AD users revealed that more than 54% have disabilities in their lower limb, and 75% of them were fit in their upper extremities, which indicates that they are fit enough to use their upper half to transfer from bed to other surfaces if a suitable transfer mechanism is provided for them. Knowing the exact impairments would help to find a solution, but in most cases, achieving such a goal becomes difficult due to the gap between the respective caregivers and those who are trying to develop a new device.

On the other hand, in order to understand which types of transfer devices or transfer methods are common in the hospital under consideration, most of the participants from the three categories responded that manual means of transfer are common, and this was evidenced by the data collected from the respondents with a mean and standard deviation of **(14.33±. 306).** Similarly, they were asked for the common type of mobility devices employed in the hospital for moving the patients from one ward to another; based on this, the majority of the respondents replayed that a manual wheelchair was the common mobility device, and this was also evidenced by the data collected from the respondents with a mean and standard deviation of **(12.67±. 5.02).** The implication of these two results shows that the caregivers are manually shifting their clients, and also, they are using a manual wheelchair for mobility, so this result will help to reframe the expected design of the new device in terms of the existing environment. Hence, a suitable device that fits within a recommended space for wheelchair movements will be conceived as one solution.

Participants from therapists and caregivers are also asked to rate their client's perception concerning the existing transfer methods; patients are also invited to rate their perception of the current transfer methods or assistive devices application on a scale of one to five with "extremely not good, fair, average, important to extremely good". The ratings given by the respective respondents reveal that the degree of perceptions as viewed from the therapists' side may not equally reflect the perception of the patients or caregivers, and this indicates that the inclusion of the potential users or, thus, patients who are seeking the above services are shown to be the best

sources to identify whether the existing devices or method of transfer needs a modification or replacing with a new device. Hence, the strategy adopted in this report was advantageous in terms of gathering appropriate information from multiple directions to enhance the user-centric design. Regarding the nature of the pain that might occur during a daily transfer activity, caregivers and their clients were also asked to indicate the type of pain they are encountering during transfer activities; the majority of the complaints that the caregivers gave are coded as "15FB" which means 15 indicates the location of the body parts (knee) whereas F and B are for frontal and back side. These results reveal that one of the leading causes of early knee joint degradation among the caregiver's community is prolonged activities of manual patient transfer. Similarly, the responses from the patient side were coded as "6FB shoulder pain,16FB shank and calf pain and 9FB triceps and biceps muscle pain", respectively. These results truly address a message about the strong need for a suitable transfer device for the respective healthcare centre, and it also highlights that the new device is expected to overcome the above issues.

One way of strengthening the attributes of the initial idea is to share and discuss the assumed design characteristics of the proposed device with the concerned stakeholders. An experienced stakeholder will provide context-driven design features to be included in the development of the new device. Based on this strategy, therapists and caregivers in the respective hospitals are given a brief understanding of the definition of design characteristics. Once they have gained a good understanding, they are asked first to discuss with each other and then choose from a list of general design attributes or characteristics that they might expect to be more suitable to be included in the design process. Their responses indicated that the majority of the respondents had chosen safety **(14.5±. 4.94)**, comfort **(13.5±. 3.53)**, cost **(12.5±. 3.02)** and reliability **(11±. 2.82)** as the most recommended design characteristics. In the previous discussion of section 2.3, various transfer devices which were listed in [42], [43], [44] and [45] were reviewed in detail by comparing their strength and their weakness, according to the review, safety and comfort were among the primary weakness that was investigated almost in all of the listed TADs. Combining the information from the literature review with the current field study results would help as additional feedback in the development process of the new device. However, more design features should be included in the questionnaire list; these are considered essential features in the context of the current research work.

The last question, containing a slightly different design characteristic from the previous question, was provided for the three categories. Also, the 3D pre-concept model of the transfer technique was incorporated into the list for the convenience of matching the ratings from the perspectives of the new concept model. This 3D pre-concept model is not a full or actual concept of the proposed concept; rather, it is a 3D layout that shows the phases of the new transfer technique. A series of digital human models while transferring from a wheelchair to another chair were also incorporated into the questionnaire to illustrate the previously proposed transfer techniques. Generally, this strategy helps as a proactive design step for early design modification (if any) from the respondents' feedback. Based on this method, participants were to visually inspect the 3D pre-

concept model and then give their ratings on a five-point scale ranging from "extremely good to extremely not good". The overall results showed that the compactness of the device, sequence of transfer, safety and design simplicity were among the design features which have been chosen by most of the respondents. This was evidenced by the data collected from the respondents with mean and standard deviation of **(4.27±.49), (4.18±.61), (3.87±.81)** and **(3.73±.75)** for compactness, sequence of transfer, safety and design simplicity as shown in table 3.1 respectively. Privacy of users and user interface were also given a substantial rating with mean and standard deviation of **(3.60±. 75)** and **(3.49±.58)** respectively. The two most rated design features, such as the compactness of the device and sequence of transfer technique, share one common salient feature from the perspectives of the space requirements; it is evident that making the device compact might not be enough while working with other auxiliary assistive devices such as transferring from wheelchair to other seats. In today's healthcare centres, most wards are too tight to accommodate two assistive devices simultaneously. Although it is evident that combining the transfer device with a wheelchair requires extra space, in order to overcome this issue, a novel transfer technique was proposed; this technique enables the proposed transfer device to work in a compact space by letting the users transfer 90 degrees in c.w or c.c.w.

Table 3-1Summary of the participants' responses related to the design characteristics.

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
Compactness	45	3	5	4.27	.495
Privacy of user	45	2	5	3.60	.751
Safety	45	3	5	3.87	.815
Design simplicity	45	3	5	3.73	.751
User interface	45	2	4	3.49	.589
Sequence of transfer	45	3	5	4.18	.614
Valid N (listwise)	45				

3.5.1 Design considerations from the reviewed literature and the questionnaire outcomes

Limited design and research activities were shown in the field of assistive technology, particularly in the development process of transfer assistive devices. This situation was found to be one of the factors for the limited accessibility and affordability of TADs in the reviewed studies. The reviewed literature also indicated that applying a new design and research approach in the area of assistive technology helps improve the current barriers to the transfer of assistive devices. Generally, this report considered a context-driven design and research methods to contextualize the design and development process. Therefore, a questionnaire-based survey was conducted with

a selected stakeholder to gain practical insight into the existing transfer device/methods and reframe the new design and concept development process based on the reviewed resources and the questionnaire outcomes. Given the existing gaps and the outcomes of the questionnaire, the following design and research activities were planned to be conducted in this thesis:

- Adopting biomechanical and DHM design approaches in a human-machine environment to keep the ergonomics of user-machine interaction, such as matching the range of motion of the users with the device.
- Conducting biomechanical evaluation experiments both during the conceptual phase and final prototype testing for estimating the effectiveness of the device from the user's safety perspective
- Design and development of a simple and novel autonomous rotating mechanism that operates in a compact space with the turning ability of 90 degrees c.w or c.c.w without any lateral tipping.
- To use an alternative design approach that helps in estimating an optimum transfer load requirement and selecting the cost-effective components
- To look for a novel approach that could help in estimating the user's biomechanical loadings at L5/S1 by developing a custom biomechanical equation concerning the virtual model and the transfer device
- Design and development of a novel under-arm support mechanism which contributes to the safety of users and for raising and lowering motion, thereby reducing the time and the motor power needed for lifting activities.
- Introducing a new method of handle design selection and evaluation techniques in the field of transfer assistive devices using an EMG-based experiment for developing a handle.
- Designing a safety wheel mechanism to maintain a high level of safety and stability of the user–device interaction throughout a transfer activity.

3.6 Preliminary Concept Development and Overview of the Initial Concept.

The preliminary concept creation and design synthesis phases are essential for developing or improving new product concepts through creative ideas and imagination. Various types of existing transfer devices and transfer techniques were presented in section 2.3, followed by a detailed discussion of their strength and weakness characteristics. The detailed review was presented by systematically grouping various types of TADs into four broad categories: Sitting transfer, Supine or laying transfer, Forward pivot transfer, and Sit to standing transfer. The grouping was determined by their functionality and the method used for lifting and transferring posture. This grouping technique was employed to evaluate each item and determine the strengths and

limitations of existing product concepts, which were then used to generate a new concept that overcomes the existing limitations.

The reviewed transfer devices were found bulky and permanently designed as floor, ceiling or wall-mounted lifting systems in a sophisticated hospital requiring a substantial space for proper operation. Today, most healthcare and rehabilitation centres, especially hospitals in developing countries, are designed with limited space to accommodate small-sized assistive devices. Almost all of these devices were also observed to require substantial effort from the users' and caregivers' sides to operate them; moreover, many researchers were not found to apply a biomechanical loading assessment from the patient's perspective. Thus, the safety of the patients who are using the above transfer devices was not considered while developing the transfer device and during the assessment process. Most of the reviewed categories of TADs and their corresponding transfer techniques were also not in line with the healthcare centres in the context of developing countries, and they are not suitable for nursing homes.

In addition to safety and cost, the sequence of transfer and compactness of the device was shown to have a strong relationship in the design and development of the device. These design characteristics were added to the questionnaire list and found to be the most rated factors by the respective stakeholders while choosing the design features of the pre-conceptual transfer technique. Generally, one of the main goals of this thesis is to find out the best transfer posture from the perspective of the user and the device's biomechanics interaction without compromising the salient features of the transfer sequence and compactness of the device. In order to maintain these features and to keep the appropriate transfer posture, the previous criteria used for choosing the SFPT technique, both from the design context and the questionnaire outcomes, were adopted for further concept selection and evaluation phases.

The overview of the pre-conceptual transfer technique of the proposed initial concept is developed virtually in the Digital Human Modeling (DHM) environment, along with the virtual human model that shows the chosen transfer sequence. The 3D model of the transfer algorithm was initially included in the last question of the questionnaire list to collect feedback and make modifications based on the given design characteristics. Its feasibility of transfer sequence was assessed by stakeholders at the healthcare centre, considering the safety and compactness of the device. By including the 3D model in the questionnaire list, the stakeholders were given the opportunity to consider the design from an overall perspective and to understand the overall experience. As a result, they were in a position to choose suitable design features that would not have been feasible in the absence of the 3D model. The proposed initial concept is intended to be used independently by the users or with the caregiver's help as an option. The transfer can be accomplished based on three phases: forward transfer, turning by +/- 90 degrees and finally, backward transfer, as shown in Figure 3.12 below. Generally, it is an ideal representation of a transfer algorithm that helps as a ground for beginning the subsequent design process, starting from mechanism identification, concept selection, system-level design, and prototype development.

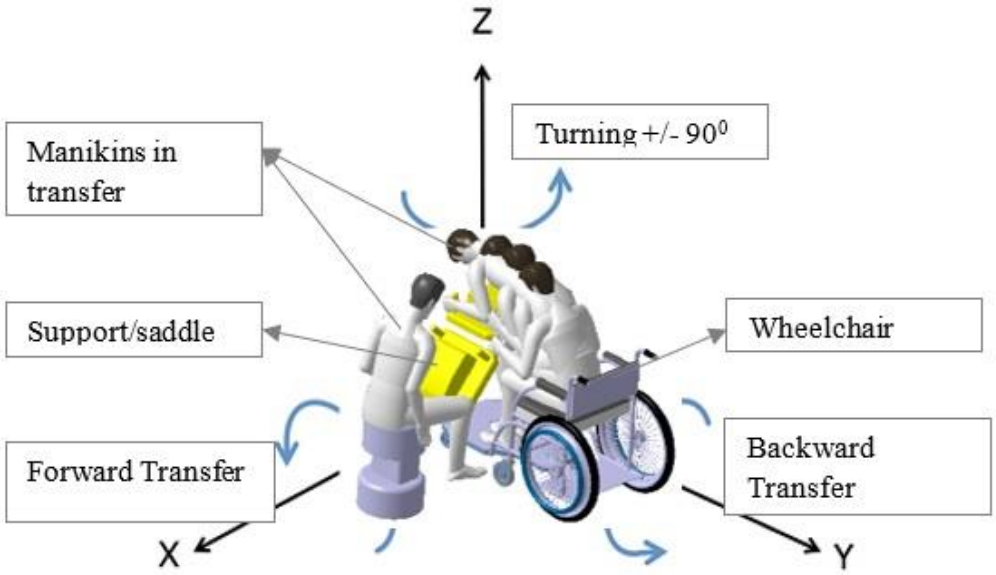


Figure 3-12 The three phases of transferring methods in the proposed concept ideation.

3.7 Virtual Motion Planning and Mechanism Synthesis

Before embarking on the mechanism design, it is necessary to study the proposed concept's kinematic behaviour, which includes the requirements and types of the mechanism that can transfer the users within the prescribed phases, as discussed in section 3.6. Selection of the optimum trajectory curve and the minimum possible degree of freedom could minimize the device's overall cost, such as by allowing the designers to choose an optimum actuator specification and other necessary components of the transfer assistive device.

Human motion analysis and synthesis is one of the research areas in the field of human biomechanics, which is used for estimating the motion of the human subject in a specific activity. Researchers have used various techniques to estimate the trajectory of human motion in a particular activity. Most of the previously reviewed studies adopted the use of a high-speed camera that can record the reflective markers attached to the human body during a complex movement; despite its advantages, such techniques require a highly sophisticated laboratory with costlier software [58-62]. Moreover, there is a frequent phenomenon of an offset error in the recorded data that occurs due to the mismatch between the virtual and real reflective markers.

In this thesis, due to the nature of the tasks under consideration, a context-driven approach was implemented for tracing the virtual motion of the human subject in the assumed forward transfer phase. Generally, the following four main steps were used in the chosen approach: first, the process

for generating the digital human model was carried out using the ergonomics design and analysis workbench of Catia v5. The anthropometric dimensions of the generated DHM / manikins were converted to known anthropometric data of the population [77]. The "variable list tool" provided in the human measurement editor workbench was used to manually input the required dimensions, geometry, and mass properties. In order to accommodate a wide range of the target population, the 5^{th} percentile female, 95^{th} percentile male and 50^{th} percentile pooled body dimensions were selected to represent the smallest, average and largest dimension of the population in the generated manikins. In the second step, the posture of the manikins was manipulated to represent the posture of the initial phase of the transfer technique; a comfortable range of the body angles was rendered over the digital manikins. Kinematic simulation and angular limitation tools such as preferred angles dialogue box, mirror and swap functionality were used to render the comfort angles of the body, and at the same time, the recommended range of motion of each body part was checked. In the third step, the digital human model with a forward transfer posture was interfaced with the assumed mechanism profile using a standard pose and "create-multi view" tools. The fourth and final step was to perform the forward kinematic simulation since ensuring adjustability of the proposed transfer device was one of the objectives of this thesis; therefore, considering these features in the proposed design would help encompass the two extreme body dimensions (5^{th} percentile female and 95^{th} percentile male). Thus, only the 50th percentile digital manikin was used in the simulation due to this option. In order to ensure the required range of adjustability, a reach analysis was performed using the compute reach envelop tool.

Because of the layout of the device and the limited space or working area, only two locations were identified for mounting the mechanisms. Based on the two options, one of the mechanisms is assumed to be mounted between the footrest with point 'o' as a pivot, R initial and Q as a final location, as shown in Figure 3.13 below. For the second mechanism, 'p' is the mounting location, whereas R and Q are the initial and final locations. Before applying the mechanism synthesis technique, the initial dimension and position of the links (the assumed pivot and end effector) for both mechanisms were generated in the ergonomics and analysis workbench by keeping the forward transfer posture of the virtual human being as a reference. The range of motion and the reach envelope in the selected posture were also analyzed from an ergonomics point of view. The dynamic compass was aligned with the pivot points 'o' or 'P' (shown in Figure 3.13 below) of the main frame relative to the position coordinates on the selected body parts of the manikin in both cases. The manikin was also attached to the virtual saddle (omitted for visualization) using the attached tool. Once the simulations started, a simulation tracking tool was invoked to track the simulations' sequence and generate multiple instances of the manikin concerning the chosen angular divisions. Thus, the final results of this simulation create the reach envelope of the 50^{th} percentile digital manikin. In this case, the generated reach envelope is considered the working or banded area of the device's end effector.

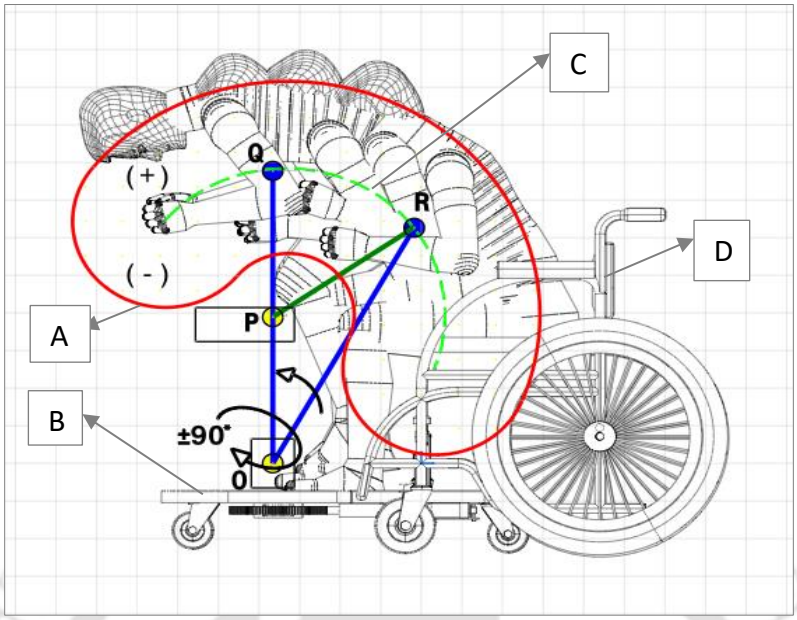


Figure 3-13 The 2D sagittal view of the reach envelopes created in the DHM environment during the transfer task. [A, reach envelope. B, platform base. C, average trajectory curve. D, wheelchair].

In Figure 3.13 above, the line (OR) represents the first category of the candidate mechanism, which is the linkage part of the mechanism. It is pivoted at 'O' and tracing a curve from point 'R' (initial point) to point 'Q' (final point) while transferring the users. Similarly, line (PR) represents the second category of candidate mechanism. Line (PR) is pivoted at point 'P', tracing a curve similar to the first mechanism. Both candidate mechanisms' line representation is structurally enough to accomplish the task within the specified reach envelope for all individuals, provided that adjustability criteria have been considered. The reach envelopes denoted by A is the region where the expected candidate mechanism should be covered with the same profile during the transfer phase. It is created during a virtual transfer of an average person with a trajectory curve QR, where point 'Q' and 'R' denotes the paths of the support/saddle and the (+) and (–) signs indicate the two extreme positions for larger and smaller individuals respectively.

3.7.1 Graphical Mechanism Simulation and Selection

The primary goal of graphical mechanism simulation in the early phases of the product layout can be examined from two design perspectives; in the first case, it will help determine the precise dimensions of the geometrical angle and linkage specifications of the device under consideration based on kinematic and geometrical constraints. Secondly, it will give an insight into the system's dynamic behaviours to quickly identify and estimate its overall motion. Additionally, the motion planning algorithm helps in generating a trajectory curve; thus, the path traced by the ends of the link (which can be a supporting end of the transfer mechanism) is essential for an overall design

process. It is known that assessing concept generation possibilities in a contemporary product development setting has been one of the most important challenges for various organizations attempting to compete in rapidly expanding global markets. As a result, several businesses have used a variety of approaches to effectively complete this complex and time-consuming process.

In this report, a computer-based graphical simulation technique was used as an approach for the mechanism synthesis and design analysis; the reason for using this technique is that the layout of the selected category of mechanism can be relatively easily performed graphically with mechanism simulation software. Hence, it does not require an extensive analytical analysis of the mechanism; moreover, this method gives the most efficient solution and physical insight to visualize the actual working phases of the mechanism. Since the visualization of the trajectory curves is considered one of the comparison criteria between the candidate mechanisms, the use of this method makes the computational process simple and allows the handling of many iterations quickly. It also gives more insight into the systems by clearly visualizing the mechanism's motion. From the perspectives of the current design requirement, the generated reach envelope is exported to an advanced sketcher workbench for examining the geometric constraints dimensional analysis and to measure the coordinate values. Once the above data is analyzed, it will be imported to Linkage software for further iterations; generally, the estimated reach envelop coordinates, which were generated virtually in a human-machine context, were used as a reference to create a candidate mechanism. These coordinate values are also exported from the DHM- CAD package to the Linkage Software to build and simulate a temporary candidate mechanism. Several temporary candidate mechanisms are iterated to determine the most innovative mechanism that precisely follows the trajectory curve in the bounding reach envelope. The Linkage Software has helped synthesize and simulate numerous mechanism alternatives to decide in the selection process of an optimum mechanism that occurs due to variations in orientation and dimension of each link; this has been done by taking the space constraints while using an external device such as a wheelchair into consideration.

The criteria for choosing the proper mechanism in the context of the present concept were conceived as follows:- First, The mechanism ought to have a minimum degree of freedom (d.o.f) to avoid the device complexity and the use of more actuators; Second, the selected mechanism should be expected to convert a linear motion to rotatory motion at least with a single actuator, Third: the selected mechanism should work and able to configure in a compact space both during forward and backward strokes. Fourth, it should have a minimum number of links and, Fifth, a lower actuator stroke/force. Generally, the ultimate goal of the mechanism in the present context is to accomplish the proposed transfer sequence; therefore, in order to fulfil the stated primary goal, various types of mechanism categories were explored and simulated to estimate the suitable mechanism. However, because of the proposed concept's topographic layout, space limitation and the chosen transfer technique, only two mechanism categories were found to satisfy the described criteria. The Four Bar Slider Mechanism and the Modified Scissor Mechanism are the two chosen categories of mechanism candidates. These are considered to achieve and accomplish the needs of

transferring the user in the forward pivoting method. These two mechanisms' end effectors are expected to follow the geometrically enclosed reach envelope, traced virtually in the DHM environment.

The scissor mechanisms have many applications compared to similar mechanisms, and they have good load-carrying capacity compared to a four-bar mechanism. Also, they are known as more compact mechanisms but usually with more links. In this section, an attempt was made to obtain a scissor mechanism with a minimum number of links (6 links) compared to similar mechanisms; however, to accomplish the transfer motion by keeping the stability of the users, it is necessary to mount two identical and parallel scissor mechanisms. This condition will increase the complexity and cost of the device; therefore, only the four-bar slider mechanism was used for the further design process.

In order to satisfy the above criteria in the selection process, parameters of the four-bar slider mechanism were further simulated by altering the combinations of position and orientation of the ground links, i.e., the coordinate values of the crank, rocker, and joint location. The selected four-bar slider mechanism shown in Figure 3-14 (Left) has four links, three revolute joints and one prismatic joint with (RRRP) representation. According to the grubler's criteria, this system's degree of freedom (d.o.f) was found to be one, which indicates the need for only one motor drive as input for partial rotation of the output link (rocker). Since the motor drive that bears a smooth drive with reduced noise is one of the design requirements in the assumed transfer device, a linear actuator within the prescribed stroke length and the simulated position of the crank orientation was considered as the main input link. The actuator's estimated length is P1=295mm and P2=396mm as the lowest and highest position of the main frame. Similarly, the corresponding link lengths were measured graphically as L1=131.5mm, L2=211mm, and L3=159mm.

After completing the simulation tasks in the Linkage software, the DXF format of the selected candidate mechanism model is exported to the Advanced Sketcher workbench for further investigations, such as to review the dimensional analysis and for matching the corresponding angular coordinates in the current orientation. Once the overall sketch is finalized, the 3D model of the initial concept has been developed by inclosing the selected mechanism linkages within a frame. Additional components were also incorporated into the new concept, such as an appropriate saddle and the under-arm supports, which are conceived and designed ergonomically from the perspective of the present posture of the DHM. These two supports are incorporated as part of the proposed sub-assembly mechanism, as shown in Figure 3-14 (Right). Additional simulation analysis was also made on this 3D model in order to check whether its layout falls within the limits of the desired space; similarly, the model was checked with interference analysis to predict any interferences that might occur between the user/DHM and the device to take a proactive measure prior to the actual model development.

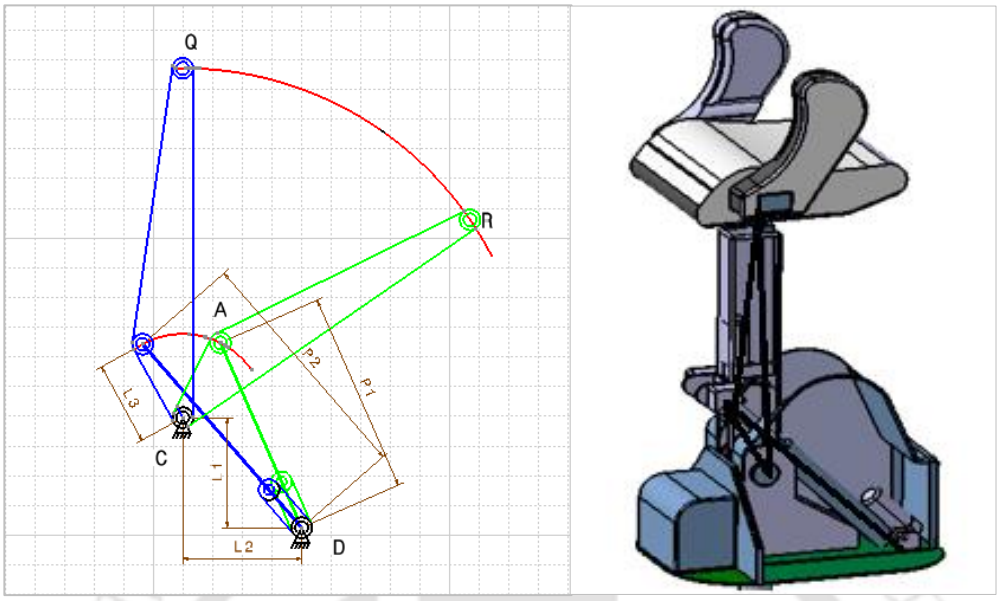


Figure 3-14 The selected linkage diagram (Left) and the 3D concept model (Right)

3.7.2 Concept Decomposition of the Selected Candidate Mechanism

The 3D model of the selected candidate mechanism has been further decomposed into three functionally similar concepts based on the initial transfer algorithms created in the previous sections. The decomposed concepts have the same working principle or transfer technique as the chosen candidate mechanism. The only difference is made in the addition of different concepts of the handle design and its orientations. These handle designs have been incorporated considering the actual transfer posture in the DHM, which is based on the individuals' assumed range of reach zone. It is known that the practical design of the handle in any product that directly interacts with humans plays a vital role in achieving that particular product's usability and comfortability. The three concepts shown in Figure 3.15 are mainly made to differ in their handle position and orientations. Postural changes concerning handle design are known as the main factors that make a postural variation in the upper body during a forward pivot transfer task. Therefore, the need for handle design assessment at various levels was intentionally incorporated into the current concept generation and refinement process to determine an appropriate handle design and orientation. Also, one of the main reasons for applying such assessments in this context is that the target group that uses this device is assumed to have insufficient grip strength or a minimum grip strength as in applying a pull exertion in the present device. Therefore, applying the handle design assessments from the biomechanics point of view during the preliminary concept development and refining process was a crucial phase. It is also known that the use of inappropriate handle design is one of the very well-known reasons for the frequent causes of musculoskeletal disorders in the human muscles, spines and joints. Hence, it has been decided to perform a rigorous handle design concept

assessment to find a suitable handle design from the perspectives of the biomechanical loadings that might occur during the transfer activities.

Generally, the three types of handle design concepts which are generated for the concept selection process have the following orientations: for Concept-1, the handle design is located below the elbow height, and it has been represented as handle below elbow height (HbEH), in case of concept-2 it was located in-line or at the elbow height, and it has been represented as handle at elbow height (HatEH). Similarly, the locational position for Concept-3 is made above elbow height and has been represented as handles above elbow height (HaEH). In this thesis, more emphasis was given to assessing the device from the safety point of the users; thus, the concept selection will be based on the biomechanical loadings point of view while considering other criteria.

Although adjustability criteria were observed in the current concepts, the differences made in handle orientations are based on the expected standard reach envelope zones, where it is estimated that an average human being could easily grip this handle. This design criterion was made due to the nature of the telescopic phenomena of the linear actuator. It has been planned to be adopted in the current concepts as one of the device's primary movers. The working principle for either of the proposed ideas shown in Figure 3.15 is similar except for postural changes of the arm and upper body due to the handle orientations. Performing such activities without considering the appropriate posture of the human is one of the critical phenomena that results in back pain and permanent dislocation of joints; hence, this section attempts to identify the proper way of transferring posture.

The decisions made during the concept ideation and design synthesis on the configuration of the overall device and the necessity of the device's kinematic, such as the type of actuator to satisfy a slow-motion drive while transferring the human user, were considered in the 3D model. Therefore, the developed concepts are planned to work using three electrical linear actuators, where two actuators are mounted at the base of the platform, the one which is mounted at the top of the base between the user’s footrest helps for partially rotate the main supporting frame about the vertical plane. At the same time, the other actuator mounted at the bottom of the base helps rotate the entire frame while supporting the user 90 degrees, either c.w or c.c.w. Because of the versatility of electric actuators, the saddle's height is supposed to be adjustable for every person. Thus, the third outermost linear actuator, connected to the saddle base, is designed to lift and lower the saddle. The key feature of the outermost linear actuator is to raise and lower the saddle to compensate for the height variations; it also helps to change the reach enclosure for a remote seat.

The average dimensional length of the assistive transfer when combined with the wheelchair during the transfer mode is approximately 1400mm as measured in the assembled workbench of the 3D model, which is below the standard limit for Americans with Disabilities Act (ADA) legislation. According to this rule, a wheelchair should rotate 360 degrees in a span of 1600mm to 1800mm; hence, the proposed concept's working range, along with the wheelchair in a transfer mode, was found to satisfy the above criteria. Similarly, the topological shape of an ergonomically built underarm support has been added as one of the crucial parts of the new concept because it

helps as safety support by raising the users after they have initiated the pre-lifting task by their own hand-pulling action and immediately they will be taken up by the underarm support. The design of underarm support was conceived in the device to avoid the users' backwards movement due to the saddle's sliding action that occurs during the initial lift. Once fully raised, this will make the centre of gravity close to the saddle, thus letting the rotation process be smooth and easy. The use of the handle generally distributes the body parts symmetrically about the mainframe and moves the C.G. of the user forward, thereby keeping the stability during the transfer task. Also, it reduces the amount of actuator load for transfer tasks. This is significant for a number of reasons. Initially, it shortens the time that the user's body, specifically the armpit and the underarm support, comes into touch. Reducing the length of contact is crucial for ensuring user comfort and averting discomfort. Secondly, it lessens the contact stress that is felt when performing the action. In summary, handles are essential for providing a symmetrical distribution of weight, moving the user's centre of gravity forward, increasing stability, and lowering the actuator load needed for transfer operations. Additionally, applying a minimum pulling force minimizes the contact time and contact stress at the armpit, which enhances user comfort and safety during these tasks. Even while handles look basic, they greatly improve the ergonomics and efficiency of a variety of tasks and procedures. This was one of the study gaps from the user safety viewpoint, as nearly all of the current transfer devices covered in the literature review did not use such components.

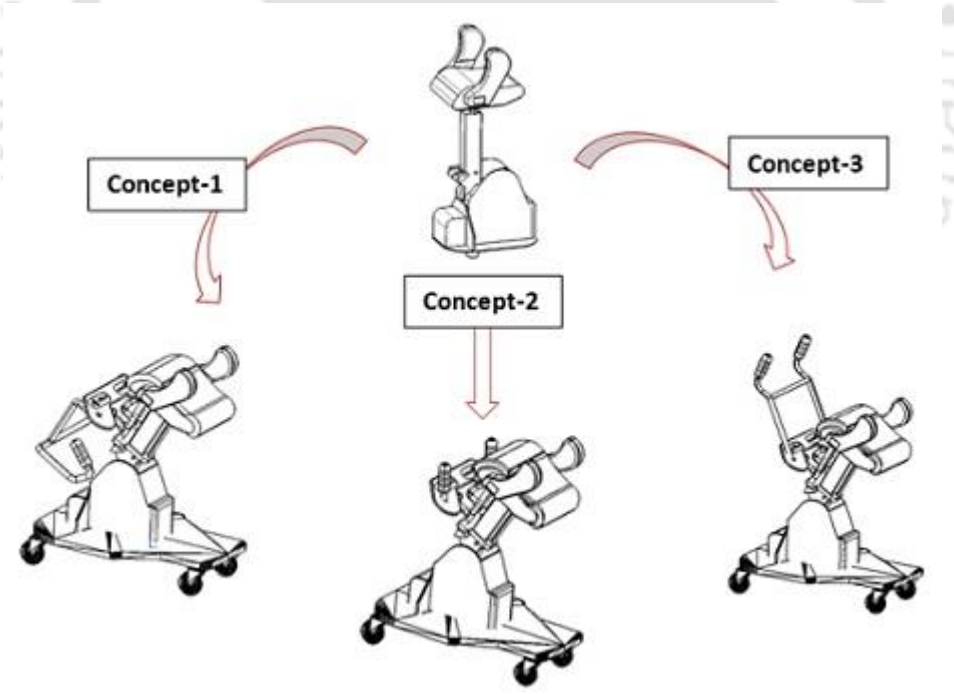


Figure 3-15 The 3D model of concept-1, concept-2 and concept-3.

CHAPTER FOUR

4 Biomechanical Assessment of the Arm Muscles for Evaluating the Handle Design

4.1 Background

The National Institute of Occupational Safety and Health (NIOSH) documented 20% of overexertion accidents to pull-push operations, which equates to 5% of all reimbursable work-related accidents [78]. The pull-push exertions are characterized by their contrasting exertion paths. Pull power is generally considered superior to push capacity [79]. Hand-arm strength has been considered an essential requirement for almost all types of patient transfer assistive devices, as reported in the literature. However, the degree of required strength may vary from one device to another device. This strength limit will be higher for wheelchair users who perform manual means of transfer by themselves and lower for the same users who can perform the transfer using a transfer assistive device such as the proposed concept used in this report. The degree of hand-pulling effort applied at different handle locations greatly depends on the upper body's posture. It should be noted that even a small amount of a pull or push action greatly influences the safety and comfort of the user's spine or backbone, provided that if the task is performed in a particular posture, it intensifies the compressive forces at the spine or at the backbone. Designers must consider several factors when evaluating the handle design of a transfer assistive device. The handle should be easy to grasp and hold securely, even for users with limited hand strength or dexterity; also, the orientation of the handle and posture of the user in a transfer technique should be taken into consideration. By carefully considering these factors, designers can create safe, effective, and user-friendly devices for individuals who require assistance with transfers. The handle should also be evaluated for its ability to provide adequate support and stability during transfers; this involves assessing the placement and orientation of the handle, as well as its attachment to the device itself.

This section's objective is mainly to conduct the EMG recordings on the test subjects' selected muscles during each lifting-up task concerning the handle orientations. Based on the experimental activities made in the three types of handle orientations, the corresponding recorded EMG data would be used to determine which handle orientations required more muscle excitations relative to the other. In this report, the criteria for recording the EMG signals from the selected muscle was established from the context of the present activities; thus, the first phase of the transfer task, which is a forward rotation about the vertical plane, was considered for evaluating the handle design. Generally, the first phase of transfer tasks has three sub-lifting motions, such as ***the Pre-lift***, where the user starts to apply a pulling action at the handle and is about to start the lifting. The second step of this phase is ***the Lift***, where the user starts lifting up by applying the maximum pull at the handle while the saddle is simultaneously lifting up the user from the upper abdominal part; in this step, the upper body part tends to slide back due to the profile of the saddle; therefore the users are requested to apply their maximum pull at the handle to counterbalance the back movement and to keep on lifting up with the saddle movement until the underarm support takes up their entire

weight. The last step is ***the Post lift***, which is the motion that starts when the user's weight is taken up by the under-arm support till the end of the lifting phase. The ***pre-lift*** and the ***post-lift*** phases have relatively too small pulling actions compared to ***the Lift*** phase. Therefore, the software-based EMG calculations are carried out based on the regions where the maximum muscle excitation activities exist; in this case, the ***Lift*** phase is considered the best region for EMG calculations.

4.2 Procedures for Evaluating the Handle Design Based on the Recorded EMG Data

To ensure an effective evaluation of the handle design for the three conceptual models, a specific experimental setup is required. This setup includes the use of a manual wheelchair, a manual lifting platform with an integrated supporting saddle, and three conceptual handle frames that closely replicate the physical 3D concept model. To come up with this combination, a manual lifting platform that works with a ratchet mechanism along with a pre-fabricated saddle and three handle frames was provided for this experiment. The customized saddle, which was fabricated specifically for the present experiment, was mounted on the manual lifting platform. Additionally, a custom-made handle frame consisting of three handles has been mounted on the lifting platform to mimic the proposed concepts of a transfer assistive device. In order to precisely match the real handle orientation or location for each of the proposed concepts, the following steps were taken into consideration. First, each of the 3D conceptual models' handle design orientations is adjusted to fit the 50th percentile combined male-female anthropometric data. This anthropometric data was used as a reference, which was taken from the database discussed in section 3.7 [77]. The same measurement has been rendered to the Manikin in the DHM workbench to match the real human in a sitting forward pivot transfer mode from the wheelchair and exerting a pull force on the handle. This creative way of simplifying the physical user-centric interactions was made to standardize the measurement and minimize tryouts while modelling the alpha prototypes. Second, the 3D lifting platform model was created after taking its detailed measurements, and the same has been made to match virtually with the human model. Finally, a one-to-one measurement was taken from each handle location coordinates of the three proposed concepts, and this has been made to match the custom-made handle frame, which is mounted on the lifting platform. The saddle height from the floor was also measured to fit the saddle's height corresponding to each of the three concepts. Figure 4.1(left) shows the virtual laboratory set-up for one of the concepts (concept-3) taken as an example, with a human manikin showing the posture for the initial lifting phase, similar to the physical set-up of the lifting platform. A, B and C are the handle locations matching the corresponding concepts designated as HaEH, HatEH and HbEH, respectively, and 1,2 and 3 represent the lifting platform, the handle frame and the saddle, respectively.

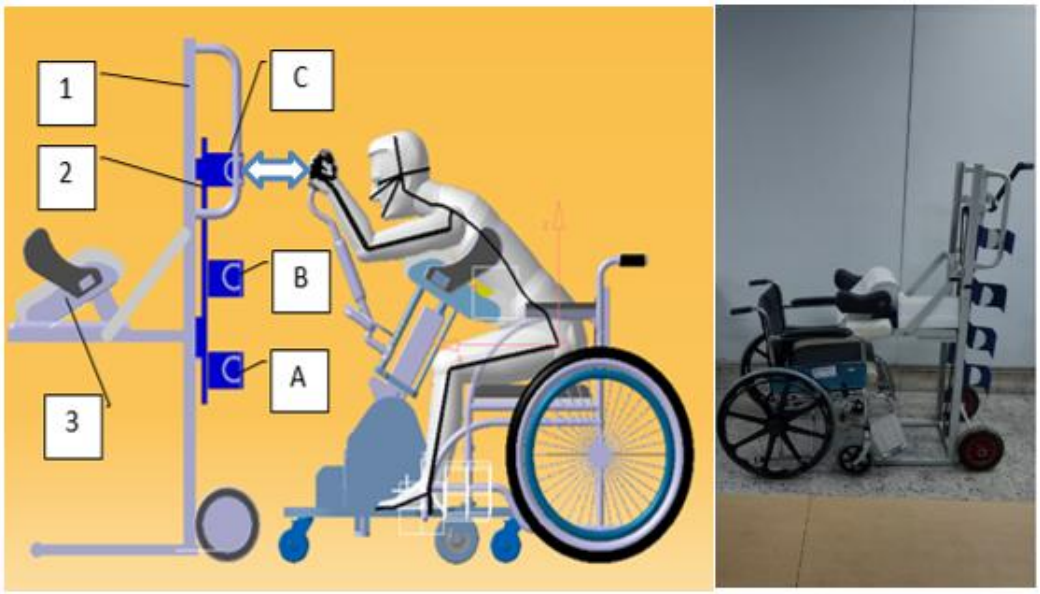


Figure 4-1 Virtual lifting platform and the proposed concept (Left) and the physical experimental set-up (Right)

4.3 Materials and Methods

Seventeen subjects (fourteen males, three females) with mean$\pm$ *SD* of age, weight, and height of (33 ± 3.18) years, (77 ± 14.84) kg, (168.29 ± 8.47) cm were recruited from the Indian Institute of Technology, Guwahati. Before proceeding with the experiment, subjects were asked about their health conditions and demographic information. They were also informed about the activities to be performed by showing them a demo task made by the study coordinators. The following materials were used in this experiment: one manual light wheelchair, a working laboratory lifting platform equipped with a custom-made three-handle frame and a supportive saddle. The mechanical force gauge (Shimpo), with a capacity of 100 pounds and an accuracy level of +/- 0.2%, was used to measure the amount of hand pull by acting as an intermediate handle between the subjects' hand and the handle frame.

The Trigno™ Wireless EMG Sensors and EMG works software shown in Figure 4.2 were also used to record the muscle signals. It is a high-performance system that ensures the accurate identification of EMG signals. It also has excellent quality in reducing the unnecessary noises that occur in most EMG measuring devices, and the sensors can be easily attached to the respective muscle's belly areas. Delsys EMG equipment is designed to support the user in performing high-quality signal recordings and acquisitions. EMG works software offers distinct benefits once utilized in conjunction with Delsys recording instrumentation. Delsys' user interface can continually recommend the best frequency to be used for a given experimental setup so that the Nyquist Theorem is ever fulfilled.

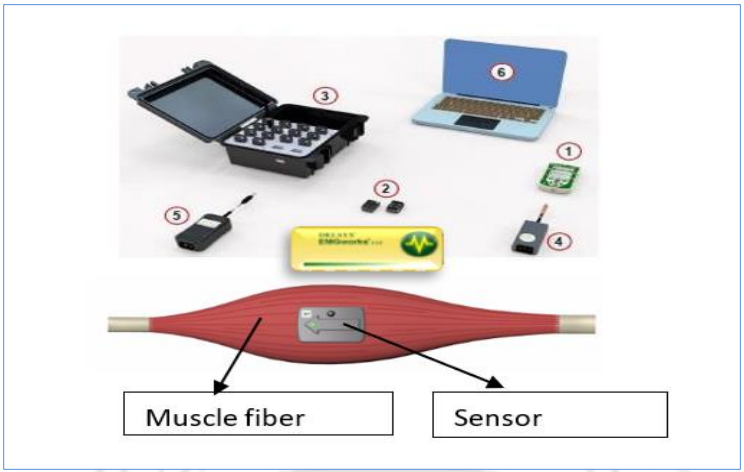


Figure 4-2 Trigno Wireless Sensor, "1. Trigno Personal Monitor Data logger, 2. Trigno Wireless Sensor ,3. Trigno Desktop Base/Recharge Station, 4. Trigno Personal Monitor Medical Grade Recharger 5. Trigno Base/Recharge Station Medical"

4.4 Data Collection and Presentation

The instruments or materials used for measurements and the data collection process were carried out at the ergonomics laboratory of the Indian Institute of Technology, Guwahati. Data was obtained from three selected arm muscles, including the Anterior Deltoid (AD) of the upper arm, Biceps Brachii (BB) of the upper arm, and Brachioradialis (BR) of the lower arm, to predict the effect of handle orientations on muscular loadings during a primary transfer phase from the wheelchair. The choice of these specific muscle groups in this experiment is based on their strong relevance to hand-related activities. Each of these muscles plays a crucial role in various hand and arm movements. For instance, the biceps brachii is the largest anterior muscle of the arm; it flexes the elbow and supinates or stabilizes the forearm towards the supination. The brachioradialis is a powerful forearm flexor muscle that works in synergy with biceps brachii and brachialis to flex the forearm at the elbow. Similarly, the deltoid muscle is also a very powerful muscle which is used in many hand-related ADLs. Three sensors, one for each chosen muscle of the dominant side, have been connected. The automatic interposes communication and labelling of EMG sensors revealed the connection relationship between the EMG sensors and the selected muscles as (EMG-2- Anterior Deltoid), (EMG-3- Biceps Brachii) and (EMG-4- Brachioradialis) muscles, respectively. In order to record the maximum voluntary contraction (MVC) from each subject and at each muscle, each subject was asked to exert their utmost effort against the resistance provided for this purpose. Subjects were orally motivated to exert their maximum possible effort and simultaneously by showing them the display of their EMG envelopes on the screen. Each participant has made three trials, and the average values were taken for further analysis of the subsequent EMG recordings. On EMG signals, MVC normalization is a standard amplitude analytical procedure; thus, this post-processing approach uses the full root mean square (RMS) output from the recording to normalize the corresponding EMG data set. The production is

represented as a percentage of the MVC value (% MVC). Generally, MVC normalization was made on each recorded raw EMG signal, and this output can also be used for comparing data between subjects. Using EMG Works Analysis Software, the software's measurement Scripts are used for amplitude analysis in this report. By contrast, the window length and overlap parameters were set to 0.125 and 0.0625. Since the workable frequency spectrum of a signal for the upper extremity is from 0 to 500 Hz, relying on the "Nyquist Theorem", the sampling frequency must be double the frequency of the initial sampled signal, so in this report, a sampling frequency of 2000Hz was used, which is located in Delsys workspace next to 500Hz. The requirement for an analogue anti-aliasing filter was found to be decreased when translating analogue EMG signals to digital signals at a high sampling rate, while processing and computational load were found to increase. The EMG recording setup is seen in Figure 4.3 as one of the participants pulls on the handle using the mechanical force gauge that is fixed to the chosen handle. Similarly, the electromyography root mean square (EMG-RMS) values that were recorded as a percentage of the maximal voluntary contraction (MVC) envelope during the three distinct activities are shown below from Figures 4.4 to Figure 4.6. (for subject S1 over the course of the tests). These graphs provide information about the degrees of muscular excitation found in three distinct muscles: EMG-2, which stands for the Anterior Deltoid (AD); EMG-3, which is associated with the Biceps Brachii (BB); and EMG-4, which is associated with the Brachioradialis (BR) muscles.

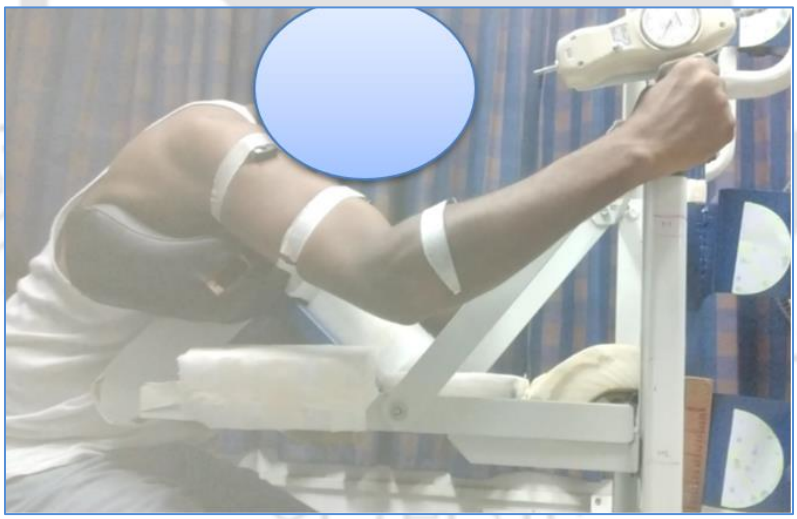


Figure 4-3 The EMG recording set-up while the subject is pulling the mechanical force gauge.

Each of these figures illustrates the EMG-RMS results as a percentage of the MVC for the three specific muscle groups: - Anterior Deltoid, Biceps Brachii, and Brachioradialis during the execution of three different handle configurations: HaEH, HatEH, and HbEH, corresponding to the three phases of the transfer task. The use of EMG-RMS as a percentage of the MVC provides valuable data on the level of muscle activation during these tasks. This information is crucial for understanding how the handle locations impact muscle recruitment and the overall ergonomics of

the transfer process. Also, it offers an insight into the effectiveness of different handle positions and their influence on muscle engagement. The present output, which was generated for subject S1, is relatively similar to the rest of the participants' EMG output. Generally, it serves as a valuable resource for analyzing muscle activation and determining the impact of handle location on the biomechanics of transfer posture and for proactively assessing the ergonomics and efficiency of the transfer process.

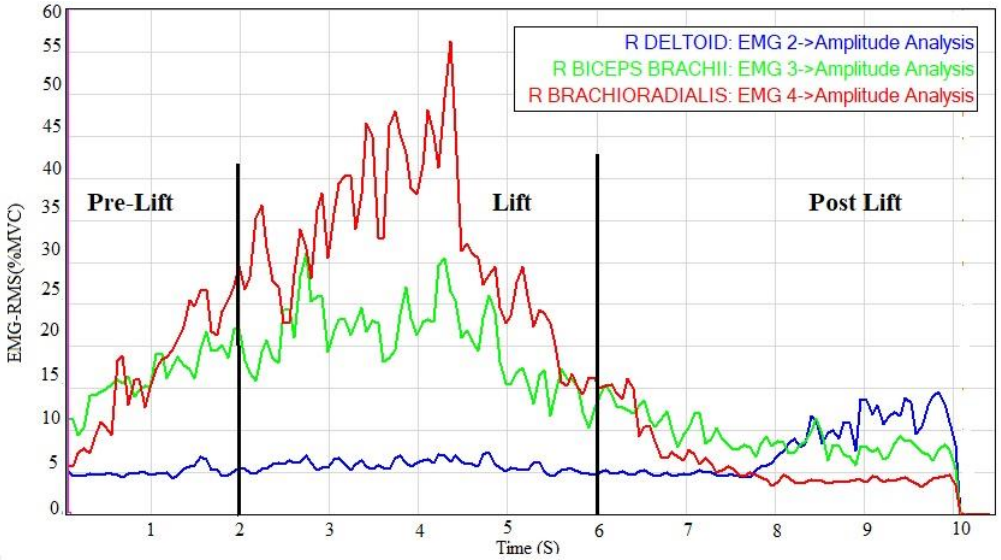


Figure 4-4 Plots of EMG-RMS (%MVC) for EMG-2- Anterior Deltoid (AD), EMG-3- Biceps Brachii (BB) and EMG-4- Brachioradialis (BR) muscles for Handle conditions of HaEH.

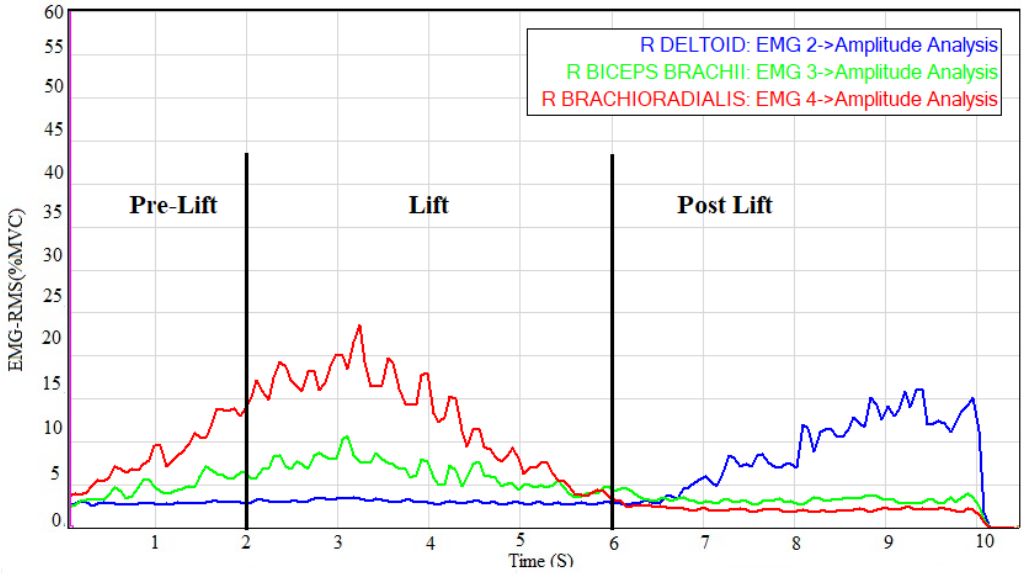


Figure 4-5 Plots of EMG-RMS (%MVC) for EMG-2- Anterior Deltoid (AD), EMG-3- Biceps Brachii (BB) and EMG-4- Brachioradialis (BR) muscles for Handle conditions of HatEH.

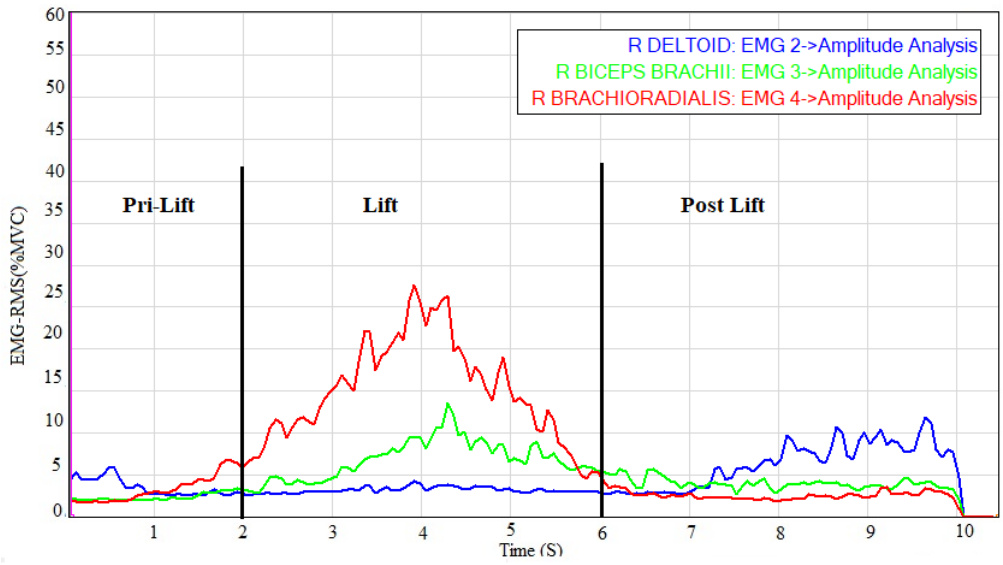


Figure 4-6 Plots of EMG-RMS (%MVC) for EMG-2- Anterior Deltoid (AD), EMG-3- Biceps Brachii (BB) and EMG-4- Brachioradialis (BR) muscles for Handle conditions of HbEH.

4.5 Statistical Analysis and Results of the Recorded EMG Data

The data collected during each task were exported to Microsoft Excel and subsequently subjected to statistical analysis for further analysis and interpretation using a statistical package for the social sciences (SPSS v20). Before proceeding with the actual statistical tests, the normality of the data distribution was assessed. This was done by examining a box plot, as shown in Figure 4.7. The box plot revealed the presence of slight outliers in the data. Additionally, the distribution of the data was observed to be both skewed and kurtotic. These deviations were primarily attributed to occasional extreme muscle excitation values that could occur during data collection in some subjects. It is important to note that these types of skewed and kurtotic data distributions are not uncommon in EMG-based biomechanical experiments. Given the sensitivity of such experiments and the potential for outliers, it is often advisable to employ non-parametric statistical tests to analyze the data. Non-parametric tests are more robust in handling data with these characteristics, ensuring that the analysis accurately reflects the underlying trends and relationships within the dataset.

The Friedman Test, followed by post hoc tests, was employed in this study to thoroughly investigate variations in the recorded electromyography (EMG) response levels during a transfer task involving a hand-pulling action. The EMG data used for analysis pertained specifically to the initial lifting-up phases for each of the three handle locations under examination. The test results revealed significant findings: a statistically significant difference was observed for the Anterior Deltoid (AD), Biceps Brachii (BB), and Brachioradialis (BR) muscles. The statistical notation [$\chi2(2) = 7.529$, $p = 0.023$, $\chi2(2) = 34$, $p = 0.001$ and $\chi2(2) = 20.235$, $p = 0.001$] for AD, BB, and BR muscles respectively indicates the significance of the results for each of these muscle groups. In other words, there was a notable variation in muscle excitations observed across the three muscle types based on the specific type of handle used by the subject to lift from a wheelchair with the

assistance of a lifting platform. This outcome underscores the impact of handle design on muscle engagement during the transfer task, with implications for the ergonomic and biomechanical loading considerations in designing assistive devices and understanding the mechanics of the transfer process. The statistical significance emphasizes that the differences observed are not likely due to random chance, providing valuable insights into the role of handle type in the dynamics of the transfer action.

Wilcoxon signed-rank tests were also used for post-hoc analysis, with a Bonferroni correction added, resulting in a significance level set at $p = 0.017$. There have been no significant differences in the degree of AD muscle excitation between the handle positions HatEH − HbEH, $Z = -1.823, P = 0.068$, and HbEH − HaEH, $Z = -1.538, P = 0.124$. However, there were statistically significant variations for (HatEH − HaEH), $Z = -2.911, P = 0.004$. The biceps brachii muscles varied greatly between handle positions of [(HatEH − HaEH) $Z = -3.432, P = 0.001$ and (HbEH − HaEH) Z= -3.337, P =0.001] respectively.

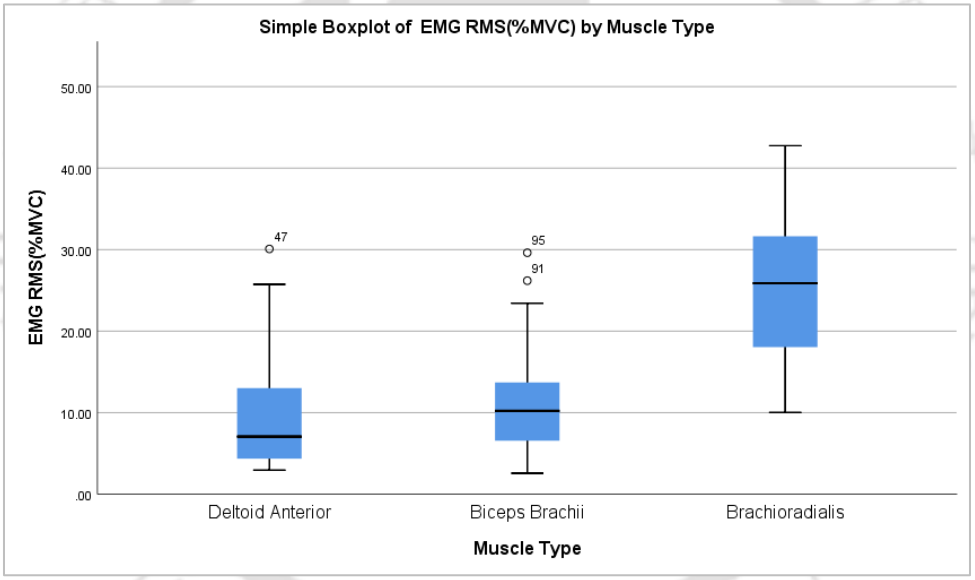


Figure 4-7 Boxplot showing the outliers from Anterior Deltoid (AD) and Biceps Brachii (BB) muscle

Similarly, Brachioradialis BR muscle showed a strongly significant difference (HatEH − HbEH), (HatEH − HaEH) and (HbEH − HaEH), with the same value $Z = -3.621, P = 0.001$ between all types of the three handles. The maximum muscle excitation for the three muscle types were observed at the HaEH and slightly on the HbEH conditions as shown in the ranks table (Appendix III). Generally, the corresponding EMG plots recorded from all participants with the handle condition of HatEH reveal that the amount of muscle excitation force required to apply on the selected handle type was relatively small as compared to the two handle orientations. In addition to this, the said handle design was also shown with a strongly significant difference when

statistically analysed with the two handle design combinations. The summary of the taste statistics tables concerning the handle orientation effect is shown below in Tables 4.1 to 4.3 for each type of muscle.

Table 4-1 Summary of the test statistics for BR muscle on the effect of handle location

Test Statistics[a]

	BR_HbEH – BR_HatEH	BR_HaEH – BR_HatEH	BR_HaEH – BR_HbEH
Z	-3.621[b]	-3.621[b]	-3.621[b]
Asymp. Sig. (2-tailed)	.000	.000	.000

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

Table 4-2 Summary of the test statistics for AD muscle on the effect of handle location

Test Statistics[a]

	AD_HbEH - AD_HatEH	AD_HaEH - AD_HatEH	AD_HaEH - AD_HbEH
Z	-1.823[b]	-2.911[b]	-1.538[b]
Asymp. Sig. (2-tailed)	.068	.004	.124

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

Table 4-3 Summary of the test statistics for BB muscle on the effect of handle location

Test Statistics[a]

	BB_HbEH - BB_HatEH	BB_HaEH - BB_HatEH	BB_HaEH - BB_HbEH
Z	-2.296[b]	-3.432[b]	-3.337[b]
Asymp. Sig. (2-tailed)	.022	.001	.001

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

4.6 Estimation of the Biomechanical Loadings at the L5/S1 Joint in the Context of the Proposed Concepts

According to evidence, the horizontal gap and vertical elevation of exertion affect the effort exertable in both static and dynamic resistance tests [80]. When creating a product, it is essential to consider the end user's needs and limitations. An industrial designer and human biomechanists should work together to produce a product that considers factors such as working posture, range of motion, and space limitations. By doing so, they can create a product that maximizes the user's capabilities and improves their overall quality of life. Previous research studies related to estimating the biomechanical loadings were conducted for load lifting or lowering cases with commonly known postures, i.e., either lifting or lowering in symmetrical or asymmetrical positions [81]. Similarly, a pull-push action of biomechanical loadings was also studied in a well-known posture. Evaluating the biomechanical loadings while using a particular product is crucial at any phase in the design process. In this section, the analytical assessments of biomechanical loading were supported through a combination of CAD/DHM systems. Still, to the best of the author's experience, no study evidence has been reviewed for estimating biomechanical loadings at the L5/S1 Joint for a subject performing a transfer (same as the present concept) in a forward-leaning posture with support under the upper abdominal region. Hence, an attempt has been made to drive a custom equation based on the proposed concepts to minimize this gap.

4.6.1 Procedure for estimating the biomechanical loadings on the selected joints

The anthropometric data, such as height and weight, was used from the previous section to estimate the biomechanical loadings for each concept in the context of human-machine interaction. The digital human model was built to fit virtually with the proposed transfer assistive device from the same data. This method helped to increase the accuracy of the analysis by digitizing each design parameter, and it could quickly and clearly show the initial transfer phase in the selected posture. This method also helps to accurately assess the potential impact of the device on the human body and ensure its safety and effectiveness for use. The posture which is used for the estimation process is the initial lifting phase, where the users are about to start exerting the necessary pulling action at the handle, and this force has been measured in the previous section.

All assumptions made in the previous sections were considered to estimate the biomechanical loadings on the lumbar spine at L5/S1 (the joint between the fifth lumbar and the first sacral vertebrae) for the posture under consideration. These loadings arise due to the compressive force coming from the load at hand and the body weight. The moment at the hip joint was expressed as a function of the bodyweight moment above the hip level plus the moment arising from the handle. In this report, the previous research assumptions for determining the moment arm based on a given force application vector on the erector spinae were taken for analysis; according to this study, it acts parallel to the compression on the L5/S1 disc with a moment arm of 5.0 cm [81]. Figure 4.8 to 4.10 below shows the biomechanical model of the three proposed concepts used to derive the predictive equation. The seven-link kinetic chain extracted from the original digital human–device interaction set-up was also used to simplify estimating the selected joints' biomechanical loadings.

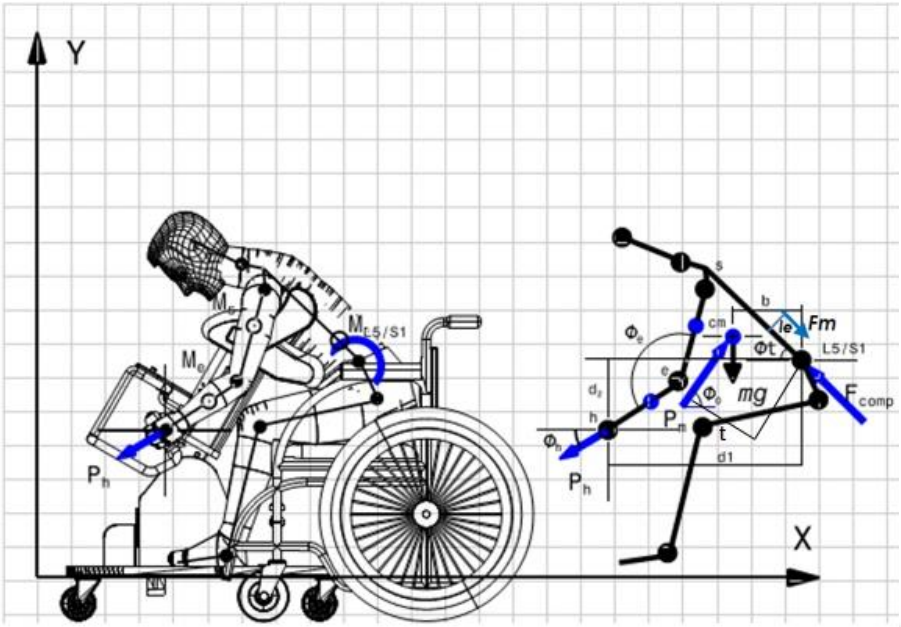


Figure 4-8 Biomechanical model for concept-1 to estimate the compression load at "L5/S1" based on the ***HbEH*** handle location.

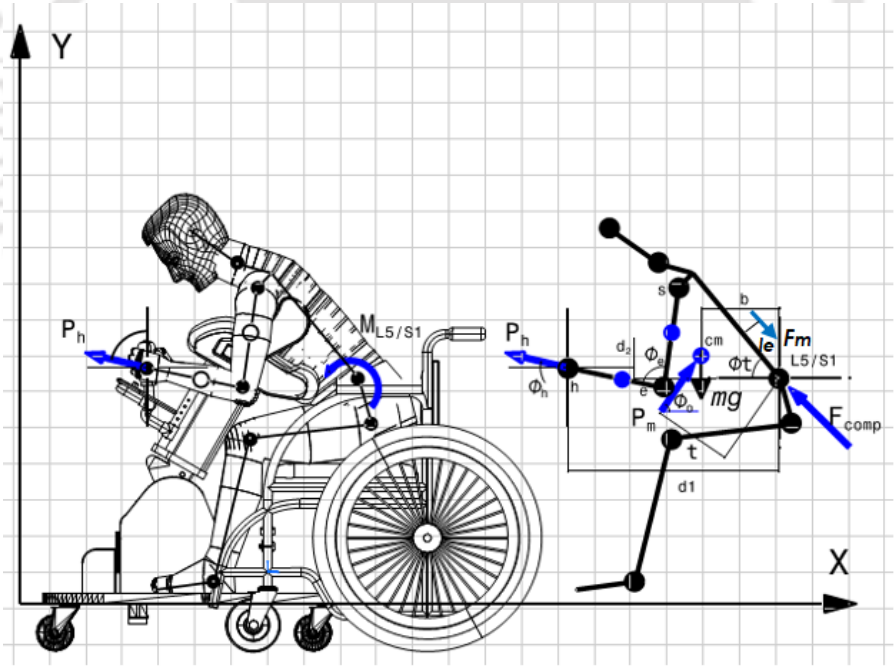


Figure 4-9 Biomechanical model for concept-2 to estimate the compression load at "L5/S1" based on the ***HatEH*** handle location.

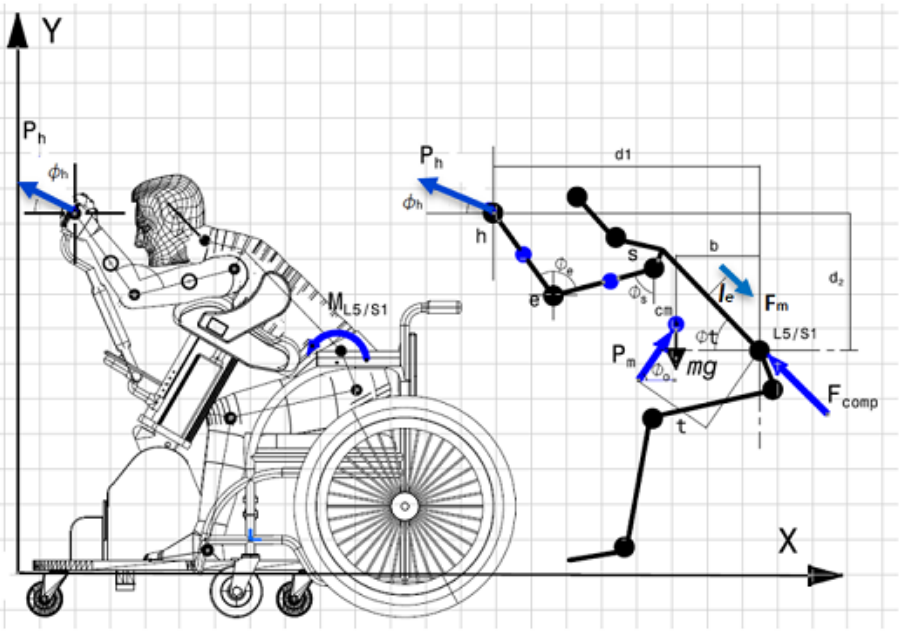


Figure 4-10 Biomechanical model for concept-2 to estimate the compression load at "L5/S1" based on the ***HaEH*** handle location.

Using the equilibrium of moments at the "L5/S1" joint, the following general equations can be derived to estimate the compressive forces. $F_{comp_{L5/S1}}$ at the lumbo-sacral spine.

$$F_{comp_{L5/S1}} = [(mgb \pm P_h(d2\cos\emptyset_h - d1\sin\emptyset_h) - P_m \times t)/l_e] +$$

$$[mg\sin\emptyset_t + P_m(cos(\emptyset_0 + \emptyset_t)) - P_h(cos(\emptyset_h \pm \emptyset_t))] \ldots\ldots\ldots (1)$$

The first equation in the bracket represents the moment load due to the spinae erector muscle used to stabilize the lumbar. Where the term mg represents the body weight of the subject performing the lifting task, b , distance from the CoM to the L5/S1 centre, P_h is load due to pulling at the handle for three proposed concepts, $d1, d2$ are the moment arm coordinates from the L5/S1 centre. P_m , is the supporting load from the saddle, and its moment arm is represented by t , the load F_m shown above the spine line is the muscle force used to stabilize the reactive moments with the arm l_e , which is the assumed value of the erector spinae moment arm. $\emptyset_t$, $\emptyset_h$ and $\emptyset_0$, are the angular measurements of the trunk, handle centre and the supporting saddle orientation, respectively. The term $P_m(\cos\emptyset_t - \emptyset_0)$ can be eliminated depending on the orientation of the saddle. Equation 1 above can be used to estimate the biomechanical loading at the lumbar joints for any handle orientations. However, it was planned to be used for the present proposed concepts, provided that the subject under consideration should be within reach envelope. The input data for estimating the biomechanical loadings at the L5/S1 lumbosacral joint are obtained from a one-to-one scaled measurement; this measurement was taken from the previously adjusted manikin's anthropometric database. The value of hand-pulling force was taken from the experiments

conducted during an EMG recording using a mechanical force gauge. The following values from Table 4.4 were used as input for estimating the lumbar loadings for the three-handle orientations.

Table 4-4 Input parameters for estimating the biomechanical loadings at the L5/S1 Segment

Handle	Max. pull P_h (N)	Support $P_{m(N)}$	$d1$ (mm)	$d2$ (mm)	b (mm)	t (mm)	$\emptyset_t$ deg	$\emptyset_0$ deg	$\emptyset_h$ deg	l_e (mm)
HaEH	173.47	458.76	755.75	389.44	236.5	235.26	50.51	60	25.5	50
HatEH	111.2	458.76	583.33	29.79	217.75	216.97	45.97	60	18.5	50
HbEH	142.33	458.76	571.05	207.49	225.95	218.42	43.77	60	30.9	50

4.6.2 Comparison of the Estimated Compressive Loads by Commercial Software

The main reason for driving the present predictive equations for estimating the compressive loads at the lumbar spine is the unavailability of a custom predictive tool, especially for the posture and loadings similar to the present transfer technique. However, most biomechanical software could predict the compressive loads for commonly adopted postures, but they do not support some of the custom loading conditions. One reason for not simulating the custom loading conditions is that such software is developed mainly for simulating the biomechanical loadings related to everyday activities, such as manual materials-handling tasks for predicting the maximum limit of load lifting in different postures. Most industrial sector tasks leading to musculoskeletal disorders are predictable using state-of-the-art science in the current biomechanical software. Still, when it comes to situations where the person is working in a supported condition and leaning forward, it is hard to get a secure modelling solution like the present transfer algorithm and most of the activities performed while transferring the disabled individuals.

The rough estimates of the present predictive method have been compared with the selected biomechanical software results. Generally, two different softwares are used for comparing the output results between each software, these tools are the three-dimensional static strength prediction program (3DSSPP) which has the ability of generating both the L5/S1 and L4/L5 load results and the other one is the single-action biomechanical analysis of CATIA V5 software, it generates the L5/L4 and other load results without considering the specific loads at L5/S1. It should be noticed that this two software, including most known biomechanical software, do not include the effect of the saddle-support while in the transfer task, similar to the present transfer device. Therefore, the tasks in this section is to make the comparison without the support conditions and only with the hand load at the given posture along with the anthropometric data. Since the present predictive equation can only predict the muscle force and the compressive force at L5/S1, thus this result is compared with the results of 3DSSPP, whereas the L4/L5 output results will be compared between the 3DSSPP and CATIA V5 software.

The 3DSSPP is a well-known biomechanical software developed by the University of Michigan; it identifies risks associated with particular activities. The program window (Figure 4.11) contains

the 3DSSPP application with view windows displaying four biomechanical views, three stick figures and one shaded, enfleshed hominoid 3D model, which can be viewed from any direction. In addition to inserting the anthropometric data, it also allows users to import an image file of a given task with a given posture, thereby reducing the time needed to alter the body segment inputs. This report compares the tools by exporting the previously used handle evaluation concept models and their graphical set-up into the respective software packages. Figure 4-11 below (lower left corner) shows one of the imported models into the 3DSSPP, which is the case of the HbEH condition. All necessary anthropometric data, body segment angles and hand loads are carefully input into the existing model. The final posture is made to match the existing imported DHM model. A similar procedure was also followed for exporting the preset pose into the Catia v5 single-action biomechanics analysis module. First, the model for each case of the handle orientation was built based on the given anthropometric data in the ergonomics design and analysis workbench of Catia V5. Using posture editor and forward kinematics menu tools the model was manipulated to match each of the transfer posture at a time. The load definition was also used to insert the loads at the handle finally the biomechanics single action analysis tool was used to run the simulation and generate the result. The difference between the two software is that the latter does not have a separate option for importing any custom image model; only its native models are used for the analysis. Additionally, this software does not produce the results for calculating the compressive loads in the lumbo-sacral L4/L5 joint. Therefore, it cannot be used as a direct comparison with the present method, but the suitability of the present model will be compared between the two softwares. Figure 4-12 shows the imported set-up of HbEH case in the single-action biomechanical window with the corresponding results summary.

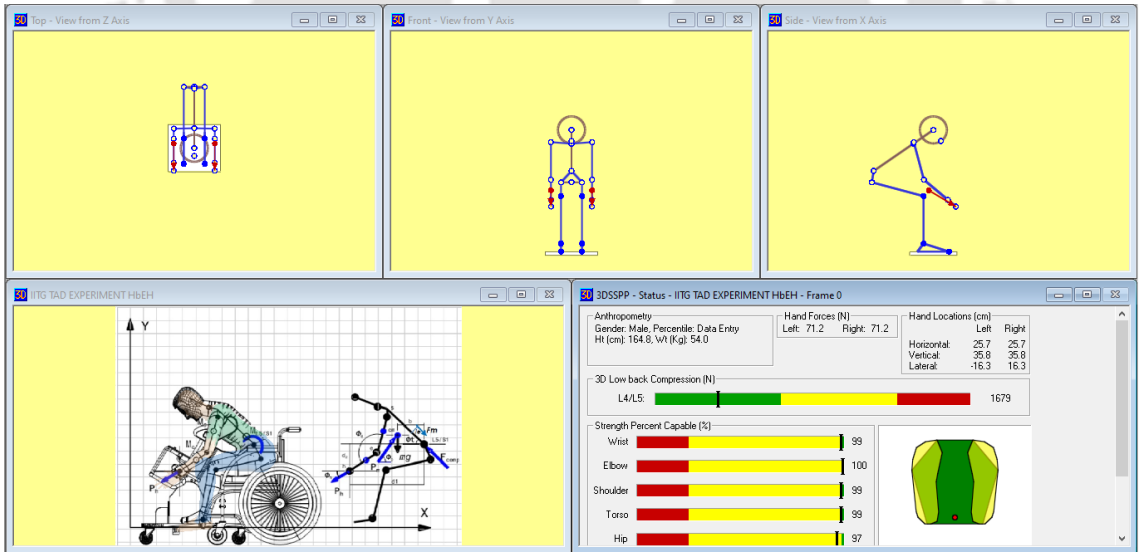


Figure 4-11 3DSSPP program window and the imported set-up of the biomechanical model

The 3DSSPP software has a more detail output results in addition to the compressive loads at L5/S1 joint, including the L4/L5 load, the shear force and the erector spinae muscle force, the output windows for HbEH condition are shown in figure 4-13 below. All other results and tables (output from 3DSSPP and Catia-V5) are also included in APPENDIX -IV.

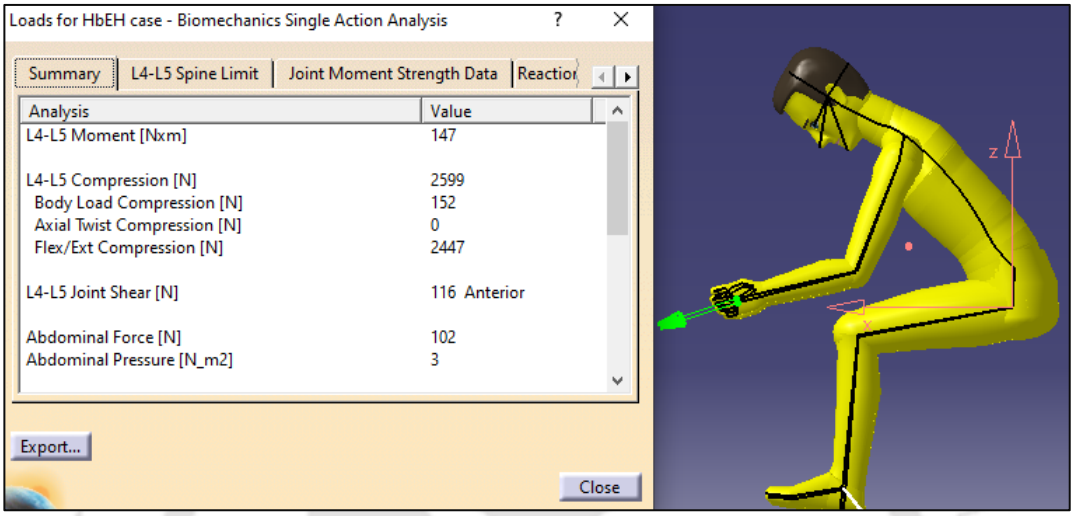


Figure 4-12 The single-action biomechanical and result summary for HbEH

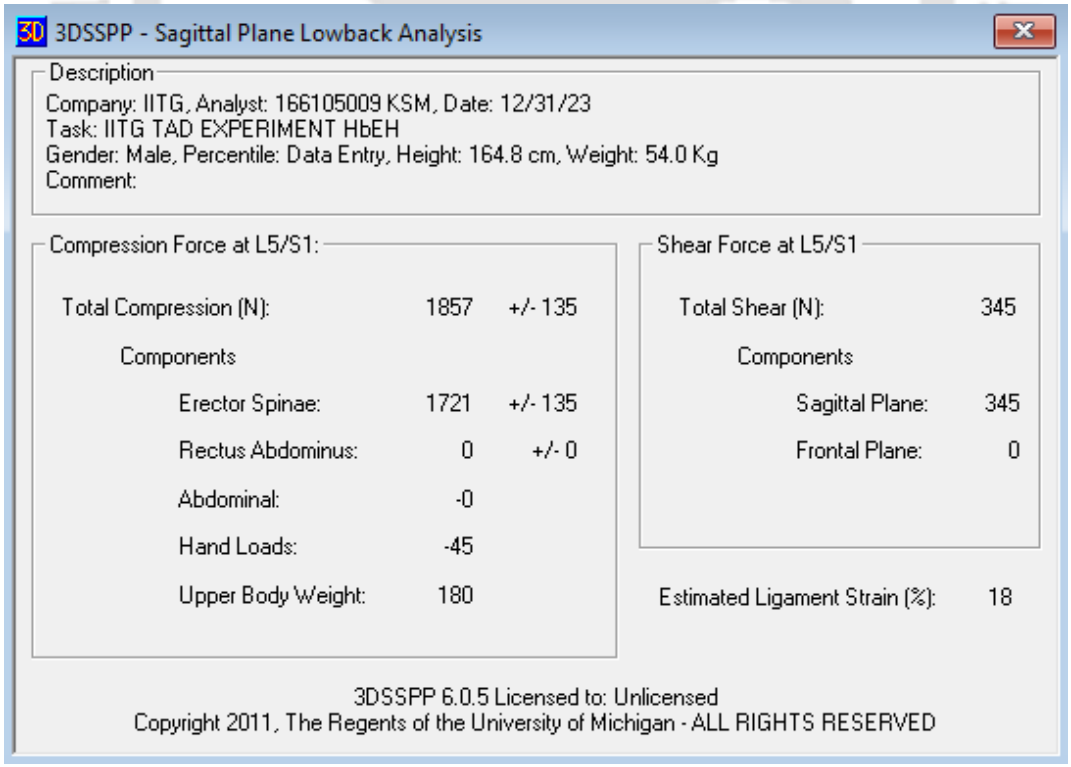


Figure 4-13 3DSSPP program window partial result summary for HbEH

The supplementary analysis explores into the application of the existing predictive equation, exclusive of support condition considerations, and contrasts its outcomes with those derived from the 3DSSPP software tools. The graphical representations in Figure 4.14 showcase summary reports generated by both the present predictive equation and the 3DSSPP software. Two distinct scenarios were examined: one where support was factored into the analysis, and another where support was omitted. Upon meticulous inspection, it becomes apparent that the current approach tends to adopt a more conservative stance when tasks are executed without accounting for support in all instances. In such cases, the results obtained are consistently lower than those produced by 3DSSPP when support is taken into consideration. Furthermore, in scenarios where support is not considered for all handle orientations, both ***Fm*** and ***Fc*** exhibit maximum values compared to all other results. This underscores the significance of support considerations in optimizing task performance and highlights the potential for more accurate predictions when incorporating support conditions into the analytical framework.

Generally, the results corresponding to the two methods have shown a lower compressive load when each method has been evaluated with a handle design designated by HatEH and HaEH, even though the HaEH case recorded slightly lower values but on the contrary at the same instance the ***Fm*** was found higher compared to HatEH, in previous section this case was shown to record a higher pull at handle with higher EMG muscle energy. On the other hand, the corresponding values of the compressive loads were observed with a higher value for the HbEH conditions. The results of the compressive load at the L4/L5 was also compared between Catia V5 and 3DSSPP softwares as shown in figure 4-15, in all cases Catia V5 output showed a higher value compared to the 3DSSPP, and both recorded a maximum result for HbEH case.

Generally, it is crucial to consider the amount of compression force applied to the L5/S1 disc to avoid developing low back disorders; it is recommended that this force never exceeds 3400 Newtons during any single task as per the NIOSH recommendations. The concept model with the HbEH case was found to record the maximum value of the compressive load at L5/S1, especially within the 3DSSPP simulation output and the present method without the support condition. The results of ***Fc*** and ***Fm*** from 3DSSPP show a lower compressive force at the L5/S1 disc in all types of handle designs and orientations compared to the present method, also the load output at L4/L5 from this software was shown too small compared to Catia V5. This comparison indicates that the 3DSSPP software is not more conservative in predicting the actual load conditions in the given posture, this phenomenon increases the design uncertainty issues by the users. The HatEH case was relatively identified as the most suitable handle design with a record of the compressive and muscle force load far below the maximum recommended limit; therefore, based on the selection criterion, the 3D conceptual model with the handle at elbow height will be considered as one of the best concepts compared to the other two concepts. Generally, this section tried to explore how transfer postures contribute to the spine's compressive load irrespective of the applied force during the transfer task. This section also attempted to explore the current limitations of existing biomechanical modelling software and emphasize the necessity for further research in creating

custom-based modelling software that can enable all types of postural loading assessment. The comparisons among the three methods have revealed that designers must exercise caution when selecting certain assessment tools, like biomechanical modelling software, because each tool has its own advantages and disadvantages, leading to variations in the simulated output. It is essential to be mindful of these differences while choosing design tools to obtain accurate and reliable results.

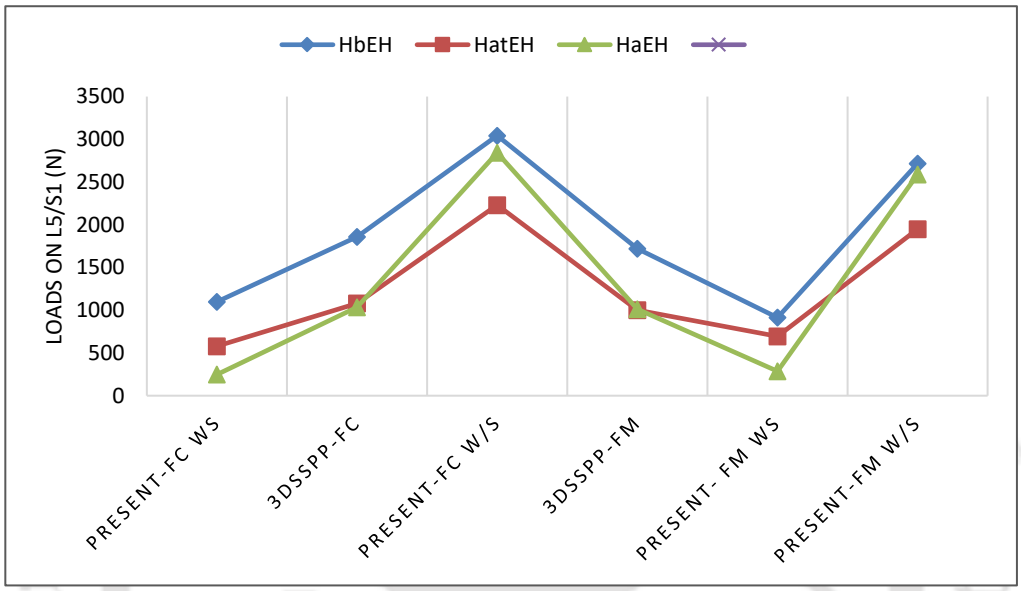


Figure 4-14 Comparison of the compressive loads using the three methods

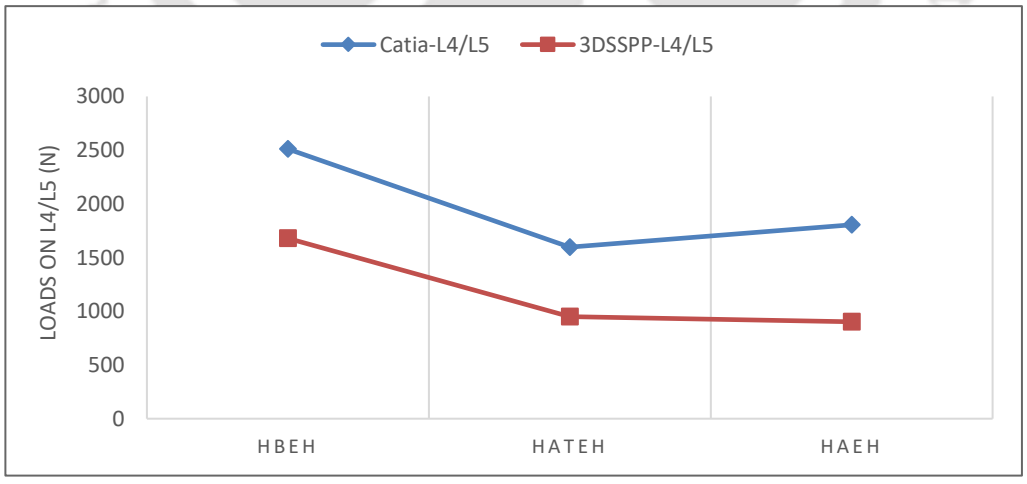


Figure 4-15 Comparison of the compressive loads at L4/L5 using the two methods

CHAPTER FIVE

5 Design and Analysis of the Transfer Mechanism Components Based on Biomechanics and Anthropometrics Data.

5.1 Introduction

Anthropometric information is essential to the field of biomechanical product design research. These data sets serve as the basis for the development of biomechanical models, which are essential instruments for the prediction and assessment of human aspects like reach, force application, and spatial needs. When planning and developing ergonomic solutions and industrial equipment, this information is crucial in the early phases. Anthropometric data is particularly valuable for optimizing human-device interaction and making sure workplaces and equipment are designed to meet the demands of a wide range of users. To sum up, anthropometric data is the starting point for creating biomechanical models that improve workstation and product design. Using this information, Designers and Engineers can create solutions that are more comfortable, safe, and efficient for a broad spectrum of users, ultimately contributing to improved human-machine interaction and reducing the likelihood of falls during patient transfer tasks. In order to tailor the fit of artificial organs, bionic and orthotic suppliers often take anthropometric measurements on persons. This report adopts the combination of human-machine-centered design analysis to determine the design parameters required for designing the proposed transfer device's component. Therefore, the virtual assembly of the transfer device, standard wheelchair, and human biomechanical model (Manikin) was modelled in the Ergonomics Design and Analysis workbench of Catia V5.

In this process, it should be understood that, for analyzing the critical components such as computing the actuator specifications, the load needed to raise/turn the users, an optimum location and the overall size, it is necessary to substitute the body dimensions of the manikin with a known anthropometric data. Although the proposed concept was designed to be adjustable to accommodate a wide range of populations (5^{th} to 95^{th} percentile), considering the worst scenario of the analysis, the upper extreme, i.e. 95^{th} percentile, is chosen throughout this section. The human manikin discussed in the previous section has been modified to match the 95^{th} percentile anthropometric data of adult Indian males. The height and weight of 1.78m and 76 kg, including other dimensions, are taken from the same anthropometric database [77]. Thus, based on the new anthropometric data, the previous DHM model will be modified to account for the present analysis.

It should be noted that the use of 95^{th} percentile data with a weight range of 76 kg is simply to establish a reference weight value while computing the centre of mass for estimating the actuator load and other components design. The selected transfer technique or posture in the present analysis tends to bring the centre of mass forward and in front of the subject under the transfer posture; as the weight of the subject increases, the corresponding CoM keeps on moving forward, thus making the load needed for transferring the subject to decrease because of the reduced

moment arm. Therefore, the actuator, designed based on the 95th percentile data with a weight range of 76 kg, can transfer users with weight values relatively above 76 kg in the same anthropometric database.

5.2 Computation of Center of Mass (C.M) in the Context of a Human-Machine Environment

The stabilization strategies have been used to generate many approaches that could help to measure an object's centre of mass. But the most popular approach, which is used to find out the centre of mass, uses two simple steps: first, to compute the centre of mass of smaller parts, then mix to obtain the centre of mass of the whole system. This technique, known as the segmental method, includes knowledge of the masses and centres of mass of each of the body's segments. In order to evaluate a segment at a time and compute the complete body centre of mass, two-dimensional coordinates from digitized data (x, y) and segment properties have been used [82]. In another study, a model approximates the entire body centre of mass location, assuming the body consists of various rigid parts. Many other scholars have submitted a formulation based on dead body experiments, which assesses the mass and position of the mass centres in different segments [83-86]. They developed regression or prediction equations that allow the mass and the position of the centre of the mass to be calculated. Others also used geometric math to estimate the division masses and positions of the mass computing centre, and the use of standard geometrical solid representations of the different body parts has achieved this approach.

Similarly, the above studies have developed a relationship to estimate the CoM of a whole body's location in a relaxed seated posture using a whole-body laser scan, and they find that the body weight impact is minimal on the centre of the mass. Table 5.1 below contains the reported prediction method of inertial data from the above investigators. It includes segment length (**Li**), Segment mass (***mi***) and distance of segment centre of mass from a proximal end (**Ci**) as a percentage of body height B_H, body mass B_M and segment length **Li,** respectively. Table 5-2 depicts the calculated result for each segment's inertial data based on the targeted subject (95^{th} percentile anthropometric data with body height B_H and body mass B_M of 1.78m and 76 kg, respectively).

Table 5-1 Inertial data relationship for predicting the CoM

Body segments	**Li (%** B_H**)**	***mi* (%** B_M**)**	**Ci = (%** Li**)**
Head and Neck	10.75	8.2	56.7
Trunk	30	46.8	56.2
Thigh	23.2	10.5	43.3
Calf	24.7	4.75	43.4
Foot	14.84	1.43	50
Upper Arm	17.2	3.25	43.6
Lower Arm	15.7	1.8	43
Hand	5.75	0.65	46.8

Table 5-2 Calculated values of segment inertial parameters

Body segments	**Li (m)**	***mi* (Kg)**	**Ci (m)**
Head and Neck	0.191	6.232	0.108
Trunk	0.534	35.958	0.300
Thigh	0.412	7.98	0.178
Calf	0.439	3.61	0.190
Foot	0.263	1.086	0.131
Upper Arm	0.306	2.47	0.133
Lower Arm	0.279	1.368	0.119
Hand	0.102	0.494	0.047

The calculated geometric and inertial data can be utilized for further design processes under static conditions or quasi-static case/movement with small accelerations. These data are useful in constructing physical and mathematical models of the human body. Thus, the calculated inertial values, as depicted in Table 5-2 above, have been used to remodify the previously invoked human model to match the present anthropometric data of the subject under consideration for this study. Figure 5.1 below shows the modified manikin's two-dimensional view, exported from the digital human modelling environment. Each segment (S1 to S8) is indicated on the link representation model with the calculated values (in millimetres) for the respective body segments. The downward arrows between each segment are the location points for the distance of the centre of mass from each segment's proximal end.

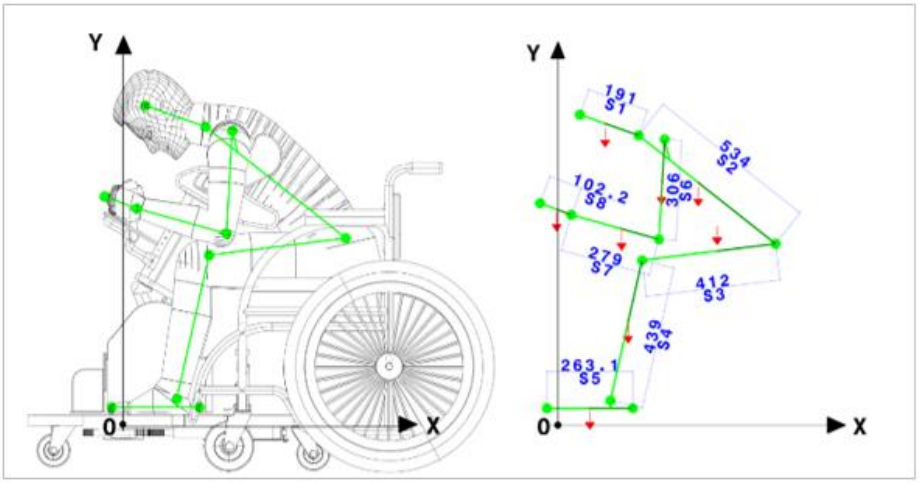


Figure 5-1.Two-dimensional view of the combined transfer setup with the modified manikin (Left) and the computed inertial parameters (Right)

The overall body's mass can be measured using the inertial parameters of each segment's centre of mass and orientation. Thus, combining the calculated centre of mass of individual segments found in Table 5.2 above can provide the centre of mass of the total system. In this report, the turning pivot of the proposed concept product is made to coincide at the origin 'O'; thus, it is used as a reference point to estimate the distance from the centroid of each segment mass to the corresponding pivot point. Once the centroidal distance of each segment mass is estimated using the geometrical coordinates X and Y axis, the overall mass centre of the subject in the current posture can be calculated using each segment mass and its location.

The subject's current posture under consideration (the manikin's posture) is slightly bending forward to initiate the transfer activities. This condition makes the centre of mass located outside /in front of the subject's body. In this analysis, the sagittal plane is considered a viewing direction of the subject; thus, due to symmetry, the segment masses from both the right and left sides of all segments except for the head, neck and trunk are taken twice during the calculation process. The general equation for estimating the centre of mass of the whole body is given in equation 5.1 below.

$$(Xcm, Ycm) = \left[\frac{\sum m_i X_i}{\sum m_i = M} \quad , \quad \frac{\sum m_i Y_i}{\sum m_i = M}\right] \qquad \ldots\ldots\ldots\ldots\ldots (5.1)$$

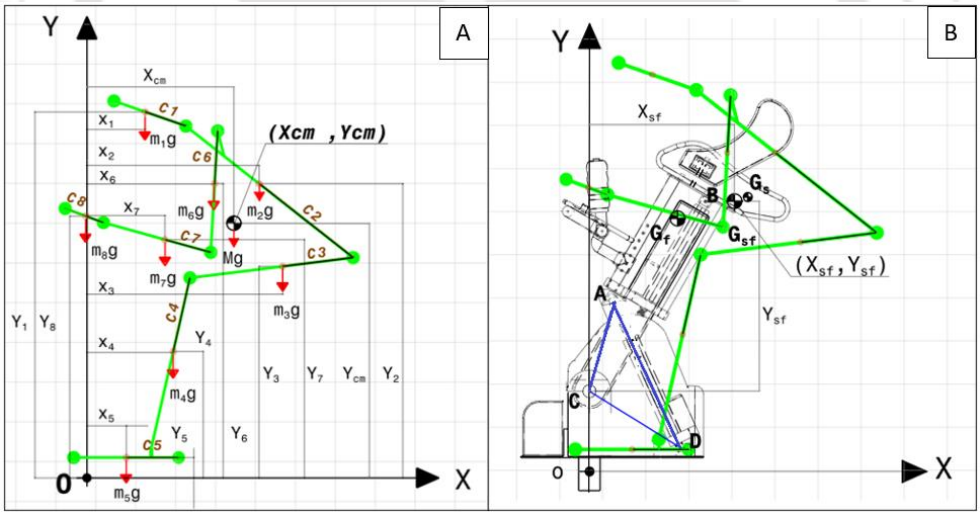


Figure 5-2 The location of the CoM of the total body for the current posture (A) and the common CoM (Gsf) as measured from the pivot of point c (B)

Where X_{cm} and Y_{cm} are the centre of mass of the whole body and *Xi, Yi* is the centroidal distance of the centre of each segment of mass from the reference axis (X, Y). It coincides with the proposed device's rotating pivot at origin '**0**', digitized directly in the software. m_i , denotes the mass of each segment ***i;*** the total mass is also denoted as $\sum m_i = M$.Based on the digitized segment centroidal distance *Xi, Yi* and the calculated segmental masse m_i , the corresponding centre of mass of the total body for the subject under consideration can be estimated as $(X_{cm,}\ Y_{cm})$ = (368.1, 636.298)

in millimetres. Figure 5.2A below illustrates the stick diagram in the sagittal plane, showing the distance of the centre of each segment of mass from the proximal end, which is indicated by (C1 to C8) on the respective segment's centroid.

The centre of mass for the rotating part of the frame can also be computed after defining its geometry and material properties. It is used as an input for computing its centre of mass using CAD software, such as CATIA V5, adopted for the current analysis. Thus, the simulated result for the centre of gravity or, more commonly, the centre of mass, CoM of the frame is located near the saddle as shown in figure 5.2 B; the coordinates are (X_f, =204.12mm and Y_f = 400.84mm) and denoted by **G_f**. Although the present analysis is undertaken with a human-machine context, evaluating the single or common centre of mass is a mandatory task to handle or apply an equilibrium equation, thus determining the typical CoM between the frame **G_f** and the subject **G_s;** the following combined equations are used.

$$\left(X_{sf,}\ Y_{sf}\right) = \left[\frac{m_s x_s + m_f x_f}{m_s + m_f}\ , \frac{m_s y_s + m_f y_f}{m_s + m_f}\right] \quad \ldots\ldots\ldots\ldots\ (5.2)$$

Where, $X_{sf,}\ Y_{sf}$ are the common centre of mass coordinates from the pivot of point c, $m_s\ and\ m_f$, are the masses of the subject and the frame, respectively. Similarly, $x_s, x_f\ y_s$ and y_f , are the centroidal distance between the subject's and frame's centres of mass with reference to the x and y axes, respectively. The common centre of mass CoM is situated slightly underneath the subject's centre of mass. **G_s,** and it is denoted as **G_{sf}.**

5.3 Computation of the Moment of Inertia of the Body Segment and the Transfer Device in the Context of a Human-Machine Environment

Moment of inertia is a term used to describe the resistance to a body's angular movement, and it is crucial to investigate the moment of inertia of a subject under consideration in the given posture. The proposed device is carefully designed to assist the transfer facility for the subject in the present posture, as discussed in the previous section, which is the chosen posture in this study. The chosen posture takes the subject's segmental masses closer to an axis of movement, significantly reducing the moment of inertia and rendering the transfer practices quick and simple using an actuator with a low load ability. Most strategies that offer indices for body segment moments of inertia also present data on the segment radius of gyration (K). The radius of gyration signifies the mass distribution of the section around the direction of motion. It is the gap between the pivot point and a point where the weight can be believed to be localized without altering the inertial features of the section [87].

In order to compute the magnitude of the moment of inertia (**I**s) for each segment, the inertial quantities such as segment mass (**mi**) and the radius of gyration (**K_F**) in the frontal axis as a percentage of segment length are used from the previous study as indicated in Table 5.3 [88].

Similarly, the total moment of inertia of each segment about the subject's centre of mass $\mathbf{I_{Gsi}}$ can be computed using the parallel axis theorem relations as shown in the last column of Table 5.3, where the centroidal distance. $\boldsymbol{r_i}$, measured graphically between the segment and the subject's centre of mass, respectively.

Table 5-3 Inertial quantities for determination of the moment of inertia of a body segment

Body segments	**Li (m)**	$\boldsymbol{mi}$ **(Kg)**	$\mathbf{K_F}$**(%Li)**	$\mathbf{K_F}$ **(m)**	$\boldsymbol{ri}$ **(m)**	$\mathbf{I_{S\,i}}$ **(** $\boldsymbol{mi} \times \mathbf{K^2_F}$**) (Kg-m^2)**	$\mathbf{I_{GS\,i}}$ **($\mathbf{I_{S\,i}} + \boldsymbol{mi} \times \boldsymbol{ri^2}$) (Kg-m^2)**
Head and Neck	0.191	6.232	31.5	0.06	0.361	2.24E-02	8.35E-01
Trunk	0.534	35.958	38.3	0.204	0.120	1.50E+00	2.01E+00
Thigh*	0.412	7.98	26.7	0.110	0.160	1.93E-01	7.95E-01
Calf*	0.439	3.61	27.5	0.120	0.353	1.04E-01	1.11E+00
Foot*	0.263	1.086	24.5	0.064	0.644	8.90E-03	9.19E-01
Upper Arm*	0.306	2.47	31.0	0.094	0.114	4.36E-02	1.51E-01
Lower Arm*	0.279	1.368	28.4	0.079	0.177	1.71E-02	1.20E-01
Hand*	0.102	0.494	23.3	0.023	0.372	5.23E-04	1.38E-01
*Considered for both sides							$\mathbf{I_{GS}} = \sum \mathbf{I_{GSi}} = 6.08$

Since a common magnitude of the moment of inertia is utilized for the whole study, the total moment of inertia of the structure and the subject is critical in the overall design of the device; for this reason, first, the moment of inertia of the frame ($\mathbf{I_{Gf}}$) about its centre of mass ($\mathbf{G_f}$) has been computed numerically in the CAD software, once the frame's geometry with the selected axis and material properties is added to the database, the corresponding magnitude of the moment of inertia of the frame concerning the axis is determined as (I_{Gf} = 0.648Kg-m^2), using this result, the combined moment of inertia $\mathbf{I_{Gsf}}$ of the subject/manikin in a present posture and the frame about the common centre of mass $\mathbf{G_{sf}}$ can be determined using equation 5.3 below.

$$\boldsymbol{I_{Gsf} = I_{Gs+(m_s} \times d_{s)}^2 + I_{Gf+(m_f} \times d_{f)}^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5.3)$$

Where d_s and d_f are the two centroidal distances of the subject and the frame from their common centre of mass ($\mathbf{G_{sf}}$), respectively, which is computed graphically in the CAD software, similarly m_s , m_f , are the masses of the subject and frame, respectively; thus, the computed values of the common moment of inertia are found as (I_{Gsf} = 7.147 Kg-m^2).

5.4 Design and Selection of Actuators for the Transfer Device in the Context of a Human-Machine Environment

Actuators are considered in this study as the most active parts of the proposed transfer device. The transfer's motions are accomplished by combining such actuators that form a closed-loop mechanism. One of the objectives of this thesis is to find a solution for optimizing the number of required components in terms of quantity or size to develop an affordable product. Therefore, carefully designing and selecting the actuators are necessary to optimize each component's design and thus reduce the device's overall cost. In this report, the actuator's design analysis is carried out using the proposed device's mechanism layout that shows details of the active part and the subject under consideration for the chosen posture (stick diagram), as discussed in the previous sections.

The combined motion of the subject and the device creates a well-known general plane motion that undergoes a simultaneous translation and rotation; thus, two coordinates, such as position and angular coordinates, are taken for designing the present actuators. The worst case of lifting is considered for this analysis, which requires the maximum output effort from the actuators and is estimated to occur at the start of the initial lifting phases. Thus, the present subject under consideration appears when the frame is at an inclination of $\emptyset = 60$ degrees with reference to the X-axis, as shown in Figure 5.3. Equation 5.4 is formulated based on the current configuration to estimate the maximum actuator force ($\mathbf{F_a}$) needed for the worst-case design scenario.

$$M_T = \begin{bmatrix} i & j & k \\ ACx & ACy & ACz \\ Fa\cos\Omega & Fa\sin\Omega & 0 \end{bmatrix} + \begin{bmatrix} i & j & k \\ BCx & BCy & BCz \\ 0 & m_{sf}g & 0 \end{bmatrix} = I_{Gsf}\alpha_a \ldots\ldots \text{(5.4)}$$

Equation 5 above shows the relation of the turning moment M_T , and the common subject-frame moment of inertia. I_{Gsf} about the center of mass, ACx…ACz and BCx…, BCz is the position vector measured graphically from the pivot **c** to the load application point along the X and Y-axis. F_a **is** the force exerted by the actuator, m_{sf} , is a combined mass of the subject and the frame, and the angles $\emptyset$, Ω are the current lifting angles measured from horizontal to the actuator and the frame, respectively; similarly, the angular acceleration of the actuator is denoted by α_a. Based on available kinematic data for an average linear actuator, the angular acceleration's constant value was considered.

The present design approach for estimating the actuator load and its location is based on the 95th % anthropometric data having a weight value of 76Kg as discussed in section 5.1. However, the relationship between the weight and the centre of mass in the chosen transfer posture has been checked in the DHM environment and revealed that, as the user's weight increases, their centre of mass tends to move towards the pivot point. This phenomenon reduces the moment arm, thus allowing easy transfer with a lower actuator load. Hence, the present actuator can lift up users with a weight range above 76 kg in the same anthropometric database.

Since the device's robustness and stability are more important from the safety point of view, combining analysis of the stability equation will sound safer. Therefore, in this report, it has been adopted to precisely compute the optimum actuator load $\mathbf{F_a}$, the stability equation states that stabilizing moment $MS \geq MD$ *dis*tabilizing moment. The effect of the stabilizing moment is due to the combined mass about the common centre of mass and the inertial product shown in the last term of equation 5.4. Thus, the actuator load $\mathbf{F_a}$ can be estimated from the stability equation as:

$$F_a \geq \frac{m_{sf} \times g \times X_{sf} + I_{Gsf} \alpha_a}{A_{CY} \cos \Omega + A_{CX} \sin \Omega} \quad \text{..... (5.5)}$$

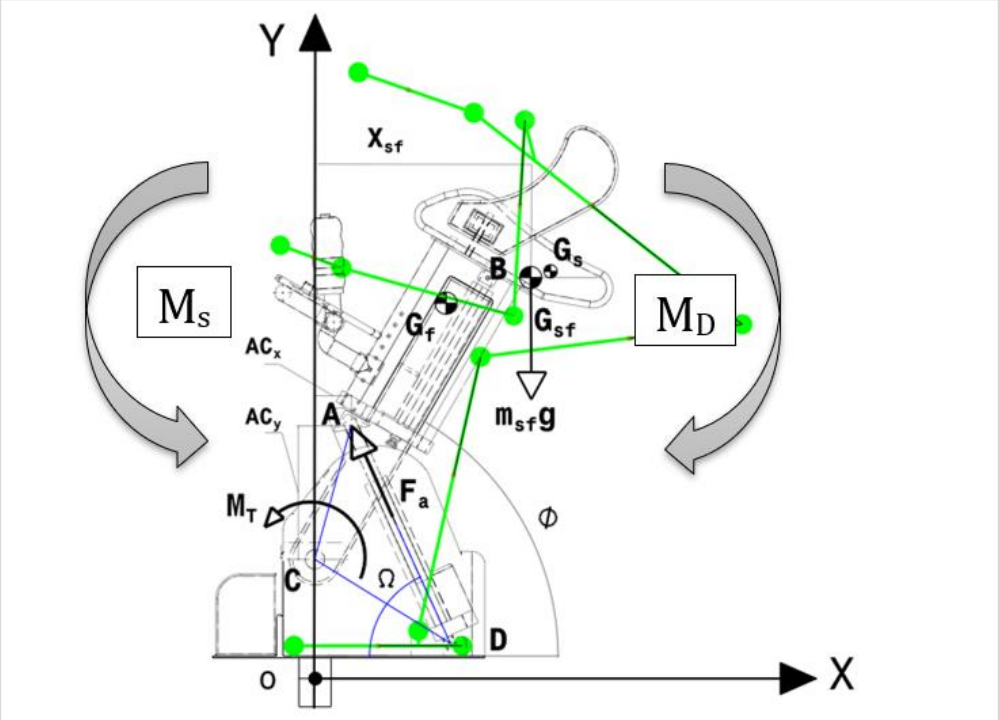


Figure 5-3 Details of Frame –Stick diagram for estimation of the actuator load using stability equation

5.5 Evaluation and Comparison of the Effective Position of the Actuator

The primary goal for computing an effective location of the actuator pin is to enable the selection of a linear actuator with an optimum force which is compact and able to operate in a limited space. Since actuators are one of the costlier components in the present transfer device, the decisions made while choosing the linear actuators are essential for reducing the device's overall costs; also, this approach has the potential to increase the affordability and accessibility of the final product. The main problems with an overdesigned product usually arise from designers who do not follow and apply an optimum component selection process with the human parameters' inclusion. Hence,

this report adopts the integration of human biomechanics in the design process to avoid an overdesigned device without compromising the device's safety, comfortability and expected service. Several alternatives for locating the coordinate point (**A**) might be possible. However, depending on the limited available spaces, the following constraints retrieved from the 3D modelling measurements were used for the following three variables: $0 \leq AC_x \leq 210.69$, $93.58 \leq AC_y \leq 258.86$ (units in mm) and the actuator angle from the horizontal is made to vary from 50 to 90 degrees in the increment of 5 degrees. These constraints of the coordinate point A (ACx, ACy) are digitized graphically and made to vary due to the change in the actuator's orientation angle. Figure 5.4 below shows the sample of four cases of such orientations. However, several coordinate points exist; they lie outside of the interested region and are not included in the computation for evaluating the actuator positions.

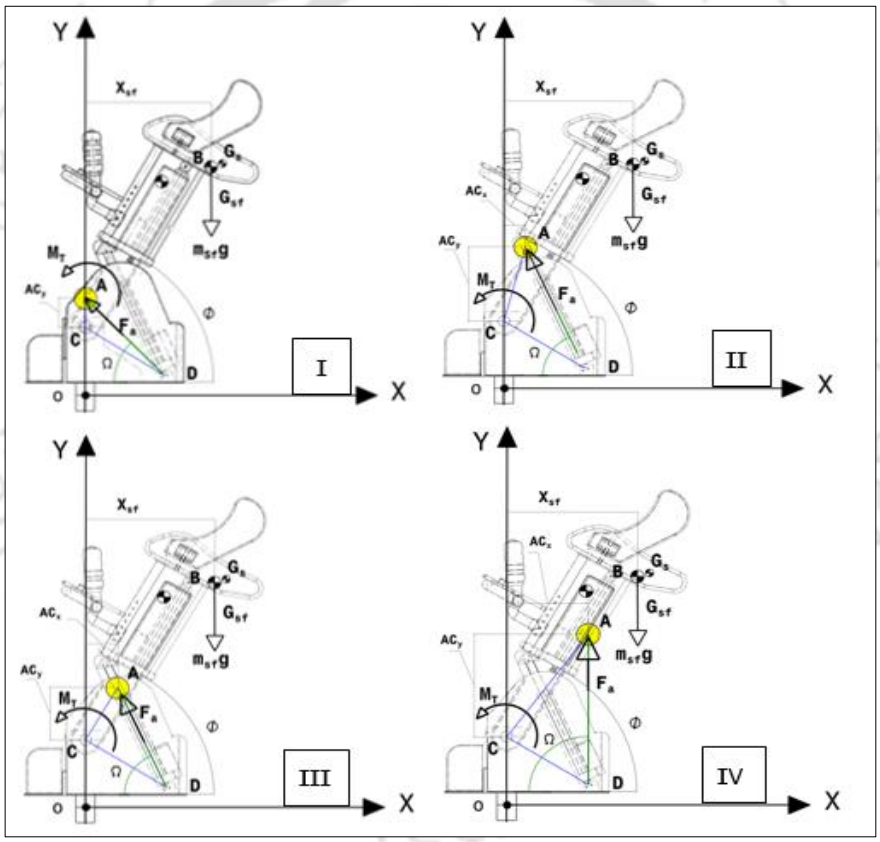


Figure 5-4 Details of the four critically selected locations of the coordinate point A.

MATLAB program (Math Works Inc Natick) is employed for computing the optimum location of the actuator pinhole on the main frame using the previously derived equations. Figure 5.5 shows the plots generated concerning the three variables. Point coordinates 1 to 9 indicate the selected nine cases for each combination of the variables falling in the interest region. The surface plots are also generated, as shown in Figure 5.6, to help in visualizing the optimum regions in each iteration

of the variables. In these plots, the main frame angle is kept fixed while the actuator angle and remaining two variables, such as AC_x and AC_y, are made to change proportionally. Surprisingly, all computed results of the actuator loads can lift the subject under consideration. However, some of the orientations, such as point coordinates 7 to 9, cannot bring enough space for the user to freely perform the activities; in addition, it needs a costly actuator with a longer stroke length to cover the required range. Layout 9 is at a right angle from the horizontal, which causes much more obstruction; hence, it is removed from surface plots. The point coordinates from 1 to 3 are a very compact design since it is made closer to the pivot point C, but due to a smaller moment arm, it requires an extremely high turning moment to lift the users; thus, it leads to the use of a special actuator to satisfy the desired requirements. The layout in 4 to 6 is somewhat compact and free from obstructing the user; therefore, these layouts are in the optimum range relative to the others. Based on this layout, the actuator's stroke length from its pivot to point A is P2=337 mm and P1=236mm, where P1 and P2 are upper and lower positions of the actuator pin respectively, and with the load in the range of 2 to 2.5 KN. Also, the new length of L3=175mm with point 'A' is slightly away from the rotating pivot point. The output of the actuator loads found from the surface plots reveals that the load needed for lifting the user increases as the two variables are close to zero values, that means when the actuator pin is getting near to the rotating pivot, which supports the result shown in the plots of figure 5-5. It should be noted that the pivot points in this case were assumed to vary while the actuator is kept fixed at a selected angle in each case. These create some points that fall outside the range, which are not of our interest and hence excluded from the computation.

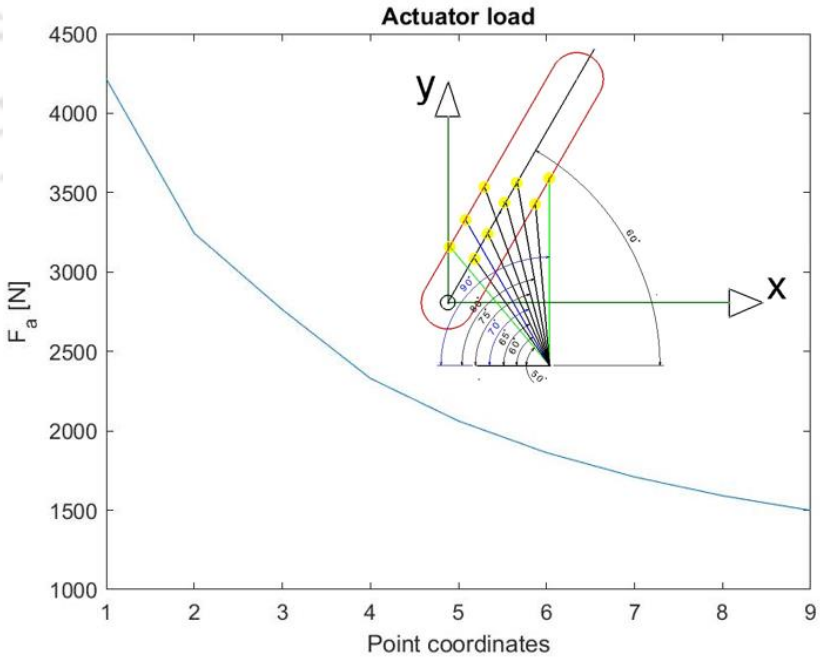


Figure 5-5 Estimated actuator load (Fa) for the changes in the point of load application

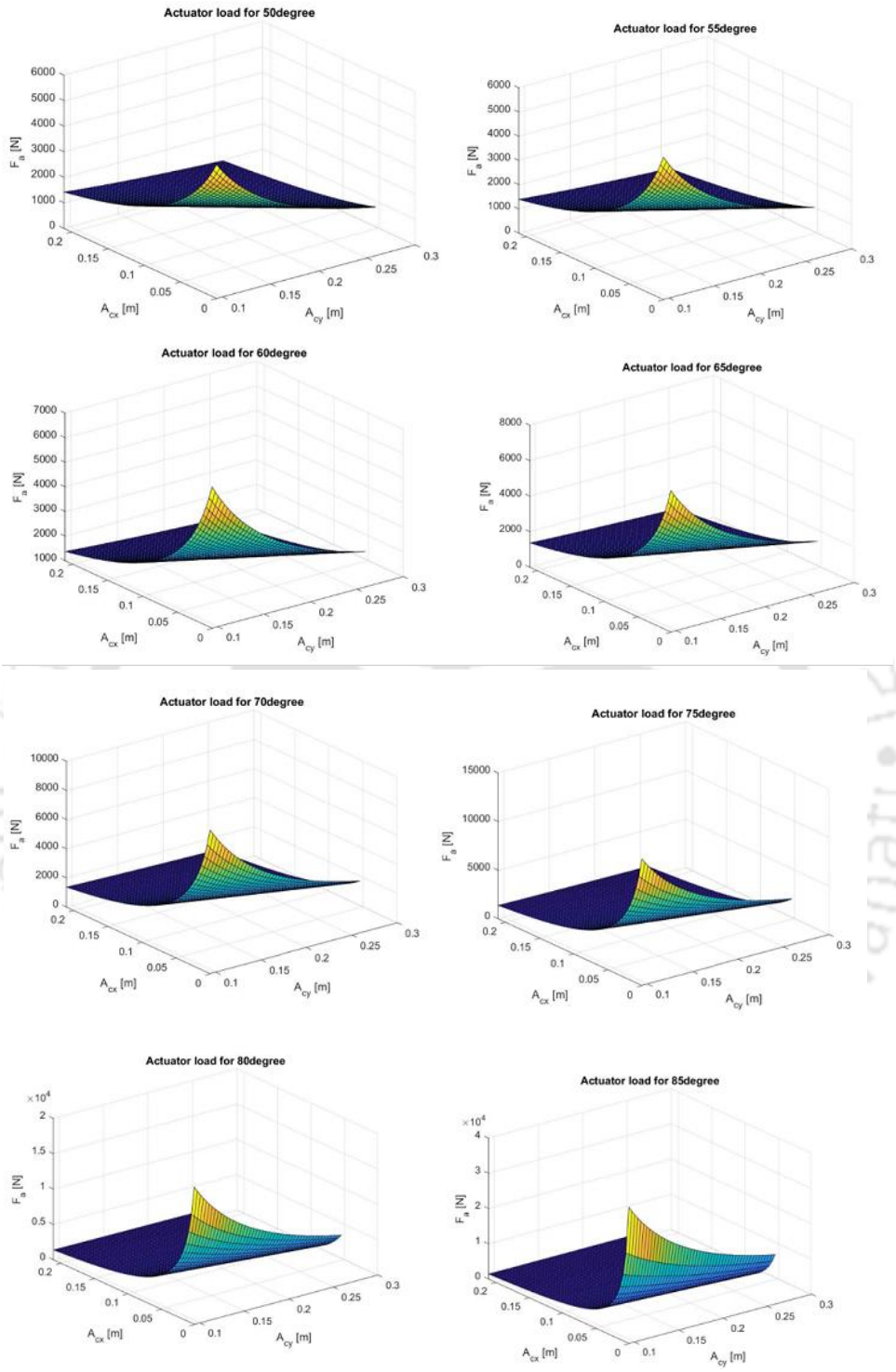


Figure 5-6 Estimated actuator load (Fa) for the changes in the angular orientations

5.6 Design of the Lower Rotating Mechanism

The lower rotating mechanism's function is mainly to shift the user with the supporting frame after being lifted in the first phase, and it is one of the three lifting steps of the chosen transfer technique that occurs in the second phase of the transfer algorithm. Generally, this task can be accomplished using various methods, but a unique mechanism has been conceptualized in this report. This mechanism's compartment comprises a rack and pinion mechanism as the main driving module. The rack is integrally locked with the linear actuator, which is firmly constrained to the base frame to prevent the lateral translation motion, as shown in Figure 5.7 below. The rotating mechanism's main requirements are viewed from two perspectives; in the first case, this mechanism should deliver a smooth motion to keep users' safety during the transfer task. Second, it should be simple in design with fewer components to reduce the device's overall cost.

The functional design of the rack and pinion systems are arranged in a reverse drive rather than used in the usual way, where the rack acts as a driver instead of the pinion, to ensure effective, efficient and straightforward actuation. The pinion rotation is also constrained to rotate 90 degrees clockwise (**–P**) or counterclockwise (**+P**) for turning the supporting mechanism and the user to the right or left directions. The present system's kinematic behaviour reveals that the pinion gear with pitch diameter ($d\ p$) should rotate one-fourth of its circumference for a given stroke ($l = \pi d\ p/4$) of the rack-actuator assembly; hence the required transfer can be achieved.

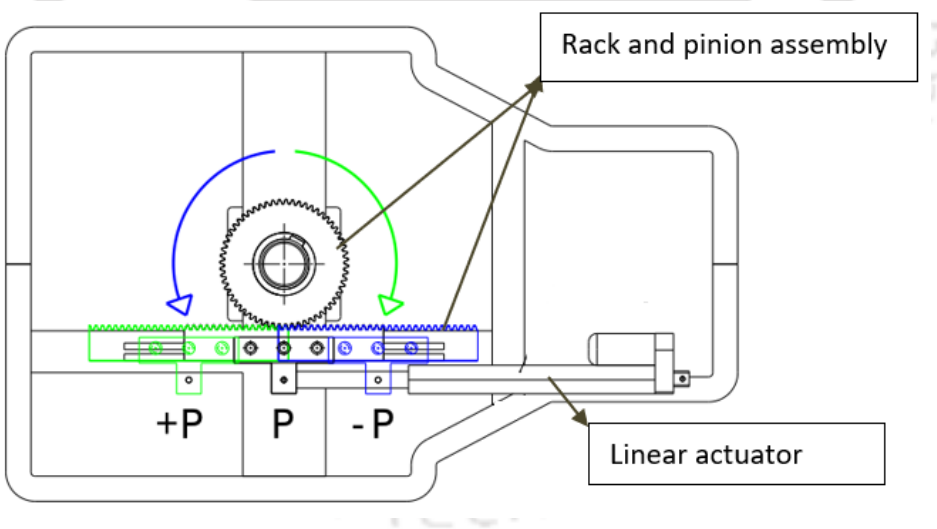


Figure 5-7 The layout of the lower rotating compartment

The application force at the rack (F_r) due to the actuator can be estimated using the following relationship:

$$F_r = F_{ex} + \sum m_t(\mu g + a) = 2T_P / d_p \quad \text{..... (6.6)}$$

Where, F_{ex}, the external force that may resist the motion, and $m_t = ms + mf + mc$ is the total mass that can be rotated, such as the subject, frame and lower carriage, respectively, μ is the "coefficient of friction", and a is the acceleration of the actuator. Similarly, the torque at the pinion and its pitch diameter are denoted by T_P and d_p , respectively. Based on the inputs under consideration, the corresponding actuator load has been estimated for varying subject weights, as depicted in Figure 5.8 below. A little consideration shows that the actuator load required for turning is much less than the lifting actuator load discussed in the previous section. In this case, the bearing assembly which is fitted to the pinion gear helps to reduce the induced load. The overall dimensions of the rack-pinion assembly are shown in Appendix-1.

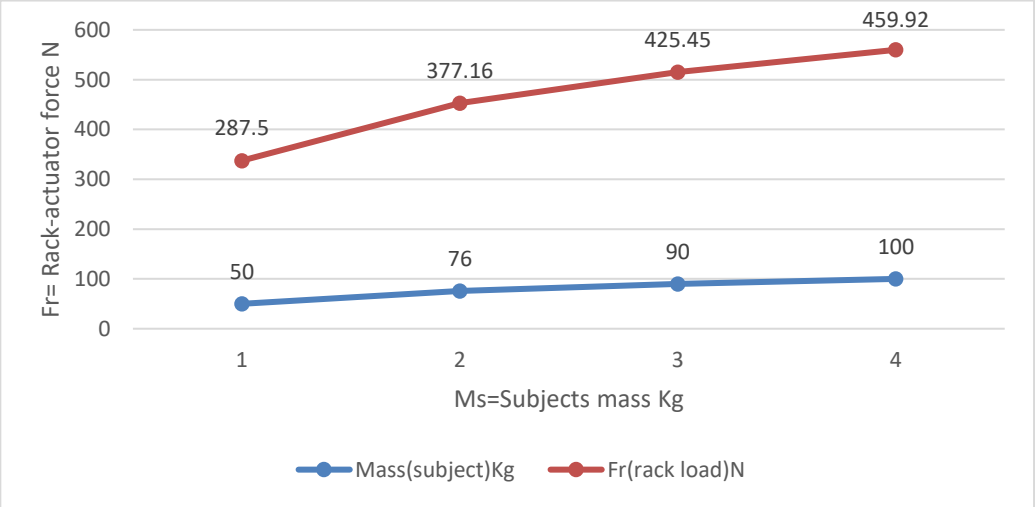


Figure 5-8 The estimated lower actuator load for varying subject's weight

5.7 Finite Element Analysis of the Transfer Device Component

In this section, the Finite element analysis (FEA) method was implemented to assess the effect of deformation and stress for two selected components. The first analysis was made to predict the interaction phenomena of the human frontal torso with the saddle cushion material, and the second analysis was made on the chassis frame, as it is one of the critical components of the current transfer device. Many researchers conducted finite element analyses to investigate the effect of the cushion-seat interface on the skin and soft tissues [89-92]. In this report, the numerical simulation for the interaction between the human and the saddle cushion was done based on the arrangement of the human torso's orientation in a transfer mode; only the upper half of the human biomechanical torso model is considered for the analysis. The 3D modelling of the saddle and human torso was created in CATIA v5 and exported to ANSYS Workbench v20. The contacting part was modelled as a hyperelastic material to replicate the effects of human torso-soft tissue. The Mooney-Rivlin material model was used for the torso, and the Ogden elastomer sample was chosen as a material model for the cushion. The polyurethane cushion located between the portion of the torso bonded on the top of the wooden saddle has a 40 mm thickness. In order to simulate the effect of the interaction between the torso and the cushion, a displacement constraint was applied

to the saddle, allowing the human torso to the downward -Z-axis movement. A total of 42080 nodes and 27595 elements with 30 contact regions were generated during the preprocessing phase, and the solver took two and a half days to complete the entire solution. Figure 5.9 shows the total and directional deformation with minimum values as depicted on the colour-coding legend; this result indicates that most deformation regions are central to the interface's lower portion. These phenomena were assumed due to the human saddle interaction configuration, which creates the backward sliding action, resulting in slight deformation at the lower edge. The top part of the torso-cushion interaction was found with no or minimum deformation due to the transfer posture and the curved profile of the saddle that keeps the user slightly upward instead of touching the chest. Based on the present result, adding a thin polyurethane sheet glued on the top of the current cushion was suggested to minimize the deformation due to the sliding action.

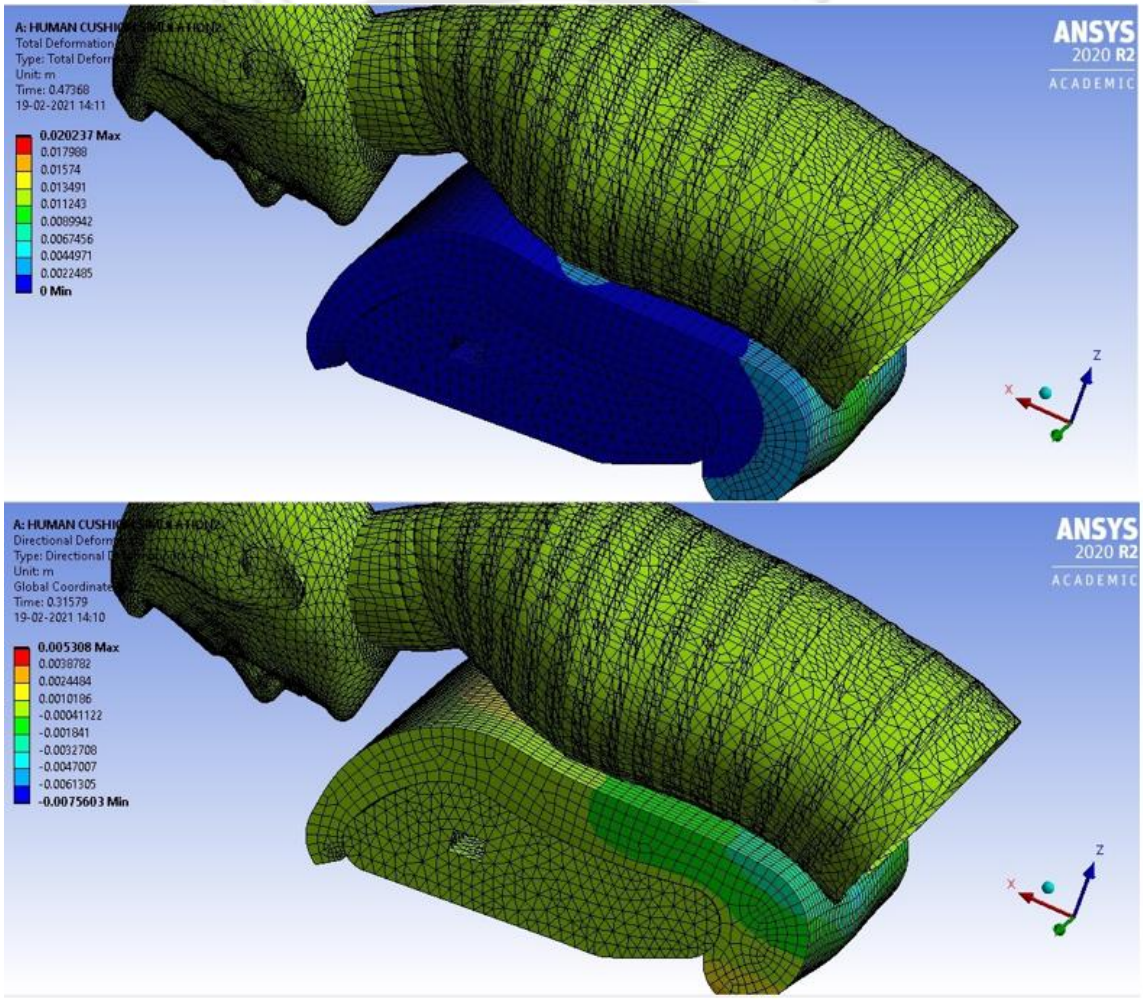


Figure 5-9 Finite element results of the total (top) and directional(bottom) deformation for the Human - Cushion interaction

The chassis frame (figure 5.10A) analysis was also conducted by exporting its 3D model into the ANSYS Workbench v14; due to the topology of the device under consideration, the 'symmetry option' is adopted to minimize the computational time, and the caster wheels are replaced with a fixed constraint in all directions; similarly, the load of the subject in each case is taken as symmetric with respect to the sagittal plane. Since the entire part is constructed from steel, the same material properties have been assumed during the preprocessing phase. Based on the selected material properties, the simulated stress and deflection values are shown below. The observed Total deformation (figure 5.10 D) slightly increased from the middle to the right, with a relatively small magnitude for steel material. The maximum stress developed in the chassis frame was also found within the limit, even under the yield stress, as depicted in Figure 5.10 C.

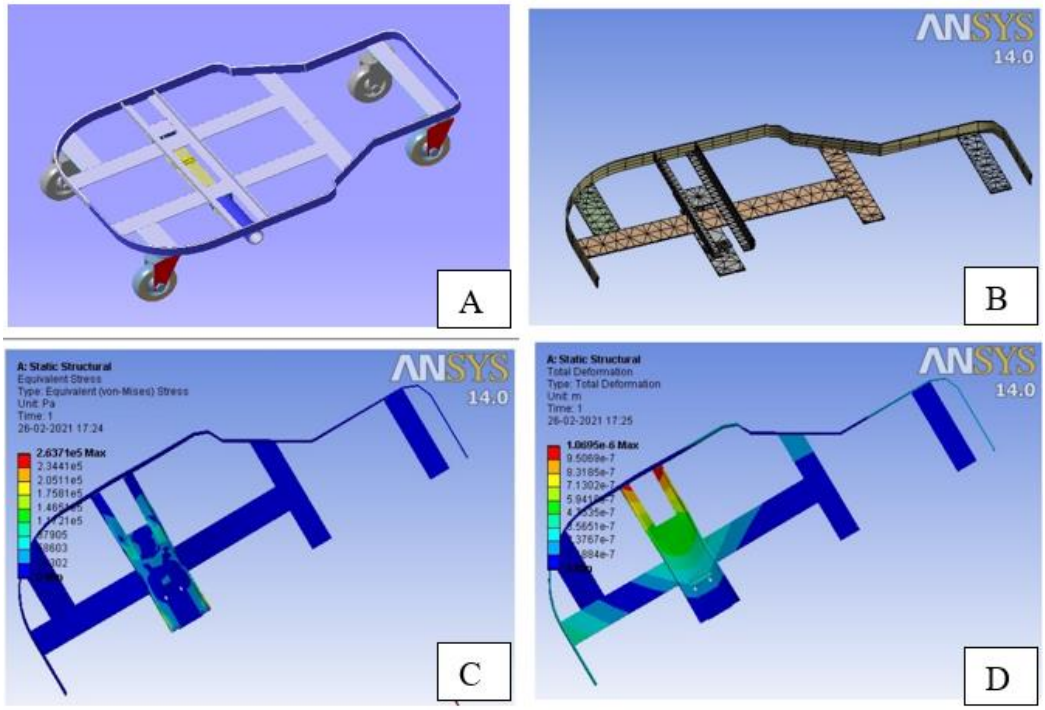


Figure 5-10 Finite element results of the simulated stress and deflection values.3D Model(A), Meshed model(B) Equivalent stress(C) and Total deformation.

5.8 Summary of the Concept Evaluation and Selection Process

A biomechanical principle integrated into a human-machine context approach was used for concept ideation, evaluation, and selection process to get insight into the actual interaction between the proposed product and the users. An attempt was made to introduce an alternative user-centric approach during concept ideation and evaluation by considering the user's biomechanical models. Generally, the concept generation and evaluation process has received more attention in the preceding chapters, as it plays a crucial role in proactive goal assessment throughout any product development process. The concept ideation and development process was also supported with virtual and real laboratory simulated experiments; this was done in order to avoid design

uncertainties, thereby minimizing the number of tryouts prior to concept development. Also, this approach helps to simplify the entire concept selection process in terms of time and cost. The present concept selection and development methods have been examined and passed through various selection processes, starting from the survey to get the stakeholders' view, selecting a mechanism based on the given posture, handle design and estimations made at the lumbar spine in the current transfer posture.

The initial concept ideation, followed by biomechanical loading assessments on the lumbar spine level of L5/S1 and L5/L4, have been investigated to identify and compare the most acceptable concepts among the three proposed concepts. Similarly, handle design and its orientation for the present concepts have been investigated based on the effort required to manipulate them using EMG-based experiments. The investigations revealed that the handle orientation labelled with HatEH, handle at elbow height, showed a relatively low muscle excitation compared to the other two handle designs. From these findings, it has been concluded that the reason was due to its geometric location, i.e., the closer the handles are to the hands at specific postures, the lower muscle exertion will occur. Similarly, the mechanical pull force gauge measurements also showed a lower reading for HatEH; thus, its corresponding biomechanical loading effects due to ***Fm*** on L5/S1 and loads on L5/L4 were also registered with a relatively lower value than the others. Hence, concept two, represented with HaEH, was chosen to proceed with further design and prototype development process. Figure 5.11 below shows the final 3D model of the selected concept with all auxiliary components, and a human manikin in operating mode is also included for realistic illustration purposes. Figure 5.12 shows the manikin in a transfer mode with the caregiver controlling the activities.

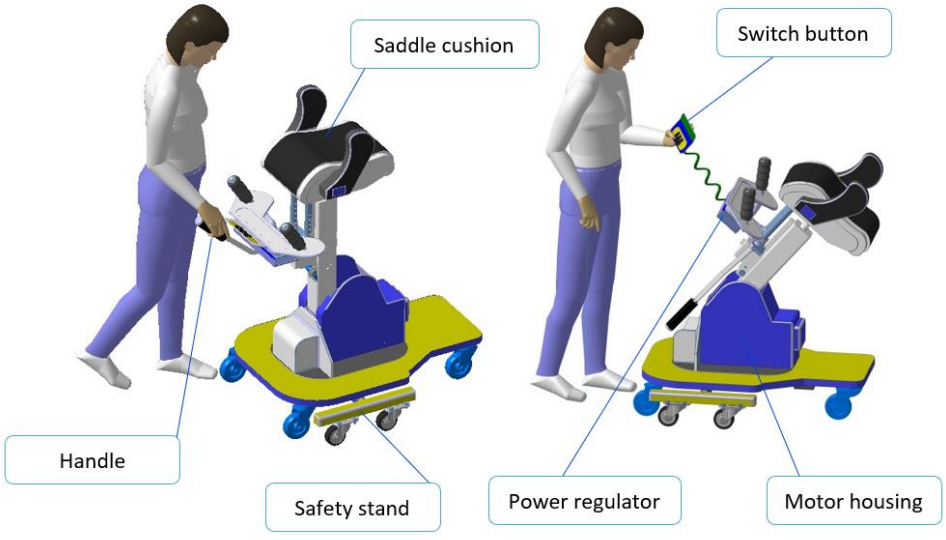


Figure 5-11 The final 3D model of the selected concept with all auxiliary components

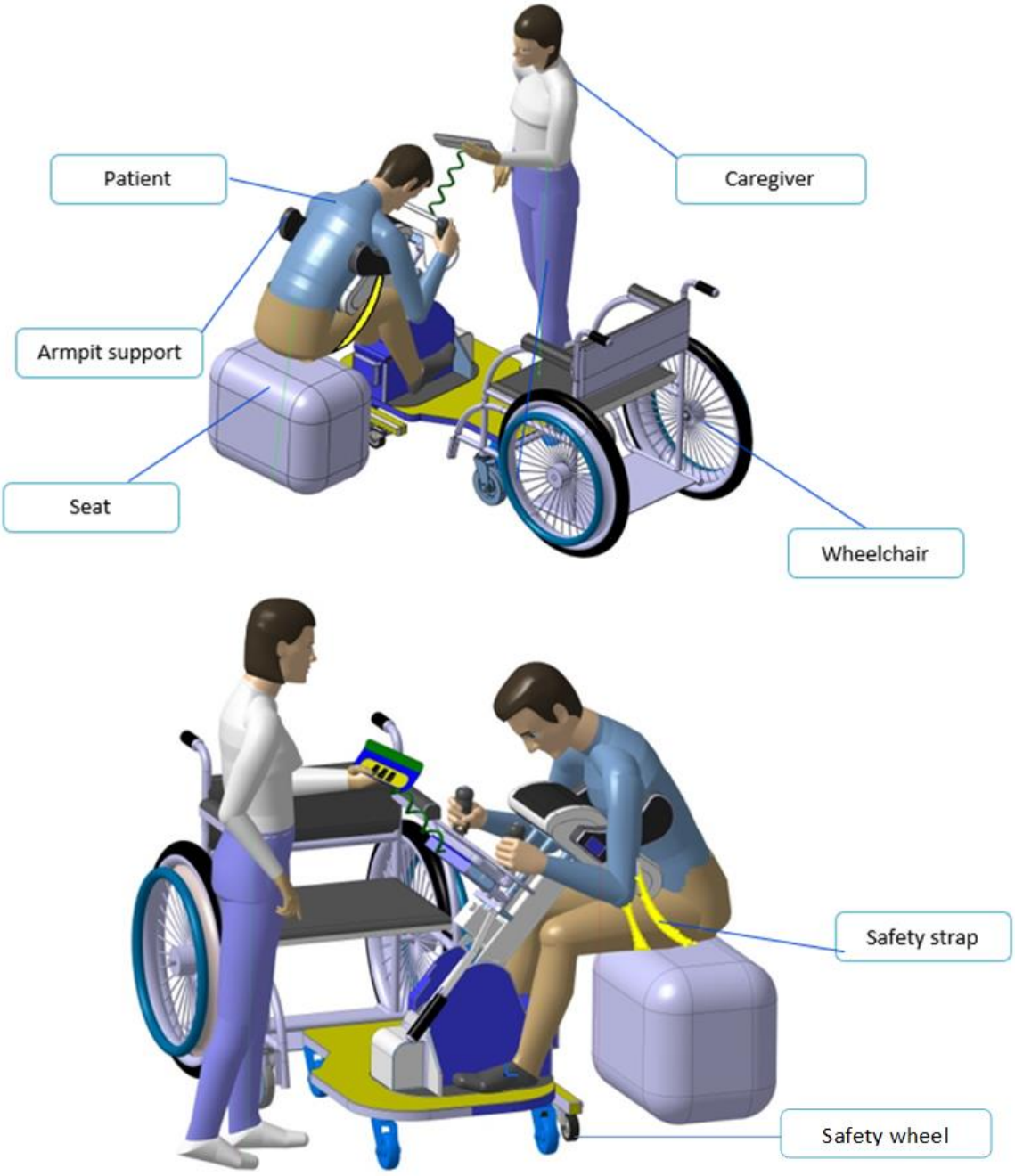


Figure 5-12 The manikin in the transfer mode from a chair to a wheelchair with the caregiver controlling the activities.

CHAPTER SIX

6 Prototype Development and Evaluation Process

6.1 Components of the Prototype and its Development Process

A prototype is a functional version of a device that is intended for research prior to mass production. Prototypes assist designers in learning about the production process, how the prototype will be used, and how it can malfunction or split. A prototype can be made of a separate material from the finished product, and it is often used to evaluate various functional features of a device before the concept is finalized. The proposed working model /prototype of a transfer assistive device (TAD) has been developed at a machine workshop of the Indian Institute of Technology, Guwahati, Department of Design. The parts or components of the potential transfer assistive device are broadly divided into two categories: electrical and mechanical. The proposed device is intended to work electromechanically by combining linear actuators and a rack-pinion mechanism. Three linear actuators were used in the present prototype. Linear actuator-1 fitted at the bottom of the base is made to move the rack, thereby rotating the pinion fitted to the main shaft of the upper frame-saddle assembly. Similarly, the lower end of the top frame pivoted to the base is made to tilt by the Linear actuator-2, and the last actuator, linear actuator -3, is used as height adjustment. Three di-pole di-throw (DPDT) switches were used to synchronize each actuator's motion with three motor drivers, which are integrated inside each actuator. Figure 6.1 below shows the electrical block diagram for the proposed transfer device.

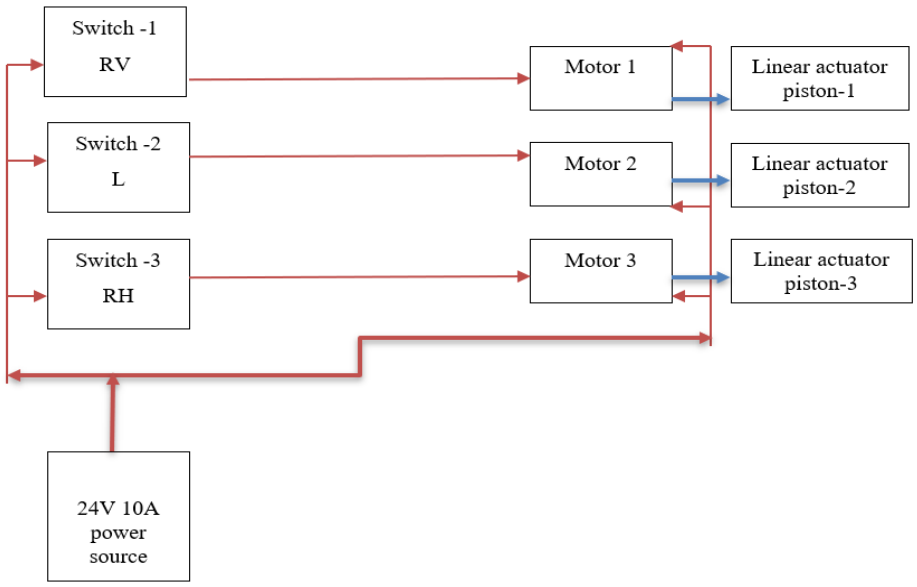


Figure 6-1 The simplified electrical block diagram of the transfer assistive device

Based on the previous section's analysis results, the actuators' design specifications, such as the pull/push capacity, were decided. Hence, for the purpose of evaluation, three identical linear actuators, each with a 24V 3A, having a 3KN pull-push capacity and a speed of 10mm/sec, were chosen as a prime mover for the current prototype of TAD. The prototype evaluation experiments used the AC power source with a power regulator output of 24V 10A. This option was done to manage the entire experiment with a uniform power source; this system also works well with two 12V 10A sealed lithium-ion deep cycle batteries to power the actuators depending on the working hour and the device's load.

The mechanical part comprises four main components, as shown below in Figure 6.2. The auxiliary components are included in the system subassembly. The power train based on the rack and pinion driven by a linear actuator is fixed below the chassis. Additionally, two more linear actuators, one for rotating the mainframe on the vertical plane and the other actuator, are for the height adjuster connected below the saddle sub-assembly. The material which is used in prototype development is the actual material that corresponds to the final product, i.e., steel material is used for the entire frame and chassis body; wood material was used for the saddle, motor housing, and underarm sub-assembly. The entire manufacturing process was performed based on the detailed manufacturing drawings depicted in Appendix I. The rough manufacturing phases, which were generally adopted to fabricate the prototype, are as follows: a) Material selection and preparation, b) Measuring and inspection, c) cutting to the required dimension, d) Machining and joining (temporary or permanent), and e) assembling and painting. Figure 6.3 shows the fabrication phases of selected components in the workshop.

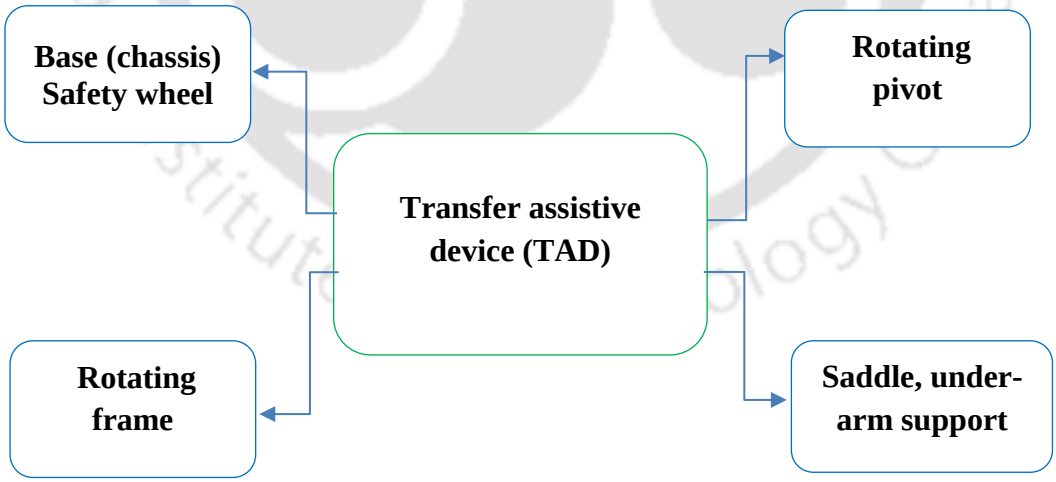


Figure 6-2 The main components of the proposed transfer assistive device (TAD)

Figure 6-3 Fabrication phases of transfer assistive device in progress

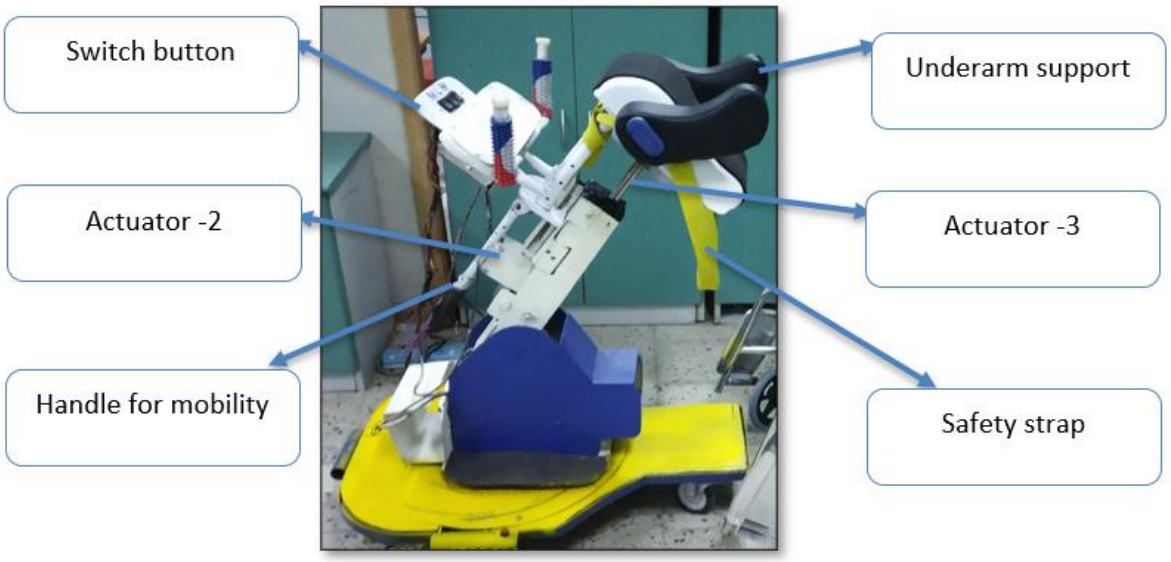


Figure 6-4 Assembly of the final prototype

Figure 6-5 Checking the usability of the developed prototype**.**

6.2 Prototype Testing and Evaluation

6.2.1 Background

Many related researches have been conducted on evaluating activity-related tasks through the combination of heart rate (HR) and the rate of perceived exertion (RPE), such as the research determining the association between RPE scores and HR during physically interactive video gameplay. They found a moderate positive relationship between heart rate and rate of perceived exertion RPE (r = 0.32). The use of a percentage of heart rate reserve %HRR is shown as a good estimator of the strain level in lower physical activities. This experiment was made based on wheelchair users while performing their daily living activities [93]. The above assessment method has one important salient feature, especially when conducting experiments related to user-device interaction: it has the ability to combine both subjective and objective evaluation processes for estimating the relationship between the heart rate (HR) and the rate of perceived exertion (RPE).

In this report, it has been decided to conduct a practical experiment with the current prototype and the corresponding users to investigate the relationship between the heart rate (HR) and the rate of perceived exertion (RPE), thereby finding out how users are feeling while using the present transfer device. Generally, the protocol of this experiment includes the continuous monitoring of the heartbeat during the transfer session using a heart rate monitoring device. The questionnaire list was also provided for the test subjects, containing a list of design characteristics that can help to rate the proposed prototype. Additionally, in order to find out the relationship between heart rate (HR) and the rate of perceived exertion (RPE), a BORG (CR20) scale/ RPE score was provided for the test subjects to express how intensely they felt while transferring from wheelchair to bed.

6.2.2 Materials and Methods

Twenty-one subjects (19 healthy adults) with mean$\pm SD$ of age, weight and height of (30.94 ± 6.3), (68.57 ± 11) kg, (170.31 ± 9.5) cm, are recruited from IITG. One paraplegic male individual with age, weight and height of (55,65kg and 154cm) and another male individual having difficulty in sitting to stand (STS) with age, weight and height of (46,63kg and 160cm) respectively, are recruited from outside of the campus. Before proceeding with the experiment, informed consent was taken from each subject and asked about their health conditions, demographic information, and activities to be performed were shown to them as a demo task made by the study coordinators. The first experiment was conducted for subjects recruited from IITG. The type of equipment used in this experiment are as follows: one manual light wheelchair, a working prototype of a transfer assistive device (TAD), a sample bed/chair and a heart rate monitoring device (Polar RS 400 heart taster), which includes a wristwatch, chest belt which are wirelessly connected to a Polar Pro 5 Software. According to the stated protocol, the heart rate recording will start once the test subject is ready in a transfer position and has started lifting, i.e. sitting on a wheelchair, wearing the wristwatch and the chest belt and starting lifting up, as shown in figure 6-6. The net time required to transfer from wheelchair to bed is around 55 seconds, but

the time taken for holding the underarm and laying on the chest support was shown to vary from subject to subject, as observed during the demonstration phase.

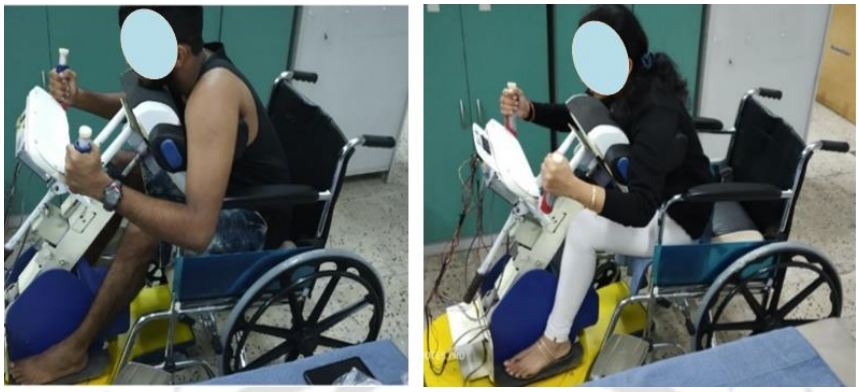


Figure 6-6 The test protocol for subjects under transfer task

6.2.3 Data Collection

The data collection and registration were started after each subject had completed the assigned transfer task; the heartbeat rate recorded during transfer activities was collected from 19 healthy subjects who had completed the assigned task successfully. For the test subjects to properly share their feelings experienced during transfer task on a BORG scale, subjects were taken out of the wheelchair, then, a questionnaire list containing the BORG scale and Likert-type questions was given to each subject who had completed the transfer task. The sample of the average heartbeat rates generated by the Polar Pro 5 Software for the two subjects is shown in Figure 6.7 below.

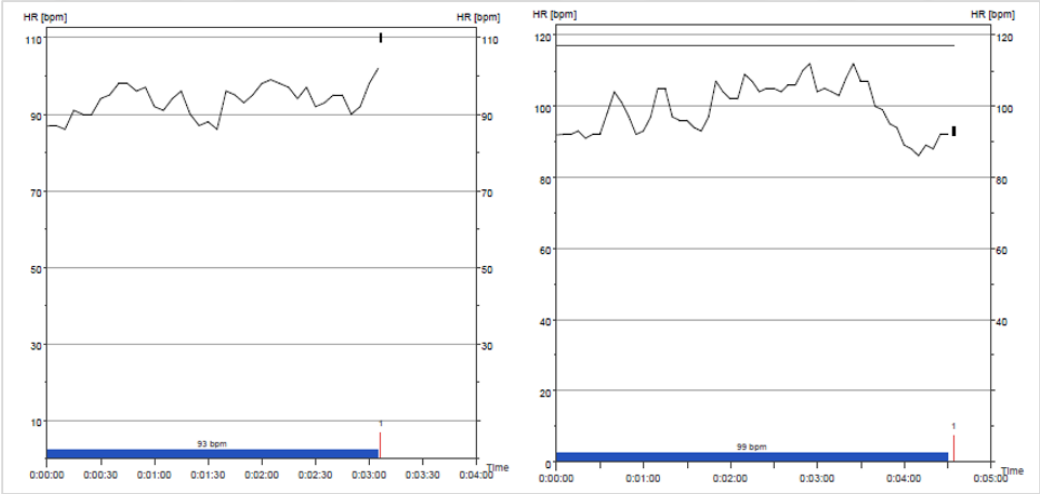


Figure 6-7 Rate of heartbeat recorded from two subjects during transfer activities.

6.2.4 Data Analysis

For analyzing the relationship between the heartbeat rate HR and rate of perceived exertion, the data collected during transfer activities from 19 test subjects are expressed in terms of mean$\pm$ SD given as (87.73 ± 8.4) for heart rate and (13.05 ± 1.7) for RPE, respectively. SPSS v20 software was used for analyzing the collected data, thus, a linear regression model has been carried out to determine the predicted outcomes from the correlation of independent physiologic response HR and RPE. The normality of the two variables is checked using the normal P-P plot, and the regression line indicates that the two variables are positively correlated, as shown below in Figure 6.8; the analysis of variance (ANOVA) significance shows the model is statistically significant with $p < 0.013$.

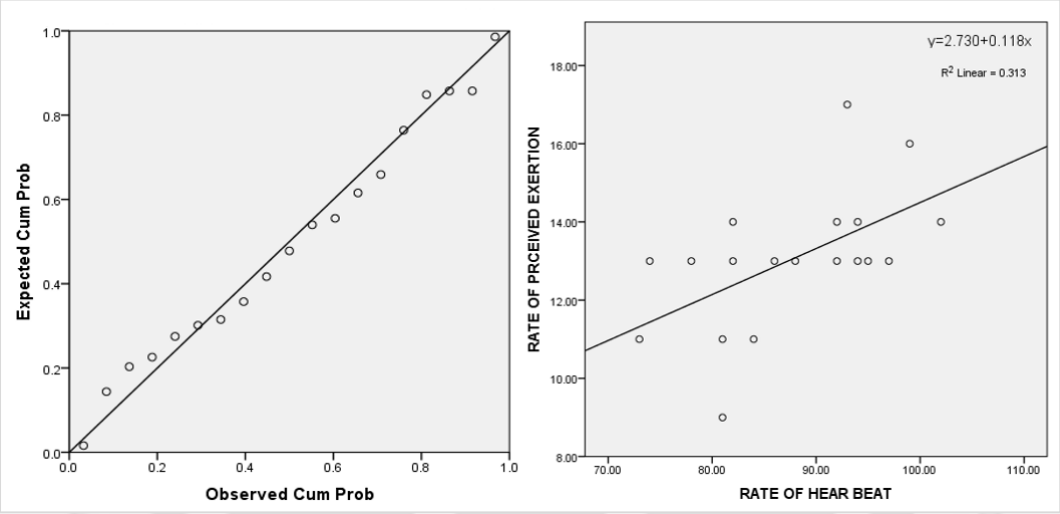


Figure 6-8 Normal p-p plot (left) and Regression plot (right)

6.2.5 Statistical Results of Prototype Evaluation

A bivariate regression was conducted to inspect how well the subject's heartbeat rate while performing a transfer activity could predict the level of the rate of perceived exertion. According to a scatterplot, the relationship between the heartbeat rate HR and rate of perceived exertion RPE was positive and linear, with no bivariate outliers. Also, it was found that the correlation between the heartbeat rate and rate of perceived exertion was statistically significant $r\ (17) = .56,\ p < 0.013$. The regression equation for predicting the RPE from HR was given as ($y = 2.730 + 0.118x$). The r^2 for this equation was 0.313, which suggests that HR predicted 31.3 per cent of the variance in RPE, indicating a relatively moderate relationship. Generally, the need for conducting such an experiment with the intention of finding the relationship between the rate of heartbeat HR and rate of perceived exertion RPE has two main advantages. Firstly, since the target group who are using such devices might have some issues related to health conditions, conducting such evaluations from the user's safety point of view is thought to enhance the safety level of the present device, especially while calculating the amount of physical strain level which be discussed

in sub-section 6.3. Secondly, it has been well-known and studied that HR and RPE have a strong correlation, especially when finding the strain level in lower physical activities. Therefore, this method was used in the current experiment to verify if this relationship holds true between the present prototype and user interaction to determine the strain level while transferring by the same device.

The assessment procedure for the existing prototype was expanded to include individuals with disabilities. Two volunteers with disabilities participated in this experiment: - one was a paraplegic, and the other experienced difficulties in the sit-to-stand (STS) movement. Informed consent was taken from each subject prior to activities, also asked about their health conditions and demographic information, and told about activities to be performed. The experiments were conducted as follows: A paraplegic male individual with age, weight, and height (55y,65kg and 154cm) participated in the experiment's last session. This individual has a stroke history from the last 11 months; hence, his lower limb was paralyzed but slightly fit in his upper limb, Despite this, he demonstrated the required activities in his upper limbs, allowing him to effectively grasp the handle of the current device (TAD). Before starting the transfer session, a demo was shown by one of the study coordinators, and then the heart monitoring devices were attached under his chest muscle and the wristwatch on the hand. However, the individual's heartbeat was at a maximum zone; hence, the transfer session was stopped until his heartbeat was lowered. This condition generally happens to other healthy subjects too, because of their feeling and perception, mainly occurring while interacting with a new environment or activities for the first time. After 30 minutes of rest, the same individual again checked for the heartbeat; it was found normal. The transfer activity was then initiated, supplemented by three steps in which data was gathered when transferring from a wheelchair to a bed and vice versa. After completing the experiment, the overall heartbeat was measured at 5-second intervals. The overall heart beat recorded at every 5 seconds interval registered at the end of the session, the recorded average HR and the %HRR are shown in Figure 6.10 (top).

The second experiment was also conducted for a male individual with difficulty in STS, having age, weight, and height (46y,63kg and 160cm) respectively; this test subject has a weak muscle in his lower limb and pain while performing the ADL tasks. A similar protocol was adopted as the previous one; thus, initially the subject was asked to look after the demo and perform the same as a trial followed by the actual test. Figure 6.9 below shows the sequence of transfer phases from wheelchair to bed/chair for a person with paraplegia (top) and who has difficulties in STS (bottom). Similarly, the recorded average HR in bpm and the %HRR are shown in Figure 6.10 (bottom). The computed average HR was found in the normal range of heart rate as measured in most similar light activities. It is essential to highlight that, owing to unavoidable circumstances, only these two individuals with health-related challenges took part in this experiment. Consequently, conducting a comprehensive statistical analysis to estimate the strain level in terms of %HRR was not feasible. These two experiments were primarily undertaken for illustrative purposes and aimed at soliciting feedback from users facing challenges in transferring from a wheelchair to other surfaces

Figure 6-9 The sequence of transfer phases from wheelchair to bed for a person with paraplegia (top) who has difficulties in STS (bottom).

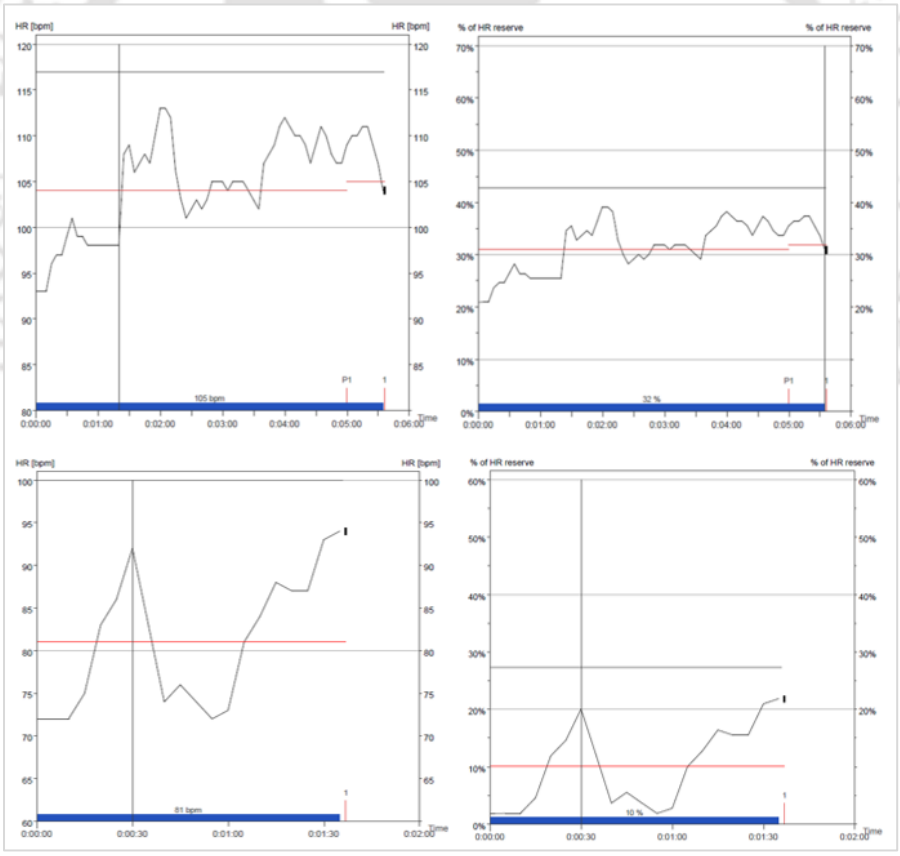


Figure 6-10 Plot of HR and %HRR for a paraplegic (top) and a person having difficulties in STS (bottom).

6.3 Estimating the Physical Strain Level During Transfer Activities

The experimental work conducted in the previous section was generally to find out the relationship between the rate of heartbeat HR and the rate of perceived exertion RPE. After examining the correlation between the rate of heartbeat HR and the rate of perceived exertion RPE, the recorded HR values are again used to estimate the physical strain level induced during a transfer activity. The heart rate value recorded with a Polar RS 400 heart monitor sampled with a 5 s interval time has been used to accurately measure the physical strain during the transfer operation. Heart rate calculated as a percentage of heart rate reserve (% HRR) is a relative measure for estimating physical pressure. HRR refers to the cushion volume between heartbeats required during any operation [93]. To estimate physical strain, according to the NASA physical activity scale formula, heart rate was calculated as a percentage of human heart rate reserve (HRR), as shown in equation (1) below. Where, HR_{AC} , HR_R , and HR_{max} , are the heart rate in a particular activity, heart rate at rest and the maximum heart rate recorded by the Polar RS 400 heart taster during transfer activities respectively; the overall computed mean % HRR values from the potential test subjects are shown in figure 6.11 below:

$$\%HRR = \frac{HR_{AC} - HR_R}{HR_{max} - HR_R} \times 100\% \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

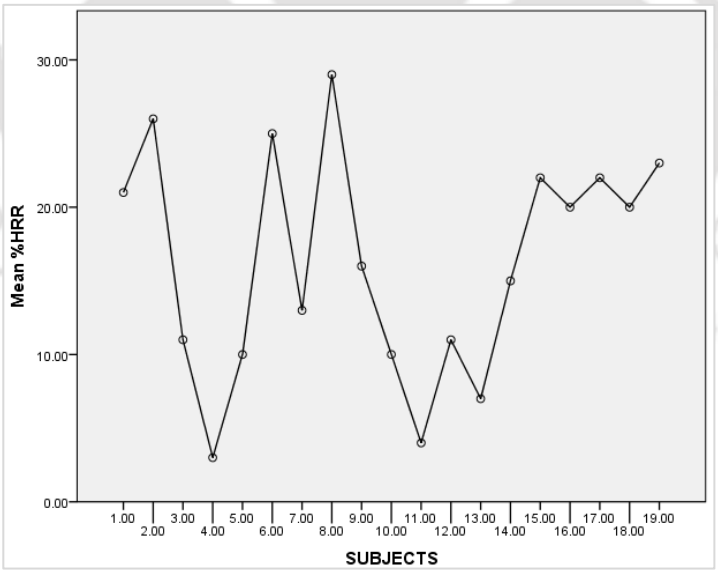


Figure 6-11 Mean percentage of heart rate reserve(%HRR) computed during the transfer task.

The approximate strain level in terms of per cent %HRR measured for the activity of transferring participants from a wheelchair to another seat surface can be stated as follows: the physical strain

averaged over the subjects who performed the task (n = 19) was expressed in terms of (mean ±SD) and calculated based on % HRR is given as (16.21±7.64%) which is a relatively more minor strain level as compared to the previous research report [58]. The results of the previous studies were based on the selected ADL tasks, such as manually transferring the test subjects from wheelchair to bed, toilet seat, and shower seat was (68.4 ± 7 %), (59 ± 72 %) and (65.5 ± 12.2 %) respectively. This result showed that employing the present prototype / transfer assistive device could reduce the physical strain level during the transfer activities. Additionally, the ratings from the Likert-type questions containing a total of six design characteristic features showed that, the developed prototype had an accepted design features as viewed by the test subjects; the list of ratings given by the test subjects are compiled in Figure 6.12 below: -

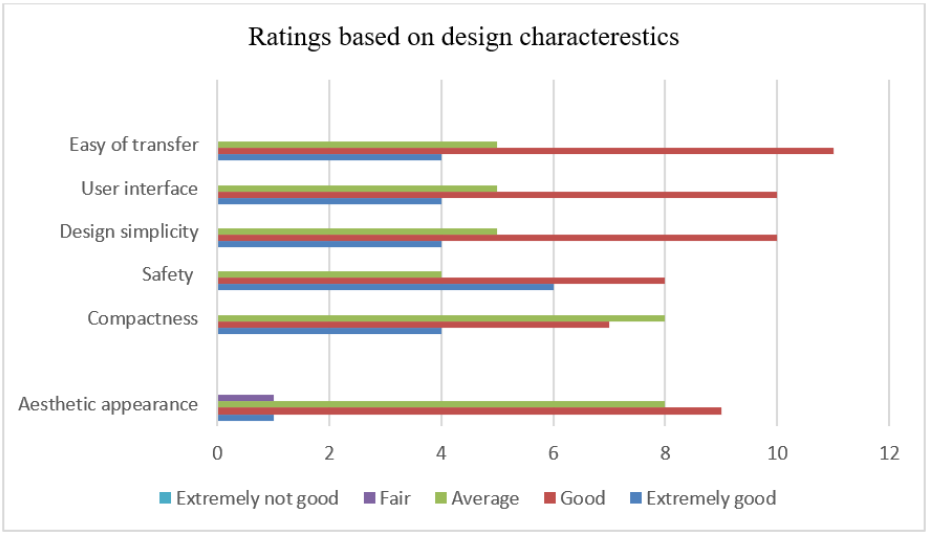


Figure 6-12 List of ratings given by the test subjects based on design features of the TAD

6.4 Experimental Evaluation on the Effect of Under-Arm Support

The present design of the transfer assistive device comprises the under-arm support as one of the central auxiliary parts. In the initial transfer phase, the under-arm support will come into action after a few seconds according to the TAD's motion until the combination of the saddle and under-arm support lifts the client's entire body. The user keeps his/her body stable by applying a minimum pulling effort on the handle while simultaneously transferring in a forward lifting mode with the device's help. One of the limitations or gaps observed in the literature review was that almost all existing transfer devices were not equipped with underarm support. Thus, considering this gap, a hypothesis was made in this report, such as: - the minimum required pull action or force is assumed to vary based on whether the transfer is accomplished using the under-arm support or not. Therefore, to answer the stated research question, this report was planned to conduct an experiment on the two conditions of the transfer tasks by recording the EMG signal from each selected muscle and to investigate which transfer conditions require more muscle excitations.

6.4.1 Data Collection and Presentation

In this experiment, twenty subjects (seventeen males, three females) with mean$\pm SD$ of age, weight and height of (35 ± 6) years, (69 ± 23) kg, (173 ± 9.2) cm, were participated voluntarily. Before proceeding with the experiment, subjects were asked about their health conditions and demographic information. They were told about activities to be performed by showing them demo tasks made by the study coordinators. An informed consent was also taken from each subject. The following equipment type was used in this experiment: one manual light wheelchair, a full Delsys-based EMG sensor and the newly developed prototype of a transfer assistive device. Data was collected from three muscles, the Anterior Deltoid (AD), Biceps Brachii (BB), and Brachioradialis (BR), for predicting the influence of the upper limb muscular loadings while performing the transfer based on the two cases, i.e., transferring with and without using the Under-Arm support.

Three sensors for each chosen muscle have been connected to the dominant hand. Auto interconnection and labelling of EMG sensors revealed the link interaction between the EMG sensors and the chosen muscles, which were identified as (EMG-2- Anterior Deltoid (AD)), (EMG-3- Biceps Brachii (BB)), and (EMG-4- Brachioradialis (BR)). In order to record the maximum voluntary contraction (MVC) from each subject and at each muscle, each subject was asked to exert their maximum effort against the resistances provided for the three muscles. All other experimental protocols were kept as in the previous section 4.4. Figure 6.13 below shows the experimental set-up for one of the test subjects showing the three EMG sensors' attachment. Figure 6.14 and 6.15 shows plots of the EMG-RMS (%MVC) outputs of muscle excitation detected from EMG-2- Anterior Deltoid (AD), EMG-3- Biceps Brachii (BB) and EMG-4- Brachioradialis (BR) muscles for tasks done with and without the use of Under-Arm Support.

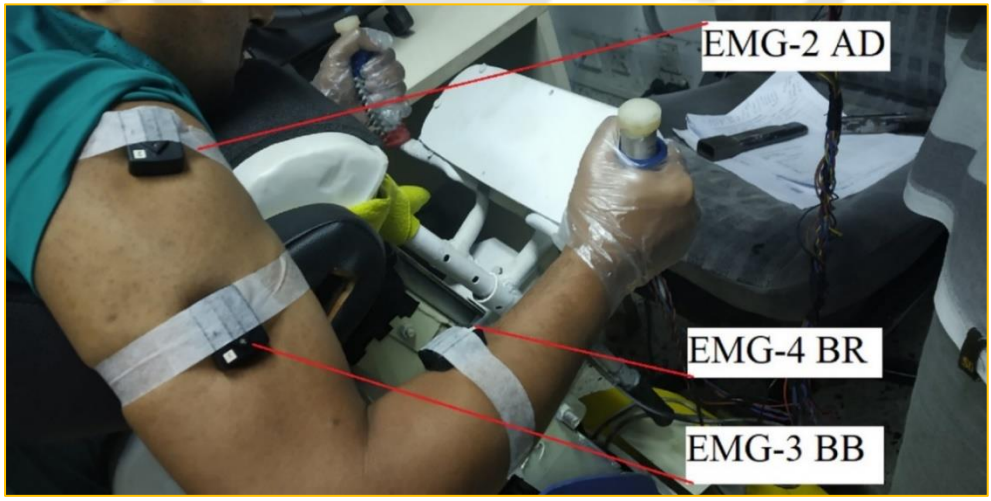


Figure 6-13 The location of the three EMG sensors (EMG-2- AD), (EMG-3- BB) and (EMG-4- BR) muscles.

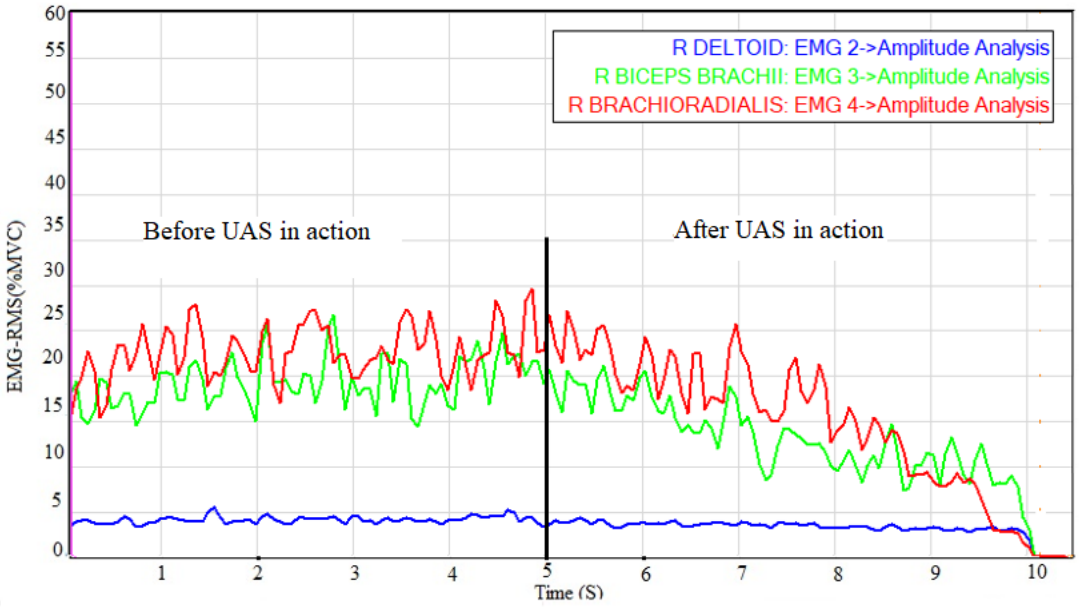


Figure 6-14 Plots of EMG-RMS (%MVC) for EMG-2- Anterior Deltoid (AD), EMG-3- Biceps Brachii (BB) and EMG-4- Brachioradialis (BR) muscles for transfer using UAS.

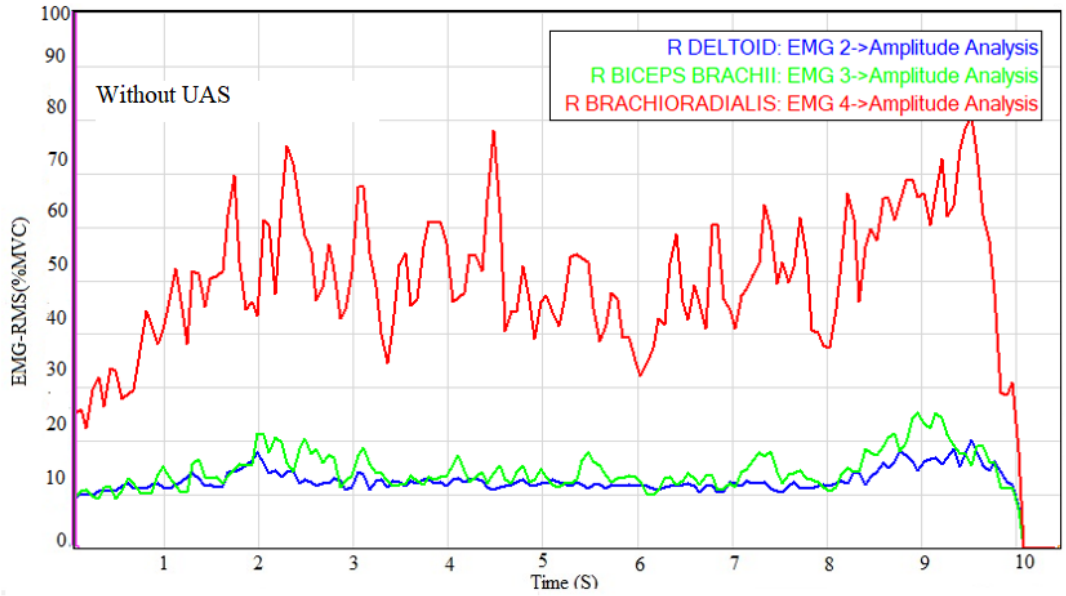


Figure 6-15 Plots of EMG-RMS (%MVC) for EMG-2- Anterior Deltoid (AD), EMG-3- Biceps Brachii (BB) and EMG-4- Brachioradialis (BR) muscles for transfer without using UAS.

6.4.2 Data Analysis and Interpretation

The data collected during each task were exported to Microsoft Excel and subsequently subjected to statistical analysis for further analysis and interpretation using SPSS. The normality distribution of the EMG data recorded during the two-transfer session (transfer with and without underarm support) was checked based on the Shapiro -Wilk test and found a value of (p=0.222 and p= 0.015) for Anterior deltoid (p=0.335and p=0.295) for Biceps brachii and (p=0.001 and p=0.024) for Brachioradialis respectively. After observing the data distribution from the histogram plots (Appendix-III) and applying the normality assumptions, it has been decided to adopt the non-parametric Wilcoxon-Sign-Rank test to determine if there is a significant difference in the degree of muscle excitations, and to test the effect of under-arm support during the two transfer conditions.

A Wilcoxon-Sign-Rank test showed that the contributions of the three muscles, Anterior deltoid, Brachioradialis and Biceps brachii, during the two transfer conditions, i.e., transfer with underarm support (WUAS) and transfer without underarm support (WTUAS), were statistically significantly different with [Z= - 2.96, P=0.003, Z= -3.82, P=0.001 and Z= -3.92, P=0.001], for AD, BR and BB respectively. The maximum recorded EMG-RMS (%MVC) values in the condition of WTUAS as shown in Table 6.1 were 29.18%,46.89% and 65.74% with the corresponding median values of 12.5%, 19.79% and 42.79% for AD, BR and BB muscles, respectively. Generally, in both transfer conditions it has been observed that, the amount of muscle excitations recorded by BB muscle was relatively higher as compared with the other two types of muscles. On the other hand, the muscle force recorded by AD muscle was relatively low which shows its lowest contribution throughout this experiment.

The Wilcoxon-Sign-Rank table also generated a negative (13,19,20) and positive (4,1, 0) ranks for AD, BR, and BB muscles, respectively. This rank indicates the existence of large variations in muscular exertion between the two cases of transfer. The effectiveness of using the new design of the underarm support during transfer has been validated, which supports the stated hypothesis. Thus, the use of underarm support during the transfer task was investigated to minimize the level of pull action or force required on the handle. This detailed examination of muscle activity sheds light on possible areas for improvement or optimization in upcoming iterations of assistive technology or transfer techniques. It also offers insightful information on the dynamic interaction of various muscle groups during transfers. Comprehending the distinct roles played by muscles under diverse transfer scenarios can aid in the creation of more focused and effective interventions for people with mobility impairments.

Table 6-1 Summary of the Descriptive Statistics for the effect of using UAS on the recorded EMG

Descriptive Statistics

	N	Mean	Std. Deviation	Min	Max	Percentiles 25th	50th (Median)	75th
AD WT UAS	20	13.160	5.79351	4.82	29.18	9.0175	12.5000	17.267
BR WT UAS	20	20.480	8.86093	7.56	46.89	17.270	19.7950	21.130
BB WT UAS	20	43.356	10.39549	21.84	65.70	40.422	42.7900	49.975
AD WUAS	20	9.5915	5.59131	3.72	21.72	4.4800	7.8750	12.387
BR W UAS	20	9.1620	4.70365	3.86	22.57	5.0325	9.4150	11.970
BB W UAS	20	15.032	3.69620	8.14	20.80	12.417	14.8300	18.522

Table 6-2 Summary of the test statistics for the effect of using UAS on the recorded EMG

Test Statistics[a]

	AD W UAS - AD WT UAS	BR W UAS - BR WT UAS	BB W UAS - BB WT UAS
Z	-2.960[b]	-3.824[b]	-3.921[b]
Asymp. Sig. (2-tailed)	.003	.000	.000

a. Wilcoxon Signed Ranks Test

b. Based on positive ranks.

Table 6-3 Summary of the Wilcoxon-Sign-Rank test for the effect of using UAS on the recorded EMG

Ranks

		N	Mean Rank	Sum of Ranks
AD W UAS - AD WT UAS	Negative Ranks	13[a]	10.69	139.00
	Positive Ranks	4[b]	3.50	14.00
	Ties	3[c]		
	Total	20		
BR W UAS - BR WT UAS	Negative Ranks	19[d]	10.00	190.00
	Positive Ranks	0[e]	.00	.00
	Ties	1[f]		
	Total	20		
BB W UAS - BB WT UAS	Negative Ranks	20[g]	10.50	210.00
	Positive Ranks	0[h]	.00	.00
	Ties	0[i]		
	Total	20		

a. AD W UAS < AD WT UAS

b. AD W UAS > AD WT UAS

c. AD W UAS = AD WT UAS

d. BR W UAS < BR WT UAS

e. BR W UAS > BR WT UAS

f. BR W UAS = BR WT UAS

g. BB W UAS < BB WT UAS

h. BB W UAS > BB WT UAS

i. BB W UAS = BB WT UAS

CHAPTER SEVEN

7. Discussion and Conclusion

7.1 Discussion

This thesis advocates that user-focused design is not just a superficial consideration but a fundamental principle that should permeate every phase of product development. In line with this approach, the research embarked on an extensive review related to transfer devices, which laid the groundwork for the subsequent stages of the thesis. From this foundational research, an initial concept was conceived, serving as a starting point for further exploration and refinement. Importantly, this conceptualization process was characterized by active involvement and collaboration with the stakeholders, a term that encompasses all those who have a vested interest in the product's performance and utility. To develop a user-focused product, the survey of stakeholders, including the physiotherapist, nurses, and users, participated during the preliminary design phase at Guwahati Medical College and Hospital GMCH. The survey outcomes helped get an initial picture of stakeholders' expectations for developing the idea. The importance of considering the stakeholder's view in the conceptual phase of a given product design will significantly help understand the current state of the art of the target product; it also provides insight into the problem areas of the existing product that need to be modified or redesigned. Generally, the following procedures were adopted in this approach: first, a comprehensive literature review was carried out on the existing transfer devices once the general research gaps had been identified. It was planned to reframe the tasks contextually or locally by observing the current needs of the stakeholders in selected healthcare centres. For this purpose, a questionnaire-based survey comprising three categories of participants was conducted at a selected hospital. Additional research activities, such as the Biomechanical evaluation process both before concept development and after the final product release, were introduced to enhance the feasibility and reliability of the proposed concepts based on the above data and the research gap.

The human-machine approach was chosen in the entire design process for determining an appropriate interaction between the device and the user; knowing the exact interaction helps in deciding the optimum hardware necessary for the optimal operation of the given product. Digital human modelling was observed to play an essential function in identifying the exact interaction between the user and the device by employing the manikin as a human model and assembling the manikin with the 3D model of the virtual product. Additionally, the DHM has helped create a human biomechanical model used to calculate inertial parameters while determining the subject's centre of mass in each posture. Recognizing where the user's centre of mass should be located in a transfer posture will let designers know the specifications of the parts necessary for the proposed product. DHM was used to model the human reach envelope in a transfer posture with proposed concepts. The use of this approach in the present research greatly simplified the concept generation, decomposition, selection and development process.

Handle design and its suitable location play a vital role, especially for a product related to a human. The EMG-based experiment was conducted to identify the appropriate handle design and locations and its effect on the selected arm muscles. Three handle locations were evaluated based on the amount of exertion required while performing the transfer tasks. Similarly, the corresponding biomechanical loadings were also assessed in the three handle cases. The compressive loads at the lumbar disk spine, i.e., L5/S1, were computed using a custom-derived equation. The custom-derived predictive equation was compared with other software for predicting the compressive loads on the same posture. In addition of determining a handle design that fosters a biomechanically suitable transfer posture, three findings were also obtained from this experiment, (which may be useful for ongoing related studies), such as (1) the compressive load at spine largely depends on posture than the hand load, (2) BR muscles had the highest contribution in the FPT tasks, in contrast AD muscles was shown to have lowest contribution. (3) the use of a predictive equation for estimating the spine load at any similar handle design, this predictive equation was compared with 3DSSPP software, and the result indicated that, the current softwares have limited tools for precisely determining the biomechanical loads in activities similar to the present study. Although, 3DSSPP software provides support as a backrest and a seat but does not consider specially designed custom support as in the present cases. The compressive load at L4/L5 for a chosen transfer posture was also evaluated and compared between Catia-v5and 3DSSPP , results showed that its maximum predicted value was far below the NIOSH RL of 3400N.

The actuator specification's design and determination of its optimum location of the pin to main frame connection were computed based on biomechanics and anthropometric analysis. This approach has the advantage of estimating the necessary actuator size and capacity, which helps reduce the design cost in terms of time and unnecessary costs that might result due to an overdesigned component. This thesis's primary objectives are to design an affordable yet simple transfer assistive device that meets the requirements of lower limb impaired individuals living in lower-income developing countries and to evaluate its comfort of use through biomechanics perspectives and physiologic measures of effort. Based on these strategies, the present prototype (TAD) comprised three low-cost and simple linear actuators as a prime mover, which the user or caregiver could easily control using ordinary DPDT switches. This new approach also helped in the selection and development of a cost-effective components of the TAD, such as selecting an optimum actuator load along with its location and the simplified design of the rotating mechanism (rack and pinion assembly), which has an impact for enhancing the accessibility and affordability of the final product.

The novel turning mechanism feature has been adopted in the present TAD that works based on a reverse rack and pinion drive system. It helps to turn/rotate the previously lifted user/patient and the top portion of TAD. The turning mechanism's unique feature reveals the unconventional use of rack and pinion; in this design, the rack gear attached to the bottom linear actuator was made to drive the pinion mounted on the main rotating shaft of the frame. This novel feature eliminated the

need for auxiliary units such as a gear reduction box, which imposes additional cost and space on the final product, leading to a high initial investment.

The combined use of linear actuators with the rack-pinion system also produced the distinct advantage of having a smooth motion with accuracy, which helped TAD stop /start at specific positions. Previous studies related to transfer devices have used different turning mechanisms, such as the use of omnidirectional wheels, which have been adopted in one study as a means of turning the user to specific locations. Manually turning the device by caregivers or users themselves, and in another study, they used an epicyclic gear as a reduction unit and a rotary motor instead of linear actuators.

The effects of the physiologic observations of the test subjects were statistically evaluated, and it was found that the regression equation for estimating RPE from HR estimated 31.3 per cent of the RPE variance, which was a moderately good relationship. The average strain frequency among all respondents who completed the activity was defined based on (mean ± SD) % HR. Compared to the previous report, the value (16.21 ± 7.64%) was comparatively lower. The previous studies' report was based on the selected ADL task, manually transferring from wheelchair to bed (68.4±7). This finding may be used as proof that the present TAD helped reduce the extent of strain produced during unaided transition or without a transfer device. Regarding safety and availability, the current technology may be an ideal transfer platform for people with lower limb impairments, especially those living in a low-income developing country. Finally, the device's evaluation based on the given design characteristics was made using a Likert scale of five from 'extremely good to extremely not good. The overall result showed that most ratings were in the range of good, followed by average and extremely good.

The novel design and adaptation of the under-arm support in the present TAD provided two unique features. Firstly, it enabled the users to smoothly move towards the chest support due to the ergonomically designed underarm support having a curved shape, as shown in figure 7-1, which creates the sliding action between the subject's armpit and the upper portion of the under-arm support while moving simultaneously upward. Similarly, the under-arm support sliding action reduced the strain level during transfer due to the direct contact force between the subject's armpit and the upper portion of underarm support. It also helped avoid muscle fatigue at the shoulder, which is the most occurring phenomenon in underarm crutch users. Secondly, the under-arm support has helped users safely and freely transfer their entire body especially for users having limited strength to hold the handle to keep stability while transferring. Many transfer devices based on sitting forward pivot transfer (SFPT) have been developed, including a commercially available one similar to the present TAD. Still, they do not have under-arm support that provides the above unique features during transfer activities. Hence, users using a transfer device without being supported by underarms are more susceptible to fatigue and sudden falls. Additionally, most such devices require a substantial effort from the caregiver to help them perform a transfer task. Many

studies discussed in the literature review have stated that such efforts during manual transfer were the main reason for low back pain and MSDs musculoskeletal disorders.

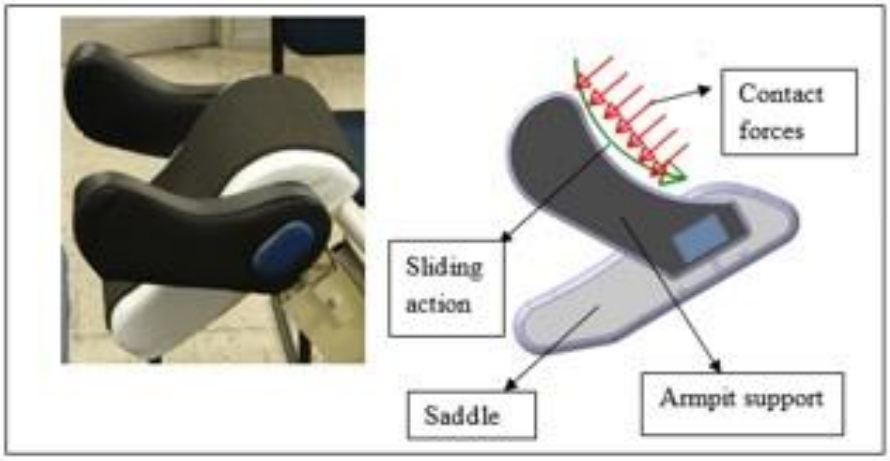


Figure 7-1 The physical (left) and the 3D model (right) of the novel saddle-under arm support

Generally, in this thesis, a context-driven research method, which is a design research approach comprising the techniques of design-based and research-based projects, was adopted; the successful completion of the overall works presented so far highlights the usefulness of the chosen research method. The benefits observed in this research activity are as follows: it offers the freedom of combining the design activities with the research activities; as a result, they will support each other to develop a new idea, and this combined activity also helps to investigate the undergoing research activities from two perspectives which increases the efficiency of arriving at an appropriate decision. Additionally, the said approach was also found to be a proactive design solution by evaluating the developed concepts based on a given design characteristics using the experiences of the concerned stakeholders as input for making a final decision. A little consideration shows that, the above approach encourages the importance of adopting a multi-directional design approach and evaluation process as a helpful tool to reach into a final solution quickly and precisely.

7.2 Conclusion

The challenges of caregivers and their clients keep rising until appropriate assistive devices and services are provided to them. One of the reasons was stated as lack of context-appropriate design of transfer device because most AT products are often manufactured using parts that are not replaceable locally, contributing to high abandonment rates. Because of a few of the above reasons, patient transferring activities, known as one of the most physically demanding tasks, tend to expose the respective caregivers and their clients to ergonomic stress. The severity of the ergonomic stress during such activities was also found to be the worst in areas with no appropriate means of transferring devices. In order to find a suitable transfer device in the proposed context, in this

thesis, a design research approach was used. Based on this approach, a comprehensive literature review was carried out on the existing transfer devices once the general research gaps had been identified. It was planned to reframe the tasks contextually or locally by observing the current needs of the stakeholders in selected healthcare centres. For this purpose, a questionnaire-based survey comprising three categories of participants was conducted at a selected hospital.

The state of the arts of the existing transfer devices showed that almost all of the prior researchers have focused on evaluating the effectiveness of the existing transfer devices, especially the ceiling and floor-based devices, rather than searching for a new means of transfer device that keeps both the caregiver and the users safe, their main criteria while assessing the existing TADs were to measure the amount of low back pain developed by the respective caregivers instead of the users. According to the review, none of the studies used biomechanical evaluations on critical components of the transfer devices, such as the handle design, supporting mechanism and the device's manoeuvrability. The advantages of conducting a biomechanical evaluation on the selected critical components were also highlighted as it would help to identify wrongly designed components that lead to low back pain. At the same time, it becomes easy to modify a particular component with a minimum cost instead of discarding the entire device.

Generally, this thesis has also introduced an alternative method to design a transfer device by integrating the biomechanics concepts in a human-machine environment using DHM and ergonomics aspects as a design tool to design the present TAD. Part of the present study investigates how the high level of compatibility between the 3D conceptual model and the final product suitable for the end-users could be achieved proactively by adopting the current techniques of a human-machine approach. Similarly, using innovative ideas in a human-machine environment at the beginning of the design process successfully optimized the overall design process by choosing an appropriate and cost-effective component that could fit and work in a compact space without an extra auxiliary unit.

The user-centred concept generation and selection process has greatly emphasized using an interactive combination of the user as a human model and the 3D model of the transfer device in a digital human modelling environment. This method represents the interaction between humans and machines to simplify the product development process throughout the conceptualization to evaluation phases. Kinematic analysis and synthesis have been shown to serve as a foundation for every product development cycle during the design processes, especially when software assists in the design synthesis; it can reduce known time-consuming rigorous tasks. The automated human modelling environment also provides a platform for evaluating the dynamics of human-machine relationships in order to detect any intrusion that could cause discomfort. The human motion's exact trajectory curve during a transfer phase is taken as a boundary range; for estimating the intended device's extreme limits, the proposed concept under the process is expected to follow the human motion path.

The result of the present study indicates that combining the product conceptualization process and biomechanics will greatly improve the product design and development process, especially when the product needs special consideration from the user's health perspective, such as designing for disabled individuals. The transfer assistive device (TAD) developed in this study also contributed a unique feature, such as the armpit support, which dynamically reduces the contact force due to the curvature profile of the under-arm support. It also helps as double safety support and prevents a sudden fall that might occur due to the device handle's unconscious release, which is the frequent fall in most transfer assistive devices. This technique generally improves the mobility of people with lower limb disabilities who use wheelchairs. It illustrates how designers can successfully use the available tools and spaces without interfering with users' free mobility or undermining the device's performance. Finally, one may infer that the results of this design process can help improve the current accessibility and affordability challenges of such technologies in both healthcare institutions and residential customers, especially in low-income, developed countries.

7.2.1 Limitations of this Research

The following limitations were observed in the present research: -

- The current study was conducted in laboratory simulation environments with students and institute staff acting as patients; therefore, more analysis is needed to examine the research under real-world patient transfer circumstances.

7.2.2 Research Contribution and Expected Outcomes

- Details about integrating the biomechanical model in a product design phase were introduced during concept ideation and selection using DHM and Advanced Sketcher workbench, which will be expected to be useful for similar product development phases.
- A simple alternative methodology for identifying an optimum handle design orientation was presented using a human-machine approach based on the EMG data recorded during the experiment.
- A novel saddle and underarm support design were developed for the present transfer assistive device that could reduce the strain level and avoid the accident of falling, which is not the case in similar existing products.
- A simple Biomechanical loading prediction equation was formulated to determine the compressive loads at the L5/S1 lumbar spine for any load and handle orientations, which would be helpful in the early estimation of musculoskeletal disorders in a similar product.
- Detailed manufacturing drawings are documented for further modification and production.
- A fully functional transfer assistive device utilizing a few components was developed.

Generally, the above points are some of the highlighted contributions of the work undertaken in the thesis. The advantages of using a context-driven design research approach opened a door for conducting a given research from two perspectives, from design and research point of view; based on this method, additional findings were also presented. The report under this thesis investigated

a novel way to estimate the orientation and location of a handle in a given product concept; manipulation of this selected handle design was observed to let the users in a biomechanically accepted transfer posture. Besides this feature, the adopted method also ensured the selected handle design from the recorded values of the compressive load at L5/S1.

Most of the software with biomechanical analysis applications does not support custom-based evaluation of the given posture. As per the knowledge of the author, no software was found to estimate the compressive loads at L5/S1 for the transfer posture, which was considered in this thesis; therefore, in this thesis, a custom formula was proposed and applied while evaluating the handle design from a biomechanics point of view. The novel method used for calculating the compressive load at L5/S1 in the transfer posture was one of the achievements in the present report, and this can be considered a general finding valid from a broader perspective. It should be noted that this method can also be used for any other similar handle design development in a particular transfer device.

7.2.3 Future Research Study

The presented thesis has attempted to develop a prototype of a patient transfer assistive device using a context-driven research approach; this device was evaluated at several stages both during product conception and after prototype development phases to ensure its reliability and suitability for the user. It has been found that the developed device was able to transfer users safely by keeping a biomechanically accepted posture and with a low level of compressive load at L5/S1. Even though the newly developed device has many more salient features than the existing transfer devices, more features are also needed to enhance its usability; therefore, additional features, such as upgrading its manoeuvrability, will be recommended as a future research opportunity.

The primary requirement of the users using the present transfer device is that they should be healthy in their upper limbs; they should be able to control it privately using normal means of control. However, some individuals are not able to control such devices using the above control method due to their health condition; therefore, in order to control such devices by individuals who have a motor neuron disease or total paralysis, the author would recommend developing mind-controlled Electroencephalography (EEG) technique that works with the existing transfer device in the future work.

The intended places for using the newly developed transfer assistive device were limited from one ward to another ward or within the ward. However, there might be scenarios where such devices should be taken out of the healthcare centre, or there might be another case, considering the device needs to be taken from the store to home. In order to solve such issues, the following design features, such as redesigning the developed transfer assistive device to be more retractable, easy to package, portable and easy for transportation, will be another future work to consider.

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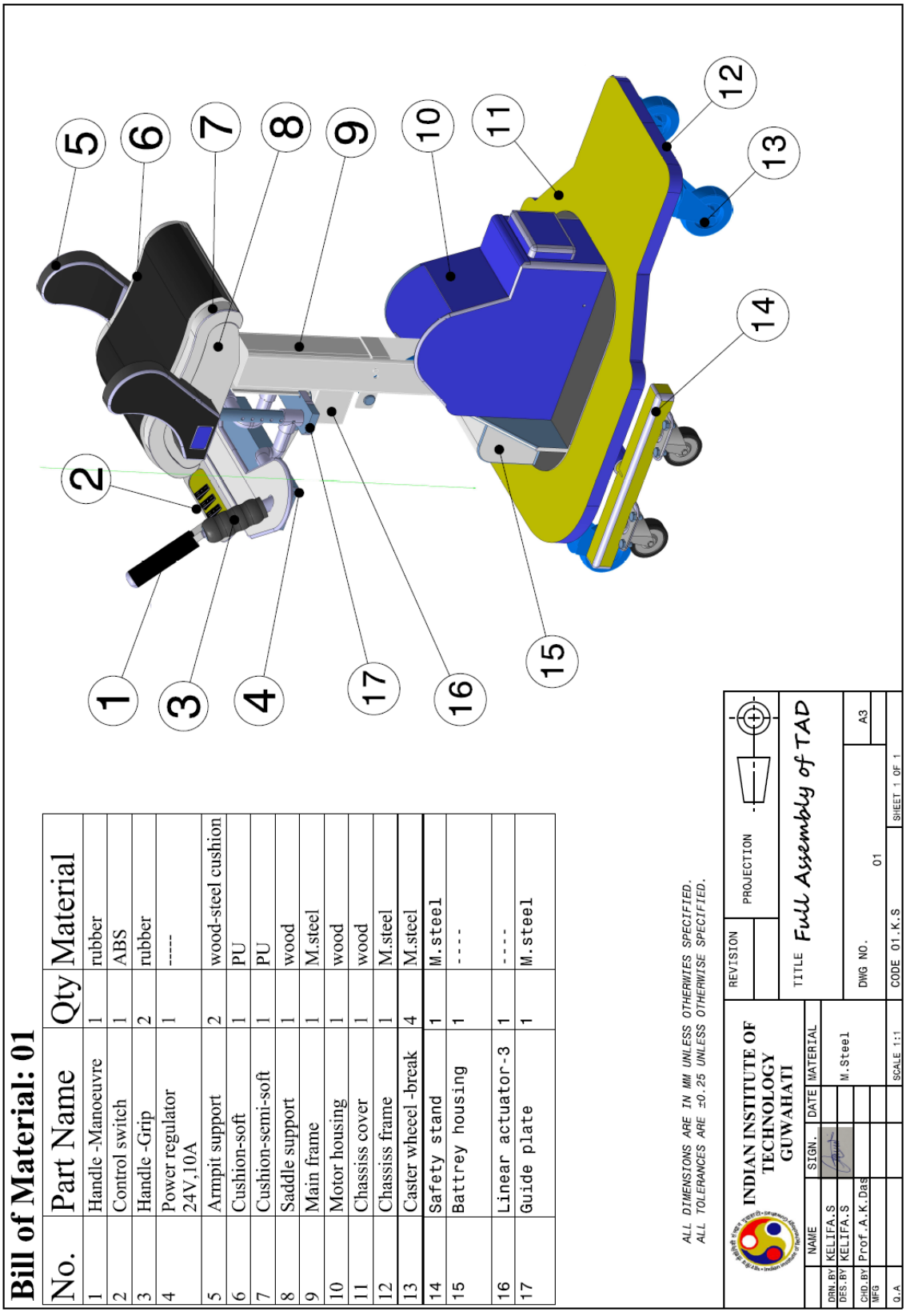
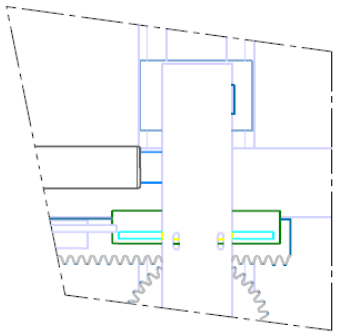
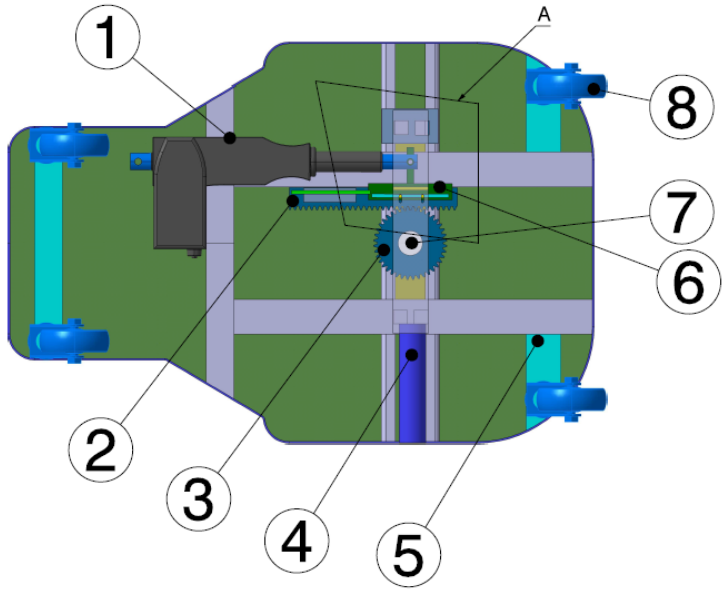
I. Appendix-1 Assembly and Subassembly of the Transfer Assistive Device

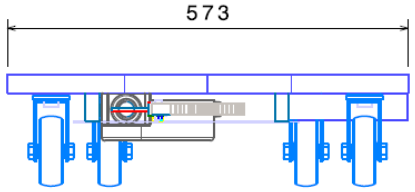


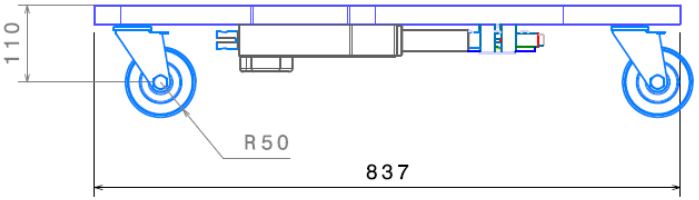
	BILL OF MATERIAL CHASSISS		
No.	Part name	Qty	Material
1	Linear actuator-1	1	----
2	Rack with attachement	1	m.steel
3	Pinion Gear	1	m.steel
4	support for safety stand	1	steel pipe
5	caster wheel bracket	1	m.steel
6	Guide way	1	m.steel
7	main shaft	1	m.steel
8	caster wheel	4	steel



Detail A
Rack and pinion mesh







ALL DIMENSIONS ARE IN MM UNLESS OTHERWIES SPECIFIED.
ALL TOLERANCES ARE ±0.25 UNLESS OTHERWISE SPECIFIED.

INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI

REVISION | PROJECTION

	NAME	SIGN.	DATE	MATERIAL
DRN.BY	KELIFA.S			
DES.BY	KELIFA.S			-----
CHD.BY	Prof.A.K.Das			
MFG				
Q.A				SCALE 1:1

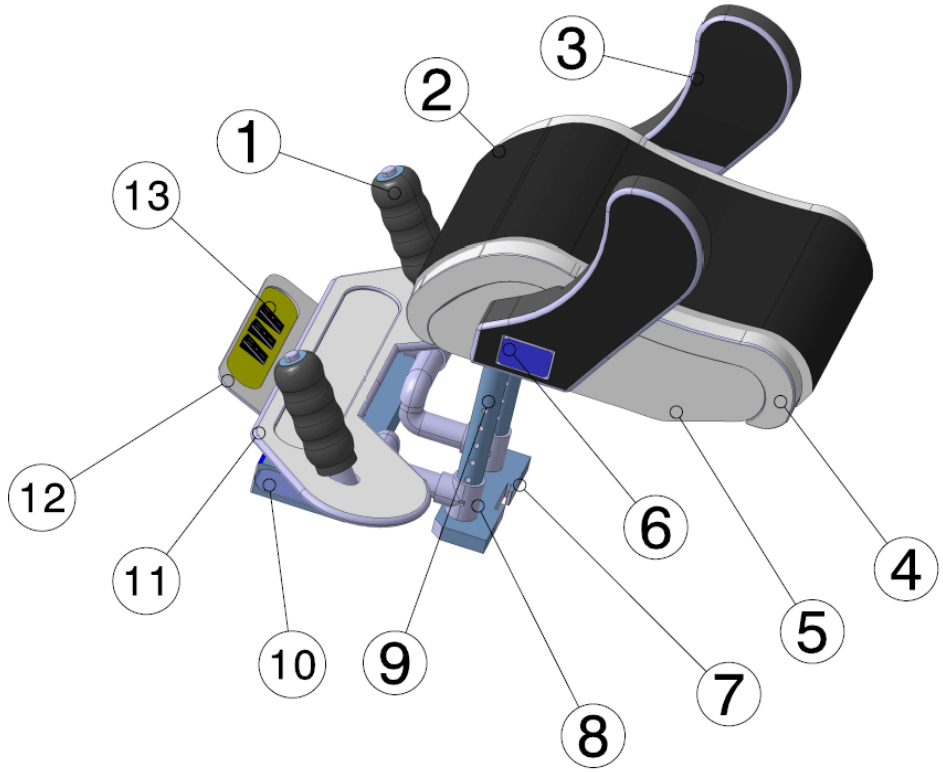
TITLE: *Full Assembly of chassiss*

DWG NO. 04 | A3

CODE 01.K.S | SHEET 1 OF 1

Bill of Material Saddle Assembly

No.	Part name	Qty	Material
1	Hand grip	2	st&rubber
2	Cushion-soft	1	pu
3	Armpit Support	2	st &wood
4	Cushion semi soft	1	pu
5	Saddle	1	wood
6	Armpit connecting rod	2	m.steel
7	Guide plate	1	m.steel
8	T-connector	4	m.steel
9	Handle adjusting rod	2	m.steel
10	Power regulator 24v.10A	1	----
11	Switch pannel	1	ABS
12	Switch movable	1	ABS
13	DPDT buttons	3	ABS



ALL DIMENSIONS ARE IN MM UNLESS OTHERWIES SPECIFIED.
ALL TOLERANCES ARE ±0.25 UNLESS OTHERWISE SPECIFIED.

INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI

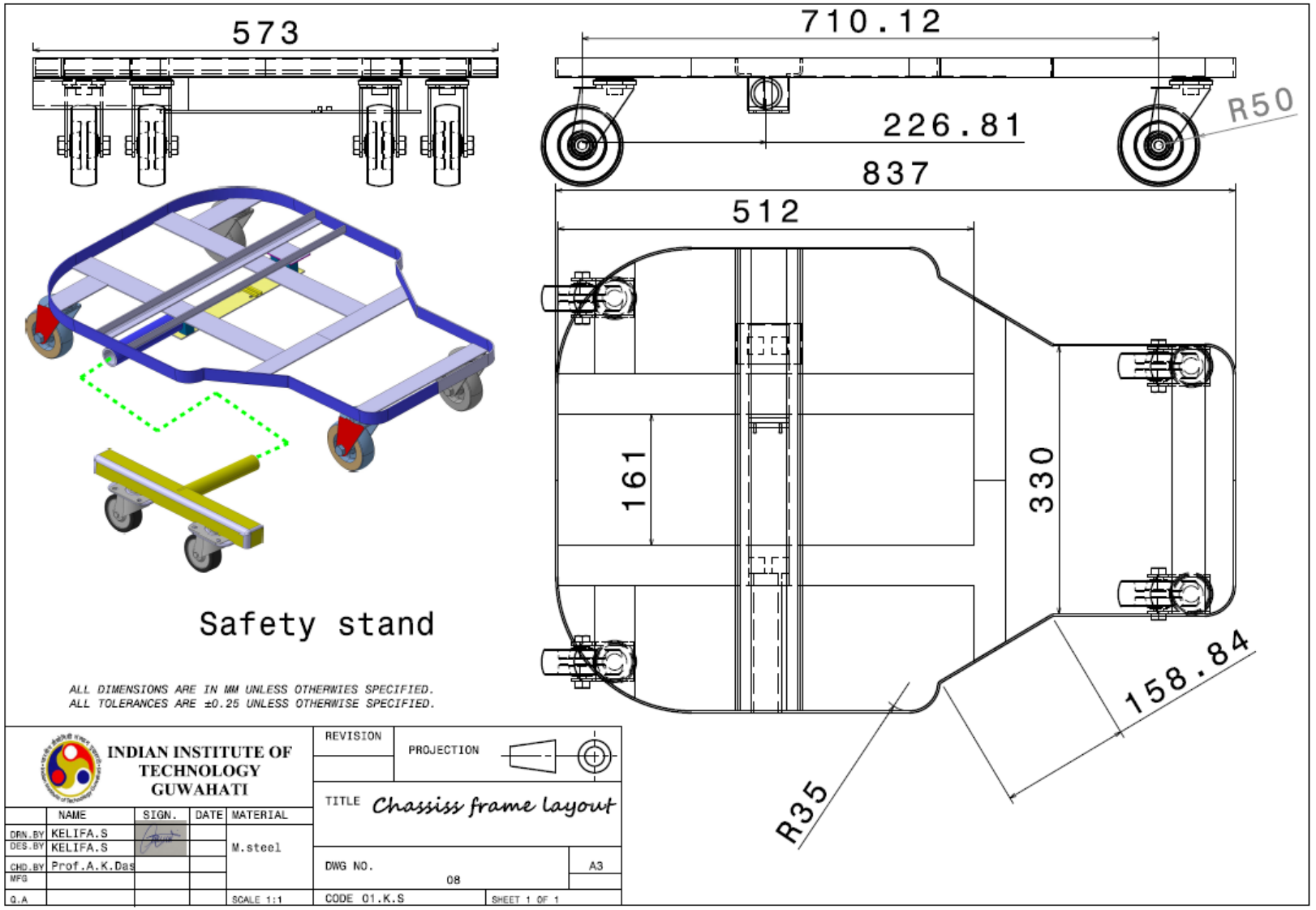
REVISION | PROJECTION

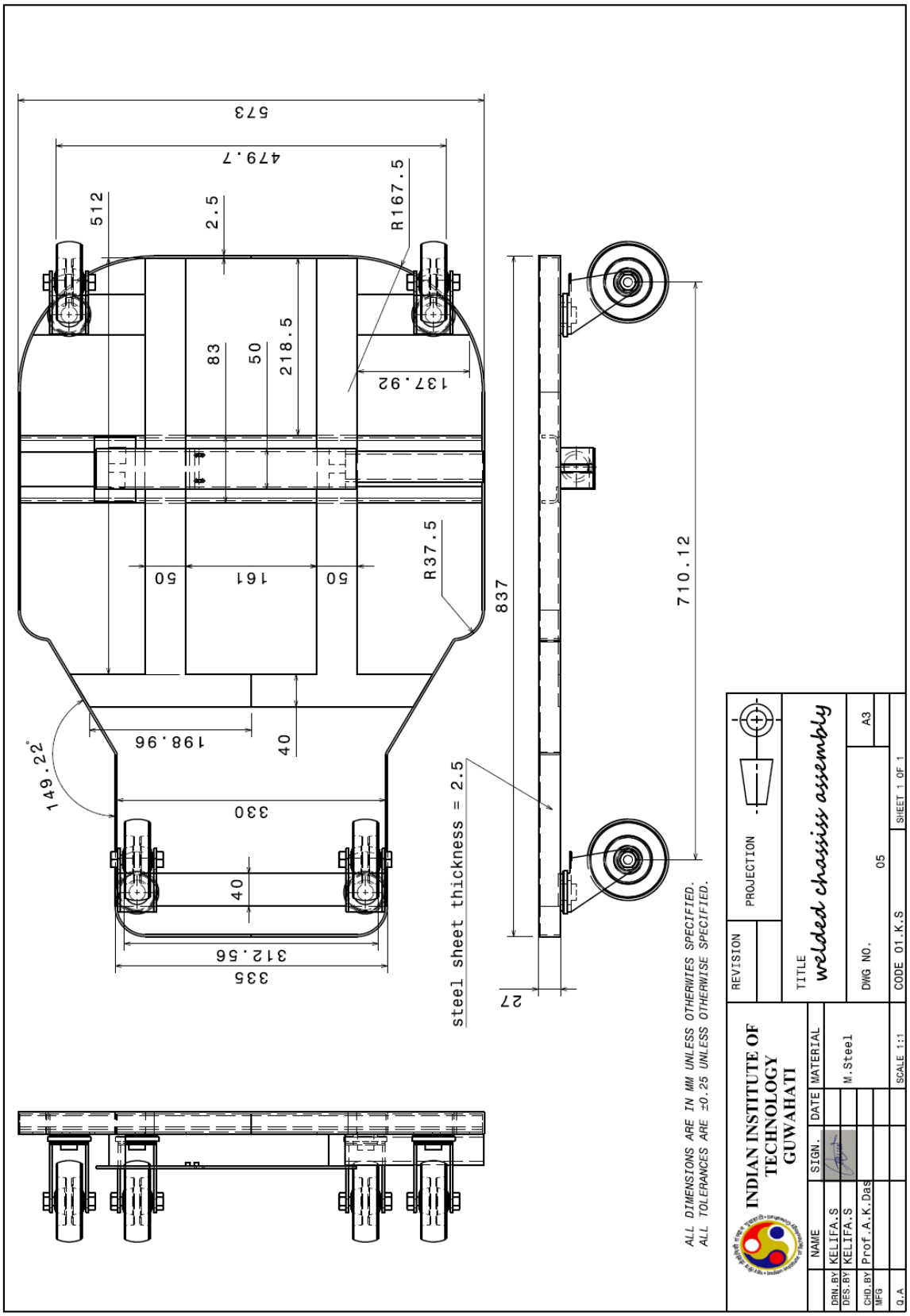
TITLE: *Assembly of top support*

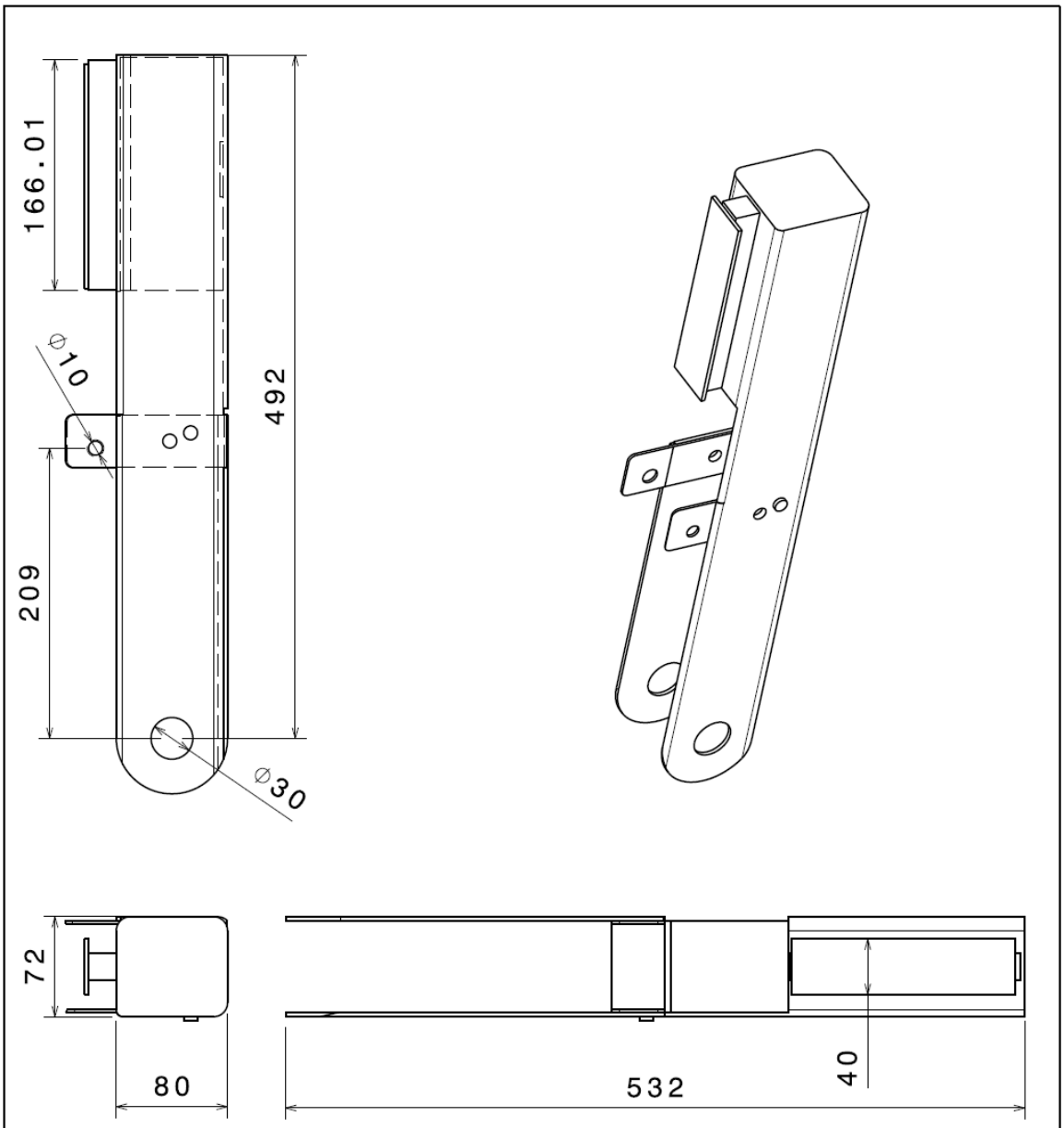
	NAME	SIGN.	DATE	MATERIAL
DRN.BY	KELIFA.S			----
DES.BY	KELIFA.S			
CHD.BY	Prof.A.K.Das			
MFG				
Q.A				SCALE 1:1

DWG NO. 06 | A3

CODE 01.K.S | SHEET 1 OF 1





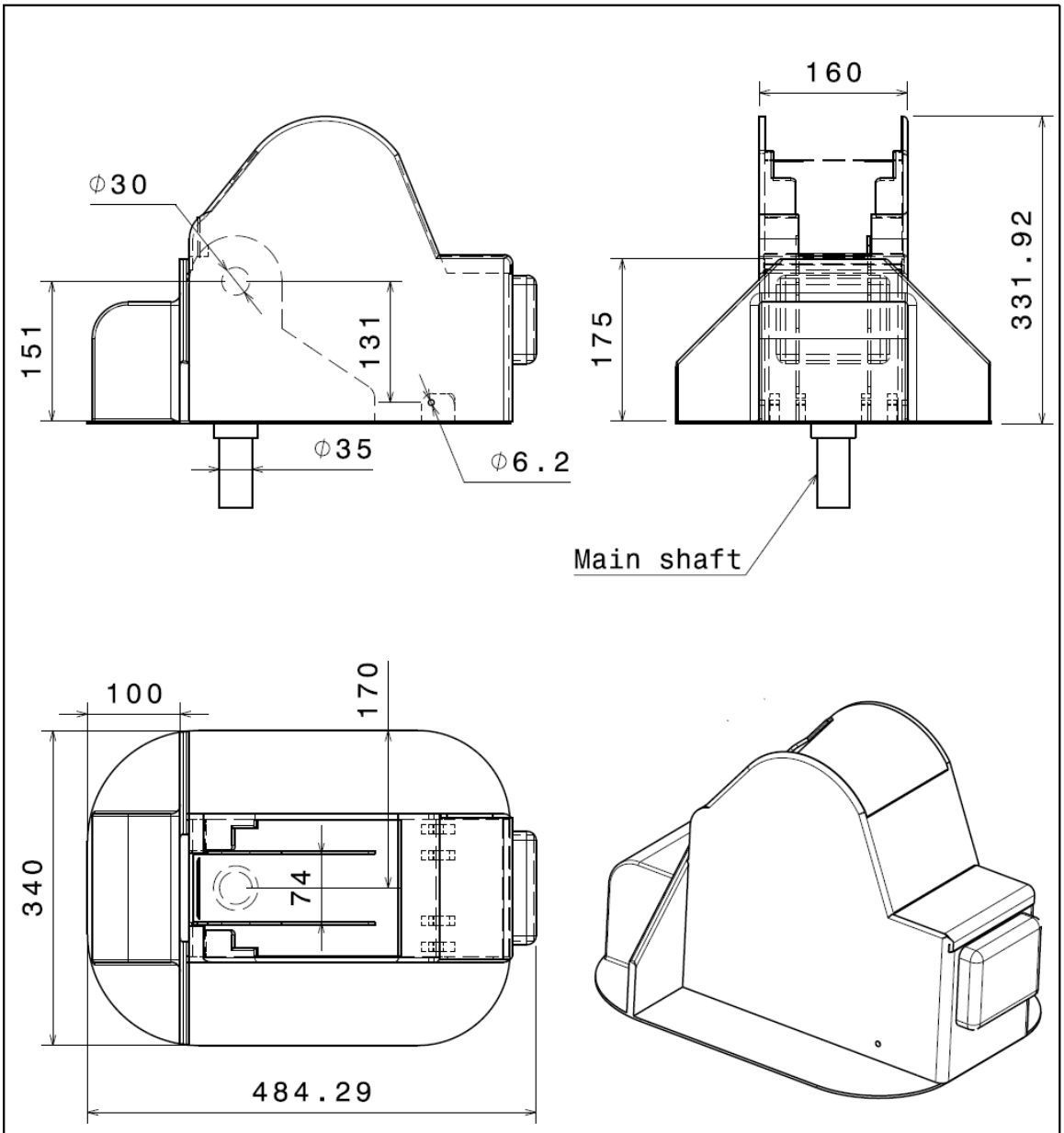


ALL DIMENSIONS ARE IN MM UNLESS OTHERWIES SPECIFIED.
ALL TOLERANCES ARE ±0.25 UNLESS OTHERWISE SPECIFIED.

INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI

	NAME	SIGN.	DATE	MATERIAL
DRN.BY	KELIFA.S			M.Steel
DES.BY	KELIFA.S			
CHD.BY	Prof.A.K.Das			
MFG				
Q.A				SCALE 1:1

REVISION	
PROJECTION	
TITLE	main frame
DWG NO.	02
A4	
CODE 01.K.S	SHEET 1 OF 1



ALL DIMENSIONS ARE IN MM UNLESS OTHERWIES SPECIFIED.
ALL TOLERANCES ARE ±0.25 UNLESS OTHERWISE SPECIFIED.

INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI

	NAME	SIGN.	DATE	MATERIAL
DRN.BY	KELIFA.S			M.Steel & wood
DES.BY	KELIFA.S			
CHD.BY	Prof.A.K.Das			
MFG				
Q.A				SCALE 1:1

REVISION

PROJECTION

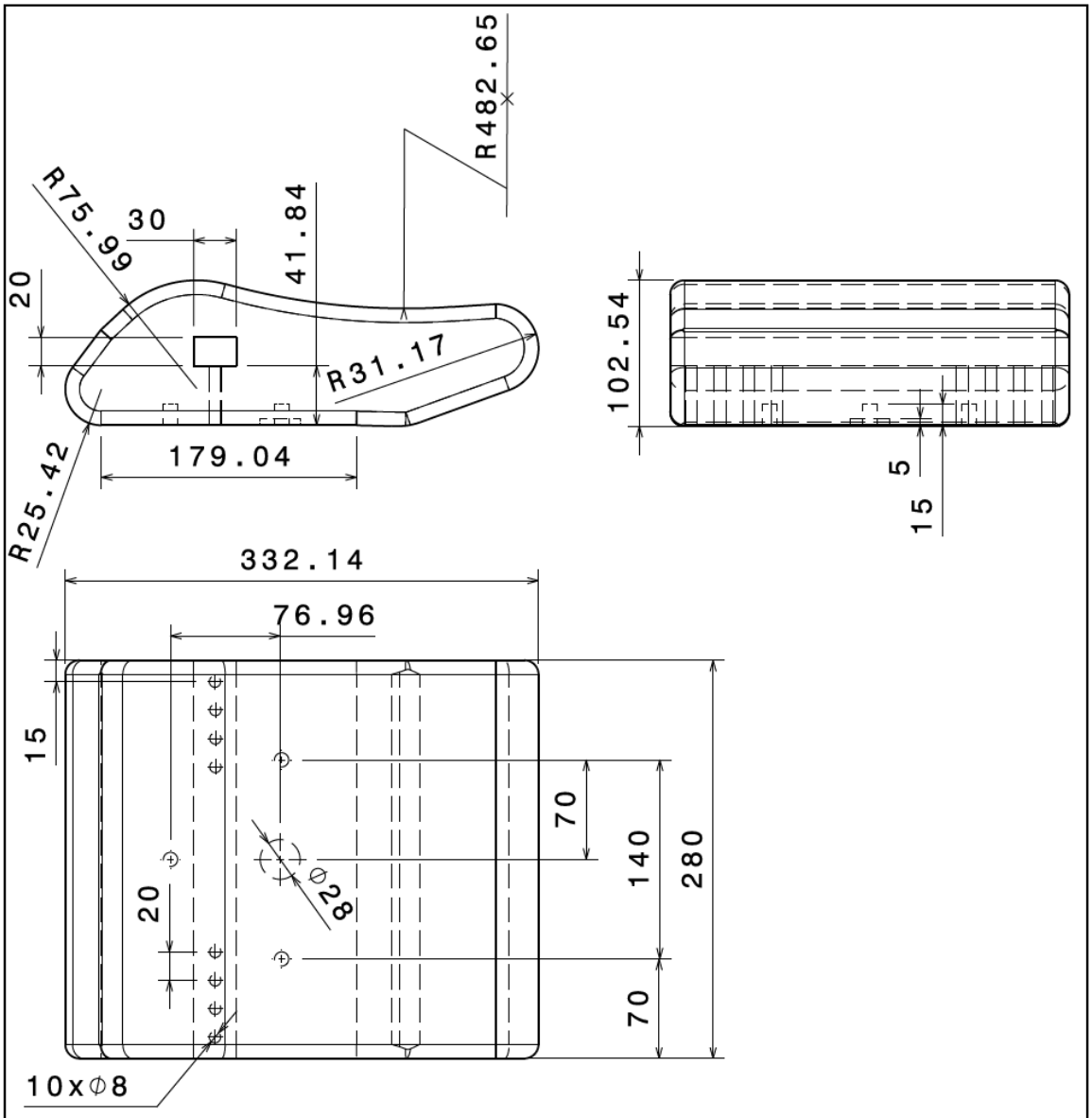
TITLE
Main motor housing and rotatig platform

DWG NO. 03

A4

CODE 01.K.S

SHEET 1 OF 1

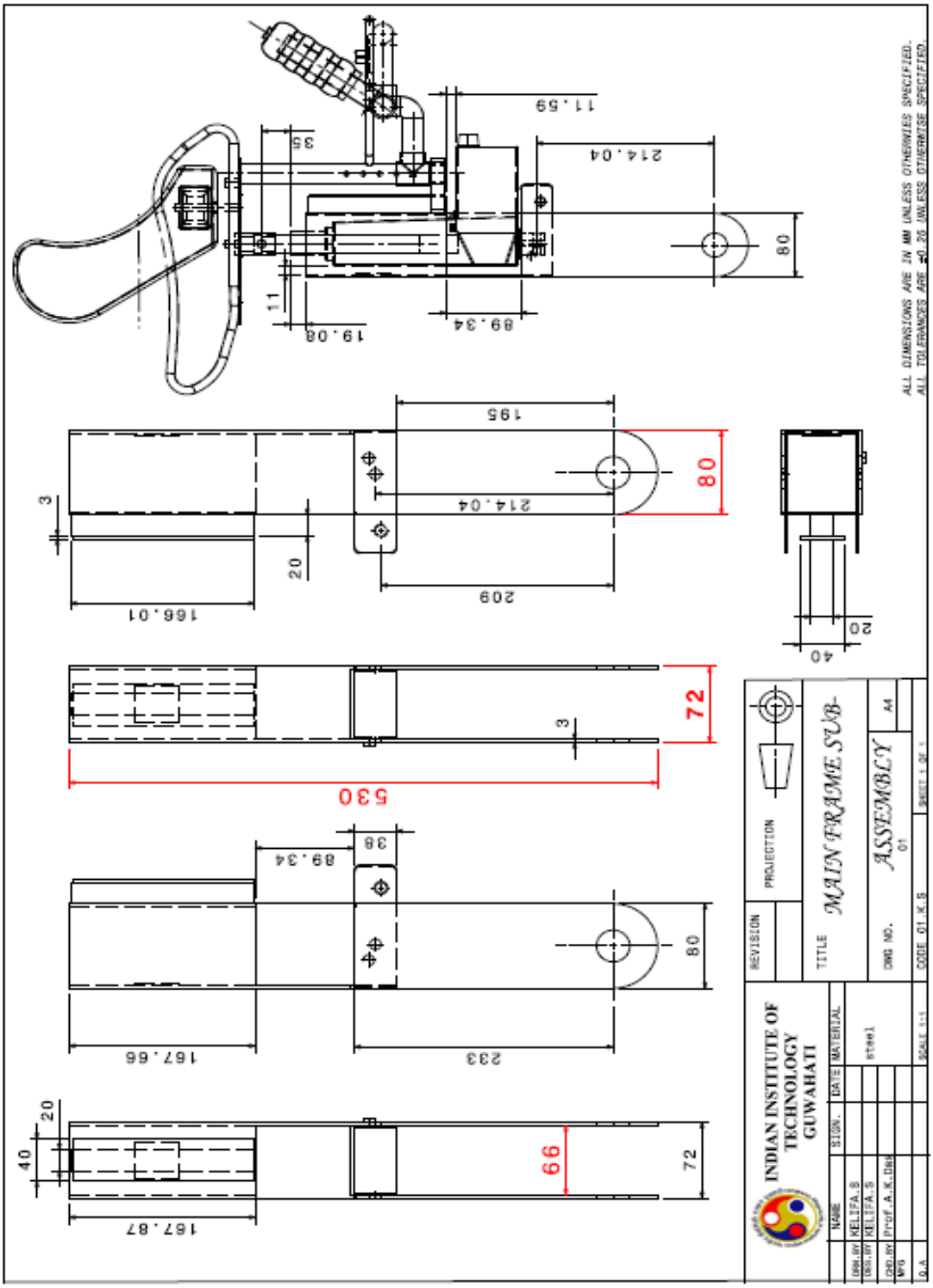


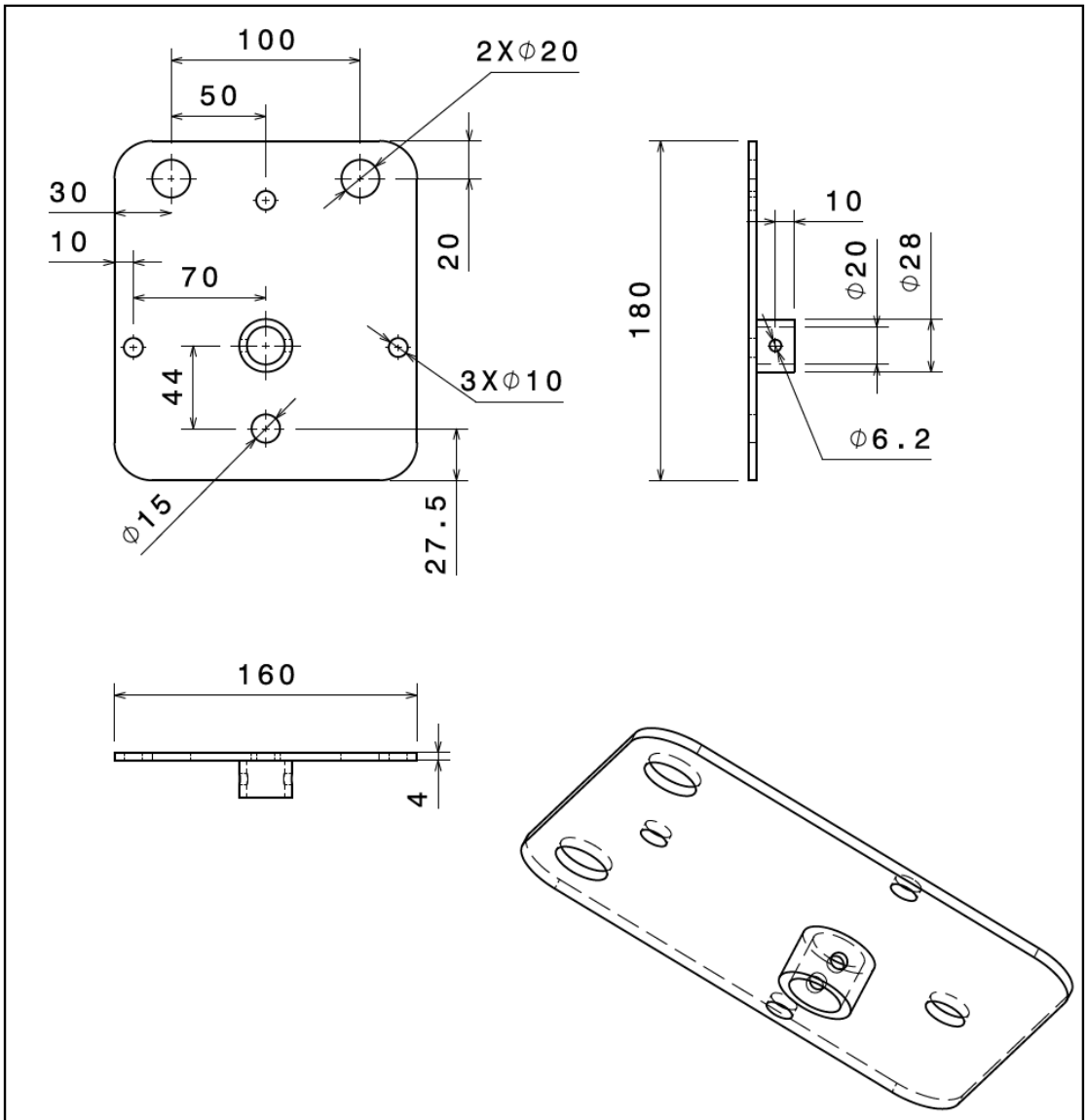
ALL DIMENSIONS ARE IN MM UNLESS OTHERWIES SPECIFIED.
ALL TOLERANCES ARE ±0.25 UNLESS OTHERWISE SPECIFIED.

INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI

	NAME	SIGN.	DATE	MATERIAL
DRN.BY	KELIFA.S			Wood with Al- Alloy
DES.BY	KELIFA.S			
CHD.BY	Prof.A.K.Das			
MFG				
Q.A				SCALE 1:1

REVISION	PROJECTION
TITLE	SADDEL
DWG NO. 02	A4
CODE 01.K.S	SHEET 1 OF 1



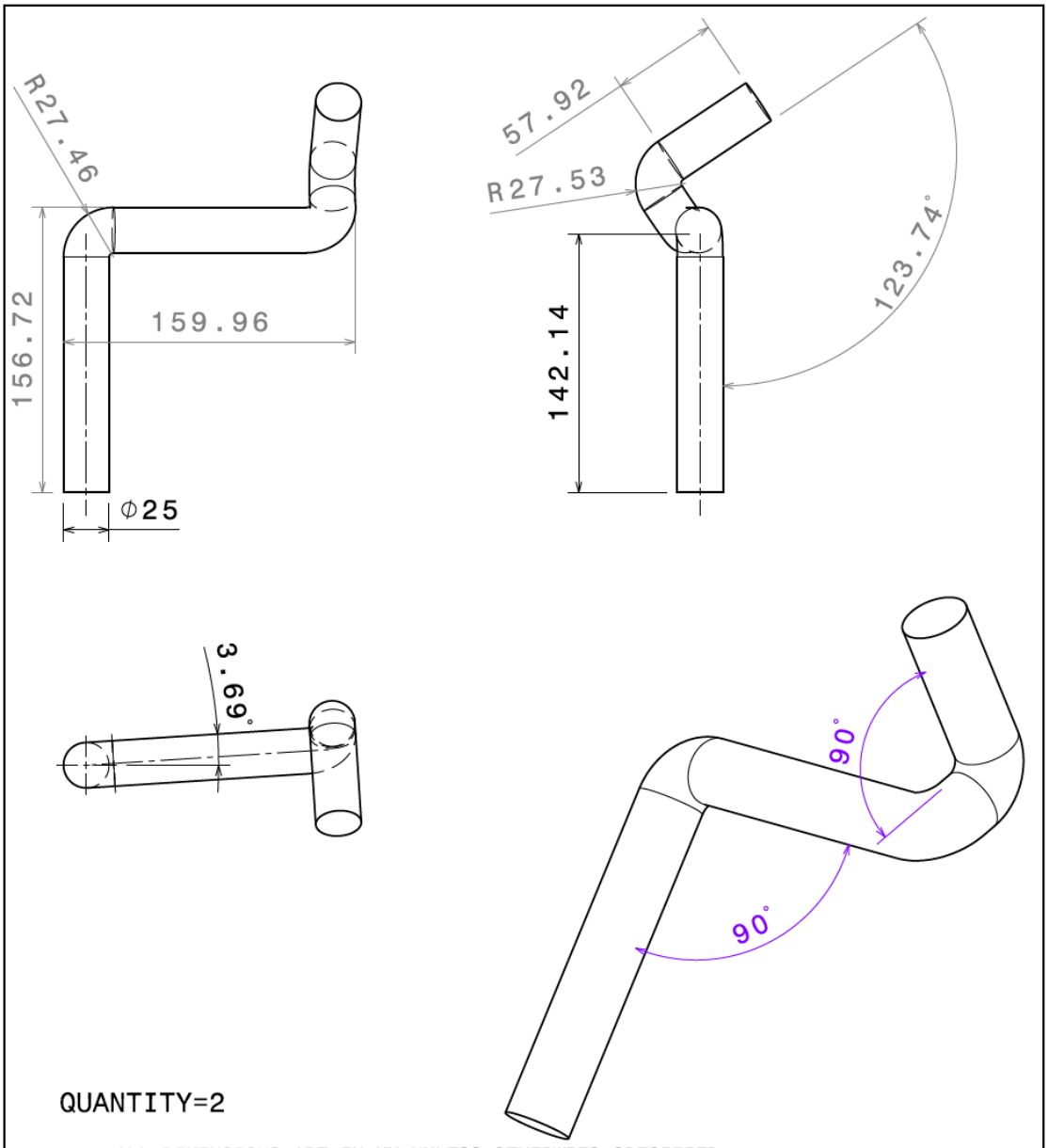


ALL DIMENSIONS ARE IN MM UNLESS OTHERWIES SPECIFIED.
ALL TOLERANCES ARE ±0.25 UNLESS OTHERWISE SPECIFIED.

INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI

	NAME	SIGN.	DATE	MATERIAL
DRN.BY	KELIFA.S			Al- Alloy
DES.BY	KELIFA.S			
CHD.BY	Prof.A.K.Das			
MFG				
Q.A				SCALE 1:1

REVISION	PROJECTION
TITLE	SADDEL SUPPORT
DWG NO. 04	A4
CODE 01.K.S	SHEET 1 OF 1



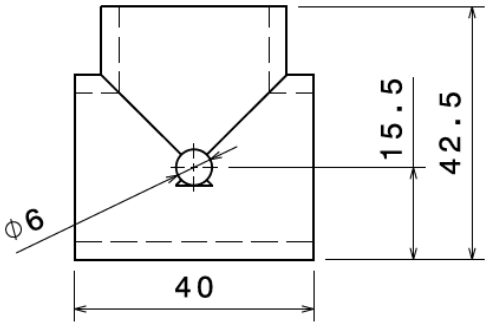
QUANTITY=2

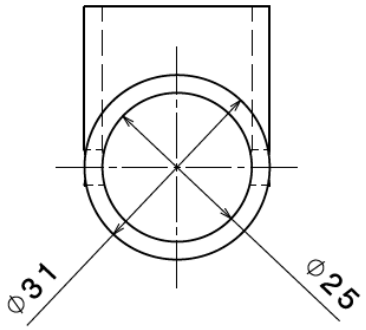
ALL DIMENSIONS ARE IN MM UNLESS OTHERWIES SPECIFIED.
ALL TOLERANCES ARE ±0.25 UNLESS OTHERWISE SPECIFIED.

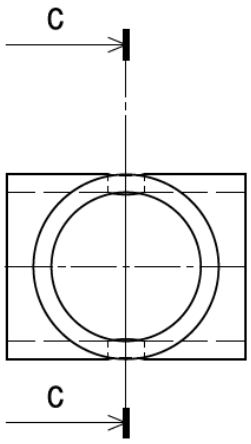
INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI

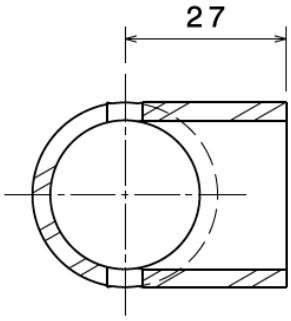
	NAME	SIGN.	DATE	MATERIAL
DRN.BY	KELIFA.S			Al- Alloy
DES.BY	KELIFA.S			
CHD.BY	Prof.A.K.Das			
MFG				
Q.A				SCALE 1:1

REVISION	PROJECTION
TITLE	HAND GRIP ROD
DWG NO. 08	A4
CODE 01.K.S	SHEET 1 OF 1







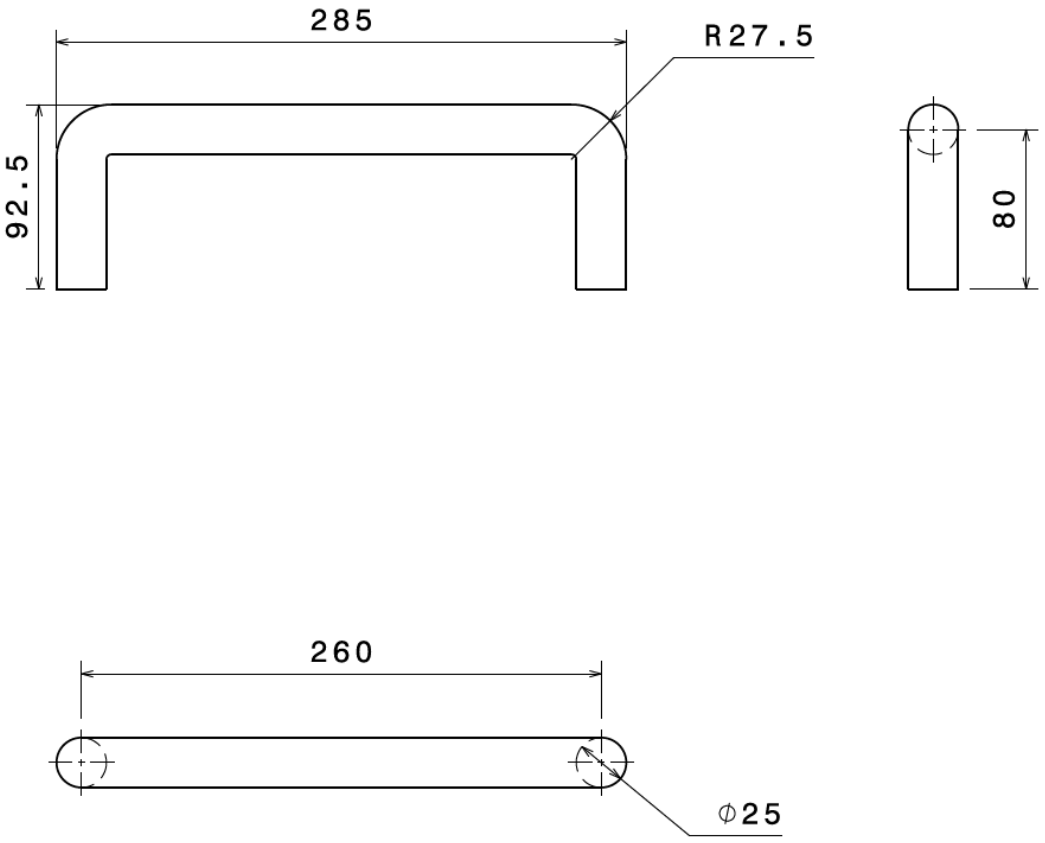


Section view C-C
Scale: 1:1

QUANTITY=4

ALL DIMENSIONS ARE IN MM UNLESS OTHERWIES SPECIFIED.
ALL TOLERANCES ARE ±0.25 UNLESS OTHERWISE SPECIFIED.

INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI					REVISION	PROJECTION
	NAME	SIGN.	DATE	MATERIAL	TITLE	T-CONNECTOR
DRN.BY	KELIFA.S			Al- Alloy		
DES.BY	KELIFA.S					
CHD.BY	Prof.A.K.Das				DWG NO. 09	A4
MFG						
Q.A				SCALE 1:1	CODE 01.K.S	SHEET 1 OF 1

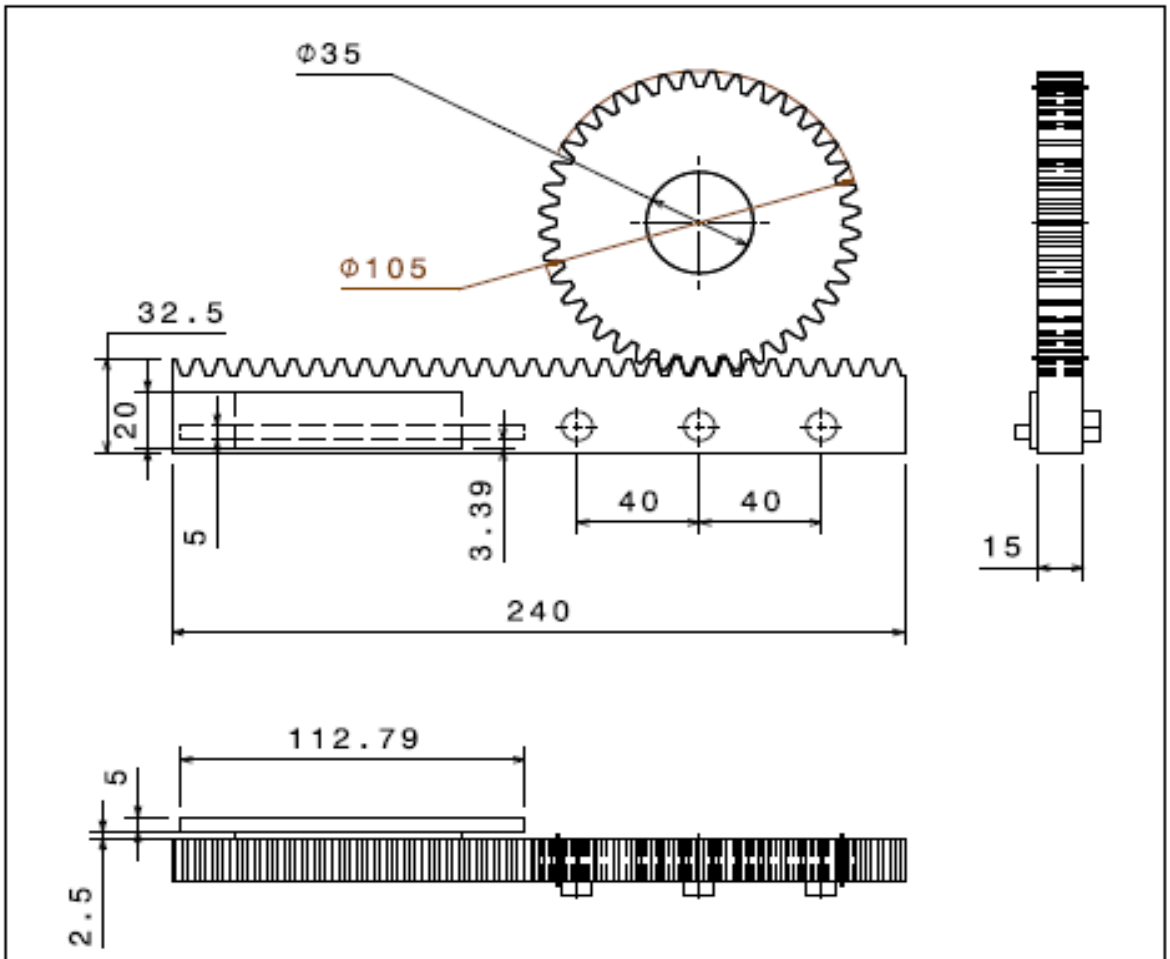


ALL DIMENSIONS ARE IN MM UNLESS OTHERWIES SPECIFIED.
ALL TOLERANCES ARE ±0.25 UNLESS OTHERWISE SPECIFIED.

INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI

	NAME	SIGN.	DATE	MATERIAL
DRN.BY	KELIFA.S			Al- Alloy
DES.BY	KELIFA.S			
CHD.BY	Prof.A.K.Das			
MFG				
Q.A				SCALE 1:1

REVISION	PROJECTION
TITLE	HAND GRIP STIFFNER ROD
DWG NO. 11	A4
CODE 01.K.S	SHEET 1 OF 1



Number of teeth,**GEAR** =40, pitch circle diameter=100mm ,module =2.5 ,face width=15**RACK**, pitch height=32mm,length 240mm,face width=15mm,module 2.5

ALL DIMENSIONS ARE IN MM UNLESS OTHERWIES SPECIFIED.
ALL TOLERANCES ARE ±0.25 UNLESS OTHERWISE SPECIFIED.

INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI				REVISION	PROJECTION
	NAME	SIGN.	DATE	MATERIAL	TITLE: RACK & PINION
DRN.BY	KELIFA.S			steel	
DES.BY	KELIFA.S				
CHD.BY	Prof.A.K.Das				DWG NO. 01 — A4
MFG					
Q.A				SCALE 1:1	CODE 01.K.S — SHEET 1 OF 1

II. Appendix-2 Sample Questionnaire

INDIAN INSTITUTE OF TECHNOLOGY-GUWAHATI

Survey Cover Letter and Questionnaire

On

Self-Transfer Assistive Device

(Rehabilitation Engineer and Therapists)

Dear Sir/Madam

I am a research scholar at Indian Institute of Technology Guwahati, this Questionnaire is conducted as part of my Ph.D. program and its fundamental aim is to examine the relationship between the needs of the assistive transfer device users, carers, rehabilitation engineers, therapists and product requirements from biomechanics and ergonomics point-of-view. Part of this aim involves at exploring the stakeholders view regarding the design features or gaps in the existing patient handling or transfer devices in order to gain a better understanding for further design improvement. I would be extremely grateful if you would agree to spare about 5 minutes to answer the questionnaire by ticking the appropriate box(s) and giving your valuable comments or suggestions when necessary, your answers will be very much appreciated and valued and will help to make the current assistive transfer devices better suited to the needs of all their users. Be assured that the data collected will be kept confidential and no firm, organization or individual will be identified in the thesis or in any report or publication based on this research.

Thank you in advance for your co-operation.

Yours sincerely
Kelifa Seid
Contact (+919127510944)

INDIAN INSTITUTE OF TECHNOLOGY-GUWAHATI

Questionnaire for Rehabilitation Engineer and Therapists

1. What is your professional background?

☐ Rehabilitation Engineer ☐ Physiotherapist
☐ Occupational therapist ☐ Others

2. Do you take part in the assistive device prescription or assessment process?

☐ Yes ☐ No

3. Have you ever been in contact with designers or manufacturers and tried to share your experience regarding the existing transfer assistive devices from your clients' point of view?

☐ Yes ☐ No

4. Which types of Transfer methods or devices are commonly practiced for transferring your clients? (please tick as many as apply)

☐ Slide sheet

☐ Slide board

☐ Ceiling hoist

☐ Sling hoist

☐ Manual (caregiver)

☐ Trolleys

☐ Standing hoist

☐ Others

Please mention if you have answered as "**others**"_____

5. Which types of mobility aids are commonly practiced by your clients? (please tick as many as apply)

☐ Elbow crutches ☐ Rollator frame ☐ Powered wheelchair ☐ Manual Wheelchair




☐ Four wheel walker ☐ Others

6. How did you rate your client's perception with respect to the existing Transfer methods or assistive devices application?

☐ Extremely good ☐ Good ☐ Average
☐ Fair ☐ Extremely not good

7. Generally speaking, based on your experience on other types of transfer devices, how do you rate the importance of implementing a combined mechatronic transfer assistive device that can be easily attached/detached to /from a wheelchair , and has the ability to transfer an immobile clients independently from wheelchair to other seats and vice versa?

☐ Extremely important ☐ Important ☐ Average
☐ Fair ☐ Not important

8. Which control option (s) do you recommend for controlling or guiding the transfer device initially attached to a wheelchair? (please tick as many as apply)

☐ Independent (only by the user) ☐ Dependent (only by the carer)
☐ Both options should be included

9. Do you think that privacy and independency of clients during their daily personal activities can be enhanced while using a combined transfer device which is attached to a wheelchair?

☐ Yes ☐ No ☐ Maybe

8. Which control option (s) do you recommend for controlling or guiding the transfer device initially attached to a wheelchair? (please tick as many as apply)

☐ Independent (only by the user) ☐ Dependent (only by the carer)

☐ Both options should be included

9. Do you think that privacy and independency of clients during their daily personal activities can be enhanced while using a combined transfer device which is attached to a wheelchair?

☐ Yes ☐ No ☐ Maybe

10. Do you think that application of Biomechanics and Ergonomics is important in the design process of a transfer assistive devices for totally immobile clients?

☐ Yes ☐ No ☐ Maybe

11. Which characteristic features do you recommend as most important to be included in the design process of a transfer assistive devices? (please tick as many as apply)

☐ Safety ☐ Aesthetics ☐ Comfort

☐ Usability ☐ Maneuverability ☐ Reliability

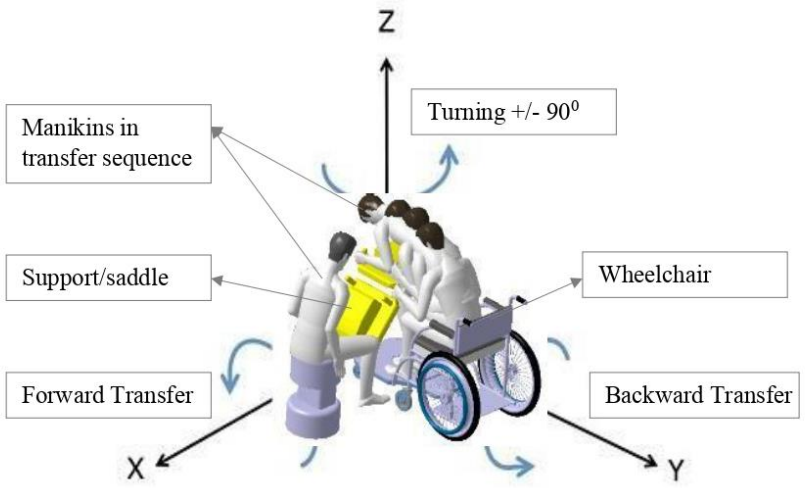
☐ Stability ☐ Adjustability ☐ Cost

12. The pre-concept of 3D model and its transfer technique / algorithm is shown below with three transfer phases, Conceptually,this device can be controlled by the user and it has the ability to lift up the whole body of the user and turn/rotate +/-90^0 from the wheelchair to other surfaces. Please rate this device in terms of the listed characteristics features based on your experience on the existing transfer methods or devices. Please also give your comments below for further modification of the concept.

Characteristics	Extremely Good.	Good	Average	Fair	Not Good
Sequence of transfer	☐	☐	☐	☐	☐
Independency /Privacy of user	☐	☐	☐	☐	☐
Safety	☐	☐	☐	☐	☐
Design simplicity	☐	☐	☐	☐	☐
User interface	☐	☐	☐	☐	☐
Compactness	☐	☐	☐	☐	☐

Definitions:-

Safety: to eliminate the risks of injury throughout the life of a product being designed.
Aesthetics: is the visual attractiveness of a product
Comfort: is a state of physical ease and freedom from pain or constraint
Usability: is the degree to which a device is able or fit to be used.
Maneuverability: is an easy to move and direct the transfer device
Reliability: is probability that a device will perform its required function, subjected to stated conditions, for a specific period of time.
Stability: is ability of a device to remain stable in its position and to avoid overturning.
Adjustability: is the quality of being adjustable to fit various users of the device
Cost: is the term to indicate the final selling price of the finished product.



Write (if any) your valuable suggestions or comments that can help in the design and developmental process of the proposed design_____

III. Appendix-3 Statistical Output Tables

- Descriptive statistics and Wilcoxon signed rank test tables.

Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles 25th	50th (Median)	75th
AD_HatEH	17	7.4100	4.80950	2.95	19.60	3.4200	5.9000	11.4950
AD_HbEH	17	9.2376	4.74840	3.83	21.38	4.6750	8.6400	12.6700
AD_HaEH	17	11.0088	4.67074	4.39	18.17	6.6200	11.0800	15.3650

Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles 25th	50th (Median)	75th
BB_HatEH	17	8.7435	4.96589	2.56	19.91	4.2150	8.8100	11.8800
BB_HbEH	17	10.5606	4.29831	3.87	17.31	6.9000	10.0900	14.4650
BB_HaEH	17	19.6312	3.58155	14.25	24.22	15.2900	21.1300	22.7150

Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles 25th	50th (Median)	75th
BR_HatEH	17	17.5771	5.02372	10.02	28.33	14.6150	16.8200	20.4250
BR_HbEH	17	24.8476	6.32496	15.00	37.74	20.0000	22.9800	28.5900
BR_HaEH	17	35.6724	5.59948	28.00	44.78	30.0000	34.9000	41.2750

Ranks

		N	Mean Rank	Sum of Ranks
AD_HbEH - AD_HatEH	Negative Ranks	5[a]	7.60	38.00
	Positive Ranks	12[b]	9.58	115.00
	Ties	0[c]		
	Total	17		
AD_HaEH - AD_HatEH	Negative Ranks	4[d]	3.75	15.00
	Positive Ranks	13[e]	10.62	138.00
	Ties	0[f]		
	Total	17		
AD_HaEH - AD_HbEH	Negative Ranks	5[g]	8.80	44.00
	Positive Ranks	12[h]	9.08	109.00
	Ties	0[i]		
	Total	17		

a. AD_HbEH < AD_HatEH
b. AD_HbEH > AD_HatEH
c. AD_HbEH = AD_HatEH
d. AD_HaEH < AD_HatEH
e. AD_HaEH > AD_HatEH
f. AD_HaEH = AD_HatEH
g. AD_HaEH < AD_HbEH
h. AD_HaEH > AD_HbEH
i. AD_HaEH = AD_HbEH

Ranks

		N	Mean Rank	Sum of Ranks
BB_HbEH - BB_HatEH	Negative Ranks	4[a]	7.00	28.00
	Positive Ranks	13[b]	9.62	125.00
	Ties	0[c]		
	Total	17		
BB_HaEH - BB_HatEH	Negative Ranks	1[d]	4.00	4.00
	Positive Ranks	16[e]	9.31	149.00
	Ties	0[f]		
	Total	17		
BB_HaEH - BB_HbEH	Negative Ranks	2[g]	3.00	6.00
	Positive Ranks	15[h]	9.80	147.00
	Ties	0[i]		
	Total	17		

a. BB_HbEH < BB_HatEH
b. BB_HbEH > BB_HatEH
c. BB_HbEH = BB_HatEH
d. BB_HaEH < BB_HatEH
e. BB_HaEH > BB_HatEH
f. BB_HaEH = BB_HatEH
g. BB_HaEH < BB_HbEH
h. BB_HaEH > BB_HbEH
i. BB_HaEH = BB_HbEH

Ranks

		N	Mean Rank	Sum of Ranks
BR_HbEH - BR_HatEH	Negative Ranks	1[a]	10.00	10.00
	Positive Ranks	16[b]	8.94	143.00
	Ties	0[c]		
	Total	17		
BR_HaEH - BR_HatEH	Negative Ranks	0[d]	.00	.00
	Positive Ranks	17[e]	9.00	153.00
	Ties	0[f]		
	Total	17		
BR_HaEH - BR_HbEH	Negative Ranks	0[g]	.00	.00
	Positive Ranks	17[h]	9.00	153.00
	Ties	0[i]		
	Total	17		

a. BR_HbEH < BR_HatEH
b. BR_HbEH > BR_HatEH
c. BR_HbEH = BR_HatEH
d. BR_HaEH < BR_HatEH
e. BR_HaEH > BR_HatEH
f. BR_HaEH = BR_HatEH
g. BR_HaEH < BR_HbEH
h. BR_HaEH > BR_HbEH
i. BR_HaEH = BR_HbEH

- Statistical output tables for investigating the effect of Under-arm support

Descriptives

			Statistic	Std. Error
AD WT UAS	Mean		13.1600	1.29547
	95% Confidence Interval for Mean	Lower Bound	10.4486	
		Upper Bound	15.8714	
	5% Trimmed Mean		12.7333	
	Median		12.5000	
	Variance		33.565	
	Std. Deviation		5.79351	
	Minimum		4.82	
	Maximum		29.18	
	Range		24.36	
	Interquartile Range		8.25	
	Skewness		.906	.512
	Kurtosis		1.738	.992
AD W UAS	Mean		9.5915	1.25025
	95% Confidence Interval for Mean	Lower Bound	6.9747	
		Upper Bound	12.2083	
	5% Trimmed Mean		9.2439	
	Median		7.8750	
	Variance		31.263	
	Std. Deviation		5.59131	
	Minimum		3.72	
	Maximum		21.72	
	Range		18.00	
	Interquartile Range		7.91	
	Skewness		.938	.512
	Kurtosis		-.013	.992

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
AD WT UAS	.128	20	.200*	.938	20	.222
AD W UAS	.160	20	.193	.876	20	.015

*. This is a lower bound of the true significance.

Descriptives

			Statistic	Std. Error
BR WT UAS	Mean		20.4806	1.98136
	95% Confidence Interval for Mean	Lower Bound	16.3335	
		Upper Bound	24.6276	
	5% Trimmed Mean		19.7312	
	Median		19.7950	
	Variance		78.516	
	Std. Deviation		8.86093	
	Minimum		7.56	
	Maximum		46.89	
	Range		39.33	
	Interquartile Range		3.86	
	Skewness		1.796	.512
	Kurtosis		4.347	.992
BR W UAS	Mean		9.1620	1.05177
	95% Confidence Interval for Mean	Lower Bound	6.9606	
		Upper Bound	11.3634	
	5% Trimmed Mean		8.7117	
	Median		9.4150	
	Variance		22.124	
	Std. Deviation		4.70365	
	Minimum		3.86	
	Maximum		22.57	
	Range		18.71	
	Interquartile Range		6.94	
	Skewness		1.138	.512
	Kurtosis		2.079	.992

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
BR WT UAS	.320	20	.000	.775	20	.000
BR W UAS	.156	20	.200*	.888	20	.024

*. This is a lower bound of the true significance.

Descriptives

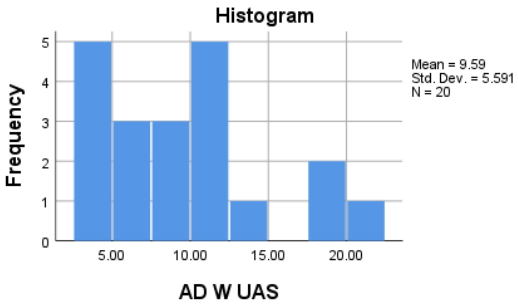
			Statistic	Std. Error
BB WT UAS	Mean		43.3569	2.32450
	95% Confidence Interval for Mean	Lower Bound	38.4916	
		Upper Bound	48.2221	
	5% Trimmed Mean		43.3109	
	Median		42.7900	
	Variance		108.066	
	Std. Deviation		10.39549	
	Minimum		21.84	
	Maximum		65.70	
	Range		43.86	
	Interquartile Range		9.55	
	Skewness		-.207	.512
	Kurtosis		.781	.992
BB W UAS	Mean		15.0325	.82650
	95% Confidence Interval for Mean	Lower Bound	13.3026	
		Upper Bound	16.7624	
	5% Trimmed Mean		15.0950	
	Median		14.8300	
	Variance		13.662	
	Std. Deviation		3.69620	
	Minimum		8.14	
	Maximum		20.80	
	Range		12.66	
	Interquartile Range		6.11	
	Skewness		-.128	.512
	Kurtosis		-.433	.992

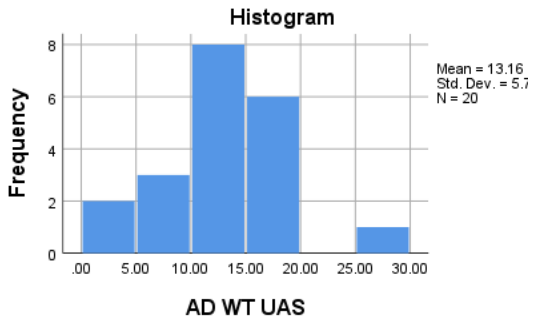
Tests of Normality

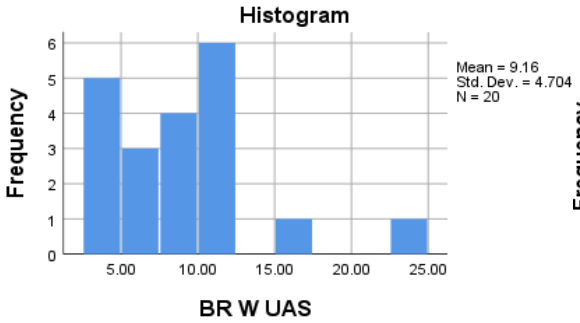
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
BB WT UAS	.184	20	.076	.948	20	.335
BB W UAS	.111	20	.200*	.945	20	.295

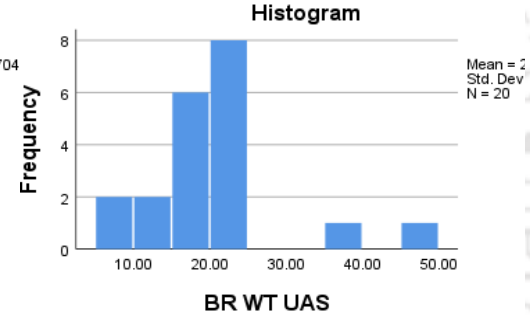
*. This is a lower bound of the true significance.

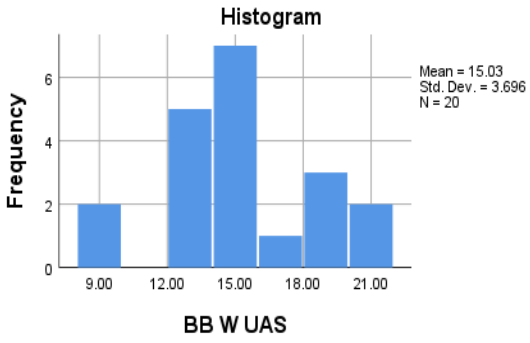
- Data distribution in Histogram

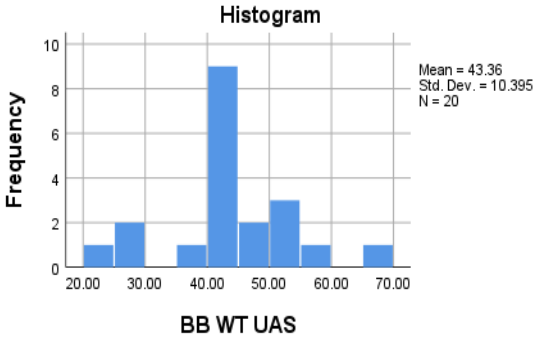












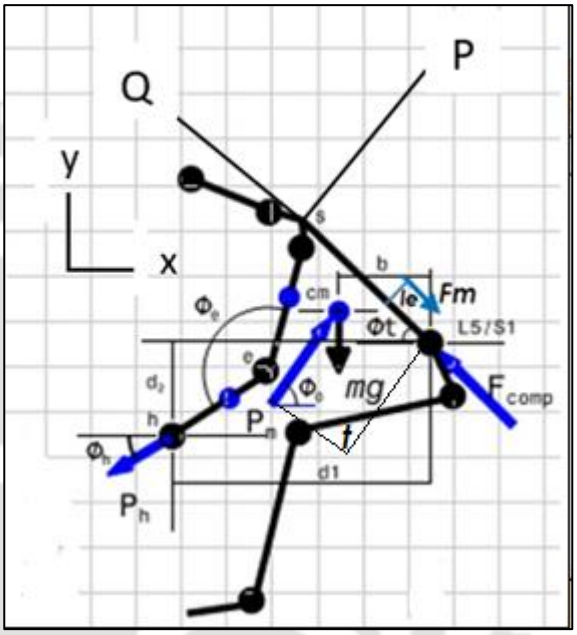
IV. Appendix-4 Biomechanical Model and Output Results

- Biomechanical models and equations
  - Steps for derivation of the compressive load at Lumbosacral joint of L5/S1 level disc for concept one -HbEH condition.

mg body weight

b , distance from the CoM to the L5/S1 center,

P_h is load due to pulling at the handle $d1, d2$ are the moment arm coordinates from the L5/S1 center. P_m , is the supporting load from the saddle, and its moment arm is represented by t , F_m is the muscle force used to stabilize the reactive moments with the arm l_e , $\emptyset_t$, $\emptyset_h$ and $\emptyset_0$, are the angular measurements of the trunk, handle center and the supporting saddle orientation



Forces	Local coordinates (x, y)	Global coordinates (P, Q)
Hand load	$P_h \cos \emptyset_h,\ P_h \sin \emptyset_h$	$P_h \cos \emptyset_h \cos \emptyset_t,\ P_h \sin \emptyset_h \sin \emptyset_t,$
Support reaction	$P_m \cos \emptyset_0,\ P_m \sin \emptyset_0$	$P_m \cos \emptyset_0 \cos \emptyset_t,\ P_m \sin \emptyset_0 \sin \emptyset_t,$
Load due to w	mg	$mg \sin \emptyset_t$
Erector spinae muscle force	----------	Fm

- Static Force and Moment Equilibrium

$$F_{c_{L5/S1}} = Fm + mg \sin \emptyset_t + P_m \cos \emptyset_0 \cos \emptyset_t + P_m \sin \emptyset_0 \sin \emptyset_t - P_h \cos \emptyset_h \cos \emptyset_t + P_h \sin \emptyset_h \sin \emptyset_t \ldots\ldots\ldots\ldots\ldots \text{(a)}$$

Assuming that, the erector spinae muscle Fm stabilizes the c.c.w moments due to the hand load, abdominal rectus and the body weight: -

Thus $Fm \times l_e = mgb - P_h(d2 \cos \emptyset_h) + P_h(d1 \sin \emptyset_h) - P_m \times t$

$$Fm \times = [mgb - P_h(d2\cos\emptyset_h - d1\sin\emptyset_h) - P_m \times t]/l_e \ldots. \text{(b)}$$

$$F_{c_{L5/S1}} = [mgb - P_h(d2\cos\emptyset_h - d1\sin\emptyset_h) - P_m \times t]/l_e + mg\sin\emptyset_t + P_m\cos\emptyset_0\cos\emptyset_t + P_m\sin\emptyset_0\sin\emptyset_t - P_h\cos\emptyset_h\cos\emptyset_t + P_h\sin\emptyset_h\sin\emptyset_t$$

Using the trigonometric identity

$$F_{c_{L5/S1}} = [(mgb + P_h(d2\cos\emptyset_h - d1\sin\emptyset_h) - P_m \times t)/l_e] + [mg\sin\emptyset_t + P_m(\cos(\emptyset_0 + \emptyset_t)) - P_h(\cos(\emptyset_h + \emptyset_t))] \ldots \ldots \text{(c)}$$

Similarly, for **HatEH** conditions the following equation can be used

$$F_{c_{L5/S1}} = [(mgb + P_h(d2\cos\emptyset_h - d1\sin\emptyset_h) - P_m \times t)/l_e] + [mg\sin\emptyset_t + P_m(\cos(\emptyset_0 + \emptyset_t)) - P_h(\cos(\emptyset_h - \emptyset_t))] \ldots \ldots \text{(d)}$$

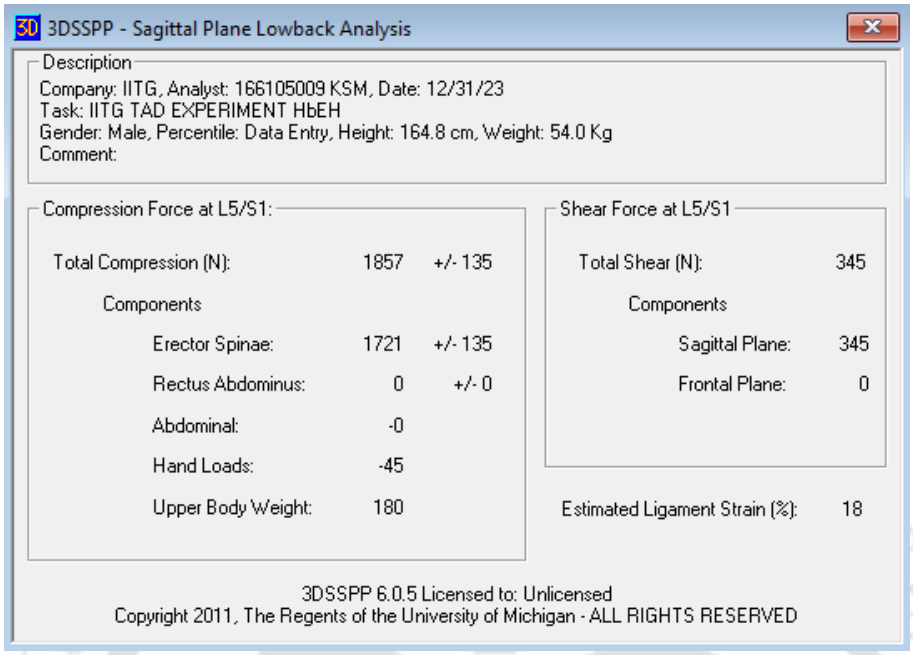
Similarly, for **HaEH** conditions the following equation can be used

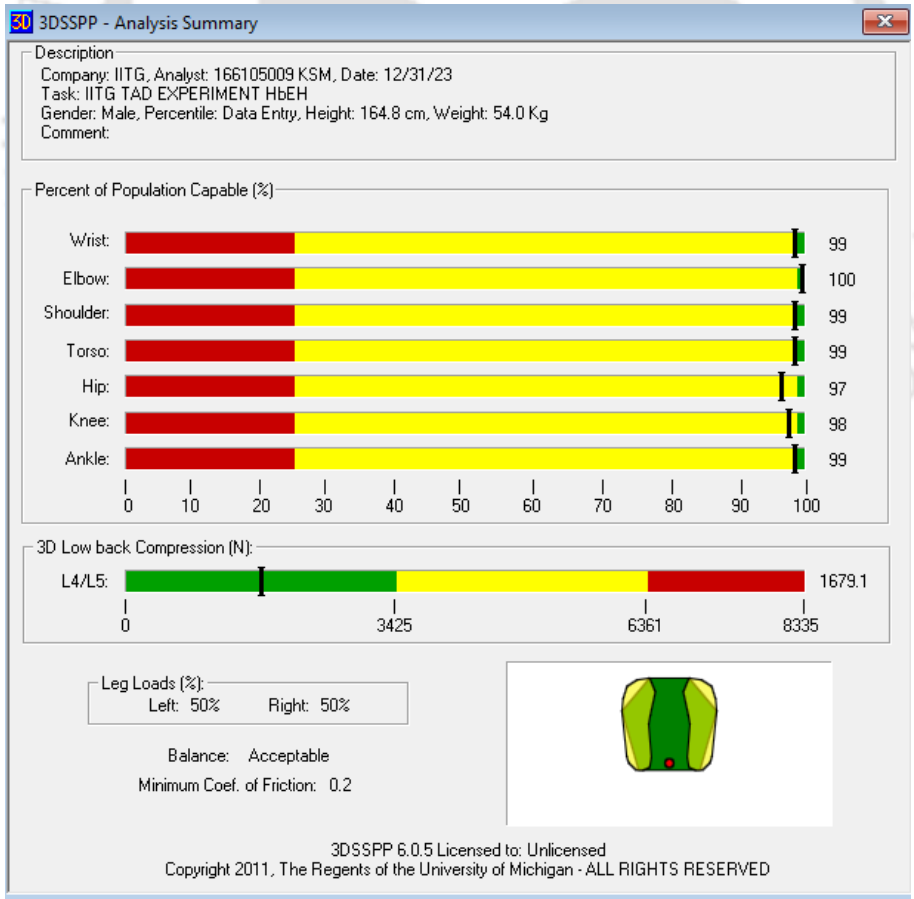
$$F_{c_{L5/S1}} = [(mgb + P_h(d2\cos\emptyset_h - d1\sin\emptyset_h) - P_m \times t)/l_e] + [mg\sin\emptyset_t + P_m(\cos(\emptyset_0 + \emptyset_t)) - P_h(\cos(\emptyset_h - \emptyset_t))] \ldots \ldots \text{(e)}$$

Equations (d) **HatEH** and (e) **HaEH** are same but equation (c) slightly differs because of its handle location which is below the L5/S1 joint. Thus, a general equation can be used to represent the above three equations, only by adding the sign alternatives before the second terms of the RHS equation and between the angles in the last term of RHS equation as shown below.

$$F_{c_{L5/S1}} = [(mgb \pm P_h(d2\cos\emptyset_h - d1\sin\emptyset_h) - P_m \times t)/l_e] + [mg\sin\emptyset_t + P_m(\cos(\emptyset_0 + \emptyset_t)) - P_h(\cos(\emptyset_h \pm \emptyset_t))] \ldots \ldots \text{(f)}$$

➢ Biomechanics analysis summary results-3DSSPP





3DSSPP - Task Input Summary

Description
Company: IITG, Analyst: 166105009 KSM, Date: 12/31/23
Task: IITG TAD EXPERIMENT HbEH
Gender: Male, Percentile: Data Entry, Height: 164.8 cm, Weight: 54.0 Kg
Comment:

Limb Angles (Deg)

	Left			Right		
	Horz	Vert	Rot	Horz	Vert	Rot
Hand:	90	-40	0	90	-40	0
Forearm:	90	-40		90	-40	
Upper Arm:	90	-75		90	-75	
Clavicle:	-20	15		-20	15	
Upper Leg:	90	-15		90	-15	
Lower Leg:	90	-90		90	-90	
Foot:	90	0		90	0	

Trunk

Angles	(Degrees)
Flexion:	43
Rotation:	0
Bending:	0
Pelvic Lateral Tilt:	0
Pelvic Axial Rotation:	0

Head/Neck

Flexion:	90
Rotation:	0
Bending:	0

Hands

Neutral	Left Horz	Left Vert	Left Lat	Right Horz	Right Vert	Right Lat
Location(cm):	25.7	35.8	-16.3	25.7	35.8	16.3
	Horz(Deg)	Vert(Deg)	Mag(N)	Horz(Deg)	Vert(Deg)	Mag(N)
Force:	90	-30	71.2	90	-30	71.2

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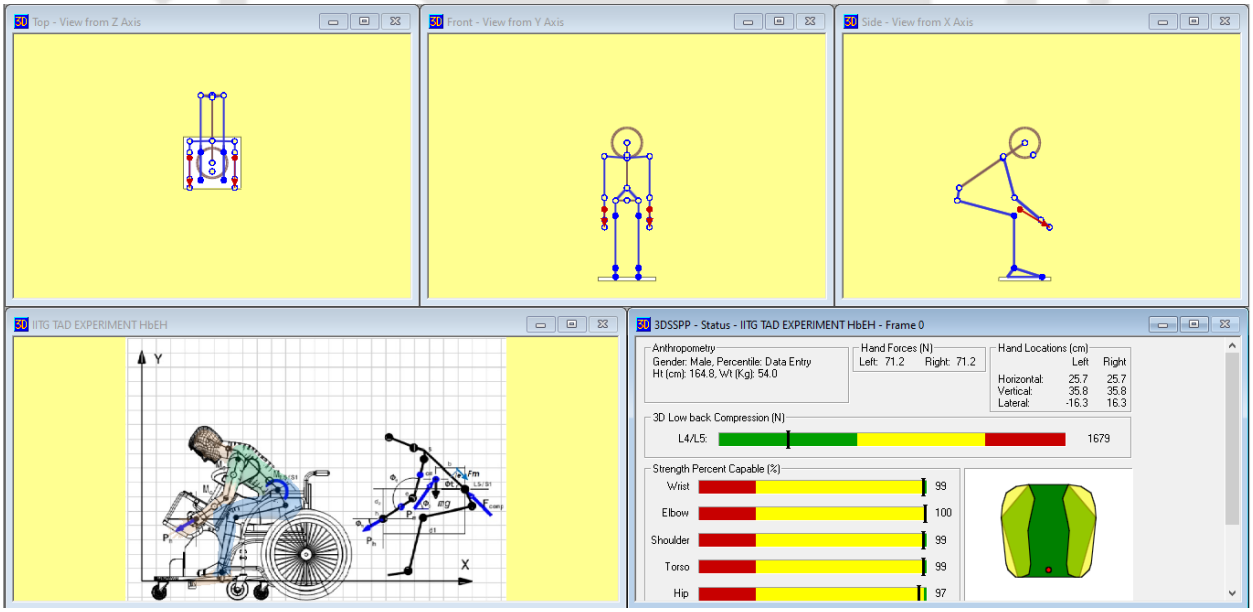

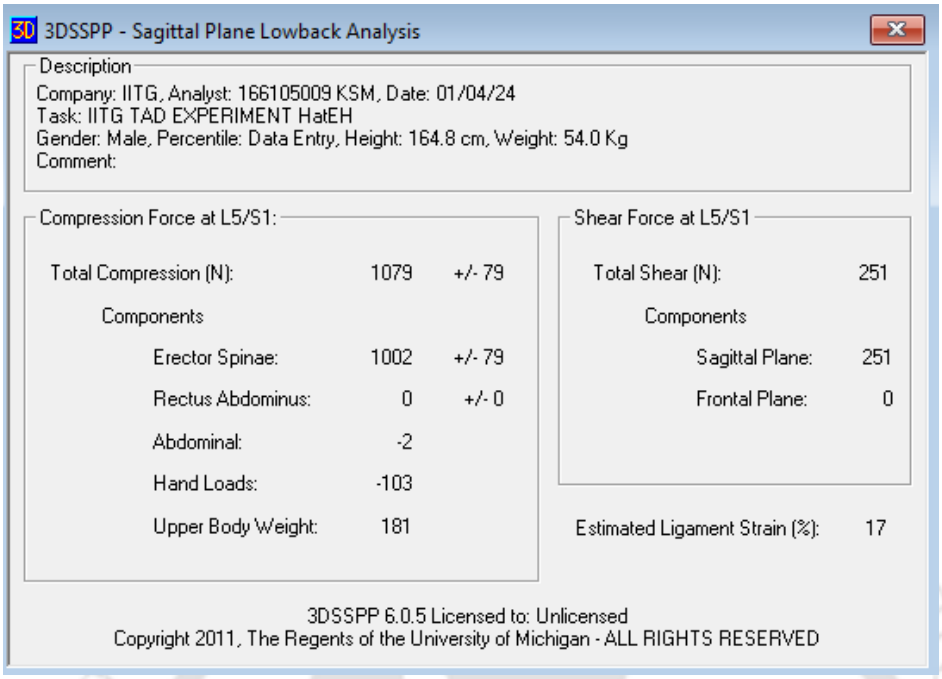
3DSSPP - Sagittal Plane Lowback Analysis
Description
Company: IITG, Analyst: 166105009 KSM, Date: 01/04/24
Task: IITG TAD EXPERIMENT HatEH
Gender: Male, Percentile: Data Entry, Height: 164.8 cm, Weight: 54.0 Kg
Comment:
Compression Force at L5/S1:
Total Compression (N): 1079 +/- 79
Components
Erector Spinae: 1002 +/- 79
Rectus Abdominus: 0 +/- 0
Abdominal: -2
Hand Loads: -103
Upper Body Weight: 181
Shear Force at L5/S1
Total Shear (N): 251
Components
Sagittal Plane: 251
Frontal Plane: 0
Estimated Ligament Strain (%): 17
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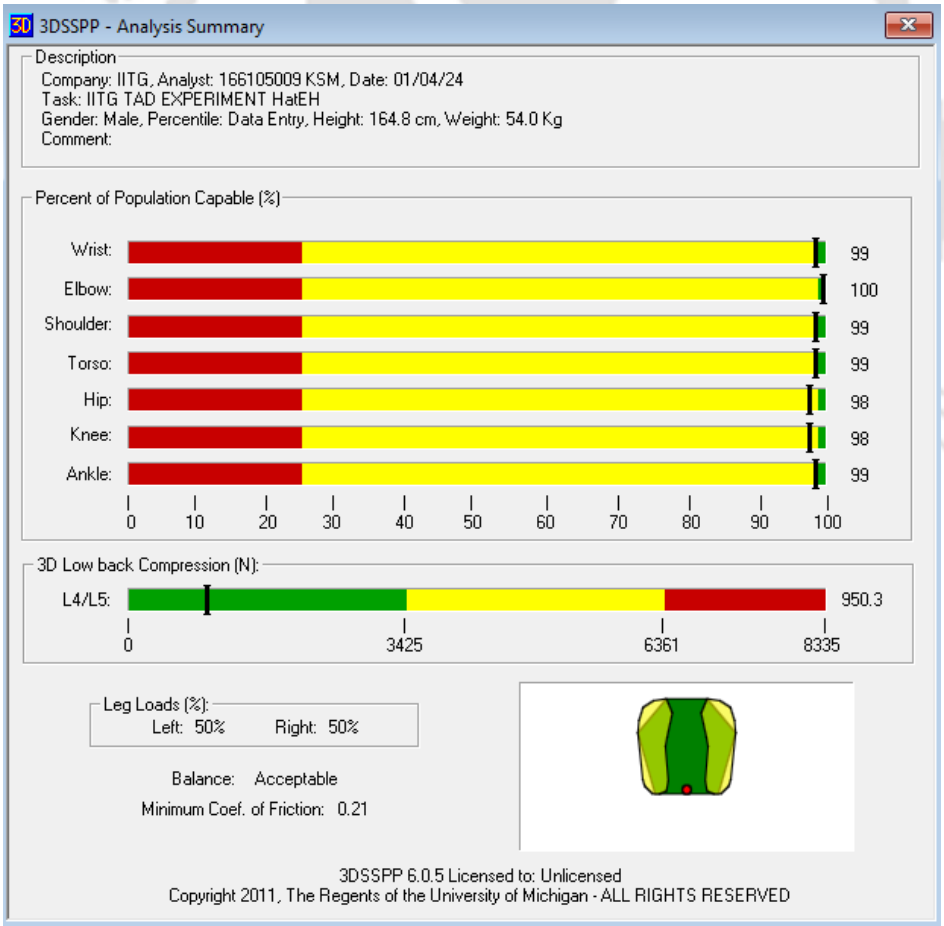
3DSSPP - Analysis Summary
Description
Company: IITG, Analyst: 166105009 KSM, Date: 01/04/24
Task: IITG TAD EXPERIMENT HatEH
Gender: Male, Percentile: Data Entry, Height: 164.8 cm, Weight: 54.0 Kg
Comment:
Percent of Population Capable (%)
Wrist: 99
Elbow: 100
Shoulder: 99
Torso: 99
Hip: 98
Knee: 98
Ankle: 99
0 10 20 30 40 50 60 70 80 90 100
3D Low back Compression (N):
L4/L5: 950.3
0 3425 6361 8335
Leg Loads (%):
Left: 50% Right: 50%
Balance: Acceptable
Minimum Coef. of Friction: 0.21
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3DSSPP - Task Input Summary

Description
Company: IITG, Analyst: 166105009 KSM, Date: 01/04/24
Task: IITG TAD EXPERIMENT HatEH
Gender: Male, Percentile: Data Entry, Height: 164.8 cm, Weight: 54.0 Kg
Comment:

Limb Angles (Deg)

	Left			Right		
	Horz	Vert	Rot	Horz	Vert	Rot
Hand:	90	10	0	90	10	0
Forearm:	90	10		90	10	
Upper Arm:	90	-85		90	-85	
Clavicle:	-20	15		-20	15	
Upper Leg:	90	-20		90	-20	
Lower Leg:	90	-90		90	-90	
Foot:	90	0		90	0	

Trunk

Angles	(Degrees)
Flexion:	45
Rotation:	0
Bending:	0
Pelvic Lateral Tilt:	0
Pelvic Axial Rotation:	0

Head/Neck

Flexion:	90
Rotation:	0
Bending:	0

Hands

Neutral	Left Horz	Left Vert	Left Lat	Right Horz	Right Vert	Right Lat
Location(cm):	27.7	66.7	-16.3	27.7	66.7	16.3
	Horz(Deg)	Vert(Deg)	Mag(N)	Horz(Deg)	Vert(Deg)	Mag(N)
Force:	90	18	55.6	90	18	55.6

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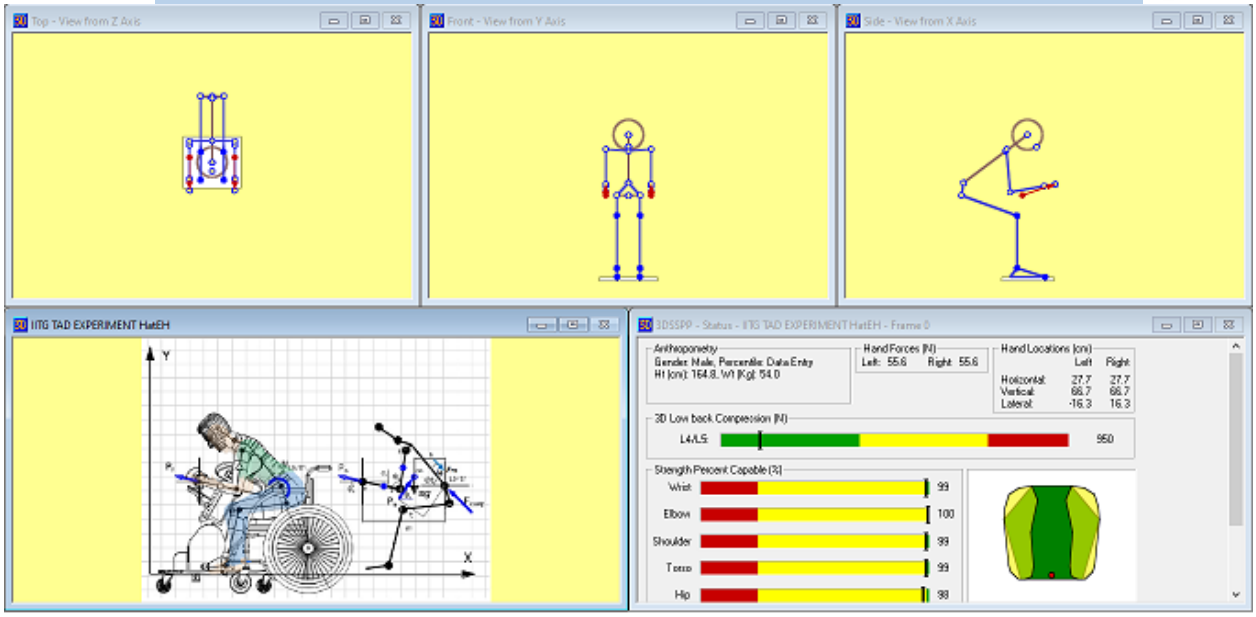

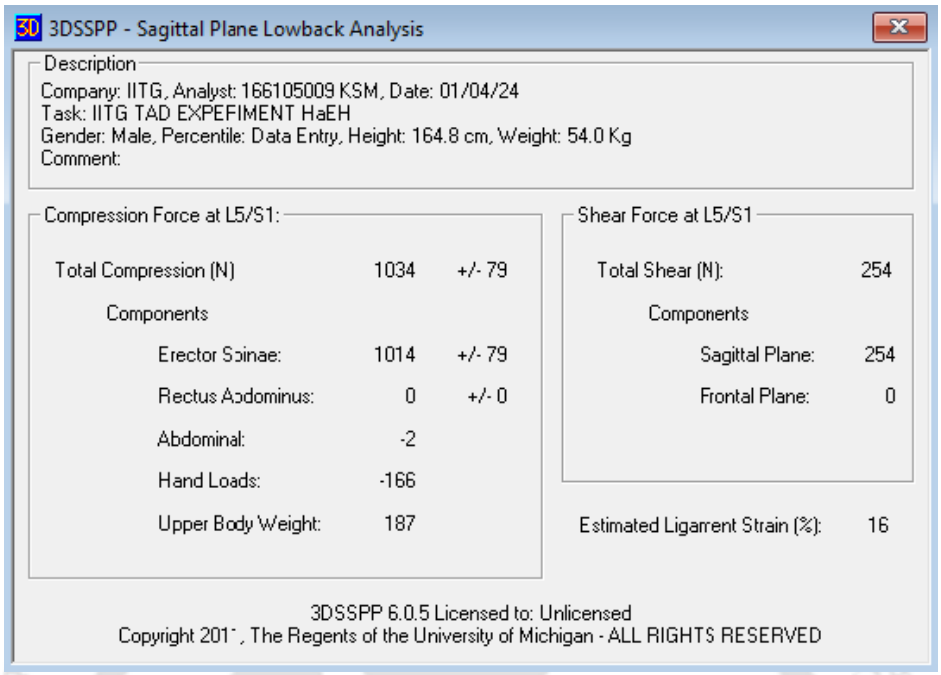
3DSSPP - Sagittal Plane Lowback Analysis
Description
Company: IITG, Analyst: 166105009 KSM, Date: 01/04/24
Task: IITG TAD EXPEFIMENT HaEH
Gender: Male, Percentile: Data Entry, Height: 164.8 cm, Weight: 54.0 Kg
Comment:
Compression Force at L5/S1:
Total Compression (N) 1034 +/- 79
Components
Erector Spinae: 1014 +/- 79
Rectus Abdominus: 0 +/- 0
Abdominal: -2
Hand Loads: -166
Upper Body Weight: 187
Shear Force at L5/S1
Total Shear (N): 254
Components
Sagittal Plane: 254
Frontal Plane: 0
Estimated Ligament Strain (%): 16
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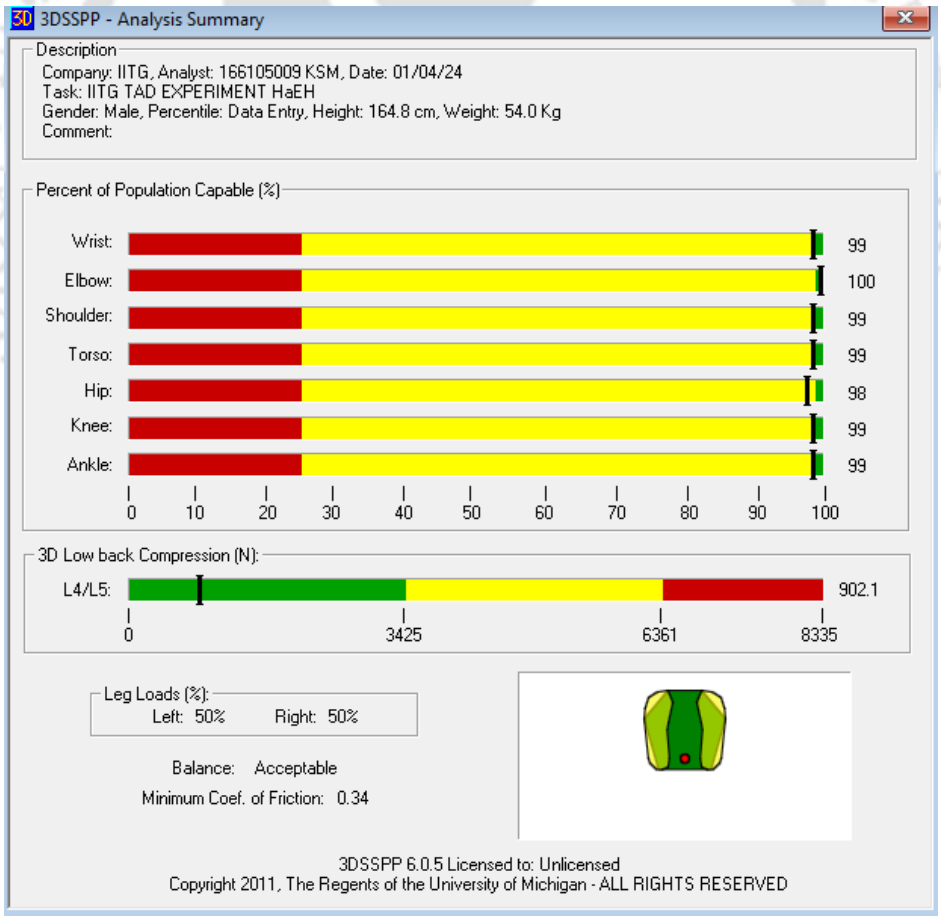
3DSSPP - Analysis Summary
Description
Company: IITG, Analyst: 166105009 KSM, Date: 01/04/24
Task: IITG TAD EXPERIMENT HaEH
Gender: Male, Percentile: Data Entry, Height: 164.8 cm, Weight: 54.0 Kg
Comment:
Percent of Population Capable (%)
Wrist: 99
Elbow: 100
Shoulder: 99
Torso: 99
Hip: 98
Knee: 99
Ankle: 99
0 10 20 30 40 50 60 70 80 90 100
3D Low back Compression (N):
L4/L5: 902.1
0 3425 6361 8335
Leg Loads (%):
Left: 50% Right: 50%
Balance: Acceptable
Minimum Coef. of Friction: 0.34
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3DSSPP - Task Input Summary

Description
Company: IITG, Analyst: 166105009 KSM, Date: 01/04/24
Task: IITG TAD EXPERIMENT HaEH
Gender: Male, Percentile: Data Entry, Height: 164.8 cm, Weight: 54.0 Kg
Comment:

Limb Angles (Deg)

	Left			Right		
	Horz	Vert	Rot	Horz	Vert	Rot
Hand:	90	30	0	90	30	0
Forearm:	90	30		90	30	
Upper Arm:	90	-45		90	-45	
Clavicle:	-20	15		-20	15	
Upper Leg:	90	-15		90	-15	
Lower Leg:	90	-80		90	-80	
Foot:	90	0		90	0	

Trunk

Angles	(Degrees)
Flexion:	50
Rotation:	0
Bending:	0
Pelvic Lateral Tilt:	0
Pelvic Axial Rotation:	0

Head/Neck

Flexion:	90
Rotation:	0
Bending:	0

Hands

Neutral	Left			Right		
	Horz	Vert	Lat	Horz	Vert	Lat
Location(cm):	32.5	85.4	-16.3	32.5	85.4	16.3
	Horz(Deg)	Vert(Deg)	Mag(N)	Horz(Deg)	Vert(Deg)	Mag(N)
Force:	90	25	86.7	90	25	86.7

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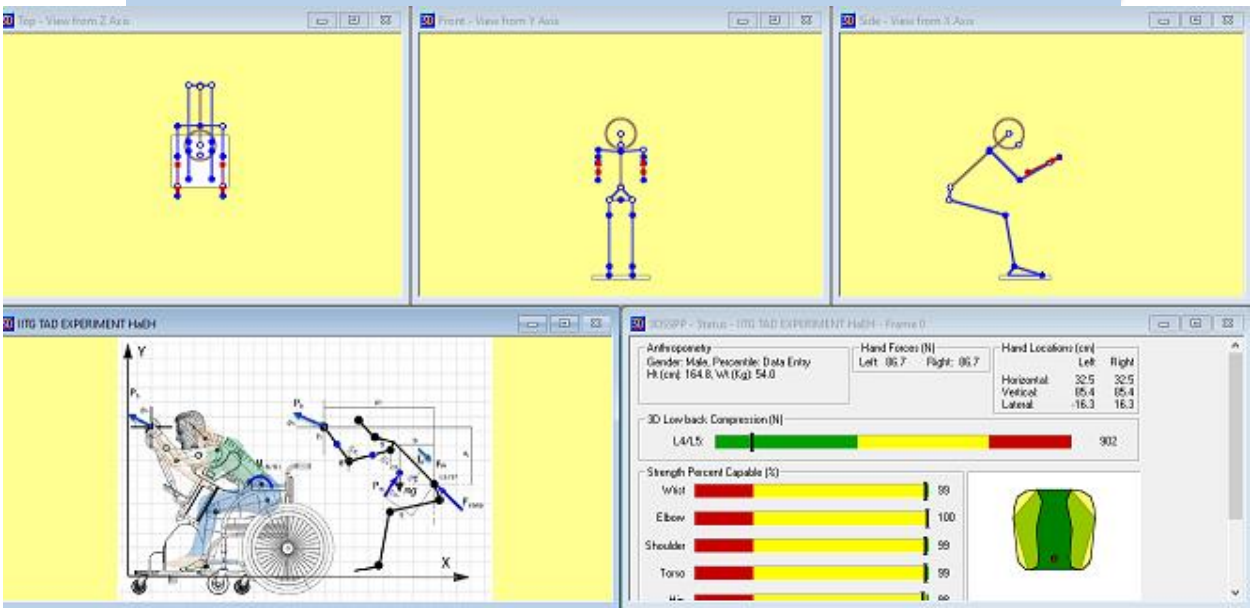

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