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Design and Physical Modelling Series Elastic Actuator for Ankle-Foot Orthosis

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Abstract*: This paper describes the development of Physical Modelling of Series Elastic Actuator for Active Ankle-Foot Orthosis by using Simscape Multibody Link. Active Ankle-Foot Orthosis is essential that can be used for the rehabilitation process to the patient. It is useful in medicine to help a patient who loses their walking ability, due to ankle weakness, to regain the walking ability. This project focuses on the design, simulate and physical modelling for Ankle-Foot Orthosis. This project was used Solidworks as a platform to design the Active Ankle-Foot Orthosis and using MatLab/Simulink for simulation by using Simscape Multibody Link tools. The Active Ankle-Foot Orthosis moves in 2 basic movement of ankle that is dorsiflexion and plantar flexion for rehabilitation. So, this project focuses on the physical modelling for the Series Elastic Actuator that drives the ankle movement mimicking the normal gait cycle.

Keywords: Ankle foot orthosis, gait cycle, impedance control, series elastic actuator, Simscape multibody link.

I. INTRODUCTION

Nowadays, due to the rapid population ageing, accidents, illness, war and genetics are among the factor that causes disability. Limitation in walking or running is a significant cause of disability. People experiencing a stroke and other neurological disorders have curtailed the walking ability, which significantly affects day by day life (Alam, M et al., 2014). Moreover, according to Yu, H et al. (2013), there is a demanding on robots' service, assistive and rehabilitation robot in both domestic and hospitality. Therefore, one of the most common types of lower limb disability is the inability to walk correctly due to an ankle joint failure. The failure in this joint causes severe pain while walking and leads to a reduction in the speed and function of the disabled person and his imbalance.

The leading cause of disability is the weakness of dorsiflexor and plantar flexor muscles and cause "Foot-slap" and toe- dragging. People with muscle disability are incapable of lifting their foot in mid-swing because of dorsiflexor muscle weakness. In previous research by Alam, M et al. (2014) "Foot-slap" is the uncontrolled and swift strike of the foot on the ground creating sound at rear area strike and "toe-drag" implies hauling of forefoot amid walking because of deficient ground freedom amid swing period of the gait cycle. Figure 1 shows the different phase in the normal gait cycle by a healthy person which divides into two-phases: stance phase and swing phase.

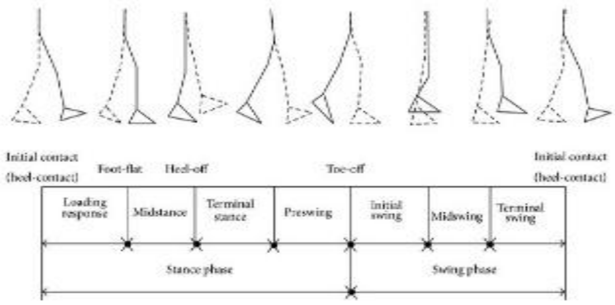

Fig. 1.Different stages of the normal gait cycle

Active Ankle-Foot Orthosis (AAFO) is a brace with Series Elastic Actuator that is made to keep the feet and ankles in a good position for standing and walking and were externally applied which intended to control the situation and motion of the ankle, compensate for weakness, or correct deformities. The actuator generates the ankle movement through dc motors and pneumatic tools that ensure the heel contacts the ground first before the toe, which mimics the normal human gait. Therefore, AAFO's can realign and control the ankle and foot joints; also, it provides protection which supports weakened joints and abnormal muscle. Active Ankle-Foot Orthosis were electromechanical devices that are worn by a human and designed to support the weakness and increase the performance of the wearer. In this case, there is a direct

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physical interaction with human limbs and safe force level must be assured where it should be able to deliver exact force/torque to human limbs as required. According to Pratt J, Pratt G (1998), an impedance- controlled interface is commonly essential when there is human-machine interaction.

Impedance control remains generally used for fine-tuning the mechanical impedance in high inertia and inflexible robotic manipulators. This approach by Hogan N and Buerger SP (2005), passive environments were allowed by stable interactions. Thus, these cases have driven the need of researcher on variable impedance, soft and compliant actuators for protected and human-accommodating apply autonomy applications. Hence, safe human-robot interaction involves with light-weight actuators with inherent compliance and low output impedance (Jardim, B., & Siqueira, A. A, 2013). Therefore, variable Impedance control is an approach to deal with the problem of dynamic interaction between manipulator and environment

II. LITERATURE REVIEW

A. Ankle Joint

The ankle functions as a hinge joint which attaches the proximal edge of the talus bone with the distal end of the tibia and fibula in the lower limb. (Tortora, G. J. 2006). Three bones form the connection of the ankle joint. The ankle bone is named the talus. A socket form lower end of the tibia and the fibula which is fitted by the top of the talus. The bottom of the talus rests on the heel bone, named the calcaneus. The talus inside the socket is responsible for the movement of dorsiflexion and plantar flexion. (Tortora, G. J. 2006).

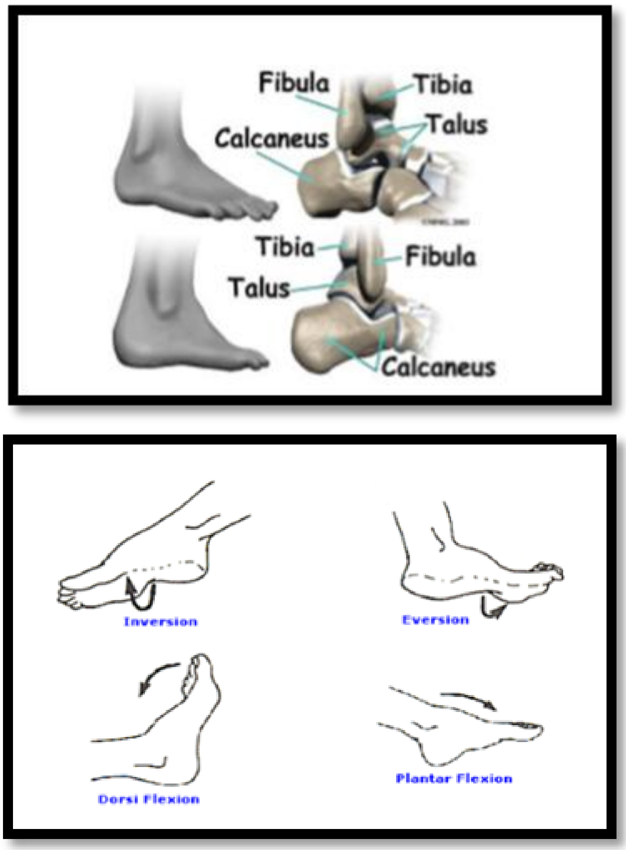

Fig. 2.Ankle anatomy and movement of ankle joint

B. Degree of freedom and range of motion

The requirements of the proposed design can be determined by analysing human movements since they are designed to perform tasks like the human body. To estimate the degree of freedom (DOF), the joint movements and exoskeleton joints in the leg, the best-known tool is the clinical gait analysis (CGA). The coherent human values can be found in the form of CGA data collected through the video in motion during the normal walking cycle. According to Onen, et al., (2014), the lower part of the human body can be modelled with one DOF in the knee, and seven DOFs (three DOFs in the hip, and three DOFs in the ankle) concerning the standard anatomical plane.

That's mean in ankle joints has 2 Degree of Freedom which is, two movements are possible in the sagittal plane, which is dorsiflexion and plantar flexion. While, the other one that occurs in the frontal plane was inversion which is a movement of the foot, which causes the soles of the feet that faces inward, and eversion is the opposite movement. During the passive motion, the articular surfaces and ligaments govern joint kinematics, with the articular surfaces sliding upon each other without appreciable tissue deformation. Figure 4 shows the movement of the ankle joint in two DOF.

Table- I: Range of motions of the human ankle, AAFO and BLEEX

Ankle movement	Human walking	Human (max)	AAFO (max)	BLEEX (max)
Plantarflexion	20°	50°	25°	45°
Dorsiflexion	15°	20°	15°	45°

C. An active Ankle foot orthosis

Orthopaedic ankles are reserved with two degrees of freedom. Both of these incorporated movements are dorsiflexion flexion and inversion movement. Among them, the dorsiflexion-plantarflexion movement actively controls the dc servomotor. Passive inversion-reverse connection with torsion spring and shock absorber. The spring and shock absorber make the virtual wall restrict movement beyond a specific range by using spring energy (Agrawal, A. et al. 2014). Ferris et al. (2005) have developed an AFO driven by artificial muscles. The orthosis has two pneumatic muscles to control the dorsiflexion and plantarflexion gestures of the ankle. Yamamoto et al. (1999) have established a dorsiflexion assist, measured by a spring. Dorsiflexion rectification is attained via the compression force of a spring within the assist device. Blaya, J., & Herr, H. (2004) has developed an AAFO with one DOF. The AAFO comprises a force-controllable series elastic actuator (SEA) capable of controlling orthotic joint stiffness and damping for plantar and dorsiflexion ankle motions.

D. Ankle ankle-foot orthosis design using Solidworks

The motivation behind this paper is to display the mechanical structure and investigation of pneumatic foot orthosis (PAFO) gadgets that can be utilised to help and reestablish lower legs with risky feet. Among these issues are cerebral paralysis,

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various sclerosis and muscle dystrophies. PAFO helps lower leg during dorsiflexion and plantar flexion with counterfeit pneumatic muscles and pneumatic turning engines. Worked in PAFO is additionally furnished with precise sensors, for example, power, position and quickening.

Light and compact structures dependent on biomechanical studies are built with carbon fibre materials. Mechanical structures are fabricated in SolidWorks. The PAFO configuration is dissected using Matlab/SimMechanics to decide the torque prerequisites of the board during usage. The consequences of the examination have demonstrated the reasonableness of the PAFO profiles gadget (Ulkir, Akgun, & Kaplanoglu, 2018).

E. Simscape multibody link

The reception of another model-based control plot for robot controllers requires critical thinking in many regards, from mechanical structure to the need to decide the fitting robot model for control, and to test the control of control execution. In a solitary arrangement, SolidWorks mix with Simscape to structure and control the robot controller has appeared in this report. This incorporation gives a stage to quick model mechanical controller control without structure a genuine model. Mechanical robots were first made utilising Solidworks and imported to Simscape, where robots were spoken to by square pictures connected to physical standards. Reproduced precedents for 7-DOF SAM ARM made by Berrett Technology Inc. Introduced to demonstrate the viability of the stage displayed (Ahn, 2014).

III. METHODOLOGY

This project discusses the method to be implemented to develop the project 'Mechatronics Design with Position Sensory of Ankle Exoskeleton for Rehabilitation'. The outcomes are used to compare the basic ankle movement using Angle measurement and the other design ankle exoskeleton. There are several critical stages, including the design Ankle Exoskeleton, hardware designs and software. It also described the tools or hardware used in this research.

A. Active Ankle foot orthosis system

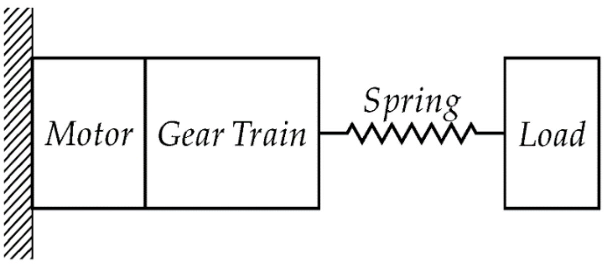

Fig. 3.Block Diagram for SEA

Figure 3 depicts the block diagram of the SEA. In AAFO, the critical part is the Series Elastic Actuator which drives the system as mimicking the muscle. According to the block diagram above, the SEA consists of four essential components which are motor, gear train, spring and load. A gear train consists of a nut, ball screw and steel plate. Hence, as in real condition, a DC motor mounted on a ball screw through the elastic coupling. The movement of the platform is guided by the nut, which changes the movement of the rotation of the ball screw in the linear motion of the platform. To obtain the power control and the drive impedance, a set of springs is introduced between the platform. When operating the DC motor, the nuts move forward or backwards, compressing a pair of springs. The springs are loaded by the load through the end effector.

B. Modelling the AAFO part

In this section, the AAFO is developed by using CAD software which is SolidWorks. An assembly of elements can be used exclusively for simulation because there exists an interaction between individual parts, which makes it possible to the control system and perform motion analysis. So, each created simulation model is an assembly of many different components. The building of each part of the geometric model in SolidWorks, begins with defining a 2D geometry that creates a solid or a surface. Then, based on the expansion or adjustment of the obtained element made by removing or adding material, the creation of parts is continued. Most CAD systems offer normalised items that can be used to build assemblies. The creation that is the result of the final assembly of components has a permanent link to the individual part files, which means that changes made in one of the files are automatically recognised to the linked files, correspondingly. The creation doesn't have its geometry. Instead, it consists of a set of links to the parts and constraints that are used to connect these elements. The created geometric models should be parametric, which allows changing dimensions of components and their positions relative to each other to analyse motion according to the same model. Geometrical models can be used not only for the construction of the simulation model but in an effortless way; they can be utilised to carry out other types of analysis, such as modal or stress analysis.

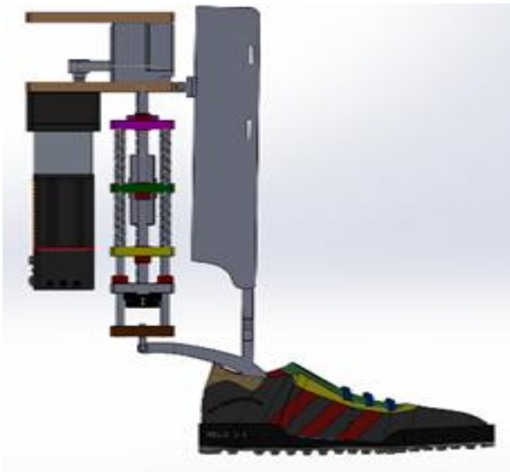

Fig. 4.All view ankle exoskeleton using Solidworks

C. Integrated model into MATLAB

The next stage is the execution of the SolidWorks assembly model in MATLAB/Simulink setting. The incorporation between CAD software and MATLAB offers a suitable interface to achieve complete control design and dynamic simulations of

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intricate mechanisms without deriving complex differential equations. MATLAB proposes to resolve complex mathematical and produce a graphical visualisation of the results.

MATLAB also provides numerous toolboxes, and one of the allowances is the SimMechanics Toolbox which simplifies the construction of kinematic chains, simulation of their dynamics and conception of results. Simulink is a tool that allows defining the development of the control system of the created models and presenting their simulation with complete control during a specified working cycle. Therefore, to transfer the model from SolidWorks to MATLAB/Simulink, the SolidWorks model designed is embedded in SimMechanics first. The CAD model file is converted to an XML file by using SimMechanics Link exporter. Then, the received data is imported into MATLAB/Simulink program and generated the SimMechanics model. The SimMechanics model is obtained after the implementation, which included a block diagram scheme. The process of CAD model into MATLAB/Simulink been illustrated in Figure 5.

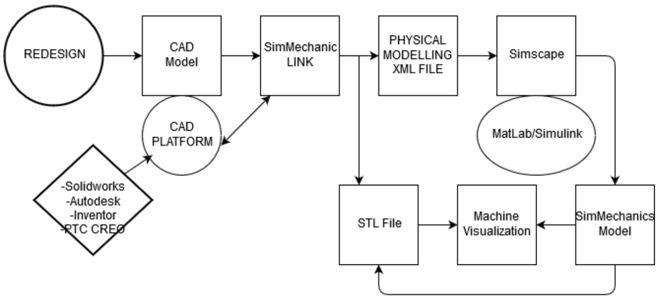

Fig. 5.Process of CAD model into MATLAB/Simulink environment

IV. RESULT AND DISCUSSION

A. Block diagram of Active Ankle foot orthosis in Simulink

Since the new design of AAFO has been successfully imported, Simulink generates a block diagram in a new window that has been shown in figure 27. Each of the block diagram representing each part that been resolved while their joint and constraint been identified and replaced with Simmechanic block diagram library such as a revolute, plantar and prismatic joint. Simscape Multibody Link has determined the design and automatically connect all the block diagram accordingly to the CAD design. As the AAFO has 32 part and was complicated, Simscape Multibody Link managed to convert all the part became a one big block diagram which including virtual environment such as gravity. Hence, to get the physical modelling by using this block diagram, run the Simulink so it can convert to the Mechanic Explorer, which the physical modelling should appear with the simulation.

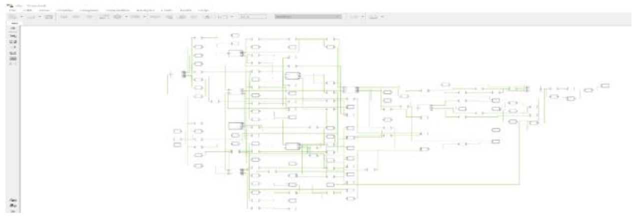

Fig. 6.Full block diagram of the AAFO in MATLAB/ Simulink

B. Diagnostic in Simulink

As we run the Simulink, it runs diagnostic for the simulation and gives a report which block diagram been an error or unconnected. Figure 7 shows the diagnostic description of the block diagram. The report shows that it detected one warning and one error for the simulation with the suggestion to fix the issue for simulation. The simulation cannot be done until this problem been solved. For the warning, it can be set by configuring the parameter in the Simscape Multibody Configuration Parameter which we can make the warning ignore from the simulation. While the error is shown at one of the block diagrams which at Revolute 4.

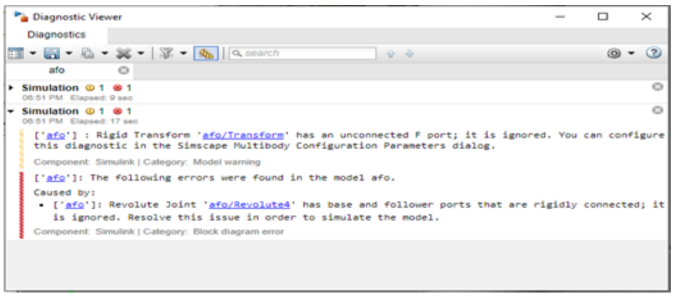

Fig. 7.Diagnostic in Simulink show error at one of the block diagram

From figure 8, it shows the answer to the issues that arise in the diagnostic viewer, which has been discussed in the MathWorks forum. Even though the joint not the same, but the cases are the same. So, this suggestion can be applied to this problem. Revolute joints are pin joints or hinge joints that are a One DOF kinematic pair used in mechanisms. Revolute joints have one DOF that define rotational actions among objects. Their configuration is well-defined by one value that signifies the sum of rotation about their first reference frame's z-axis.

Fig. 8.Mathworks forum answers for the issues

In figure 9, we can see the Revolute 4 block diagram been connected in between F1 port of ball screw and F2 port of FF12 block diagram.

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B port is based frame for Revolute 4 which connected to world frames while the F port is the follower as robot body. As our finding in the forum, it has been suggested to remove anything connected to the based and leave the follower only connected. By trying this suggestion, the issues had solved, but the diagnostic detected more unconnected block diagram, which causes the whole system interrupted. Because of that, we try to connect the block diagram to any other block diagram to see whether it can perform the simulation as expected.

However, nothing changed on that behave modification. In the Simcape Multibody Configuration Parameters, the irrelevant line has been set to none (ignore) because it should not affect the simulation. After updating the block diagram, we perform the simulation shown in figure 10. Physical modelling for AAFO has been released in the Explorer Mechanics, and the simulation is implemented, but it is not implemented as expected, which means that the block diagram has not been appropriately connected or defined. This simulation runs as scheduled if either fixes the block diagram or illustrated the subset in each block diagram.

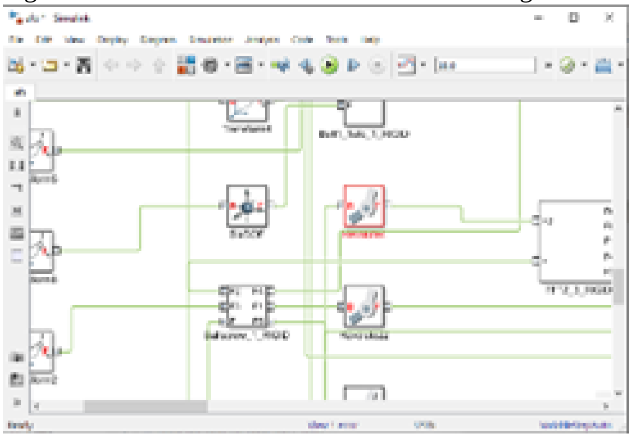

Fig. 9.Revolute 4 where the error been showed

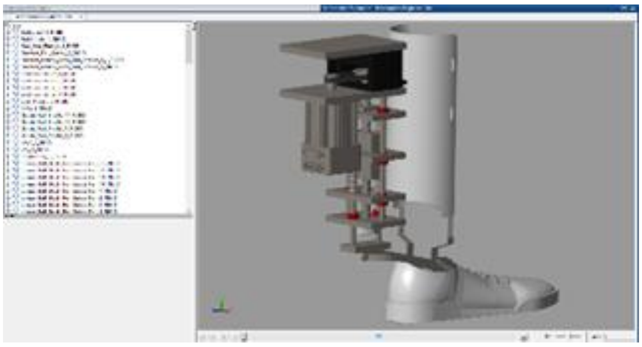

Fig. 10. Physical modelling of AAFO has been come out in Mechanic Explorer

Once we get the physical modelling in Mechanics Explorer, we can troubleshoot the model assembly by using the model report. Mechanics Explorer provides access to Model Report, a Simscape Multibody utility that summarises the assembly status of each joint and constraint in a model. By open this utility to determine which joint has failed to assemble. To do this, in the Mechanics Explorer menu bar, select Tools, then click Model Report. Model Report opens in a new window. A red square indicates that the model, as expected, has failed to assemble. There were three things that it troubleshoots, which are joints, constraint and assembly status. This information enables to concentrate troubleshooting efforts on a small block diagram region that surrounding the Pg joint block. We can use the Model Report tool to verify the assembly status by check that the assembly status icons for the model and its joints are green circles. The green circles indicate that the model has assembled correctly. The error message that Simscape Multibody issued during model update identifies position violation as the root cause of assembly failure. The error suggests that the frames connected are improperly aligned. By referring to model report figure 9, we can see that all joints and constraint were correctly aligned while the assemble status also indicated successfully.

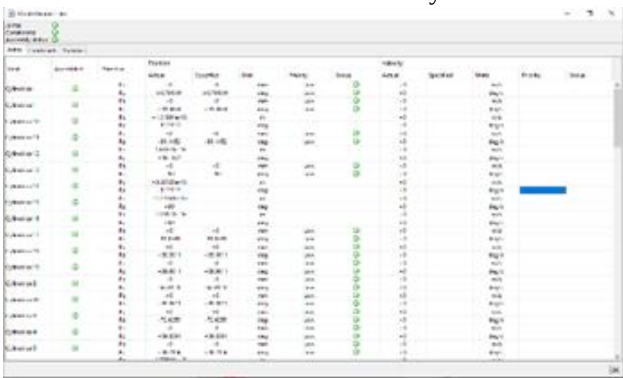

Fig. 11. Mechanics Explorer Model

V. CONCLUSION

Design and physical modelling for Active Ankle-Foot Orthosis were successful in this project. Based on the results obtained, we can extend research into many topics, such as creating a control system for the Series Elastic Actuator, which is impedance control by using physical models and block diagrams. Impedance control can be obtained by configuring block diagram or sub-sector by adding a PID controller. Simscape Multibody Link simplifies the robot control process when changing it from the CAD platform. Then, all transfer functions can be used in Simulink after obtaining a block diagram. This method shows that it is faster than using the SimMechanic library.

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