PRODUCT DESIGN AND DEVELOPMENT USING VIRTUAL REALITY AND CAD/CAM SYSTEM

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DECLARATION

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LIST OF ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
ADL	Activities of Daily Living
AI	Artificial Intelligence
BOM	Bill of Materials
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CNC	Computer Numerical Control
CPS	Cyber-Physical Systems
DFE	Design for Environment
DFMA	Design for Manufacturing and Assembly
DOF	Degree of Freedom
FDM	Fused Deposition Modelling
FPV	First-person View
FYP	Final Year Project
GLB	Graphics Language Transmission Binary Format
GLTF	Graphics Language Transmission Format
HTC	High Tech Computer
I4.0	Industry 4.0
PDD	Product Design and Development
PDP	Product Development Process
PLA	Polylactic Acid
PTPM	Pusat Teknologi Pengajaran & Multimedia
RIM	Reaction Injection Moulding
RoHS	Restriction of Hazardous Substances
ROM	Range of Motion
USM	Universiti Sains Malaysia
VM	Virtual Manufacturing
VP	Virtual Prototyping
VR	Virtual Reality
Wrist-T	Wrist Rehabilitation Therapy
XR	Extended Reality
3D	Three-Dimensional

REKA BENTUK DAN PEMBANGUNAN PRODUK MENGGUNAKAN REALITI MAYA DAN SISTEM CAD/CAM

ABSTRAK

Proses penilaian produk yang kompleks boleh menjadi mahal dan mengambil masa sepanjang pelbagai peringkat proses reka bentuk. Oleh itu, projek ini bertujuan untuk membangunkan suatu produk ke arah I4.0 dengan mengintegrasikan teknologi VR dan sistem CAD/CAM dalam process PDD untuk menjalankan penambahbaikan terhadap keterbatasan malah mengurangkan masa dan kos dalam kitaran pembangunan. Maka, peranti pemulihan pergelangan tangan telah dipilih sebagai produk yang berpotensi untuk dibangunkan dengan teknologi VR selanjutnya melalui proses penyaringan dan pemarkahan. Kos penghasilan peranti ini dijangka lebih rendah dan mekanismenya yang lebih sederhana dapat memenuhi keperluan pesakit. Malahan, spring dari konsep AC telah digantikan dengan jalur rintangan untuk membekalkan pelbagai gerakan 3-DOF secara semi-automatik. Selain itu, 3D CAD model peranti telah dicipta dengan aplikasi SOLIDWORKS 2021 dan juga visualisasi model dan animasinya dalam persekitaran VR telah dijalankan dengan aplikasi EpicCADVR dalam Oculus Quest 2. Dengan ini, proses PDD boleh diteruskan secara lebih mudah kerana VR mengawalkan pemeriksaan dan verifikasi reka bentuk komponen peranti secara maya bagi pengubahsuaian jika diperlukan. Di samping itu, demonstrasi penggunaan peranti boleh menjadi contoh untuk mengalakkan pesakit dalam perjalanan terapi dengan ROM yang sesuai. Jadi, produk peranti terakhir yang telah dibina ini mempunyai anggaran berat sebanyak 600.66 g dan prestasi operasinya telah dibuktikan dalam gerakan 3-DOF, seperti lenturan/peluasan, pronasi/supinasi, dan sisihan jejari/sisihan ulnar. Menurut analisisnya, ROM yang dicapai telah melebihi ROM minimum untuk melaksanakan ADL. Akhirnya, anggaran kos penghasilan produk terakhir yang berjumlah RM 121.41 adalah lebih rendah daripada produk lain dalam penandaarasan. Peranti yang dibangunkan dalam kajian ini telah menunjukkan potensi untuk menggunakan teknologi VR dalam fasa PDD pada masa hadapan akibat pengalamannya yang agak mengasyikkan. Justeru, pelaksanaan sistem VR dalam PDD adalah disyorkan untuk mengeksplorasi kemungkinannya terhadap keterbatasan tersebut. Kesimpulannya, kerja yang dijalankan dalam projek ini merupakan sesuatu langkah penting untuk merealisasikan produk terakhir dengan bantuan sistem VR.

PRODUCT DESIGN AND DEVELOPMENT

USING VIRTUAL REALITY AND CAD/CAM SYSTEM

ABSTRACT

The complex product evaluation process can be costly and time-consuming throughout various stages of a design process. Therefore, the present project aims to develop a product towards I4.0 by integrating VR technologies and CAD/CAM systems into the PDD process to make possible improvements against the limitations while reducing the time and costs in the development cycle, ensuring its quality and usability. Throughout the screening and scoring processes, a wrist rehabilitation device is selected as a potential product for further development using VR technology. In expectation, the device has a lower production cost and a simpler working mechanism for fulfilling the requirements of the patients. Hence, the spring feature in the proposed concept AC is replaced with a resistance band for providing various semiautomatic wrist motions in 3-DOF. On top of that, a 3D CAD model of the device is created using SOLIDWORKS 2021 and the visualization of its assembly model and animation in a VR environment is carried out with the EpicCADVR application using Oculus Quest 2 VR device. Thus, the continuous PDD process can be much simpler as it allows the users to examine and verify the initial design of parts virtually for further necessary modification. Also, the demonstration of device usage in FPV instructs the wrist mechanism and encourages the patients to move their wrists through an appropriate ROM, emulating the movement therapy. Eventually, the final device product has been constructed by combining the 3D-printed parts with some standard parts acquired, possessing an approximate weight of 600.66 g. Testing of the product has proven the operating performance of 3-DOF wrist motions, such as flexion/extension, pronation/supination, and abduction/adduction. From the analysis, the achieved ROM exceeds the minimum ROM required to perform ADL. Finally, the total estimated production cost of the final product is RM 121.41, which is comparatively lower than other benchmarking products. The device developed in this study demonstrates the potential for utilizing VR technology in the PDD phase with its immersive experience in FPV. Thus, further implementation of VR systems in PDD has been recommended to explore its possibilities against the limitations. Work undertaken in this project represents a significant step towards the realization of the final product with the aid of a VR system.

CHAPTER 1

INTRODUCTION

1.1 Brief Overview of VR Technology in PDD and CAD/CAM System

The application of the VR technology in I4.0 encompasses a different orientation because of the extent of immersion it provides to the user. Through VR, exact simulations of products, processes or production plants are often created to visualize their operation in FPV. In combination with the right data, VR is also used in the product design phase and validation of prototypes, as it allows designers to examine the details and progress made more visually and interactively through a virtual simulation. It provides more possibilities in the PDD phase as the engineers can completely mobilise their inspiration, create eclectic designs, and demonstrate their design concepts in real-time, giving a unique visual experience by exploiting VR technology (Min, 2021). In this way, the development time and costs can be decreased because fewer errors will be made in this phase, thus the quality and usability of the products will be improved when compared to those without using the VR technology (Ottosson, 2002). Therefore, a mature VR technology is an important tool in the conceptual design stage because it enables faster 3D modelling, as compared to traditional CAD 3D modelling software.

As the development of an appropriate CAD solid modelling is the most significant stage in the fabrication of the prototype, the CAD/CAM system is therefore integrated extensively to design a product and program manufacturing processes against the limitations (Caligiana et al., 2017), specifically for CNC machining. In recent trends, the new manufacturing technology of incremental shaping has developed dynamically, which is commonly known as 3D printing. In contrast to traditional subtractive technologies, its production takes place in one cycle, which means a very short time and lower cost will be required. It is particularly useful for the production of creative solutions since it allows for manufacturing based on the CAD module (Mikolajczyk et al., 2019).

The major focus of this research is on how VR can be utilised in the field of PDD when it should be used to create product modelling, and how it integrates with CAD/CAM systems to fabricate the product, by interacting with CNC machines, 3D printers, and other engineering tools.

1.2 Research Background

Changes in technology play a vital role in several areas of human life, it allows data access to be much quicker and faster, hence changing the way how to consume and relate to it. Similarly, I4.0 brings dramatic changes to the company’s structures, which involves the digital transformation of the industry with the revolution of automation, digitalisation, process integration, CPS, and personalized production techniques (Urban et al., 2020). However, the companies are perpetually concerned about maintaining their competitive advantages in the current market and looking for approaches to enhance performance and improve productivity. To compete for a broader space in the market, PDD is increasingly considered an essential process to ensure the competitiveness of companies. According to Arromba (2021), the product option to be developed should account for factors such as anticipated opportunity, potential market demand, legal protection of new technologies and products, strengths and production capabilities of rivals, the investment required, and corporate production capacity.

One of the main focus areas in I4.0 is the bridging of digital/cyber/virtual and physical worlds, known as CPS. This is where VR technology makes its entrance, which is certainly important to allow optimization and enhanced flexibility in the typical earlier stages, which are more important than the later stages of innovation and execution. VR technology is ideal for activities in the early phases of the PDP when the product's form has not been finalised and is still being developed and tested, as well as for design overview and inspection (Vlah et al., 2021). Somehow in a global market, time compression strategies in PDD are critically important to attain competitive advantages. In some cases, certain products have long cycle times in development and fabrication due to the constraint of technological obsolescence (Pandey et al., 2016). Therefore, an integrated CAD/CAM system with a CNC machine and 3D printer will be needed to produce the product as CAM software takes the 3D models and assemblies created in CAD software to generate machine tool paths and turn the virtual designs into physical products, which is usually used for machining of prototypes and finished parts (Andrei et al., 2015).

However, there is doubt that the usage of VR tools in further phases due to its limitation in achieving accuracy and precision, whether it was capable to transfer the models into later stages of product development if the product had a complex geometry.

It was an opportunity to investigate the advancement of VR tools in discovering new ways of experiencing the real world, and simulating complicated manufacturing and assembly processes to accelerate understanding and improve product quality and reliability. For example, Peng (2007) has shown some VR projects that were performed before final verification with physical prototypes, including operation simulation, instrument assembly, customization, performance trials, skills training, communication with third parties, ergonomics studies, time and space studies, etc.

1.3 Problem Statement

In more recent times, 3D printing technology was exploited to create prototypes that demonstrate functionality and interactivity with real products. However, the complex product evaluation process can be costly and time-consuming throughout various stages of a design process, and yet there are limited tools available to provide better support to the whole PDD process. Therefore, the present research aims to report a project in developing a product towards I4.0 by integrating VR technologies and CAD/CAM systems into the PDD process to make possible improvements against the limitations while reducing the time and costs in a product development cycle.

1.4 Objectives

- To determine the most suitable product from several options based on various criteria.
- To develop a product for designing towards I4.0 by using VR technology.
- To fabricate a product by integrating the CAD/CAM system with fabrication tools.

1.5 Project Scope

The current market demands are studied to understand the customer requirements based on the limitations of some product designs. The potential of multiple product options will be compared in terms of a few criteria, such as the involvement of assembly operation, time study, space study, ergonomics, simulation, customization, impact on society/environment, industry-related, project complexity/risk, and advantages in VR. The options will either be eliminated or combined with other options to innovate the best product design idea. A 3D model will be designed using VR technology and its product will be fabricated by integrating the CAD/CAM system with fabrication tools.

CHAPTER 2

LITERATURE REVIEW

2.1 Concept of I4.0 in the PDP

In the concepts of I4.0 and green automation, sustainability is relatively significant and its factors include the consumption of energy, time, costs, space, waste, compact design, flexibility, stability, repeatability, maintenance, quality, and safety. The concept of I4.0 in the PDP had its benefits and difficulties that might influence the future of society, as illustrated in Table 2.1.

Table 2.1 Benefits and difficulties of I4.0 related to the PDP

Benefits	Difficulties
Reduction of costs and time	High capital due to new technologies
Increase in product quality	Develop new materials and processes
Optimization and flexibility of processes	Resistance to new technologies
Mass customization of products	Absence of data pattern
Reduction of production errors and waste	Risk environments if miscommunicated
Focus on customer perception	Meeting customers' new requirements
Increase worker efficiency	Lack of knowledge in intelligent systems

2.2 Futures of PDD

The idea of sustainable PDD is getting greater attention in recent studies as a result of increased demand to meet sustainability goals, that is to integrate the environmental aspects into it. However, it is found that the implementation of product design tools is still not encouraging in the industry, and hence, the tools should be user-friendly and mature enough to show the results of sustainability improvements clearly. Also, how to cope with uncertainties and stochastic data is another major difficulty in PDD. Consequently, one of the most effective methods is a simulation, which is potentially a direction to improve the reliability of a sustainable product (Ahmad et al., 2018).

PDD is critical to gaining a competitive advantage and achieving success in new product development. To connect PDD more with innovation, efficient project management is crucial to ensure the product fulfilling the customer requirements successfully, by resolving the challenges of project team member selection, team leader selection, identifying potential customers, and DFE especially related to the adaption of I4.0 (Othman and Bamasood, 2021).

2.3 Implementation of VR Technology

One of the most exciting features of VR technology is that it allows design evaluators to see design representations made in computer 3D environments at any scale without the need for tangible materials, which means it can help to enhance the effectiveness of the process, improve systematic procedures, save the prototype fabrication cost, shorten the time required to physically demonstrate and explain the product design in details. In contradistinction to CAD, only VR allows one to experience, interact, and take actions with it as if it were a real-world object, devoid of any physical entity. In short, VR can be used as (Hamurcu et al., 2020):

- An inspirational material before creating the design representations
- A sketching, modelling, prototyping and visualisation tool in the creation of design representations
- A presentation, demonstration, experience, usability evaluation and ergonomic evaluation tool after creating the design representations
- A tool for collaboration during and after the creation of design representations

Many problems in product design and production may be solved with VR. Furthermore, the more difficult, complicated, and expensive the set-ups are, the more helpful it is to adopt VR to explore and discover viable alternatives in engineering design (Wagner et al., 2019). For example, VP may overcome the physical rapid prototyping methods, which are more costly and less comprehensive, in the considerations of insufficient fidelity of tactile feedback, uncomfortable devices, risk of inaccurate imitation of the product, lack of technical knowledge of users, and high time effort to learn the handling of VR tools. Moreover, VM enables innovative digital methods for developing, analysing, and simulating complex systems, as well as a method for evaluating the outcomes of new production decisions before generating the physical product. Consequently, the high economic threshold needs to be overcome with more repetitive use of VR devices.

According to Saghafian (2021), one of the challenges to develop and implementing VR solutions is technological maturity and compatibility. In such cases, the VR headsets with low-quality resolution will lead to difficulties in decision-making and justifications of the product design projects. Also, there are challenges that the developer faced in managing, coordinating, and communicating, which include increased workload and reduced role clarity, managing involvement of multiple stakeholders, and challenges of communication and support. Before the creation of new technologies, the structure and dynamics of the group must be assessed. Involving users from the start may aid with a variety of technological difficulties, improve trust and communication, and inspire other user groups to embrace VR-solution technology.

2.4 Hand Rehabilitation Therapy in VR System

According to Henderson et al. (2007), stroke is reported to afflict 15 million individuals globally every year, and about 55% to 75% of survivors have continued to experience upper limb motor impairments and a worse quality of life. These motor impairments like dual-task coordination abilities, fine motor skills, and motor control, can have a substantial impact on a patient's independence in life. (Saposnik and Levin, 2011). Hence, VR systems were created to aid in these people's motor rehabilitation.

On the topic of exploiting VR systems for hand rehabilitation, the researchers emphasize more on constructing a virtual environment that takes a practical and versatile approach to rehabilitation for individuals affected by stroke (Fluet et al., 2021). The idea is to provide a training solution that is built to be used on the VR platform, including a headset and VR gloves as controllers (Adamovich et al., 2007). By placing the users in a virtual environment, they need to follow and cooperate with the AI trainer to accomplish tasks related to hand movement. In the long run, this kind of treatment can potentially enhance the ROM, muscle strength, and mobility of the hands (Merians et al., 2009). The patients will be encouraged to carry out therapeutic hand exercises enjoyably while minimizing their discomfort, especially in a gamified VR environment, making it easier for them to exercise their hands during the treatment (Hoffman et al., 2020). By doing this, it is possible to enhance traditional physiotherapy for hand rehabilitation while concentrating on resolving persistent issues with limited movement and exercise variety, complex calibrations, and exclusion of patients with open wounds or other hand disfigurements that have been reported in most technological solutions to the issue (Pereira et al., 2020). Moreover, VR may also be used to assess how effectively patients are performing their hand therapy exercises and to determine whether executing a treatment strategy improves long-term effectiveness (Adamovich et al., 2003). It is advocated that further work would be done on developing VR as a tool for therapists who treat patients with both acute pain and chronic pain.

However, one of the major obstacles to putting this notion into practice was creating a solution that would affect how patients were treated. Establishing it to be safe and adhere to medical standards was quite different when the stakes were higher than with other applications that were only focused on producing a fun experience or improving a few minor abilities (Feng et al., 2019). Thus, it was essential to implement a state-of-the-art tracking system with excessively high accuracy and precision to come out with a solution to perform as envisioned, that is to meticulously capture and record every movement of the hand and wrist no matter how slight or fast, to gain reliable data result and analysis of the result, which allows to precisely record the bending angles of the hand and fingers (Boeldt et al., 2019). To meet the specific requirements for the experience, a lot of effort is required to create the simulation's appearance and feel that the users desired. For the users to comprehend exactly what they needed to accomplish and how everything worked, the content and information that would be included in the simulation had to be modified (Boian et al., 2002). Therefore, it took a lot of physical testing using a VR glove in getting this system to operate precisely and deliver a truly immersive experience that mimics real-life rehabilitation. As a result, much of the development time and effort was spent on creating excellent motion tracking in the hand and wrist.

As the first order of this project, additional study is required to determine how a ROM improvement takes place in the users' experience, by developing a wrist rehabilitation device that will be combined with VR gaming and enable stroke patients to engage in rehabilitation activities for recovering and regaining their hand function.

2.5 Development of Wrist Rehabilitation Device

According to Mandeljc et al. (2022), the future of rehabilitation may be seen in telerehabilitation due to the ageing population and an increase in stroke patients, which might reduce the workload of occupational therapists and physiotherapists. Hence, devices targeted toward automatic and independent usage at home need to be developed to facilitate the use of telerehabilitation for stroke patients. Despite its efficacy, providing task-specific and high-intensity rehabilitation exercise protocols with highly repeated motions might be challenging for many patients. Therefore, robotic devices in stroke rehabilitation protocols are recommended because they can lower labour costs and therapists' physical exertion, providing customised interactive exercises as well as enabling objective and reliable monitoring of the patient's progress.

To perform ADL, a person uses the distal sections of his or her arm, which are the wrist and forearm, in conjunction with the proximal regions of the arm, that is the elbow and shoulder. As shown in Figure 2.1 and Figure 2.2, the wrist joint has 2-DOF: radial deviation/ulnar deviation or abduction/adduction and flexion/extension. Flexion is the wrist bending such that the palm gets closer to the anterior surface of the forearm while its opposite is called extension. Next, the wrist bending in the direction of the thumb side is known as abduction/radial deviation while the opposite of this motion is adduction/ulnar deviation. On the other hand, the motions of the forearm are pronation and supination. When a hand is pronated, the palm curves backwards or downward, while supination is the rotation of the forearm such that the palm faces anteriorly to its anatomic posture (Kütük et al., 2019).

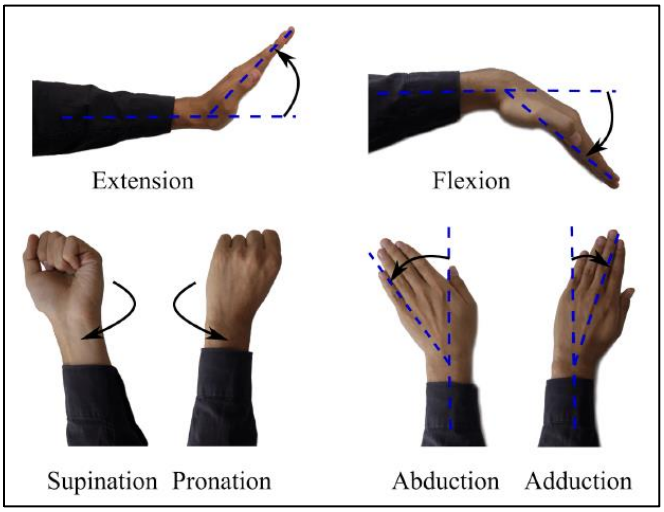

Figure 2.1 Human wrist DOF (Omarkulov et al., 2016)

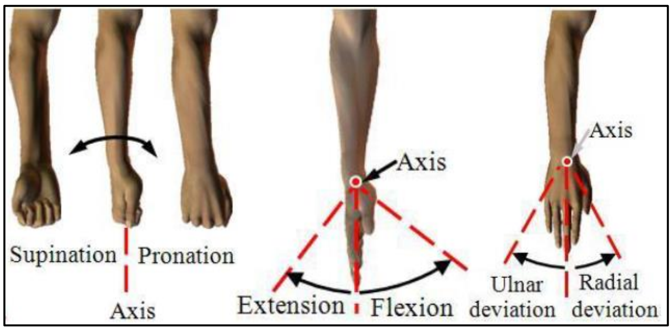

Figure 2.2 Kinematics of forearm and wrist (Gopura et al., 2016)

Shalal and Aboud (2021) present a paper that concentrated on rehabilitating wrist and forearm joints to regain the ADL by creating and building a robotic exoskeleton, as shown in Figure 2.3. With a 3-DOF that includes flexion/extension, adduction/abduction, and pronation/supination motions, the exoskeleton was made to rehabilitate the patients' wrists. It was required to give a speed and ROM comparable to those seen in healthy people while also being portable, pleasant, lightweight, and consistent with the human anatomical structure. The suggested exoskeleton therefore significantly increased wrist and forearm joint ROMs and helped restore muscle activation. These findings in results demonstrate that physiotherapy activities can be carried out with the proposed exoskeleton.

Figure 2.3 CAD models of the exoskeleton assembly (Shalal and Aboud, 2021)

Robotic devices have been scientifically proven to be useful in the long-term and intense therapy required for motor recovery following neurological impairment. To restore the ability to carry out ADL, hand and wrist therapy that is focused and coordinated is necessary. This therapy is sometimes disregarded in rehabilitation robots. Thus, a novel paired hand-wrist exoskeleton has been created to do this, as shown in Figure 2.4. Pezent et al. (2017) present the design of the wrist module and various human-related factors taken into account to fully realize its potential as a coordinated hand-wrist device. The serial wrist mechanism has been designed to make donning and doffing easier for patients and to guarantee compatibility with the hand module in tasks requiring virtual and aided grasping. Other practical considerations such as physician-friendliness, ambidextrous reconfigurability, and device ergonomics have also been addressed. Experimental evaluation of the functional workspace and dynamic features of the wrist module as a rehabilitation tool. Comparing the device to existing ones reveals that it performs better specifically in terms of ROM, friction, torque output, and closed-loop position bandwidth. Hence, the presented performance and operational factors for the wrist module allow its application in a variety of upcoming clinical studies.

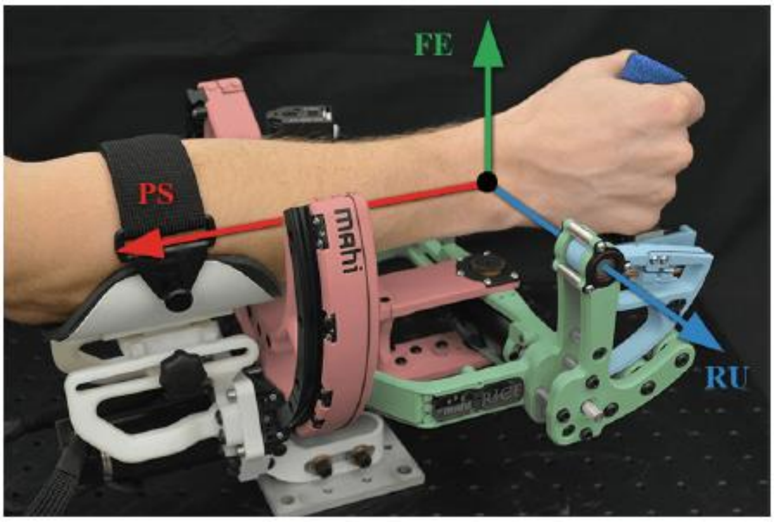

Figure 2.4 3-DOF forearm and wrist exoskeleton (Pezent et al., 2017)

Soft robotics has recently come to light as a viable route in delivering robot-aided rehabilitation due to its compliant nature, which makes it safe for interaction with people. Multiple upper limb joints must be mobile for task-specific rehabilitation activities, however, the bulk of soft robotic exoskeletons on the market today are focused on hand rehabilitation. Thus, soft robotic wrist exoskeletons cannot yet give the wrist enough DOF under secure working conditions. In Figure 2.5, Ang and Yeow (2019) present a 3D printed soft robotic wrist sleeve that has enough torque and bending to restore at least 70% of the ROM of a healthy person's wrist in 2-DOF.

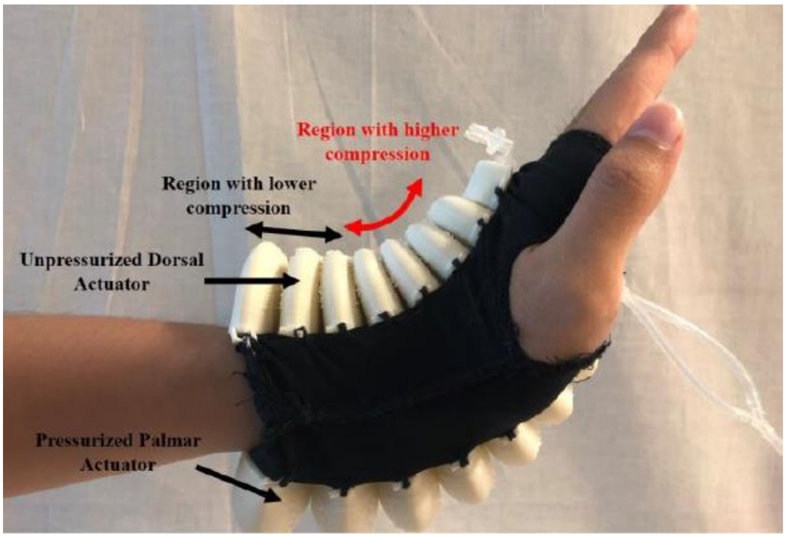

Figure 2.5 3D-printed soft robotic wrist sleeve (Ang and Yeow, 2019)

Since it is the fact that the hands serve as the main interface with the outside world, rehabilitation of the wrist and hand is particularly important for functional recovery. Even years after a stroke, robotic devices are still excellent choices for offering repeated and rigorous practice while regaining functional use of the upper limbs. However, the robotic devices that concentrate on hand rehabilitation are constrained by their excessive cost, limited functionality, or complexity. It is worth mentioning, that a key challenge in robotic rehabilitation now is to provide aided movement to the multiple DOF of the hand to restore motor coordination and function with a feasible system for deployment in a clinical environment. Therefore, it is crucial to develop a design and control approach for such devices that fills this gap.

Continuous passive motion, a technique that involves moving the injured joint physically without using the patient's muscles, can be used to treat wrist injuries. This is made feasible by using equipment that was exclusively developed to provide the wrist with the finest rehabilitation motions (Petre et al., 2018). As an alternative, there is a simple solution for achieving continuous passive motion, which is to employ the resistance bands and the right muscle movements. To assist develop strong wrists and forearms, resistance bands are quite helpful in this respect due to their retractive characteristic that gives semiautomatic motions. For instance, the muscular strength in the wrist and forearm region can be increased while doing the wrist flexion/extension exercises with the resistance bands, as demonstrated in Figure 2.6. These exercises typically involve single joints moving in one direction and are meant to target certain muscles that give joint stability and exhibit overuse problems, which are commonly used in rehabilitation.

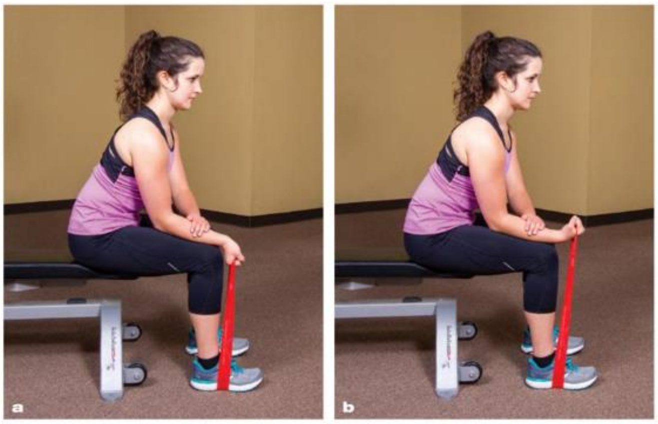

Figure 2.6 Wrist exercises using resistance bands (Page and Ellenbecker, 2008)

The ultimate goal is to enable the patients to complete the complex wrist joint rehabilitation using active, self-assisted exercises that are required to restore the functions of the anatomical motions of the wrist. Therefore, a comprehensive PDD procedure is required to create such a complicated device, and it will be much simpler if VR technology is exploited at this stage to visualize the assembly of detailed components and simulate the movement of wrist rehabilitation exercises in 3-DOF.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Project Flowchart

Figure 3.1 below illustrates the project development flow. Three objectives had been specified to resolve the difficulties mentioned in the problem statement. From the literature review, the importance of PDD using VR technology towards the concept of I4.0 in the future was raised to bring awareness to the researchers. Therefore, a few potential product options were proposed to go through the product screening and scoring processes for further development possibilities Then, various concepts of the selected product option were generated, followed by the screening and scoring processes, and came out with the best idea for concept testing. Next, the 3D CAD models were created and animated for demonstrating its user tutorial. To view the models in a VR environment, the files needed to be converted to either GLB or GLTF format so that they could be uploaded and opened by the VR application for acquiring more modification ideas. Lastly, the product of the finalized models was fabricated using the 3D printing technology and assembled with the existing components.

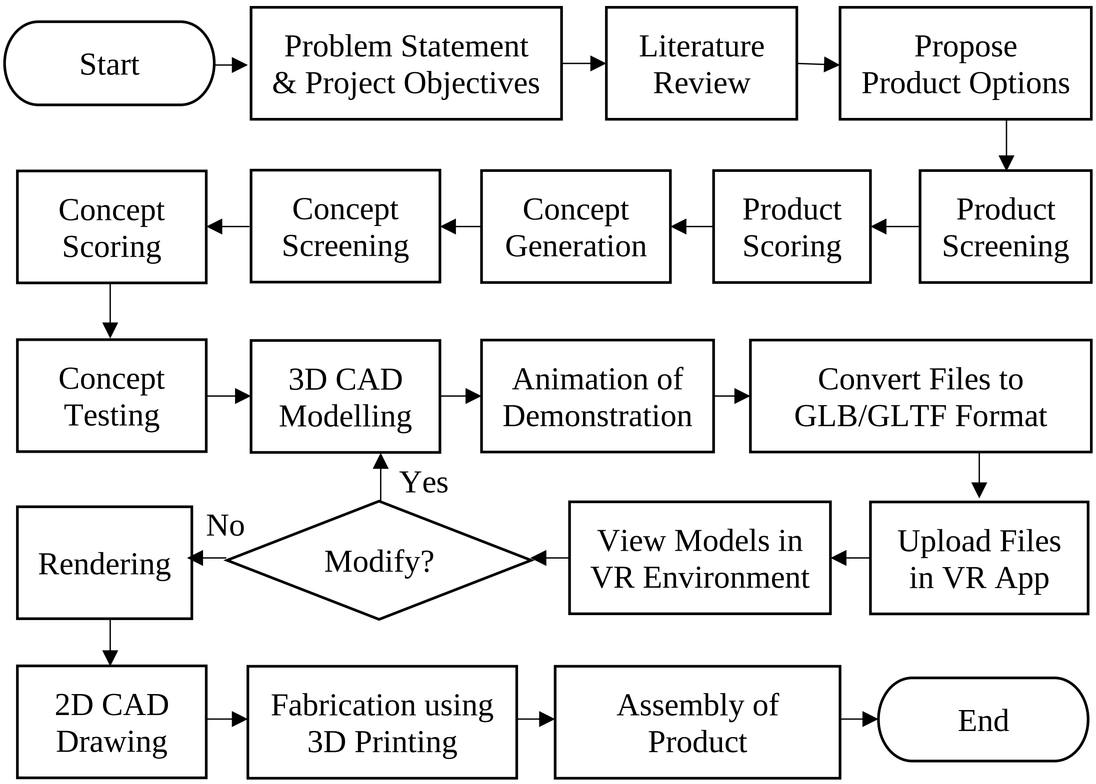

Figure 3.1 Flowchart of the project

3.2 Product Selection

To further understand the current market demands, some applications of VR in various industries were studied to find out multiple product options that were potential for further development based on their design limitations. After that, the product options were compared based on various criteria and then either eliminated or combined with others to innovate the best idea of product option for PDD.

3.2.1 Proposed Product Options

Nine product options from different categories were labelled and proposed with their limitations and possible improvements for developing any of them towards the I4.0 direction, as illustrated in Table 3.1.

Table 3.1 Potential product options with limitations and possible improvements

Product Options	Limitations	Possible Improvements
Furniture Assembly (A)	People often struggle with self-assembly as the step-by-step process is challenging while referring to its manual instruction. Especially when it comes to a flat-pack design, there will require a variety of components in the assembly process that might confuse the users.	To put assembly manuals into VR and help users to understand the product in greater detail and analyse its ergonomics by visualizing the prototypes in available space from different angles.
Profile Assembly (B)	In reality, much time is required to identify many areas before fabricating the prototype, including working environments, geometric modelling of objects, real-time collision detection, incorporation of geometric constraints, swept surfaces, and volumes.	To implement VR technology that allows evaluations to manipulate and assemble parts and result in reduced time and costs for product design. Also, the work steps are simulated virtually to optimize 3D models and it enables time-study for the overall assembly process.

Table 3.1 (cont.) Potential product options with limitations and possible improvements

Product Options	**Limitations**	**Possible Improvements**
Robot Gripper (C)	The tip of gripper fingers which are usually made of rubber needs to be replaced with new parts after some time due to its surface abrasion during the grasping process, to avoid slipping the object out of the gripper.	To design and develop a universal gripper that can adapt to the shape in the ranges of all available products. Also, it can avoid damage to sensitive objects in the high-speed grasp contact process.
Folding Bicycle (D)	The gadgets are making a folding bicycle more likely to break or suffer damage. Also, it might not be appropriate for the human body type since it is not customized, as the discomfort experience can lead to pain and injuries.	To allow the user to customize their appropriate folding bicycle based on ergonomics, and understand the assembly by visualizing the prototypes in available space from different angles.
Beach Cleaner (E)	There is a lack of solutions and machine designs suitable for cleaning the coastal strip, which includes the shoreline area land, water, and the strip of shore and land onto which water is thrown from falling waves.	To design a user-friendly cleaner that is adaptive to many environments and simulates the cleaning process, easing the worker to perform the process daily, to increase its efficiency and effectiveness.
Car Roof Cover (F)	The car covers can trap moisture next to paintwork, scratch and damage the beloved car, and it is easy to buy the wrong size or type of car cover, bringing troubles to users in the windy weather.	To design user-friendly and high-quality car roof covers to reflect and shield ultraviolet rays, cool down interior temperatures, and protect the car from dust, acid rain, bird dropping, deciduous, etc.

Table 3.1 (cont.) Potential product options with limitations and possible improvements

Product Options	**Limitations**	**Possible Improvements**
Wrist Rehabilitation Device (G)	The available devices for Wrist-T require constant guidance from the occupational therapist for ensuring appropriate diagnosis, assessment, and rehabilitation to prevent long-term adverse effects and possible disability.	To implement VR technology that visualizes the appropriate rehabilitation work steps to demonstrate its proper usage to the patients and allow them to complete the training tasks independently and recover as soon as possible.
Insect Trap Catcher (H)	The available devices in the current market lack satisfaction due to their low efficiency and effectiveness in solving insect problems as compared to conventional methods or tools like insecticide.	To design a high-efficient insect trap to monitor or directly reduce populations of insects or other arthropods, by trapping individuals and killing them.
Grocery Shopping Cart (I)	Grocery shopping carts are heavy, clumsy, child-unfriendly (despite kiddie seats), space-consuming, and hard to pull out of their clumps. Sometimes, these could bring inconvenience for the users in driving them safely and avoiding collision with others. Also, the loading space is limited and difficult for classifying the collected items accordingly, causing the messy stacking of items.	To design a foldable and user-friendly cart with the integration of safety features and a staircase to allow the user to get the items at high-level places in a supermarket, which brings convenience to the users.

3.2.2 Product Screening

To narrow down the number of product options effectively and further improve the available options; a selection matrix was made with a short list of criteria for the screening process on the nine labelled product options, as illustrated in Table 3.2.

Table 3.2 Product screening selection matrix

	Product Option				
Selection Criteria	**A**	**B**	**C**	**D**	**E**
Assembly operation	+	+	0	+	–
Time study	+	+	0	0	–
Space study	+	+	0	+	–
Ergonomics	+	0	0	+	+
Simulation	+	+	+	+	0
Customization	+	+	+	+	0
Impact to society	+	0	–	+	+
Industry-related	–	+	+	–	–
Low complexity/risk	0	+	–	–	–
Necessity in VR	+	+	0	+	–
Sum +'s Sum 0's Sum –'s	8 1 1	8 2 0	3 5 2	7 1 2	2 2 6
Net score Rank Continue?	7 2 Combine	8 1 Combine	1 4 No	5 3 No	-4 6 No

Table 3.2 (cont.) Product screening selection matrix

	Product Option			
Selection Criteria	**F**	**G**	**H**	**I**
Assembly operation	0	+	0	0
Time study	+	0	–	0
Space study	+	+	+	+
Ergonomics	0	+	–	+
Simulation	+	+	–	+
Customization	+	+	–	0
Impact to society	+	+	+	+
Industry-related	–	0	–	0
Low complexity/risk	0	0	+	+
Necessity in VR	+	+	0	0
Sum +'s Sum 0's Sum –'s	6 3 1	7 3 0	3 2 5	5 5 0
Net score Rank Continue?	5 3 No	7 2 Yes	-2 5 No	5 3 No

Note: The product options are rated with their relationship to the various selection criteria using a simple code ("+" for "highly related", "0" for "moderately related", and "–" for "poorly related") to identify some options for further consideration.

From Table 3.2, the result showed that product options A and B needed to be combined and option G would proceed to the next stage, which was product scoring.

3.2.3 Product Scoring

In describing the scoring process, the differences relative to screening were focused on. To better differentiate among competing options with increased resolution, the relative importance of the selection criteria was weighed and more refined comparisons were focused on each criterion, as illustrated in Table 3.3.

Table 3.3 Product scoring selection matrix

		Product Option			
		AB (Reference) Profile Assembly in Furniture Application		**G Wrist Rehabilitation Device**	
Selection Criteria	**Weight (%)**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Assembly operation	10	**3**	0.30	2	0.20
Time study	10	**3**	0.30	1	0.10
Space study	10	**3**	0.30	3	0.30
Ergonomics	10	**3**	0.30	5	0.50
Simulation	10	**3**	0.30	5	0.50
Customization	5	**3**	0.15	4	0.20
Impact to society	15	**3**	0.45	4	0.60
Industry-related	5	**3**	0.15	1	0.05
Low complexity/risk	5	**3**	0.15	2	0.10
Necessity in VR	20	**3**	0.60	5	1.00
	Total Score Rank	3.00 2		3.55 1	
	Continue?	No		Develop	

Note: A scale from 1 to 5 indicates the progressive rating of the options from "much worse than reference" to "much better than reference". While option AB serves as the overall reference option, the separate reference points for each criterion are signified by **bold** rating values.

From Table 3.3, the result showed that product option G of wrist rehabilitation device was identified as the most promising and would be developed in this research.

3.3 Concept Generation

Before generating the conceptual designs of the wrist rehabilitation device, the mission statement had been created as a research guideline to set a direction for continuous development and define the design requirements, as illustrated in Table 3.4.

Table 3.4 Mission statement of a wrist rehabilitation device

Mission Statement: Wrist Rehabilitation Device	
Product Description	• A portable, durable, flexible, and user-friendly device for Wrist-T.
Benefit Proposition	• The mechanism can move in three human wrist DOF. • The device can fit on the wrist of anyone. • The device is semiautomatic to exert constant tension or absorb movement.
Primary Market	• Wrist-T patients.
Secondary Markets	• Casual customer who needs stretching.
Assumptions and Constraints	• User-friendly and independent use for the patients. • Design of lightweight and simple device. • Long-lasting and durable to be used. • New product platform. • Limitation of materials.
Stakeholders	• Purchasers and users. • Service operations.

After having a systematic exploration of ideas externally and internally, a few concepts and solution fragments had been collected to navigate the space of possibilities by organizing and synthesizing them accordingly, as illustrated in Table 3.5.

Table 3.5 Exploration of concepts and solution fragments for each function

Essential Functions	**Concepts and Solution Fragments**
Forearm Support	• Hard and durable material • Lightweight • Fitting to the forearm
Motion in 3-DOF	• Electric actuator • Spring • Resistance band

3.4 Concept Selection

In this process, concept screening and concept scoring would be undergone to narrow the set of concept alternatives under consideration by comparing the relative strengths and weaknesses of the concepts, then either eliminated or combined. Each was supported by a decision matrix to rate, rank, and select the best concept.

3.4.1 List of Conceptual Designs

To illustrate the conceptual designs, a few concepts were brainstormed and sketched on paper, as shown in the following figures. Figure 3.2 showed a hand device in which the motion in 3-DOF would be exerted by the tension from springs, which were mounted on it. The design had a simple mechanism but lacked refinement.

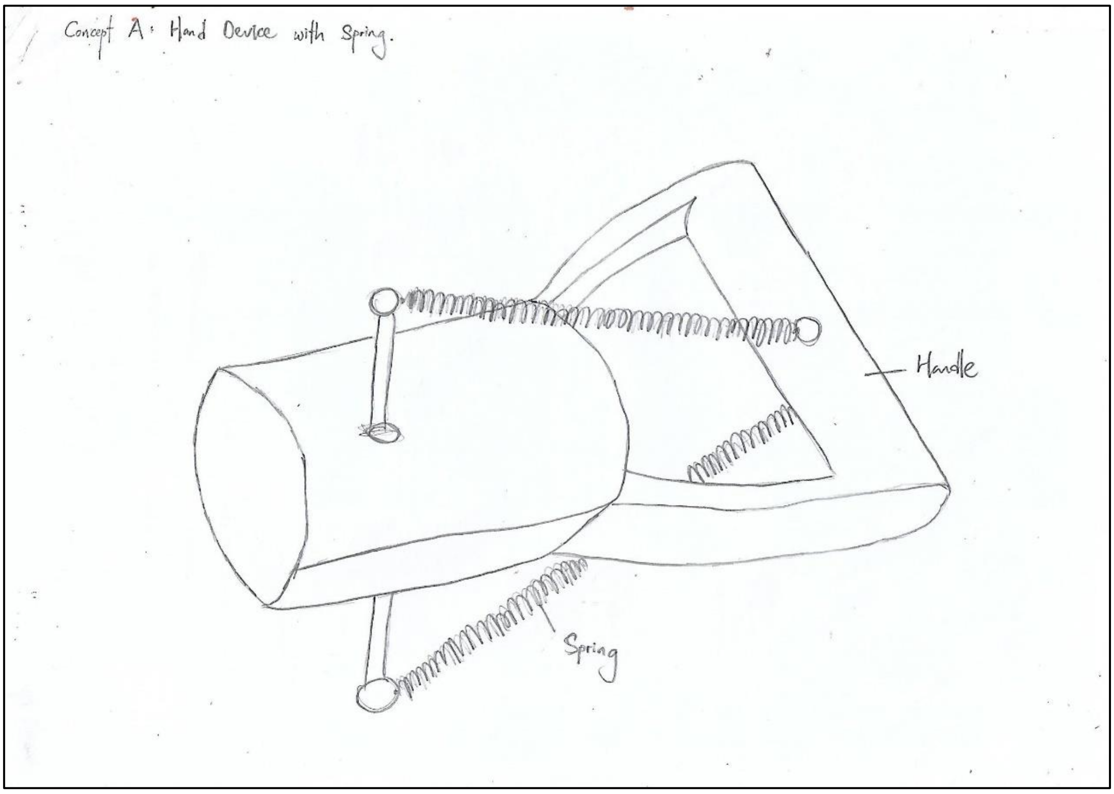

Figure 3.2 Hand device with spring (Concept A)

Figure 3.3 showed a wearable hand device in which the motion in 3-DOF would be controlled by the pneumatic soft actuators that could bend, twist, contract, and extend simultaneously. With the pneumatic tubing, the soft actuators could be driven to exert positive or negative pressure to generate motion that was pre-programmable.

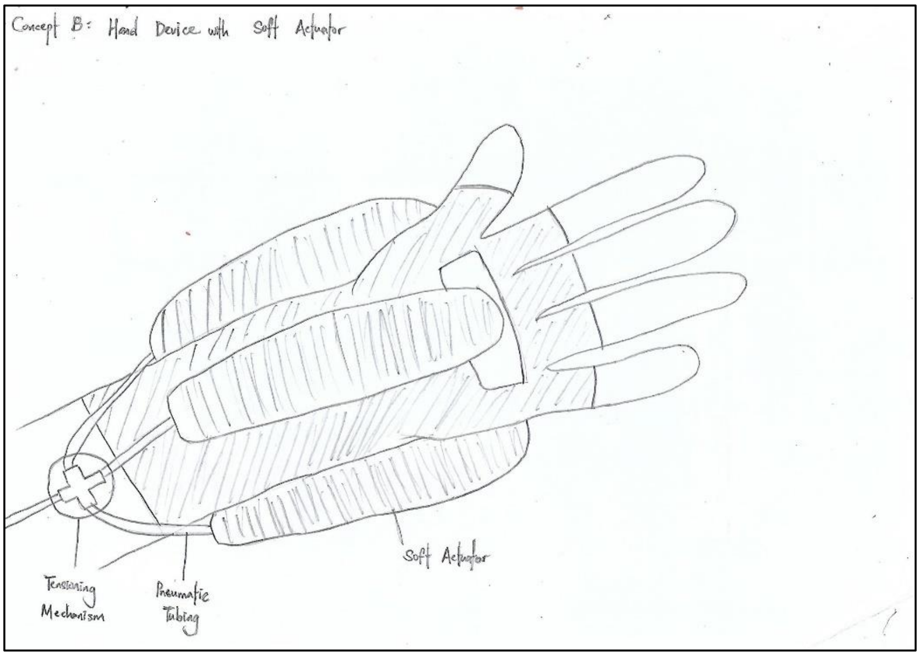

Figure 3.3 Hand device with the soft actuators (Concept B)

Figure 3.4 showed a supporting device with a controllable handle in which the motion in 3-DOF would be controlled manually by the users while placing it on a flat surface. It aimed at the independent usage for the users at home without the guidance of therapists but refinement was necessary as it was quite bulky at the current phase.

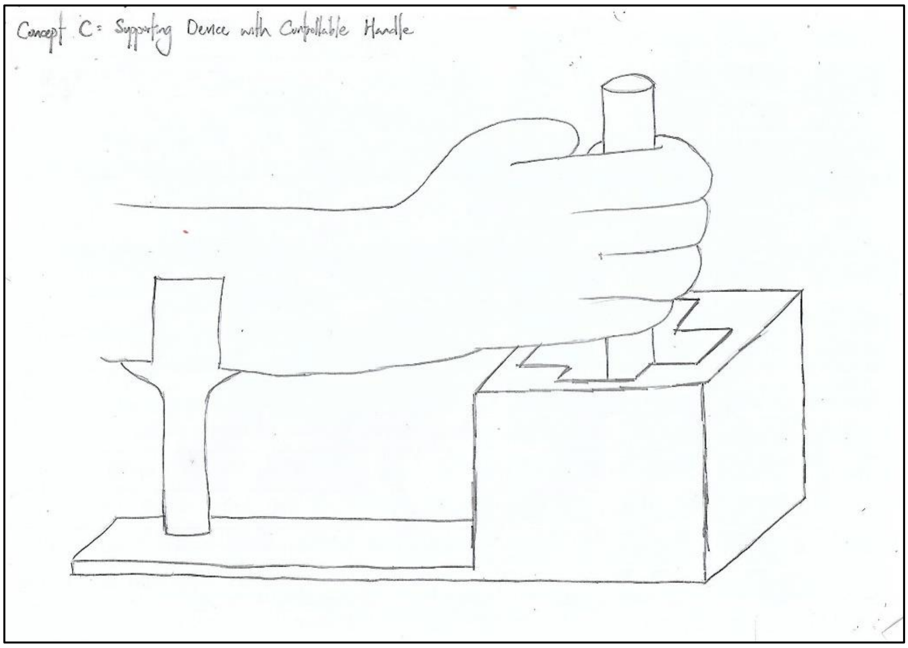

Figure 3.4 Supporting device with a controllable handle (Concept C)

Figure 3.5 showed a supporting device with a guided path in which the motion in 3-DOF would be controlled manually by the users also. Instead of moving the hand, it allowed the users to train their wrists by moving the forearm while the hand remained in an upright position.

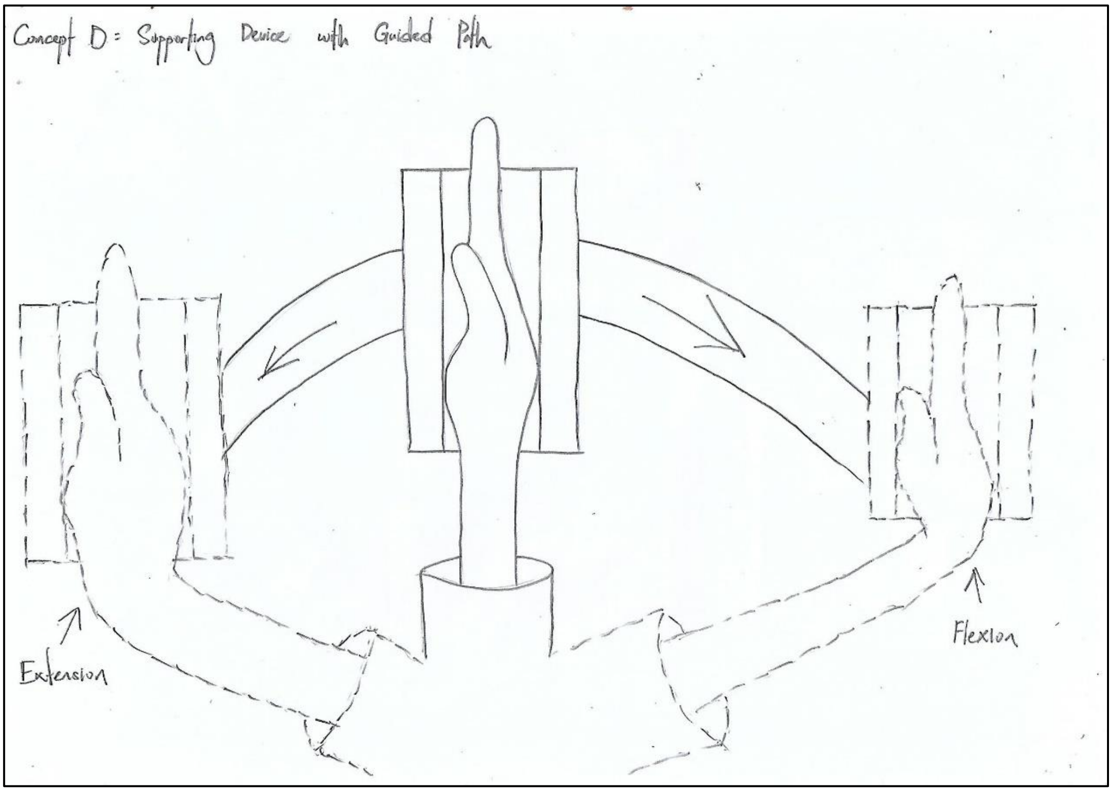

Figure 3.5 Supporting device with a guided path (Concept D)

3.4.2 Concept Screening

To narrow down the number of concepts effectively and further improve the concepts; a selection matrix was made with a short list of criteria for the screening process on the four concepts, as illustrated in Table 3.6.

Table 3.6 Concept screening selection matrix

	Concept			
Selection Criteria	**A**	**B**	**C**	**D**
Durability	0	+	0	0
Portability	+	+	-	-
Flexibility	+	+	+	-
Effectiveness	0	+	+	+
Attractiveness	0	+	+	-
Maintenance	-	+	0	0
Ease of use	+	-	+	+
Ease of manufacture	+	-	0	0
Sum +'s Sum 0's Sum –'s	4 3 1	6 0 2	4 3 1	2 3 3
Net score Rank Continue?	3 2 Combine	4 1 Yes	3 2 Combine	-1 3 No

Note: The concepts are rated with their relationship to the various selection criteria using a simple code ("+" for "highly related", "0" for "moderately related", and "–" for "poorly related") to identify some concepts for further consideration.

From Table 3.6, the result showed that concepts A and C needed to be combined and concept B would proceed to the next stage, which was concept scoring.

3.4.3 Concept Scoring

In describing the scoring process, the differences relative to screening were focused on. To better differentiate among competing concepts with increased resolution, the relative importance of the selection criteria was weighed and more refined comparisons were focused on each criterion, as illustrated in Table 3.7.

Table 3.7 Concept scoring selection matrix

		Concept			
		AC (Reference) Supporting Handle with Springs		**B Hand Device with Soft Actuator**	
Selection Criteria	**Weight (%)**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Durability	10	**3**	0.30	2	0.20
Portability	10	**3**	0.30	4	0.40
Flexibility	20	**3**	0.60	2	0.40
Effectiveness	20	**3**	0.60	2	0.40
Attractiveness	5	**3**	0.15	2	0.10
Maintenance	5	**3**	0.15	4	0.20
Ease of use					
- Installation setup	5	**3**	0.15	2	0.10
- Storing	5	**3**	0.15	4	0.20
- Controlling	5	**3**	0.15	2	0.10
Ease of manufacture					
- Fabrication cost	5	**3**	0.15	1	0.05
- Complexity	5	**3**	0.15	2	0.10
- Finding material	5	**3**	0.15	2	0.10
	Total Score	3.00		2.35	
	Rank	1		2	
	Continue?	Develop		No	

Note: A scale from 1 to 5 indicates the progressive rating of the concepts from "much worse than reference" to "much better than reference". While concept AC serves as the overall reference concept, the separate reference points for each criterion are signified by **bold** rating values.

The result from Table 3.7 showed that the concept AC of supporting handle with springs was identified as the most promising and would be developed in the project.

3.4.4 Concept Testing

In this step, the concept AC would be reviewed about its advantages and disadvantages so that it could be modified further to fulfil the requirements. Figure 3.6 showed that concept AC had a mechanism to provide motion to the wrist in 3-DOF. Also, it was semiautomatic as the springs could exert tension in assisting the users to move their wrists. Last but not least, it was designed with the features of lightweight, portable, and ergonomic to the wrist position so that the users could secure the forearm and put it on the thigh with adjustable padded elbow and knee supports for convenience.

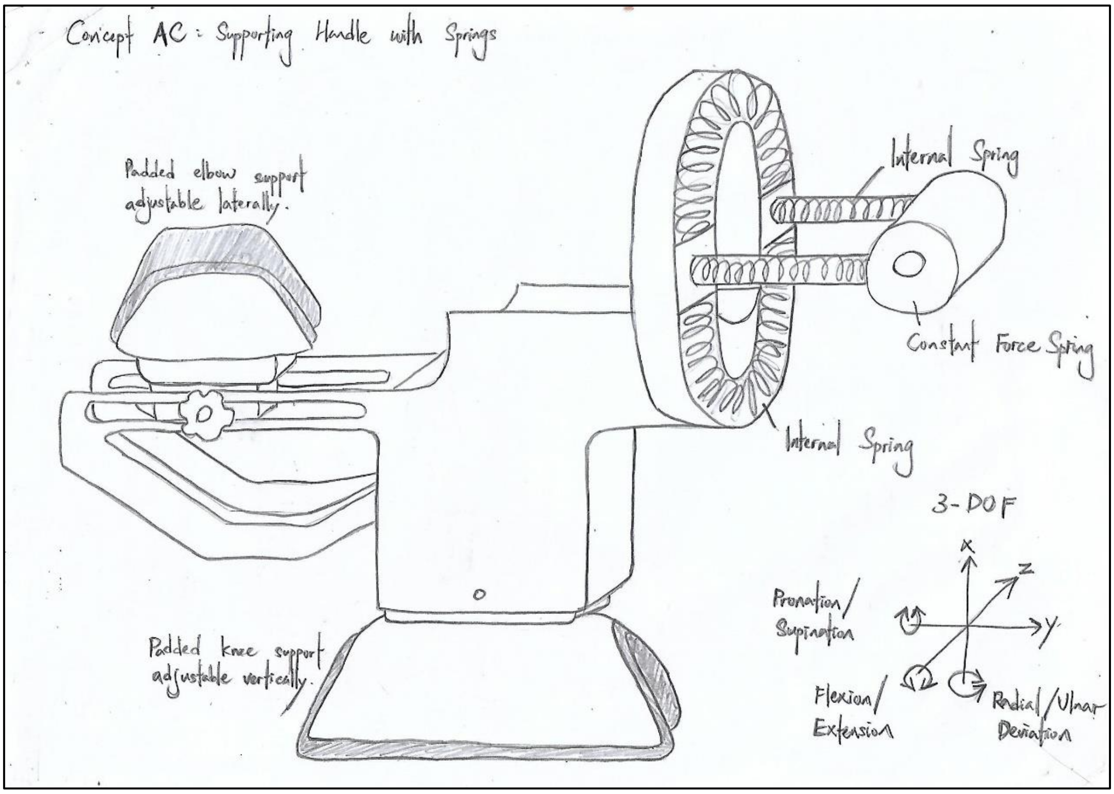

Figure 3.6 Supporting handle with springs (Concept AC)

Although the springs were initiated to provide the semiautomatic motion for assisting the user in drawing back the handle during the exercise, somehow the spring loads were estimated to be quite large and inconstant, in which the users needed to exert much more force than expected to move the handle. Thus, the spring feature was assumed to be not user-friendly and unsuitable, especially for wrist-T patients. To develop the product in providing the dynamic force for strength, tubular resistance bands with five multi-function levels (10 lbs, 15 lbs, 25 lbs, 30 lbs and 35 lbs) were introduced for replacement so that the adjustable tension could minimize the wrist joint stress while maximizing the impact on the targeted muscle groups in different DOF.

3.5 Implementation of VR Technology in PDD

At first, the 3D CAD models were created from the sketching of concept AC using SOLIDWORKS 2021. To further illustrate its usage conditions, the CAD models of the human arm and leg were added and assembled to the wrist rehabilitation device to show the user the proper way for equipping it and what it would be looked like.

There were two ways to visualize the models in a VR environment, that was either using the VR devices of HTC Vive Pro or Oculus Quest 2. For HTC Vive Pro, the device model and its animation were converted and opened in eDrawings Professional to exploit the function of opening the file in a VR environment using the HTC Vive Pro for further modification in PDD, as shown in Figure 3.7 and Figure 3.8.

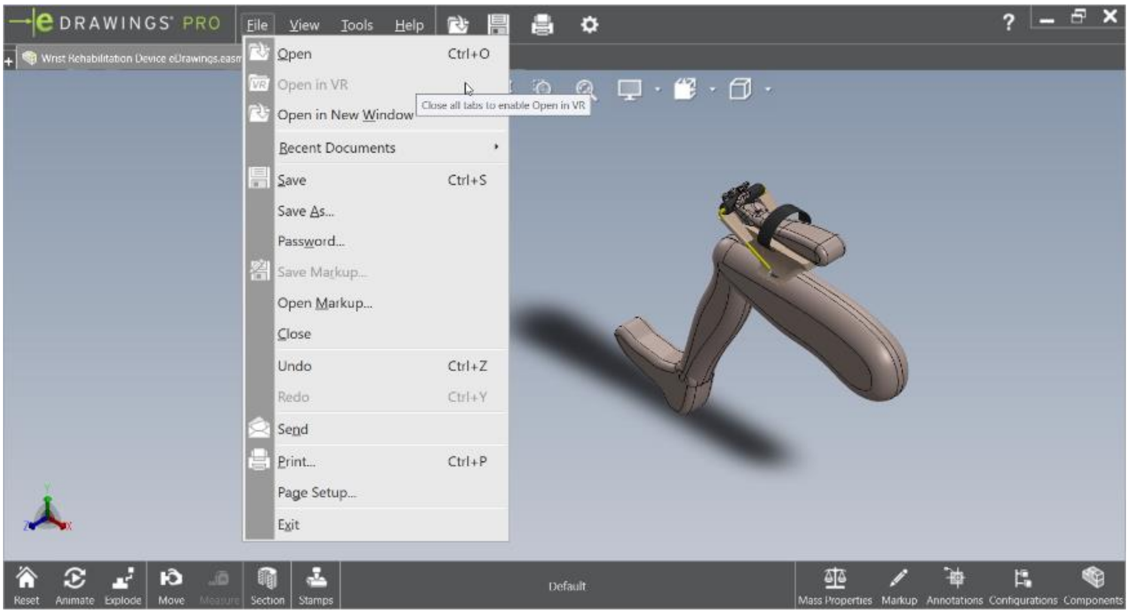

Figure 3.7 Device model in eDrawings Professional for opening in VR

Figure 3.8 HTC Vive Pro VR headset with PC and controllers