Development of a Crutch Substitute for Mimicking Human Natural Walking Gait

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Abstract: In order to resolve some of the disadvantages of conventional crutch designs, as well as some of the existing crutch-substitute devices, available on the market, a novel Exo-Limb crutch design is presented. The Exo-limb is a hands-free crutch meant to enhance and replace standard underarm crutches and other competitive products during injury rehabilitation. The focus of this research has been on creating a cost-effective passive device that mimics humans natural walking gait using purely mechanical components. Prior to the design, human natural treadmill walking was monitored by a 3D Motion Capture System and a reference end–foot trajectory with a '*teardrop shape*' was acquired. Considering the design objectives, natural human walking and comfort, and other factors such as load capacity and weight of the device, the final design was determined. In order to satisfy the design objectives a kinematic synthesis, previously developed by one of the co-authors, is applied to test if the end–foot trajectory of the designed crutch substitute smoothly follows the desired reference, '*teardrop shape*' in the vicinity of two specified task points, heel strike and toe off. A prototype of the final design was fabricated and its performance was tested by 2 mph treadmill walking. The research and developments made in this project with regard to mimicking the natural walking gait are important contributions that find applications in different areas, such as military, robotic locomotion, injury recovery and physical therapy.

Keywords: Human walking gait, crutch substitute, "teardrop" trajectory.

1. INTRODUCTION

Recent advancements in technology have helped people with debilitating injuries, amputations, and effects of paralysis to regain their independence and live without limitations. The goal of the Exo-Limb project is to push the boundary of what humans can accomplish by adding to the research and development passive methods to accurately reproduce the natural walking gait of a human being, and by creating a device in a market that is currently small and ripe for potential: the hands-free crutch market.

Each year, approximately 2 million people are treated for ankle sprains. They account for over 85% of all ankle injuries and about 45% of all sports-related injuries. The standard recovery treatment consists of using underarm crutches for about 8 weeks [1]. The design of the underarm crutch has not changed in several years. Using them requires increased energy expenditure and results in fatigue, skin chafing, and muscle atrophy [2]. Alternatives such as wheelchairs and scooters relieve some of the stress involved in using underarm crutches, but do not allow the user to navigate in difficult terrain and around obstacles.

The recently emerged hands-free crutch market addresses the flaws in other recovery alternatives. They are more comfortable, natural, and energy efficient than underarm crutches and also robust enough to navigate over and around obstacles (such as stairs) that a user may come across during daily life. The crutch is the simplest and reliable way to compensate the mobility of people with lower limb injuries by supporting their body weight during locomotion in daily life (e.g. ascending/descending stairs and walking). It provides a stable environment for recovery by allowing the injured body part in a load free condition. It is known that the crutches have been used for 5,000 years [3]. People used fallen tree branches as supporting sticks to help balancing or ambulating wounded body. From its primitive forms, the current configurations of underarm and forearm crutches have been evolved through various empirical designs. The first US patent for a crutch was issued to Tuttle (US patent No. 332,684) [4]. The first commercialized form of forearm crutch design was patented by a French mechanical engineer, Schlick, as a *walking stick* in 1917 (US patent No. 1244249) [4]. From these patented designs, numerous modification works have been patented for comfort and safety.

Though the current crutch designs are inexpensive solutions to fulfill their main function, i.e. body weight support, they have the following disadvantages:

(1) since the armpit or forearm are not supposed to support a large load, normally, continuous stress on them can cause degraded motion control and even nerve damages [5],

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(2) important upper limb functional motions in daily living (e.g. arm reaching motion, hand grasping and manipulating) are limited,

(3) decreased degrees of freedom (DOF) can induce compensatory joint motions and unnatural locomotion, which can be possibly developed as chronic pathologies after long term of usage, and

(4) ambulation with underarm and forearm crutches demands high cost of energy consumption [6].

The iWalk–Free (iWALKFree, Inc., USA) [7] shows a typical example of novel crutch design to overcome the disadvantages described above. With a stable load support through 90° flexed knee, the device could reduce discomfort significantly by freeing upper limb motions. However, due to lack of knee joint DOF, the hip and pelvic joints tend to make an abnormal motion pattern to ensure the foot clearance during the swing phase of gait.

The idea behind the proposed Exo-limb crutch design is at assisting ambulation of patients who have injured one of their lower legs (i.e. below femur, including knee joint). These injuries include ankle sprain, fractures and/or cracks on tibia, fibula, foot bones, or any combination of them. The skeletal anatomy of human leg is shown in Figure **1**.

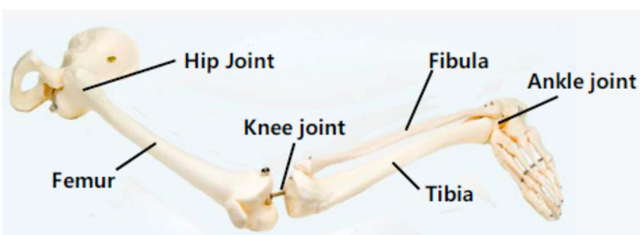


Figure 1: Skeletal anatomy of human leg (image source [5]).

Currently, there are two similar products out on the market: the already mentioned iWalk Free and the Flex-Leg (Figure **2**). Two student design teams from Texas A&M and Cal State Fullerton have also created their own hands-free crutch designs (Figure **3**).

The functional design requirements of the Exo-Limb project are as follows:

The device shall be hands-free, meaning the user does not need to use their hands except when putting on and taking off the device;

The device shall mimic the natural human walking gait;

Figure 2: The iWalk Free and FlexLeg.

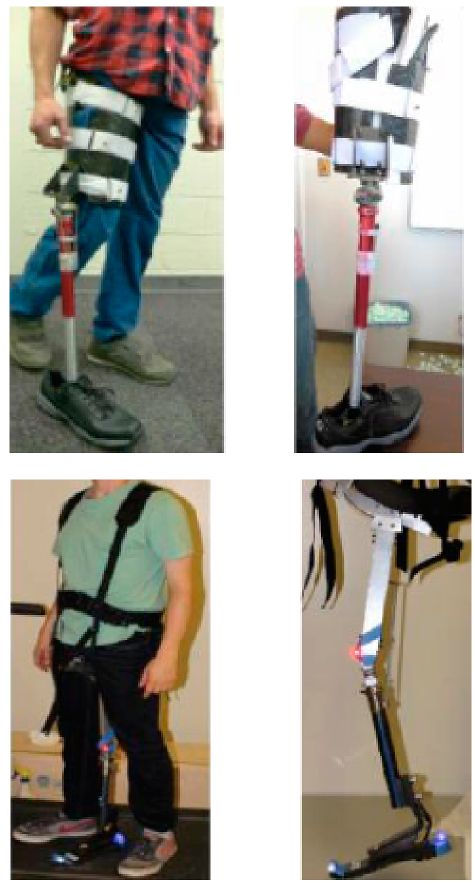


Figure 3: Texas A&M and CSUF Previous Designs.

The device should consist of purely mechanical components (no motors or electronic devices), and thus be cost-effective;

A knee joint degree of freedom should be incorporated into the design;

The device should be able to support a 300 lb person;

The device should be adjustable to fit users of different size.

These functional design requirements and other project goals are summarized in Table **1**.

Table 1: Project Requirements and Goals

Project Requirements	Expected to Meet?
Hands-free	Y
Mimic the nutural human walking gait	Y
Purely mechanical components (no motors or electronic devices)	Y
The device shall be able to support a 300 lb person	Y
The device shall be adjustable to fit users of different height	Y
Project Goals	**Expected to Meet?**
Mimic the nutural walking gait within 20%	N/A
Design for an infinite life cycle (1,000,000 steps)	Y
Design with a Safety Factor of at least 3.0	Y
Outoerform other competitive products in the Survey	Y

2. MATERIALS AND METHODS

2.1. Mimicking the Natural Gait

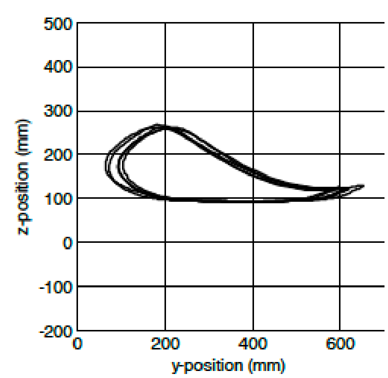
An important part of the Exo-Limb project is to develop an alternative method for mimicking the natural walking gait. Current devices typically use a hinge joint and control the movement using actuators. This is an expensive approach, thus one of the goals of the Exo-Limb project is to create a cost effective mechanism that accurately mimics the natural walking gait.

In order to acquire reference gait data, a person's normal treadmill walking with 2 mph speed was collected *via* 3D Motion Capture System (Vicon MX, Vicon Inc., UK). Eight reflective markers were attached on the subject's right leg as shown in Figure **4a** with highlighted circles. Figure **4c** represents the single gait cycle obtained by the 3D Motion Capture System. For visualizing the actual end–foot trajectory, the positions of ankle marker on the sagittal plane was plotted (see Figure **4b**). Note that the geometrical shape of the reference trajectory for each gait cycle looks like a 'teardrop'.

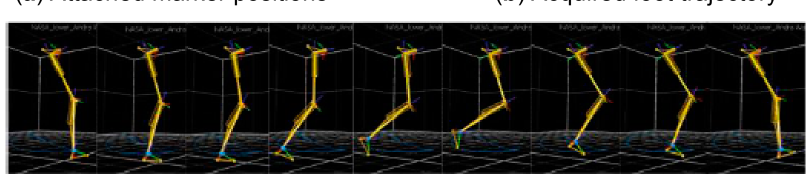
Four different mechanisms (hinge, peg-leg, four-bar linkage and cam and follower system) were considered and compared for the knee design. Ultimately, a four-bar linkage mechanism was selected based on its ability to mimic the natural walking gait, provide overall stability to leg-crutch system self-locking ability, as well as ease of manufacturing.

The design and optimization of the knee linkage was implemented in Mathematica using a novel algorithm to model the natural walking gait. The model is based on Robson *et al.* [8] and applies velocity and acceleration constraints at the start and end locations of the foot during the gait cycle. These task velocities and accelerations are derived from contact and curvature specifications between the foot and the

(**a**) Attached marker positions



(**b**) Acquired foot trajectory



(**c**) A cycle of walking motion in the 3D Motion Capture System

Figure 4: Capturing a normal treadmill walking cycle.

natural walking "teardrop" shape and then are used in defining the position, velocity and acceleration design equations. After solving the equations, the resulting linkages produce a motion profile at the knee that closely resembles the natural walking gait. When attached to a coupler, the motion profile that was generated at the knee amplifies at the foot (Figure **5**).

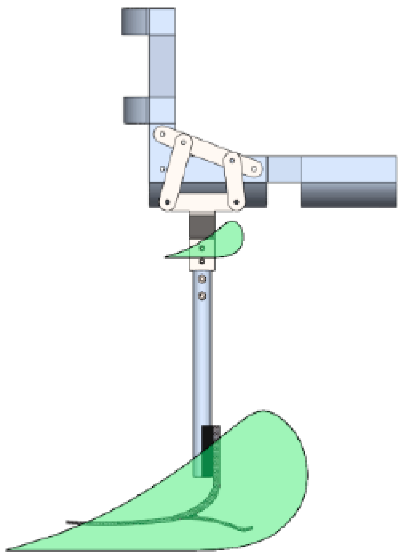


Figure 5: Amplification of the Motion Profile.

2.2. Leg Attachment Design

Apart from the walking trajectory, another main goal for the Exo-Limb was to be comfortable for the user to wear. This requires attaching the device in a way that is non-invasive and sturdy. Multiple attachment points (hip, glute, thigh, and seat) were considered and compared. Overall, the design matrices showed two preferred methods, a combination of knee and thigh support was chosen for the final design.

The design of the leg attachment was completed using statistical averages of anthropometric data. By determining the average leg sizes of possible users, a design was created to fit people of different sizes by providing adjustable strapping. The end result was a form-fitting, comfortable, and adjustable leg attachment that is strong, sturdy, and lightweight.

In order to feel natural and comfortable, the device had to provide enough stability for the user to control. Several features of the Exo-Limb increase the stability of the device. The four-bar linkage knee design allows for a more stable range of motion than a hinge joint knee design due to a large range of motion where the instant center of the four-bar linkage lies within a stability region. That compared to a hinge joint, which is only stable when the user's body weight is directly over the hinge, is a huge increase in the stability of the device.

The form-fitting design of the leg attachment also provides enhancements to stability. The design fits securely to the user's leg and the foot extension touches the ground where the user's own foot would be expected to be. This natural location allows the user to quickly respond to slight deviations in ground level and provides for a smaller learning curve. Since the stability of the device will also depend on the dexterity of the user, a smaller learning curve will make for a more stable device.

Lastly, the toes of a human's foot help provide stability. They essentially grab the floor and provide a stable platform when ground surfacing is uneven. The prosthetic foot chosen for this project contains a split-toe feature that helps the user grip the floor when standing on the device. This helps provide lateral stability.

2.3. Final Design and Results Discussion

The first iteration of the design can be seen in Figure **6**. Marginal improvements were made to enhance key areas. The manufacturability of the leg attachment was improved to lower production times and weight-bearing components were adjusted to increase the strength and fatigue life of the device. The

Figure 6: First Design Iteration.

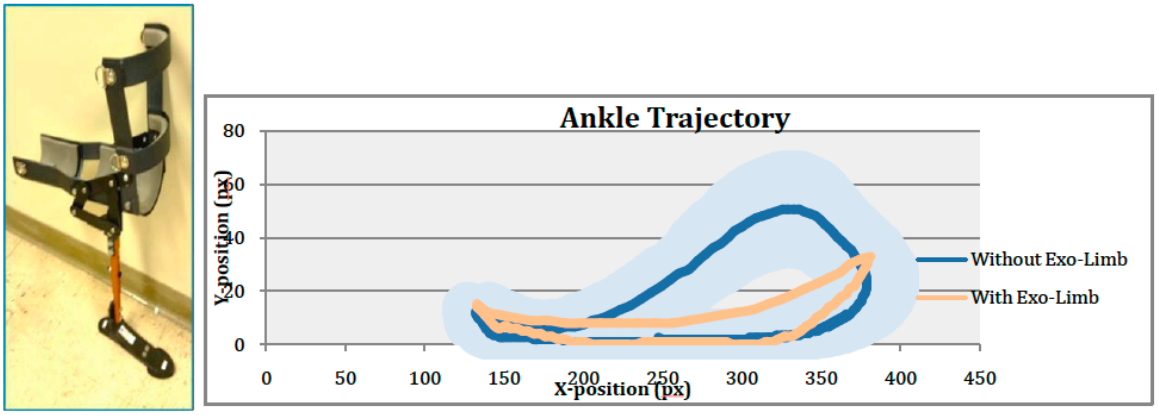


Figure 7: Prototype of the Exo-Limb and Motion Profile.

four-bar linkages in the knee joint were optimized using an algorithm developed by Robson *et al.* [8] to allow the device to more accurately mimic the natural walking gait. The prototype of the device can be seen in Figure **7** on the left.

For validation, the Exo-Limb project was tested to determine if the design requirements and project goals are met. This verification process included two methods: Dynamic and Mechanical.

3. RESULTS

3.1. Dynamic Testing

Dynamic testing was performed at the biomechanics laboratory with the help of the Kinesiology department at Cal State Fullerton. The lab contains a state of the art motion tracking system that will be used to analyze and evaluate the device. Users initially walked without the device attached to determine the trajectories of three key body points: the hip, knee, and ankle. The users then walked with the device attached. The trajectories of the key points with the device attached were then compared to the trajectories of the key points without the device. The result from the motion profile of walking on the threadmil with the Exo-Limb device is shown in Figure **7** on the right. The results show that the device is not able to mimick the natural “teardrop” shape throughout the profile successfully. However, it is necessary to emphasize that walking on the treadmill is very different from walking on the ground. The foot, which is made of rubber, sticks easily on the treadmill and so it is harder to walk. This did not prevent the team to realize an experiment, where a number of subjects were walking on the floor with the device attached. The result was pretty impressive, and the comparison between the natural teardrop and the device teardrop showed that the device is able to achieve about 60%-70% of the natural human gait.

3.2. Mechanical Testing

The mechanical performance of the device was analyzed using Finite Element Analysis (FEA). Loads on key structural components were simulated in SolidWorks to determine static loading limits. The results from the static simulation were then used to perform a fatigue analysis.

Figures **8** and **9** show the von Mises stress on the leg and foot attachment subassemblies when a *300 lb.*load is applied. The resulting factor of safety is at least 5.00.

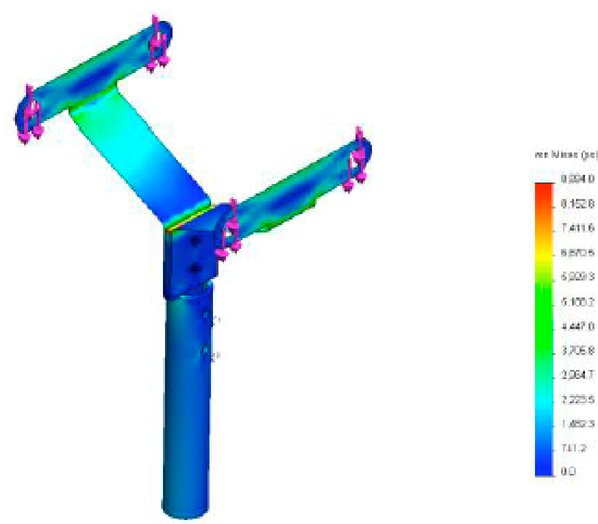


Figure 8: Stress on the Foot Support.

Static simulation was used to determine the fatigue life of the Exo-Limb. The results of the simulation show that the device will be capable of withstanding *1,000,000* cycles. This is well past the standard recovery time for a sprained ankle, which is approximately 7.5 weeks. This comes out to be about *300,000* steps [11].

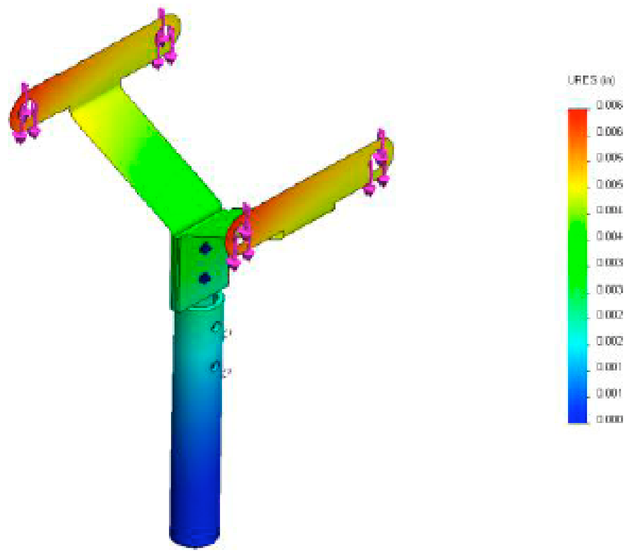


Figure 9: Displacement on the Foot Support.

3.3. Cost

Commercialization of the Exo-Limb project can be made possible by developing large-scale production methods. The scope of this project focuses mainly on research and design, which is a major component of the overall budget. Future goals for the project, if continued, would be to develop large-scale production methods.

The raw materials for the Exo-Limb are relatively cheap. The cost for the metal components totals about $40 for one device. Other materials, such as the straps, padding, and miscellaneous components, total at about $20. The Exo-Limb uses a clinical prosthetic foot made by Össur to assist in the research and development of the natural walking gait. If large-scale production methods were to be developed in the future, an alternative would be to design a cost effective foot attachment.

The groundwork has been laid for the research and development of a hands-free crutch. If the project were to continue, the planning and implementation of large-scale production methods would certainly decrease the cost to produce the Exo-Limb.

4. DISCUSSION

In this paper, the disadvantages of conventional designs, underarm and forearm crutches, are studied. In order to overcome them, required design objectives and specifications are setup. Closed–loop linkage design is considered for the knee mechanism. To fulfill the main design objective, natural walking motion, a kinematic synthesis was applied. The kinematic specifications (i.e. position, velocity and acceleration compatible with contact and curvature constraint between the foot and the ground) at two gait events (i.e. heel strike and toe off) are derived from the foot trajectory obtained from a motion capture system. By imposing the position and higher derivative kinematic specifications to the synthesis design equations of the knee mechanism, the locations of the fixed and moving pivots, as well as the foot trajectory have been defined. Our future directions are primarily related to further experimental tests on safety, comfort and stability while walking with the developed prototype.

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