Design Brief

1. Problem Statement/Research Question and Background (AS)

The goal of the project is the development of a passively actuated (through the hip movement) orthotic device that utilizes the kinematic coupling of hip-knee-ankle joints to accurately reproduce the natural walking gait of a person to aid with reduced mobility in their lower extremity (i.e. below femur including the knee joint).

While the terms orthosis and exoskeleton are sometimes used interchangeably, Dollar and Herr [1] classify an orthosis as an anthropomorphic wearable device that is used to increase the ambulatory ability of a person suffering from a leg pathology by working in concert with the operator's movements. One of the earliest orthotic devices that used a simple mechanism to simulate walking was patented by Cobb [2]. The device consisted of a leg brace with a crank located at the hip that was used to wind up a torsional spring located at the knee joint, and produced a reciprocating motion at the knee via a cam and follower. Another early example of a design that reduced the difficulties encountered in the control of a large number of servo systems to obtain a certain gait trajectory by using kinematic coupling between the hip and the knee can be seen in the "kinematic walker" [3]. A combination of springs and linkages are used by the passive leg orthosis developed at University of Delaware in order to geometrically locate the center of mass of the leg - orthosis system, and then, balance out the effect of gravity [4]. Some of the major concerns related to the mechanical design of the orthotics include the problems associated with closely matching and obtaining close alignment between the structure of the exoskeleton to the wearer, portability, and the affectation of the biomechanics of locomotion. Some commonly used techniques for interfacing an orthotic with the lower limb of a wearer include foot connections [3] or specialized shoes [5] and straps, cuffs or harnesses around the thighs [5] and calves [6].

It is important to note, that while most of the underactuated parallel or muti-loop exoskeleton devices in literature show satisfactory performance, there still does not exist a systematic methodology for the design of these systems that made use of human's anatomic structure. In addition, due to lack of knee and/or ankle degrees-of-freedom, the hip and pelvic joints tend to make an abnormal motion pattern to ensure the foot clearance during the swing phase of the gait. The aforementioned highlights the need for the development of design techniques for customized passive multi-loop linkage skeletal structures that are able to couple/synchronize and adapt to the movement of all the lower extremity joints. Our work extends upon the novel techniques proposed by our faculty advisor Robson and our mentor Ghosh et al [7], [8], [9], [10], [11] regarding designing multi-loop linkage devices for physical support of patients that have reduced mobility in one of their lower legs (i.e. below femur including the knee joint). Here, we would like to note that unlike other wearable device design techniques that use parallel mechanical linkages, we offer a novel alternative approach: a comprehensive systematic process to create wearable lower extremity devices that incorporate anthropometric backbone chain and physiological task. Future research directions include extending the method to upper extremity and exploring techniques for 3D printing of the device with incorporated flexible joints.

2. Methods/Approach/Solutions Considered (AS)

This project aims to create a methodology for transforming a mechanical linkage design of a lower extremity into a lower limb wearable orthotic device that mimics the natural gait of a person with reduced leg mobility. The latter includes identifying the desired limb motion by using motion capture system, mathematically describing the limb trajectory as physiological task, linkage topology selection, dimensional synthesis, linkage assessment, replacing the anthropometric backbone chain with the human's limb and manufacturing (see Figure 1).

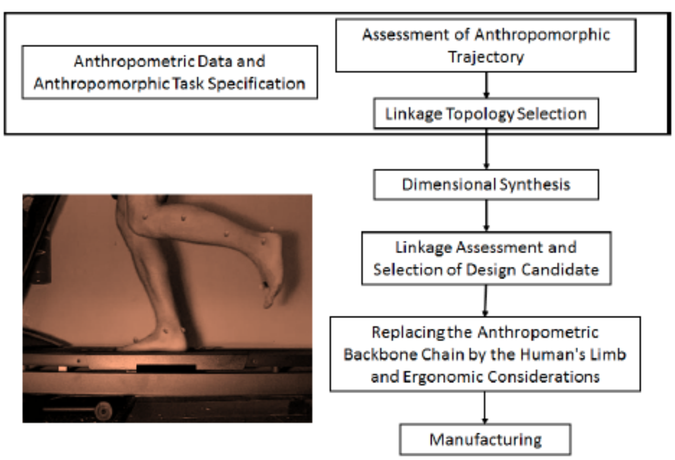

Figure 1. The systematic process for developing customized upper and lower extremity assistive devices for physical support and training of persons with reduced limb mobility.

In order to specify the physiological design task, motion capture data from a person walking at 1m/h on a treadmill was gathered and analyzed. Tracking points were attached on the subject's (5'11" male) leg through which the data was generated for the subject's walking motion. The data was then inputted in a function generation system and the limb lengths of the anthropometric backbone chain were specified (see Figure 2 on the left). As a next step, a six bar linkage, based on the physiological task and the anthropometric RR backbone chain was synthesized using Mathematica software [10], [11]. Note that the general form of the Stephenson six bar can be found in [12] and [13].

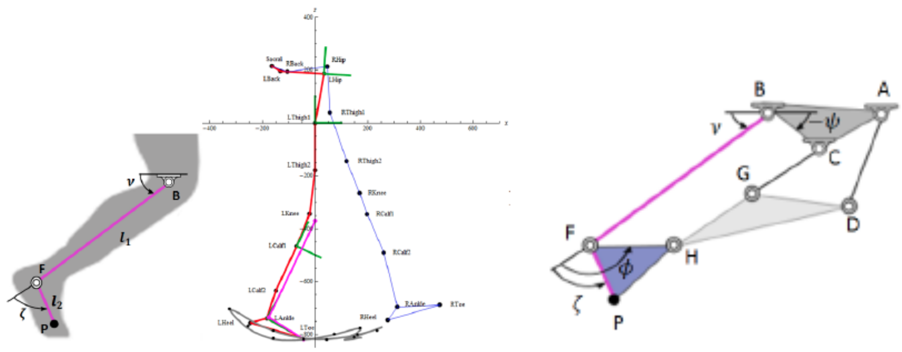

Figure 2. Left: RR backbone chain representing the lower leg in sagital plane, and the walking trajectory, obtained experimentally. Right: A six-bar linkage with the RR backbone chain BFP.

The synthesis process resulted in six design candidates, shown in Figure 4, of which the most compact and aesthetic design # 1 was chosen. Note, that out of the eleven specified task positions, all six solutions were able to go through ten of them (see Figure 3).

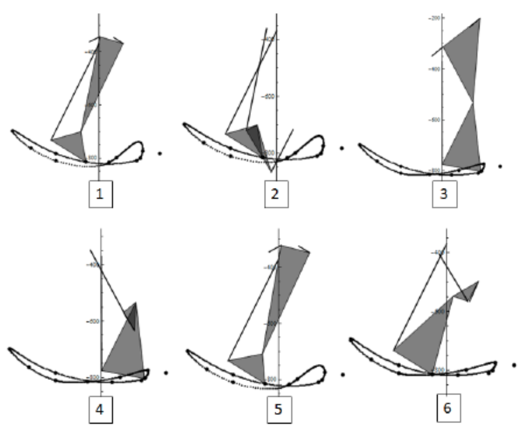

Figure 3. The six design candidates.

The linkage assessment stage in Figure 1 incorporated considerations, such as ergonomics related to co-location of joints of the device with wearer's biological joints and eventually replacing some of the serial chains that mimic the leg anatomical structure with the original human limb.

3. Description of Final Approach and Design

During the development process of the orthotic device, the RR anthropometric backbone chain of the synthesized six-bar linkage was replaced by the wearer's limb, providing the skeletal structure for the multi-loop wearable device. The RR backbone chain was relocated to the radial part of the affected leg, co-locating with the rotational axes of the human's limb joints to mimic the desired physiological walking trajectory. The chosen design leaded to increased safety for the user and a weight balance on both sides of the leg.

Figure 4 on the left shows a CAD model based on the synthesis of the six bar linkage. As a next step, a reduced-scale prototype was 3D printed (see Figure 4 in the middle) to ensure that the parts fit and work well together. Based on tests and evaluations some modifications on the model were made, which consequently led us to build the full-scale model of the device (see Figure 4 on the right).

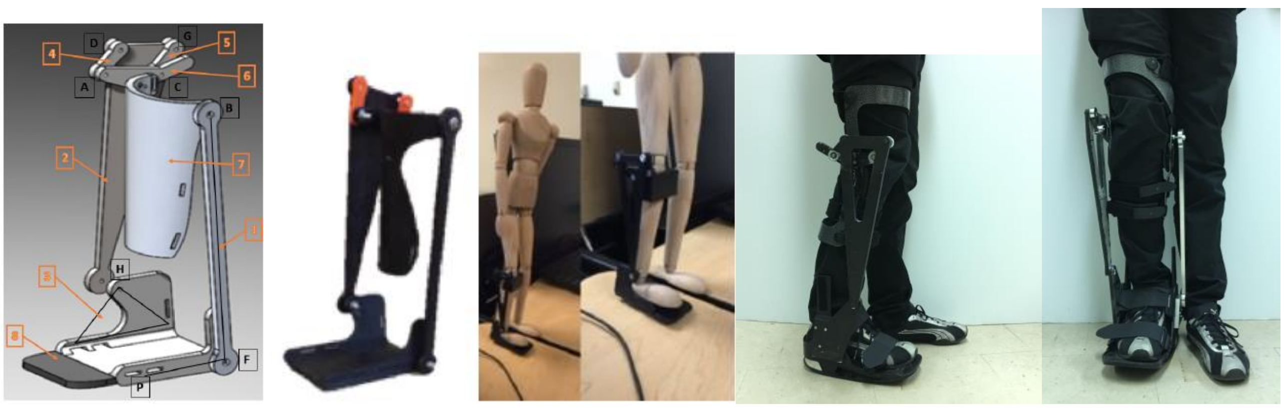

Figure 4. Left: A CAD model of the designed orthotic device; Middle: A reduced-scale 3D printed prototype of the orthotic device. Right: The developed orthotic prototype.

4. Outcome (Results of any outcomes testing and/or user feedback)

4.1. Performance Evaluation of Mechanism for Orthotic Design Using OpenSim: To evaluate the operation of the linkage solution #1 as a walking device, a dynamic simulation was created in the open-source multi-body simulation package OpenSim [14] environment as shown in Fig. 5 top left. The six-bar mechanism is attached to the thigh in such a manner that the fixed pivot **B** of the linkage, shown in Figure 2 on the right, is collocated with the human knee.

Simulation results are presented in terms of the computed joint angles at the knee and the ankle of the supported limb while applying anthropomorphic rotational input at the hip (see Fig. 5 (a) and (b)). These results can be considered as performance characteristics for evaluating the feasible operation of the proposed orthotic device.

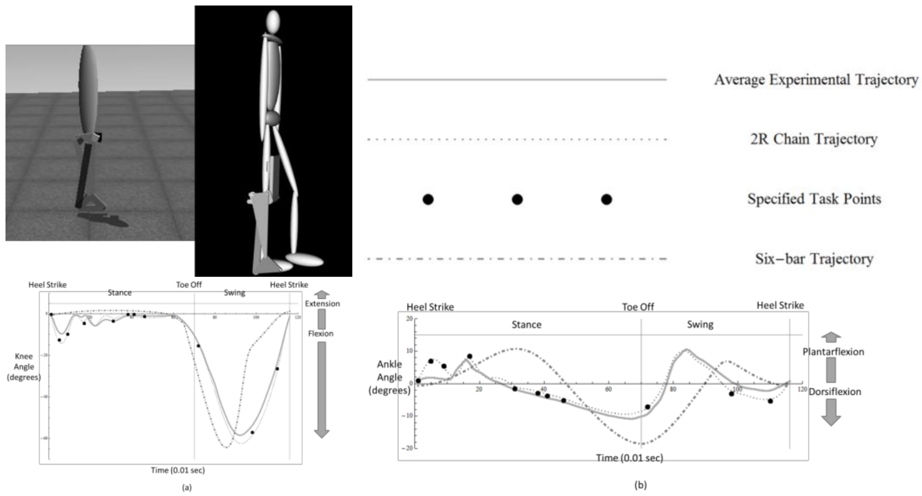

Figure 5. Top Left: A 3D dynamic model of the six-bar mechanism attached to the human body in OpenSim. Top Right and Bottom: Comparison of (a) knee angle and (b) ankle angle of the experimentally obtained human walking obtained with the simulated device trajectory in OpenSim.

The simulation results indicate that knee and ankle angles obtained with the proposed orthotic device lie within $\pm 10°$ of the experimentally obtained values. The simulation results also indicate that augmenting the human limb by collocating the kinematic chain as a ‘backbone’ for the orthotic device assists in providing greater support, balance and stability to the device as well as the user.

4.2. Dynamic Testing: The device was tested on a healthy subject with a height 5’11” at the Human Interactive Robotics (HIR) laboratory at California State University, Fullerton. The subject was asked to walk on the ground with a normal speed (i) with and (ii) without the device attached. Note, that during the first phase of testing it was realized that the device was not tightly secured to the lower extremity of the subject. The issue was solved by replacing the leg holder (part 7 in Figure 4) with a commercially available clinical brace, which resulted in a slight moderation of the design (see Figure 4 on the right). During the second phase of the testing, trajectories of three key points hip, knee and ankle and toe were obtained using motion capture system and then analyzed using Mathematica software. Figure 6 on the right shows the results from comparing the subject’s walking on the ground with (dashed line) and without the orthotic device. It can be clearly seen that the toe trajectory is sufficiently close to the experimental trajectory (within $\pm 12\%$ calculated) to guarantee natural motion of the supported leg. The difference can be further compensated, by adding a passive spring that will dampen the motion during the swing phase. This result is an improvement compared to some of the previous passive orthotic devices designed in the HIR lab in 2012 and 2015 (see Figure 6 on the left and middle).

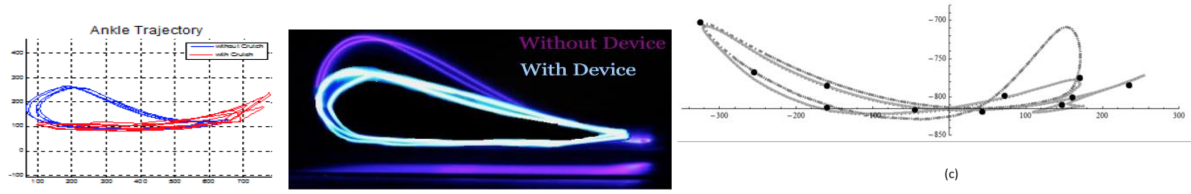

Figure 6. Left and Middle: Walking trajectories results from previously designed orthotic devices in 2012 and 2015. Right: Motion profile of a 5’11” subject walking on ground with (dashed line) and without the developed orthotic device.

4.3. Cost

The raw materials for the development of the orthotic device were relatively inexpensive (see Table 1). Since a clinical lower extremity brace at $400 was incorporated, if production methods are to be developed, the main goal would be the design of a cost-effective leg brace.

Table 1: Cost to produce the orthotic device

Cost per unit	**Orthotic device**	
400 USD	**DonJoy Armor**	**Knee Brace**
97 USD	Aluminum (1.93 USD/Kg)	**Material per Kg**
497 USD		**Total Cost**

5. Significance

The ground work has been laid for the development of passive hand free orthotic devices to accurately reproduce the natural walking gait of a person with reduced mobility in their lower extremity. While most of the orthotic devices in literature and on the market show satisfactory performance, there still does not exist a systematic methodology for the design of these systems. In addition, the hip and pelvic of the wearer tend to make an abnormal motion to ensure the foot clearance during the swing phase of the gait, resulting in a non-natural gait pattern.

Here we offer a novel alternative approach: a systematic process to create passively actuated by the hip joint orthotic devices that incorporate anthropometric backbone chain and physiological task. We use kinematic coupling of the leg joints to accurately reproduce the natural walking gait of a person with reduced mobility in their lower extremity (i.e. below femur including the knee joint). Future directions include exploring the application of these techniques to upper extremity, as well as the multi-material 3D printing of these devices with incorporated flexible joints to avoid the labor intensive and time consuming assembling process and reduce weight. This will allow persons with reduced mobility in their limbs to input the anthropometric data of their impaired limb and 3D print their own custom wearable assistive devices.

Acknowledgements:

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