Conceptual Design for Ankle Rehabilitation Robot by Using Morphological Chart and Pugh Method

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Abstract. Lateral ankle sprains are among the most common injuries in competitive sports and recreational activities according to studies. Ankle sprains accounted for 70% or more of all reported ankle injuries in high risk sports. However, ankle sprains often only partially treated and there are more than 40% of ankle sprains are recurrent. Even though the ankle rehabilitation treatment exists, but there are some limitations that relates to the current situations. Firstly, the cost for ankle rehabilitation treatments are high and may be a burden to the patients while the traditional rehabilitation treatment performance highly relies on a physiotherapist's experience and the manual training method makes physiotherapist exhausted. Therefore, ankle rehabilitation robot can help to solve these problems. Morphological Chart are used to generate the concept design while Pugh Method are used to choose the best design. Concept design A (4 DOF Pulley Driven Cable Based Parallel Mechanism Ankle Rehabilitation Robot) are chosen as the best design among 5 concept design due to its advantages in aspect of low cost, easy to use, high portability, high back drivability and fulfilment of ankle rehabilitation exercises.

1. Introduction

Many studies have been shown that ankle injuries occupied 10% to 30% of all athletic injuries. Ankle sprains accounted for 70% or more of all reported ankle injuries in high risk sports. However, ankle sprains often only partially treated and there are more than 40% of ankle sprains are recurrent. Hence, this can lead to Chronic Ankle Instability (CAI) and Ankle Osteoarthritis. Apart from sports, there are about 25,000 sprained ankles every day and 30% people who use rest and ice alone will still have pain one year later. Even though the ankle rehabilitation treatment exists, but there are some limitations that relates to the current situations. The costs for ankle rehabilitation treatments are high and may be a burden to the patients while the traditional rehabilitation treatment performance highly relies on a physiotherapist's experience in which the manual training method makes physiotherapist exhausted. Patients may act confrontational on this passive training method which reduces the rehabilitation efficiency. Therefore, development of robotic systems may reduce physiotherapist's workload and enhance patients' rehabilitation performance in order to address the manipulation challenges in ankle rehabilitation. Hence, ankle rehabilitation robot can help to solve these problems.
1.1 Ankle Joint Structure and Motion

Ankle joint can revolve under three axes, hence several movements for examples walking, running and jumping can be performed by the ankle joint. The ankle joint can be revolved under any direction with limited motion range which make it unique. The ankle joint can rotate around three axes (x, y and z), thus motion such as Inversion; Eversion, Dorsiflexion; Plantarflexion and Adduction; Abduction can be performed by the ankle joint [1].

![Figure 1. (a) Structure of Ankle [7]; (b) Ankle Joint Motion [8]](image)

1.2 Robot-aid Ankle Rehabilitation Robots

Robot-aid ankle rehabilitation device can be classified into two types which are Platform Based ankle rehabilitation robot and Wearable ankle rehabilitation robot [1][2][3][4]. Additionally, most of ankle musculoskeletal and neurological injuries are treated by platform-based ankle rehabilitation robot, while ankle-related gait training is focus more by wearable ankle rehabilitation robot [2]. Platform based robots are static robots which have a few actuators to performs ankle rehabilitation exercise [4]. The parallel mechanism ankle rehabilitation robots have advantages such as high stiffness, large payload capacity, and also accuracy in safe workspace compared to serial mechanism ankle rehabilitation robots [5]. Parallel ankle rehabilitation robot can be divided into two classes according to the rotation center which are Actuators Below the End Effector (AbEE) and also Actuators Above the End Effector (AaEE) [2]. In additional, platform based ankle robots could be further categories into single DOF and multiple DOF robots. In general, single DOF ankle rehabilitation robot for specific applications whereas multiple DOF ankle rehabilitation robot for comprehensive ankle rehabilitation exercises [2]. Multiple DOF basically are used in parallel mechanism to reduce the robot’s size [6].

![Figure 2. (a) AbEE, (b) AaEE. A is moving platform; B is fixed platform. [2]](image)

2. List of Criteria for Generating Concept Design

Morphological chart is a design tool to generate the concept design. It was firstly proposed by Swiss astronomer, Fritz Zwicky. Conceptual design is efficiency generated by Morphological charts due to the huge number of designs with limited data and also under limited time. Also, Morphological charts is capable to generates early results. There are 8 criteria for designing suitable ankle rehabilitation robot which are Mechanism, Actuation, User Interface, Sensors, Type of Platform, Degree of Freedom, Rotational Joint Range and Materials by using Morphological Chart.

1. Mechanism – The transmission or lifting power from the actuators to the foot platform are determined by using the mechanism criteria. Besides, the simplicity and complexity of mechanical operation of the ankle rehabilitation robot will also be determined due to this criterion. Examples of potential mechanism for the design are: Cables (Pulleys), Swing Arm Quick Return Mechanism, Gears
2. Actuation – Actuation is the criteria of making a machine start to work or a process start to happen. Most commonly actuation of ankle rehabilitation robot are electricity and pneumatic source due to electricity is coupled with electric motor and driving mechanism to improve torque, control ability and back drivability [4]. However, extra equipment such as compressor is required by pneumatic actuator to operate [4][9]. Hence, the portability for pneumatic actuator are hindered compared to electrical actuator due to the additional weight and equipment. Ease of maintenance, high power-to-weight ratio, and cleanliness are the advantages of using pneumatic actuators. Pneumatic Cylinder, Hydraulic Cylinder, Linear motor, DC rotary motor, Shape Memory Alloy, Pneumatic Muscle Actuators and Solenoids are the potential actuators for ankle rehabilitation robot design [9].

3. User Interface – User Interface are the medium to communicate among human and computer system with the help of input devices and software. Hence, there are some user interface that are suitable for the robot such as PC, Control Panel which is connected to the robot and lastly Remote Control (Wireless Transmission) [9].

4. Sensors – The installation of variety sensing components will affect the robot design in terms of robot functionality, safety and movement control of the robot. The integration of sensors can be easily implemented with the robot structure of parallel mechanism with physical rotational axis. Displacement-based sensors such as potentiometer and encoder are used to facilitate position control scheme while Force-based sensors are used as feedback in the force control scheme. Hence, Force Sensor, Encoder, Pressure Sensor, Displacement Sensor, Linear Potentiometer, Torque Sensor, Redundant Sensor, Axis Inclinometers, Accelerometer and Proximity Sensor are the potential sensors for the ankle rehabilitation robot [9].

5. Type of Platform – The shape of foot platform for ankle rehabilitation robot are chosen and determined. Circular shaped platform has been used by Saglia et al. while rectangular shaped foot platform has been used by both Jamwal et al. and Yoon et al.. Besides, Tsoi et al are using a U-shaped foot platform. Hence, the potential types of platform are circle-shaped, rectangular-shaped, triangle-shaped and hexagon-shaped [9].

6. Degree of Freedom (DOF) – Degree of Freedom are the number of independent ways by which a dynamic system can move, without violating any constraint imposed on it. There were various ankle rehabilitation robots with different Degree of Freedom (DOF) which 1-DOF ankle rehabilitation robots are mostly developed for specific applications, while multi-DOF devices are more suitable for comprehensive ankle rehabilitation exercises. Hence, the potential DOF for the device are 1-DOF, 2-DOF, 3-DOF, 4-DOF and 6-DOF.

7. Range Joint Rotational – The angle range for the axis x, y and z of each ankle motion such as inversion, eversion, dorsiflexion, plantarflexion, adduction and abduction need to identified and design accurately to perform the efficient rehabilitation and to prevent discomfort to patients. Hence, the table for ranges motion of each ankle axes have been list out in the Table 1.

| Axes | Name of the Motion   | Range of Motion |
|------|---------------------|-----------------|
| X    | Inversion           | 14.5° - 22°     |
|      | Eversion            | 10° - 17°       |
| Y    | Dorsiflexion        | 20° - 30°       |
|      | Plantarflexion      | 37° - 45°       |
| Z    | Adduction           | 22° - 35°       |
|      | Abduction           | 15° - 25°       |

Table 1. Ranges of angle for ankle motion [9]
8. **Material** – This criterion is to choose the best material that is suitable for the ankle rehabilitation robot. The potential materials for the ankle rehabilitation robot are plastic, aluminium and stainless steel [9]. Table 2 is a Morphological Chart that are generated by the criteria needed to designing ankle rehabilitation robot. The parameters in each criterion are freely mix and match to generate five concept design of ankle rehabilitation.

### Table 2. Morphological Chart

| Criteria         | Parameters                          |
|------------------|-------------------------------------|
| **Mechanism**    | Screw Mechanism Helical Gear Belts Chains Lever Mechanism |
| Rack and Pinion  | Pulleys Cams 4-Bar Linkage Peaucellier Cell |
| 2-way Cylinder   | Shafts and Gears Robotic Arm Magnetic Levitation Slider Crank |
| Spring Mechanism| Spur Gears Internal Gear Swing Arm Quick Return Ball Joint |
| **Actuator**     | DC Rotary Motor Solenoids Hydraulic Cylinder Pneumatic Cylinder Linear Motor |
| Shape Memory Alloy| Pneumatic Muscle Actuators (PMA) |
| **Shape of Platform** |                                 |
| **Sensors**      | Force Sensor Optical Encoder Pressure Sensor Displacement Sensor Linear Potentiometer |
| Torque Sensor    | Magnetic Rotary Encoder Axis Inclinometers Accelerometer Proximity Sensor |
| Inversion (14.5° - 22°) | Eversion (10° - 17°) | Dorsiflexion (20° - 30°) | Plantarflexion (37° - 45°) | Adduction (22° - 35°) |
| Abduction (15° - 25°) |
| **User Interface** | Remote Control (Wireless Transmission) Control Panel (Wire Connection) |
| **Degree of Freedom** | 1 2 3 4 6 |
| **Materials**    | Plastic Aluminium Stainless Steel |

3. **Concept Generation Design**

The following are the 5 conceptual design of ankle rehabilitation robot that have been designed and drawn out using SolidWorks based on the criteria from the Morphological Chart.
Design A is a 4 DOF Pulley Driven Cable Based Parallel Mechanism Ankle Rehabilitation Robot. Dimension of Design A are 37.6cm x 20cm x 38cm. Four rotary DC Motor with pulley cables are attached on the side of the top platform. The rotary motor will pull the cable to achieve the specific angle for the foot platform. A ball joint is attached between the bottom of the foot platform and the robot’s base for the motion exercise stability of the robot. This design is suitable for sitting type ankle rehabilitation exercise. Ankle rehabilitation exercise motion such as inversion, eversion, dorsiflexion, plantarflexion, adduction and abduction can be done by this design. Besides that, for controlling motion and resistance of the robot, the sensor such as force sensor and accelerometer will be used. The PC will be selected as the user interface for this design.

Design B is a 2 DOF Rotational Ankle Rehabilitation Robot. Dimension of Design B are 48cm x 40cm x 31.5 cm. Four DC motor will be used for this design, two DC motor drive on the right and left side of the robot while another two DC motor will drive on the front and back of the robot. This design is suitable for both sitting and standing mode ankle rehabilitation exercises. Ankle rehabilitation exercise motion such as inversion, eversion, dorsiflexion and plantarflexion can be practise by this design. Moreover, the detection of the robot movement will be done by encoder while the motion and resistance controlling of the robot will be done by additional sensors such as accelerometer and also force sensor. The PC will be selected as the user interface for this design.

Design C is a 3 DOF Ankle Rehabilitation Robot. Dimension of Design C is 45cm x 40cm x 30cm. Three DC motor is used as actuator for the robot. This design is suitable for sitting mode ankle rehabilitation exercises. Ankle rehabilitation exercise motion such as inversion, eversion, dorsiflexion and plantarflexion can be practised by this design. Moreover, the robot movement will be detected by proximity sensor while detecting resistance of the patients’ foot and control the position and movement of the robot will be done by additional sensors such as force sensor and accelerometer. The PC will be selected as the user interface for this design.

Design D is a 3 DOF RRR Parallel Ankle Rehabilitation Robot (PARR). Dimension of Design D is 32cm x 20cm x 30cm. Two identical linear actuators and a stepper motor are used. The active joint P1 and P2 are employed by the linear actuators while stepper motor stepper motor drives the joint R1 via a planetary reducer. This design is only suitable for sitting ankle rehabilitation exercise and ankle motion such as inversion, eversion, dorsiflexion, plantarflexion, adduction and abduction can be practised by this design. The sensors such as encoders are used to monitor the angles and angular velocities. Additional sensors such as force sensor and torque sensor are used to measure the interaction force between human and the robot. The PC will be selected as the user interface for this design.

Design E is a 2 DOF Over-Actuated Parallel Mechanism Ankle Rehabilitation Robot. Dimension of Design E is 34cm x 34cm x 30cm. Three pneumatic cylinders are used to control the position and angle. A ball joint is used to stabilise the foot platform. This design is suitable for sitting mode ankle rehabilitation exercises. Ankle rehabilitation exercise motion such as inversion, eversion, dorsiflexion, plantarflexion, adduction and abduction can be practise by this design. Moreover, the detection of the robot movement will be done by encoder while the motion and resistance controlling of the robot will be done by additional sensors such as accelerometer and also force sensor. The PC will be selected as the user interface for this design.

![Figure 3. Concept Design A](image1)

![Figure 4. Concept Design B](image2)

![Figure 5. Concept Design C](image3)
4. Concept Selection

Pugh Method is a method to select the concept design and is used generally in the conceptual design stage which are developed by Stuart Pugh. A simple graphical method that revolves around a matrix with rows showing decision criteria and columns which shows concept is provided by Pugh Method. Hence, Pugh method is used to decide the best concept design for ankle rehabilitation robot. The concept design with the highest score of Pugh method will be selected. In this section, 3 DOF soft parallel ankle rehabilitation robot proposed by Jamwal et al. will be used as reference design (DATUM) and compared with the other five concepts design to overview which design is better. The 3 DOF soft parallel ankle rehabilitation robot is chosen as the reference design because it is AaEE robot which have better workspace and is more portable compared to AbEE ankle rehabilitation robots. Besides, AaEE are more suitable for multi-DOF ankle robot to practise comprehensive ankle therapy.

The baseline score as “0” to against all criteria. The DATUM will compare with each concept design and if the criteria of concept design is the same as the DATUM, it will score 0. If concept design is better than DATUM, it scores +1 while if worse than DATUM, it scores -1.

The following are the scale for concept design selection:

| Scale | Descriptions                  |
|-------|-------------------------------|
| +2    | Much Better than DATUM        |
| +1    | Better than DATUM             |
| 0     | Same as DATUM                 |
| -1    | Worse than DATUM              |
| -2    | Much Worse than DATUM         |

The following are the criteria for Pugh Method concept selection:

1. **Cost** – This criterion is to figure out the assumption cost of the concept design. The higher the cost of the design, the lower the scale for Pugh method. The costs for actuators only will be calculated due to it consumption high rate for the cost. This is to give an overview which concept design is more economic. For example, a device which used pneumatic actuator cost higher compared to electrical actuator.

2. **Easy Maintenance** – This criterion is to figure out which concept design is easier for maintenance. For example, ease of maintenance, high power-to-weight ratio, and cleanliness are the advantages of using pneumatic actuators. The more simplicity of the robot, the easier the maintenance.

3. **Easy to Use** – This criterion is to figure out which concept design is easier to use. Compared complex mechanism, simple mechanism is easier to use. This is due to simple mechanism which is easier to control. Besides that, the energy source for actuator is also important due to electrical actuator only need electricity to actuate while pneumatic actuator need compressor to actuate. Electricity is available everywhere but compressor can be only found in specific place.
4. **Safety** – This criterion is to figure out the safety of the concept design robot. The safety factor is very important for ankle rehabilitation robot especially the motion angle practise by the robot. If the angle of robot is overturned, this may cause serious damage to the patient’s ankle. Hence, there must be sensors or limit switch to stop the robot if the angle is overturned. For example, linear sensor and load cell are used by both Jamwal et al. and Yoon et al to ensure the robot operate safely to patient’s ankle.

5. **Back drivability** - This criterion is to figure out the back drivability that concept design ankle rehabilitation robot. Back drivability is important due to back drivability allows the actuators with high force capability and high impact resistance to adapt quickly to external forces. This will help to minimize the damages for patient when carry out rehabilitation due to environmental impacts or other unexpected external and internal events. High back drivability is generally overcome by having low inertia robot, hence allowing the patient to move the foot comfortably without feeling any significant resistive force from the robot.

6. **Re-configurable** – This criterion is to figure out the ability of re-configurable of concept design ankle rehabilitation robot. Configurability is an ability for a robot to be adjusted according to the ankle rehabilitation exercise whether is manual or automatic adjustment. For example, the robot can switch range of motion exercise which is Eversion/Inversion and Dorsiflexion/Plantar flexion to balancing exercise which is Abduction/Adduction. The robot configured by Yoon et al. can practise three main ankle exercises including heel toe raising.

7. **Portability** – This criterion is to figure out the portability of concept design ankle rehabilitation robot. If the robot is portable, it can take to any place needed easily and without much effort. For example, if the patient is unable to go to the hospital for ankle rehabilitation treatment, the hospital staff can take the robot to the patient’s house for treatment. The ideal estimate weight of ankle rehabilitation robot is between 5 kg to 15 kg and the smaller the size of robot, the more portable the robot. Moreover, the actuation of the robot will also affect the portability of robot. Electrical actuator robot is more portable compared to pneumatic actuator robot due to extra equipment such as compressor which is required by pneumatic actuator to operate.

8. **Fulfilment of ankle rehabilitation exercises** – This criterion is to figure out the ability of concept design robot to carry out the ankle rehabilitation exercise motion. The more motion that can be practised by the concept design robot, the better the design of ankle rehabilitation robot. For example, a robot developed by Yoon et al. has the ability to fulfil most of ankle rehabilitation exercises such as balancing and ROM.

Table 4 is a Pugh Method for concept design selection. The weightage is the level of important criteria for selecting the best design. The purpose of ankle rehabilitation robot is to carry out various ankle rehabilitation exercises. Hence, the fulfilment to practise various ankle rehabilitation exercises is the most important criteria for selecting the design and thus it is the highest weightage.

| Measurement Criteria          | Weightage | Concept Design | DATUM          |
|------------------------------|-----------|----------------|----------------|
| Low Cost                     | 5         | A: 2 [10]      | B: 2 [10]      | C: 2 [10] | D: 1 [5] | E: 0 [0] |
| Easy Maintenance             | 10        | A: 0 [0]       | B: 0 [0]       | C: 0 [0] | D: 0 [0] | E: 0 [0] |
| Easy to Use                  | 10        | A: 2 [20]      | B: 2 [20]      | C: 2 [20] | D: 2 [20] | E: 0 [0] |
5. Results
Concept design A ankle rehabilitation robot is the best design compared to others design. The concept
design A have the advantages in aspect of low cost, easy to use, high portability, high back drivability
and fulfilment of ankle rehabilitation exercises while having disadvantage in re-configurable.

6. Discussion
Concept Design A is chosen due to its ability to fulfil most of the ankle rehabilitation exercises. Portability is also the advantages of Concept Design A due to it is using electrical actuator (rotary DC
motor) which does not require any extra equipment which make it easy to use. Hence, it has the
advantage in weight compared to the other designs which used the pneumatic actuator. Besides, the
portability of Concept Design A can enable the hospital staff to carry the robot to patient’s home for
treatment when patient is unable to go to the hospital. Concept design A is parallel cable-driven robot,
hence it can offer a potential large workspace and high-speed motion while maintaining a light- weight
structure. Moreover, the sensors such as force sensor and accelerometer are used by Concept Design A
to control the motion and resistance of the ankle rehabilitation robot to operate safely. But, there
nevertheless the limitation of Concept Design A is it can only perform passive mode ankle
rehabilitation exercise but not active mode.

7. Conclusion
In conclusion, the number of patients for ankle injuries are huge and often only partially treated.
Therefore, ankle rehabilitation robot can help to solve these problems. The recent ankle rehabilitation
treatment required high costs, limited physiotherapist and also the passive training method of the
treatment. Hence, the ankle rehabilitation robot may help to solve these problems. Morphological
Chart have been used to generate the concept design while Pugh Method is used to choose the best
design. Concept design A has the highest rank in Pugh Method in which fulfilled the requirements of
low cost, easy to use, high portability, high back drivability and fulfilment of ankle rehabilitation
exercises compared to others design. Thus, concept design A is chosen as the best ankle rehabilitation
robot.

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