User-Device Interaction Considerations and Testing of A Novel Orthotics for Restoration of Natural Physiological Gait

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Abstract: When developing orthotics, a major concern is wearability. Wearability is defined as the interaction between the human body and the wearable object. In case of orthotics, the definition extends to include the effects of the human body in motion, or Dynamic Wearability. Major concerns include matching and obtaining close alignment between the structure of the exoskeleton to the wearer, affectation of the biomechanics of locomotion due to added mass and inertia of the device itself as well as the additional kinematic constraints inadvertently imposed on the wearer. Portability and stability are three other major factors that need to be considered. Portable orthotic devices can be used as a part of the wearers everyday life without the need for constant medical supervision that would limit the application of orthotic to clinical settings.

In this paper the user-device interaction considerations, manufacturing and testing of a recently designed passively actuated hand free orthotic device is presented. The six-bar device is designed to coordinate the motion of both knee and ankle joints simultaneously that mimics the natural walking gait. Test results from comparing the subject's walking on the ground with and without the orthotic device show only about 3.93% difference in stride length. It is also clear that the toe trajectory is sufficiently close to the experimental trajectory (within ±9.6% root-mean-square deviation calculated) to guarantee natural motion of the supported leg.

Keywords: User-device interaction, orthotics, restoration of physiological gait.

1. PROBLEM STATEMENT AND BACKGROUND

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 synchron 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 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 multi-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 techniques proposed by Robson *et al*. [7-11] 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). Unlike other wearable device design

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E-ISSN: 2409-9694/17

techniques that use parallel mechanical linkages, the above-mentioned works offer a novel alternative approach: a comprehensive systematic process to create wearable lower extremity devices that incorporate anthropometric backbone chain and physiological task. In the next section we briefly discuss that.

2. BACKGROUND

Recent research of Robson *et al*. [7 - 11] aims to create a methodology for transforming a mechanical linkage design of a lower or upper extremity into a wearable device that mimics the natural motion of a person with reduced limb 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** for the application of the process for lower extremity).

Specifically, in order to specify the physiological design task, motion capture data from a person walking at 1m/h on a treadmill is gathered and analyzed. Tracking points are attached on the subject's (5'11" male) leg through which the data was generated for the subject's walking motion. The data is then inputted in a function generation system and the limb lengths of the anthropometric backbone chain are 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 is synthesized using Mathematica

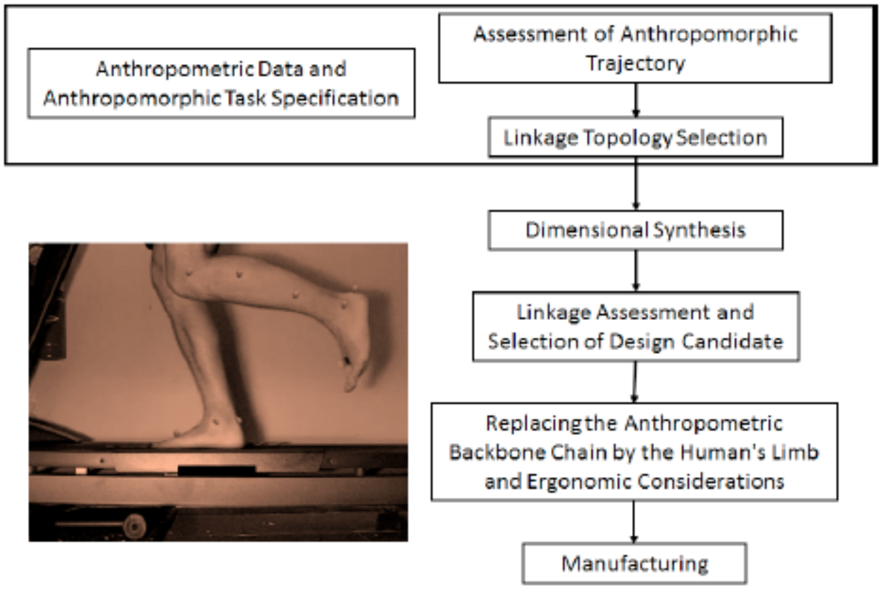


Figure 1: The systematic process for developing customized upper and lower extremity assistive devices for physical support and training of persons with reduced limb mobility.

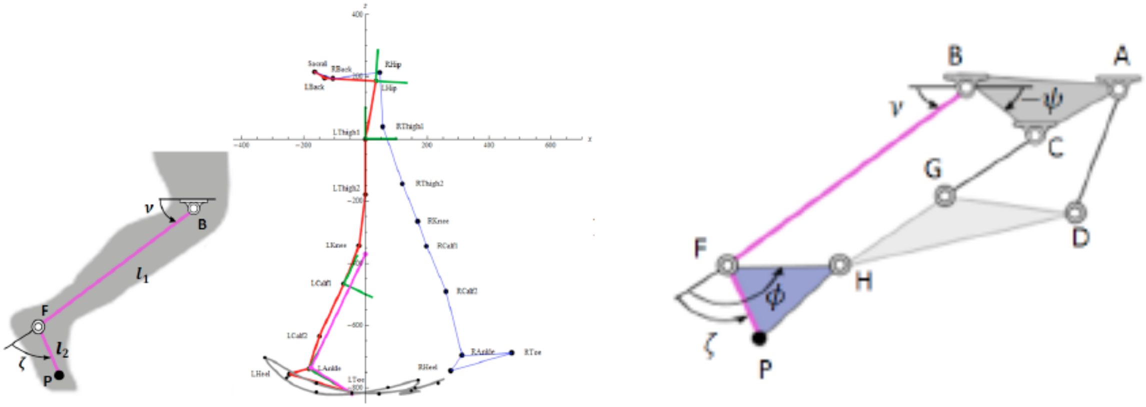


Figure 2: Left: RR backbone chain representing the lower leg in sagital plane, and the walking trajectory, obtained experimentally. Right: A six-bar linkage with the RR backbone chain BFP.

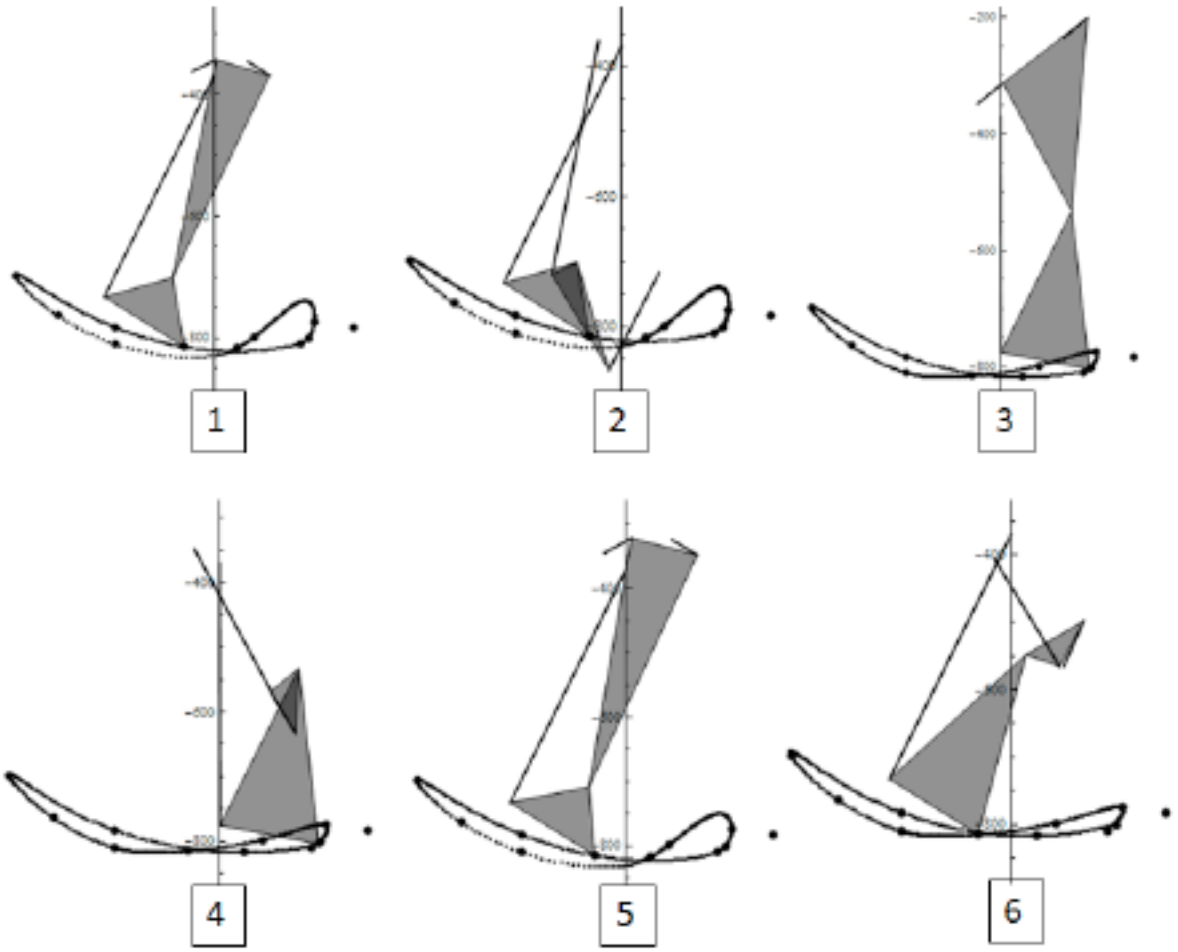


Figure 3: The six design candidates.

software [10, 11]. Note that the general form of the Stephenson six bar can be found in [12] and [13].

The synthesis process presented in [10] resulted in six design candidates, shown in Figure **3**, of which the most compact and aesthetic design seemed to be number 1 and 5. Note, that out of the eleven specified task positions, all six solutions were able to go through ten of them (see Figure **3**).

In what follows we discuss the Linkage Assessment stage in Figure **1** in order to select a design candidate, as well as the user-device ergonomic considerations.

3. LINKAGE ASSESSMENT/SELECTION AND USER-DEVICE INTERACTION CONSIDERATIONS

The design candidate for the development of the lower leg orthotic should not only go smoothly through the specified task positions in a desired order, but should interface well with the limb of the user and not impede their natural movement according to the principles of wearability. Gemperle *et al*. [14] identify the most unobtrusive locations on the human body for placement of wearable devices. These locations, shown in Figure **4**(**a**), consist of the shins and the tops of the feet on the lower leg. In accordance to this, we identify areas around the lower leg where it is unsuitable to locate the linkage or parts of it (see Figure **4**(**b**)).

The shaded area locates the region below the second link of the kinematic backbone chain that mimics the foot. The presence of any component of the linkage in this region is undesirable as it will cause collisions with the ground and impede natural walking motion. On the other hand, the presence of the mechanism in the crosshatched region behind the calf could increase the chances of collision with the upper leg segment during flexion of the knee, affect the gait and cause injuries to the user. Based on these criteria, Linkage solution number 2 in Figure **3** is eliminated from the list of suitable designs.

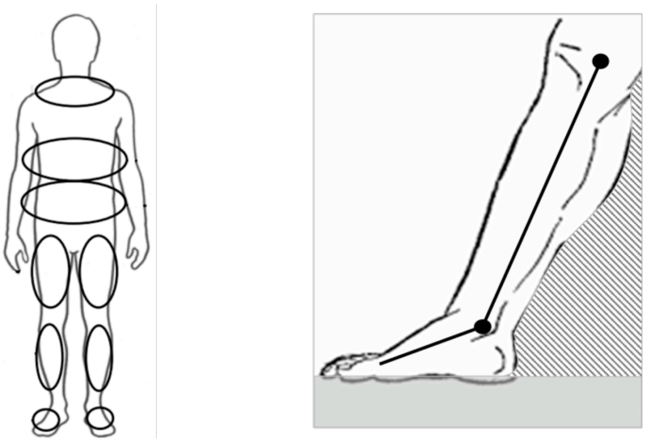

(a) (b)

Figure 4: (**a**) The general areas found to be the most unobtrusive for wearable objects include shin, and top of the foot on the lower leg (adapted from [4]). (**b**) Conversely, the shaded regions around the lower leg are undesirable for locating the linkage based wearable device.

Next, the linkage designs are evaluated on compactness of the human leg - orthotic system using the following equation (1);

$$\min S = r_1 + r_2 + A_1 + A_2 \tag{1}$$

where *r1* is the distance of the fixed pivot A from the fixed pivot B at the knee, *r2* is the distance of the fixed pivot C from the fixed pivot B at the knee, *A1* is the area of the ternary link DGH, *A2* is the area of the ternary link HFP. The most preferred linkage was the one with the lowest *S* score and it is found to be linkage solution number 1 in Figure **3**.

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. To ensure user-orthotic system stability, 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 **5** on the left shows a CAD model based on the synthesis of the six bar linkage. In Figure **5** each part of the device has a specific number. Parts 1 and 2 are the side links that holds the system. Part 3 is the bottom which supports the foot. Parts 4 is the driver (Crank) that makes a complete cycle while part 5 is an oscillatory part (Rocker). Part 6 attaches the crank and rocker to the shin part. Part 7 is the shin part which attaches the device to the wearers leg. Finally, part 8 is a flexible material that help a smooth walking motion. The main subsystems are the six-bar linkage denoted by ADGC with the backbone chain BFP. As a next step, a reduced-scale prototype was 3D printed (see Figure **5**) to ensure that the parts fit and work well together. Based on tests and evaluations some

Figure 5: A CAD model and a reduced-scale 3D printed prototype of the orthotic device.

Figure 6: Front and side view of the developed orthotic prototype.

modifications on the model were made, which consequently led to building a full-scale prototype of the device (see Figure **6**).

4. RESULTS

4.1. Performance Evaluation of the Orthotic Device Using OpenSim Software

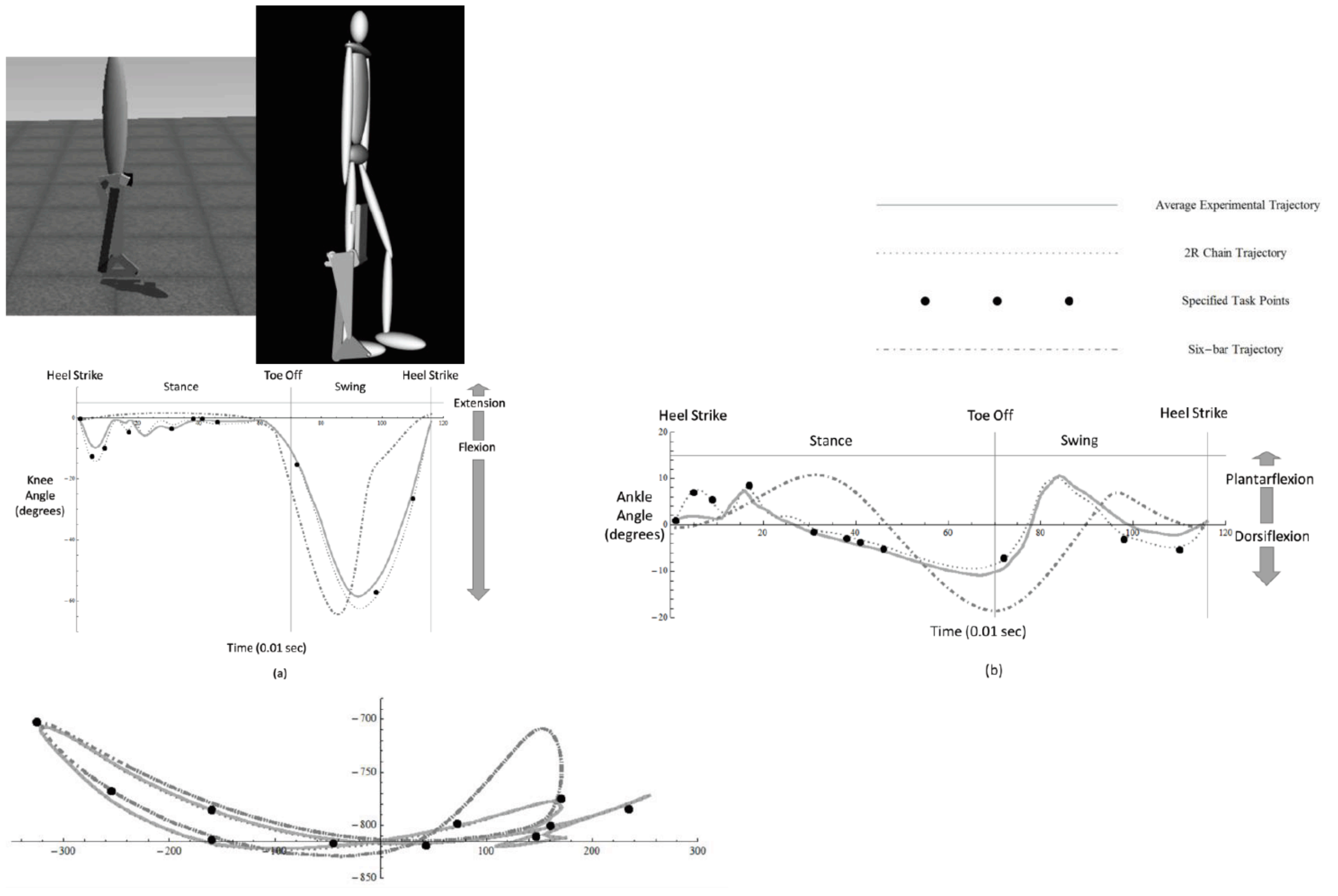
To evaluate the operation of the linkage solution number 1 as a walking device, a dynamic simulation was created in the open-source multi-body simulation package OpenSim [15] environment as shown in Figure **7** top left. The six-bar mechanism is attached to the thigh in such a manner that the fixed 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 Figure **7**(**a**) and (**b**)). These results can be considered as performance characteristics for evaluating the feasible operation of the proposed orthotic device.

The simulation results in OpenSim indicate that knee and ankle angles obtained with the proposed orthotic device lie within ±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. Experimental Dynamic Testing of the Orthotic Device

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 **5**) with a commercially available clinical brace, which resulted in a slight moderation of the final design prototype (see Figure **6**). During the second phase of the testing, trajectories of three key points hip, knee/ankle and toe were obtained using motion capture system and then analyzed using Mathematica software. Figure **7**(**c**) shows the experimental results from the comparison of a test subject walking on the ground with (dashed line) and without the orthotic device. Test results show about 3.96% difference in stride length. It is also clear



(a)

(b)

(c)

Figure 7: Top: A 3D dynamic model of the six-bar mechanism attached to the human body in OpenSim. Bottom: Comparison of (**a**) knee angle using OpenSim; (**b**) ankle angle of the experimentally obtained human walking in OpenSim; (**c**) Experimental Testing Results: Motion profile of a 5’11” subject walking on ground with (dashed line) and without the developed orthotic device.

that the toe trajectory is sufficiently close to the experimental trajectory (within ±9.6% root-mean-square deviation calculated) to guarantee natural motion of the supported leg. The difference could 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 Human Interactive Robotics (HIR) lab in 2012 and 2015.

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

	Orthotic Device	Cost Per Unit
Knee Brace	Don Joy Armor	400 USD
Material per Kg	Aluminum (1.93 USD/Kg)	97 USD
Total Cost		497 USD

5. DISCUSSION

The goal of this paper was to present user-device interaction considerations, manufacturing and testing of a passively actuated hand free orthotic device, which design was presented in [10], [11]. The device is based on 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).

The experimental test results comparing walking with and without the orthotic device show about 3.96% difference in stride length and a toe trajectory that is sufficiently close to the experimental one (within ±9.6% root-mean-square deviation calculated). Future directions include exploring the multi-material 3D printing of the device with incorporated flexible joints to avoid the labor intensive and time consuming assembling process and reduce weight.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the National Science Foundation (NSF), award Id #1404011.

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Received on 15-12-2017 Accepted on 20-12-2017 Published on 31-12-2017

DOI: http://dx.doi.org/10.15377/2409-9694.2017.04.3