

Design of a Spring-Integrated Crutch for Ascending Stairs

by

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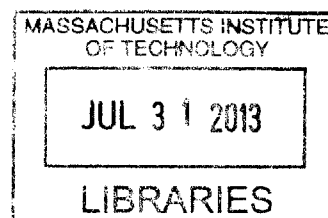
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ABSTRACT

Using conventional underarm or forearm crutches is uncomfortable and awkward. Further, underarm crutches make climbing stairs difficult and unsafe. One may climb stairs with forearm crutches, which do not impede elbow movement, but doing so is fatiguing and requires upper body strength. In 2011, MIT Media Lab researcher Madalyn Berns demonstrated that incorporating into the crutch an elastic element that spans the elbow joint could reduce the metabolic cost of crutching up stairs. The elastic element stores energy when compressed by the biceps; the stored energy then aids the triceps in levering the user up the stairs. This thesis developed a safer, sleeker, and more comfortable spring-integrated crutch. The novel design uses a torsion spring to store energy during elbow flexion. The spring is compressed between a forearm cuff and an upper arm cuff. The design allows the patient to reduce metabolic cost by using upper arm muscles more effectively.

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1. Introduction

Many groups with limited walking ability rely on the increased mobility provided by crutches. In the United States, there are over 566,000 long-term crutch users with disabilities [1]. However, crutches are still uncomfortable and awkward to use. Long-term crutch use is associated with a number of painful and debilitating pathologies [2][3]. Furthermore, common underarm crutches make it difficult and unsafe to climb stairs or steep terrain. It is possible to climb stairs with forearm crutches, which do not impede elbow movement, but doing so is fatiguing and requires significant upper body strength.

The goal of this thesis is the development of a crutch that aids in ascending stairs while improving user comfort. This is a continuation of work by Berns, who demonstrated that a joint-spanning parallel spring incorporated into the crutch effectively reduced the metabolic rate of a crutch user ascending stairs. However, this previous study focused on proving the feasibility of joint tuning for metabolic efficiency, and not on user comfort or device usability. It was noted that:

While the crutch device described here was designed for experimental use, an alternative version could be constructed for patient use. To make this device into a product, more research would be required, especially focusing on the optimal design of the cuff-arm interface to make chronic cyclic loading more comfortable [4].

These early experimental crutches (Figure 1) were zip-tied to the upper arm, causing considerable pain in the user. The improved design must both fulfill functional requirements and be safe for general use.

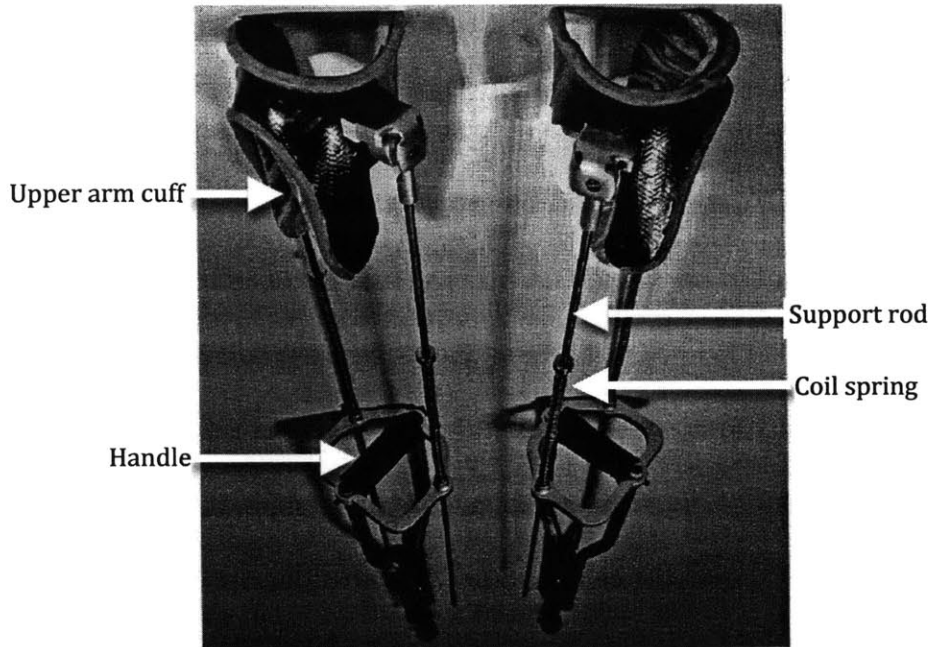


Figure 1: Berns's elbow-spring experimental crutches [4]. The handles move freely on the support rods and can be drawn upwards to compress the coil springs.

1.1 Current Crutch Options

Figure 2 shows a number of common and lesser-known crutch designs. The most common crutch styles are axillary crutches (or “underarm” crutches) and Lofstrand crutches (or “forearm” crutches). Patients using axillary crutches must rest their weight on their hands; bearing weight on the axilla, or armpit, can compress the brachial plexus nerves and should be avoided. A properly fitted axial crutch will rest 1-2 inches below the armpit. When climbing stairs with axillary crutches, patients are instructed to move both crutches to one hand and to “hop” on the unaffected limb, using a handrail and the crutches for balance [5].

Forearm crutches are less stable than axillary crutches, but also allow for more maneuverability. Fluid use of forearm crutches requires good to normal

upper-body strength, making them unsuitable for some patients. Weight is still borne on the wrist and hands. A common variation on the forearm crutch is the platform crutch, which allows distribution of the body's weight over the entire forearm [6]. Using either variation, patients climbing up stairs are instructed to begin by flexing the elbows and bringing the crutches up to the next step. Patients can then extend their arms to lift the body into the air and up to the next step [7]. This repetitive motion is highly strenuous.

Inventors and medical device companies have tried numerous variations on these designs, but so far none has been widely adopted. These variations focus on improving the ergonomics of the crutch, for example by angling the handles or adding padding. Some companies have also added springs in the crutch tip; this may reduce the load transmitted to the body, decreasing injuries over time [8][9]. Alternatively, in 1995, a patent issued for a crutch incorporating both a series elastic element in the tip and a parallel elastic element spanning the elbow [10]. This design both reduces loading on the body and could assist with climbing stairs. However, little progress has been made in this direction since.

1.2 Crutch Specifications

A crutch for ascending stairs must meet the following specifications:

Effectiveness: The patient using the spring-assisted crutches to climb stairs expends less energy than he or she would with unmodified crutches. The patient can still walk with the spring-assisted crutches on level ground. Spring resistance must

be within the physical capabilities of the patient to compress, where maximum torque production of the human elbow is estimated as 35-40 Nm [11].

Safety: Crutches must be safe for patient use under all circumstances. The patient must feel stable during their use, and the crutches should not contribute to injury if the patient falls. Proper crutch usage should avoid nerve compression, particularly of the brachial plexus nerves in the underarm.

Comfort: Patient should not be asked to operate the crutches in a way that is unnatural or uncomfortable for the body. Climbing stairs should be strenuous but not painful.

Aesthetics: Crutches should constitute a visually appealing product. The form of the crutches should imply the intended use.



Figure 2: Common and lesser-known crutch designs. From left to right: Axillary or “underarm” crutch; Lofstrand or “forearm” crutch; “SmartCrutch” with platform arm rest [12]; “OnlyOne” crutch with knee rest [13]; “Mobilegs Ultra” ergonomic underarm crutch [14]; Crutch with upper and lower elastic elements [10].

1.3 Upper Arm and Shoulder Muscles

Figure 3 illustrates the upper arm and shoulder muscles most involved in using crutches. The biceps brachii and triceps brachii act as a pair to flex and extend the elbow, respectively. They are assisted by the shoulder muscles as well as the brachialis (beneath the biceps brachii, not pictured) and the brachioradialis in the forearm. In addition, the muscles of the shoulder and wrist act by their relative stiffness to stabilize the user over the crutch stanchion. In normal stair ascension with forearm crutches, the triceps provides the most force, extending the arm and lifting the user up to the next step. However, the biceps could store energy in an elastic element during elbow flexion; the energy would be returned to the body during elbow extension. The use of multiple muscle groups would reduce the patient's rate of fatigue [4].

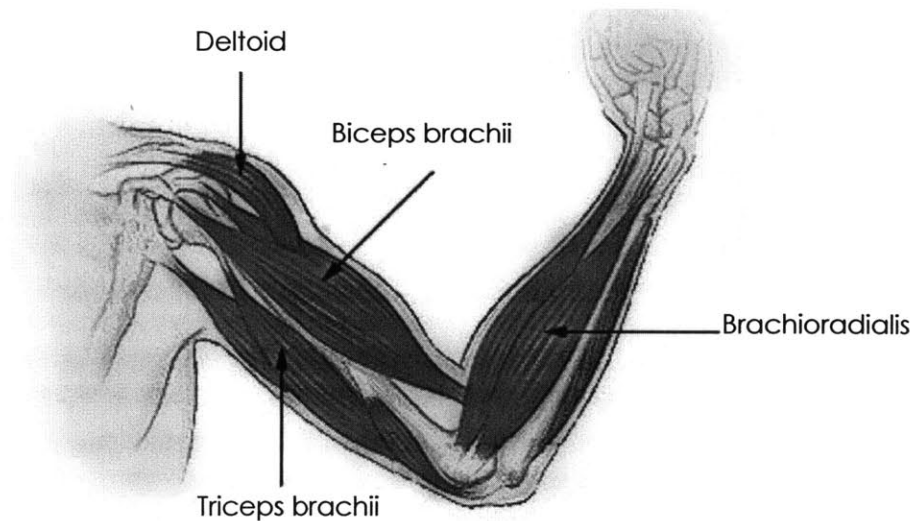


Figure 3: Arm and shoulder muscles.

2. Device Design

The final spring-integrated crutch incorporates an upper arm cuff and torsion spring that attach to a forearm crutch produced by Invacare Corporation. Figure 4 shows a computer rendering of the full spring-integrated crutch, and Figure 5 shows a detailed view of the novel portion. Figure 6 shows an assembly view of the integration of the torsion spring and forearm cuff.

The upper cuff is secured using a nylon strap with a hook-and-loop closure. The torsion spring is fully extended when the patient walks on level ground. When approaching a step, the patient compresses the spring by flexing the elbow to bring the crutch upward. The spring then expands during elbow extension to assist the patient in lifting the body. With a standard forearm crutch, the triceps produce the majority of the energy expended to lift the body during elbow extension. By storing energy in the spring during elbow flexion, the biceps assist the triceps and the user distributes force production more optimally [4][10]. Energy is stored in the spring as the patient draws the handle upward while keeping the shoulder relatively still.

As the spring is compressed, the top must press somewhere against the patient's body. The final design of the cuff eliminated potential damage to the brachial plexus nerves by avoiding contact with the underarm. Instead, the design of the upper arm cuff prevents the cuff from slipping when pressed upward, so it provides "push-back" against the spring.



Figure 4: Computer rendering of the full spring-integrated crutch.



ITEM	PART NAME	QTY.
A	Neoprene Shell	1
B	Plastic Cuff (not visible)	1
C	Velcro	1
D	Nylon Strap	2
E	Torsion Spring	1
F	Upper Torsion Mount Cap	1
G	Screw M3x16	2
H	Upper Torsion Mount	1
I	Screw M3x10	4
J	Invacare Forearm Crutch	1
K	Lower Torsion Mount	1
L	Lower Torsion Mount Cap	1
M	Screw #10x0.75	2

Figure 5: Detail view of the novel portion of the crutch and a bill of materials.

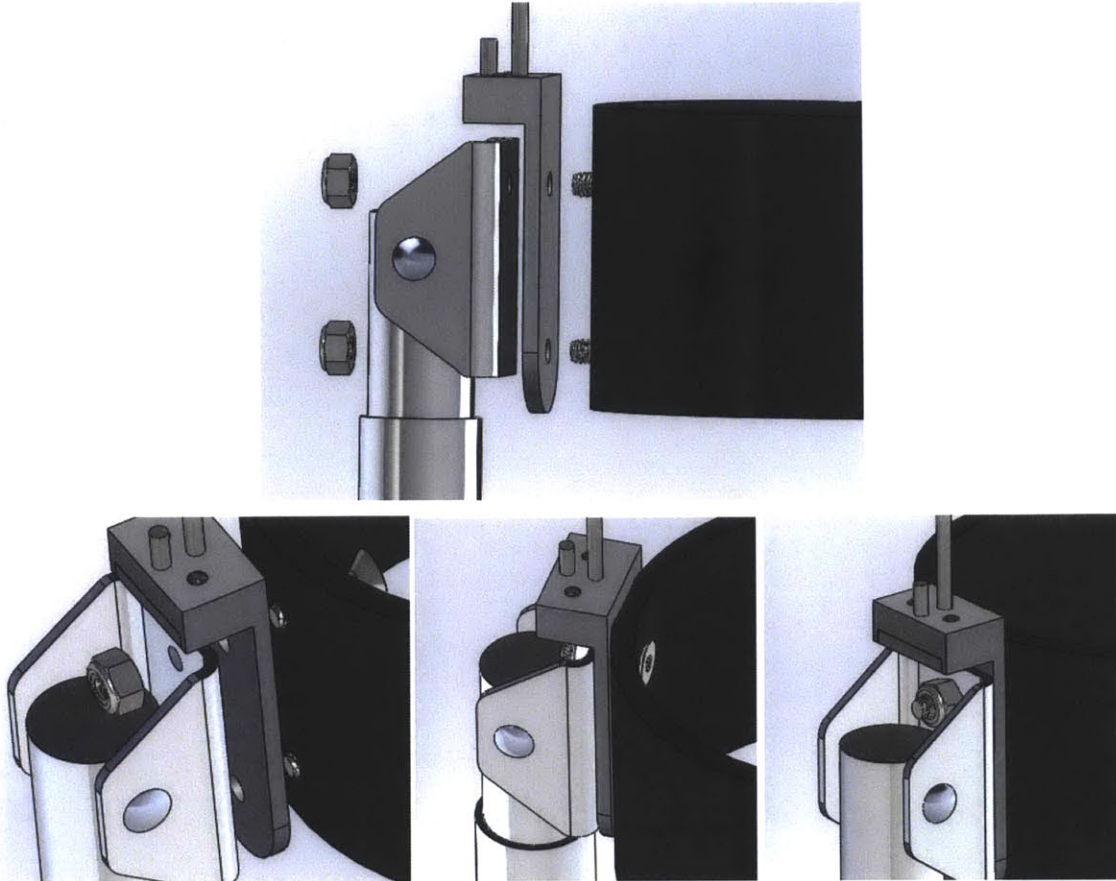


Figure 6: Assembly view of the lower torsion spring mount, the forearm cuff, and the stanchion. Counterclockwise from top: exploded front view, exploded angle view, fully assembled inside view, and fully assembled outside view. Note that the screws included with the Invacare forearm crutches were discarded and replaced with longer #10 screws in the new assembly.

The torsion spring aligns with the elbow along the back of the arm. The legs of the torsion springs are fed into the mounts, bent 180°, and fed back through the mounts; the caps are then attached with M3 screws. This prevents the spring from moving up or down and from twisting left or right, while allowing the overall height of the spring to be adjusted.

2.1 Upper Arm Cuff

Early iterations on the cuff focused on a design that would not slip when applied to bare skin. A mock-up of this concept included a hard, inflexible plastic shell lined by skin-safe silicone of the type used in socket liners for amputees (Figure 7). Two nylon straps lined with Velcro were used to supplement the friction of the silicone in holding the cuff in place. Based on previous experience with cuffs held in place by zip-tie, 1" wide straps were chosen that would distribute pressure more widely over the skin without pinching.



Figure 7: Photo of early upper arm cuff mock-up.

However, the first users found that while the straps were comfortable, the hard plastic shell dug uncomfortably into the underarm and frequently pinched the skin. Moreover, it was found that users were more likely to be wearing a shirt or sweater with sleeves than to be wearing the cuff over bare skin. This widened the

range of possible materials that could be used for padding. A $\frac{1}{8}$ " thick neoprene foam was chosen for its texture and compressibility.

The final cuff design incorporates a smaller plastic core inside a neoprene shell (Figures 8 & 9). The core is held centered within the shell by stitching in the neoprene. The opening of the shell tapers to allow greater freedom of bicep contraction. The number of straps has been reduced to one to allow the cuff to be taken on or off more easily; the strap is anchored to the plastic core to prevent tearing the neoprene when the strap is pulled. The plastic core also provides shape and an anchoring point for the upper elastic element mount.



Figure 8: Photo of the upper arm cuff.

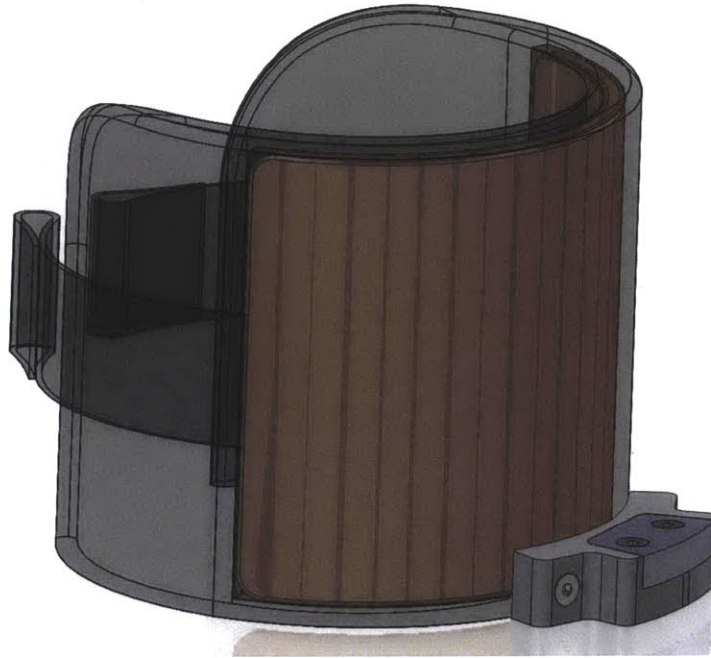


Figure 9: Computer rendering of the upper arm cuff. In the top image the neoprene has been made transparent to show the placement of the plastic core.

2.2 Elastic Element and Attachment

Three types of elastic elements were considered during the design process: a compression spring, a leaf spring, and a coil spring. The leaf spring initially appeared favorable because of the elegant shape it lent to the finished product. Curves were formed for testing from spring steel of .015" and .032" thickness (Figure 10). Unfortunately, these early mock-ups did not provide the correct mechanical advantage. Rather than resisting elbow flexion and thereby storing energy, the curve bent with the elbow, presumably following the path of least resistance.

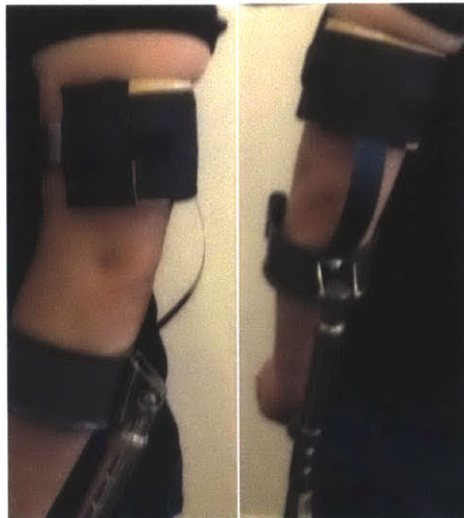


Figure 10: Photo of crutch mock-up with leaf spring.

The compression spring, used previously in Berns's experimental crutch, was briefly considered (Figure 11), but the torsion spring was chosen as the better alternative. The motion of a torsion spring is analogous to that of the elbow; the torsion spring also functions by flexion and extension around a fixed point. Based on the stated output torque of the elbow and the geometric constraints of the system, a variety of torsion springs from McMaster-Carr [15] were chosen for

experimentation (Table 1). The #7 torsion spring provided a noticeable “push” without being too strenuous to bend.



Figure 11: Computer rendering of an attachment mechanism for a compression spring.

The attachment mechanism between the spring and the cuffs went through many iterations (Figure 12). The attachment had to withstand the outwards and upwards forces applied by the torsion spring legs during use. Manufacturing and assembly were also considered. The final design for the upper torsion mount is shown in Figure 13. This mount can also be used between the forearm cuff and the spring if the spring is moved out of line with the elbow. However, the separate lower torsion mount shown previously in Figure 6 was designed to integrate smoothly into the pre-existing Invacare crutch.

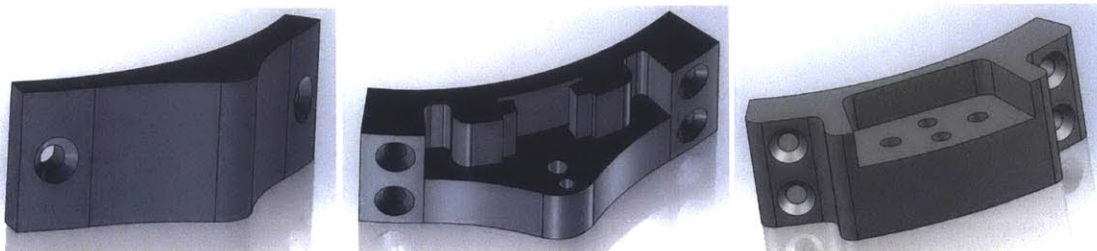


Figure 12: Early variations on attachments between the upper arm cuff and a torsion spring.

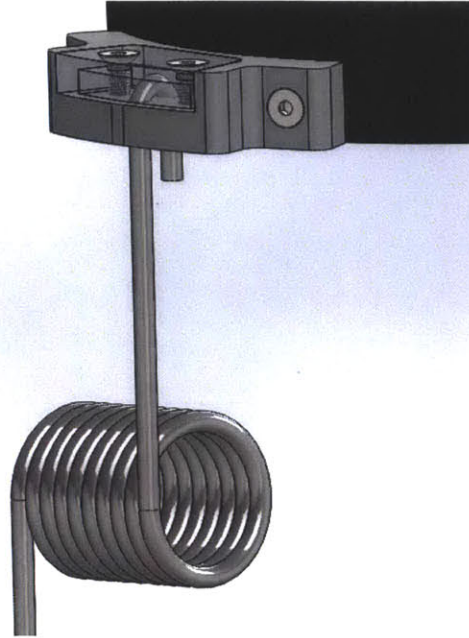


Figure 13: Computer rendering of the final design of attachment between the upper arm cuff and a torsion spring. The cap is represented as transparent to show how it is shelled and so that the bend in the torsion spring leg can be seen.

Table 1: Mechanical properties of the torsion springs tested during design. In materials, 'MW' refers to steel music wire and 'SS' refers to Type 302 stainless steel. Geometric terms are illustrated in Figure 14.

Spring No.	Torque, in-lbs	Spring OD	Wire Dia.	Leg Length	No. of Coils	Materials
1	4.50	0.526"	.059"	2"	8	MW
2	7.50	0.635"	.070"	2"	8	MW
3	10.45	0.781"	.078"	2"	7	MW
4	17.14	0.920"	.095"	3"	8	MW
5	22.50	0.982"	.106"	3.5"	7	MW
6	21.16	1.348"	.115"	4"	8	SS
7	28.00	1.348"	.115"	4"	7	MW
8	34.28	1.082"	.125"	4"	9	MW

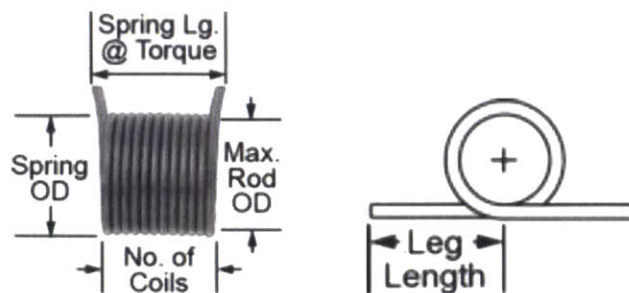


Figure 14: Geometric diagrams of torsion springs [16]

2.3 Safety

In assessing the adherence to the guidelines laid out in the crutch specifications, the final spring-integrated crutch design has both strong and weak elements:

Strengths: spring compression is achieved by pressing against the upper arm, avoiding pressure against the brachial plexus nerves. Additionally, the crutch is operated with normal elbow flexion and extension, without requiring the patient to learn a novel or awkward movement.

Weakness: in the event of a fall, a patient could become tangled in the straps. A safer crutch would avoid this risk. However, many commercially available platform crutches employ quick-releasing straps, and this device, with only hook-and-eye closure, is comparable.

Patient stability when using crutches is also a concern. More testing needs to be performed to determine if patients feel comparably stable with the spring-integrated crutch as compared to an unmodified forearm crutch.

3. Patient Feedback

Early crutch users reported that the crutch “looked cool” and was “easier to use than an underarm crutch.” Users reported no discomfort from the cuff. However, the leg length of the torsion springs needed to be adjusted for different users, which was difficult in this configuration.



Figure 15: Photos of final spring-integrated crutch being used by a patient.

4. Conclusions

A crutch incorporating a parallel elastic element spanning the elbow was built. The crutch incorporates a novel upper arm cuff and torsion spring module with a commercially available forearm cuff. Preliminary users found the crutch comfortable to use. However, further metabolic studies should be performed to verify that the metabolic cost of crutching up stairs has been reduced. Safety requirements have been met in the case of normal use; safety in cases of the patient falling or becoming unstable could be considered further.

4.1 Future Design Work

Early sketches of the crutch design incorporated an elastic element parallel to the elbow and in series with the stanchion (Figure 16).

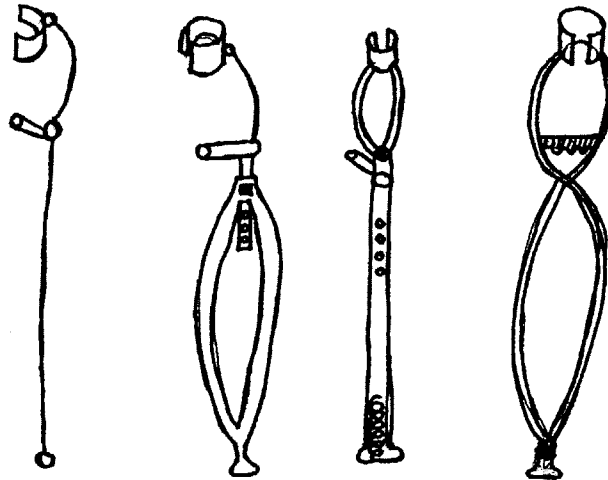


Figure 16: Early sketches of crutch with both series and parallel elastic elements.

The project was broken into modular units—upper arm cuff, elastic element, lower arm cuff, and stanchion—to better pursue manageable goals within the time

allotted. The final cuff and elastic element design can be used in its current form or improved upon by continuing to modify the lower arm cuff and stanchion. Figures 17 and 18 show examples of future designs with both parallel and series elastic elements. The final goal would be a comfortable and aesthetic crutch with the elastic elements fully integrated into the design.

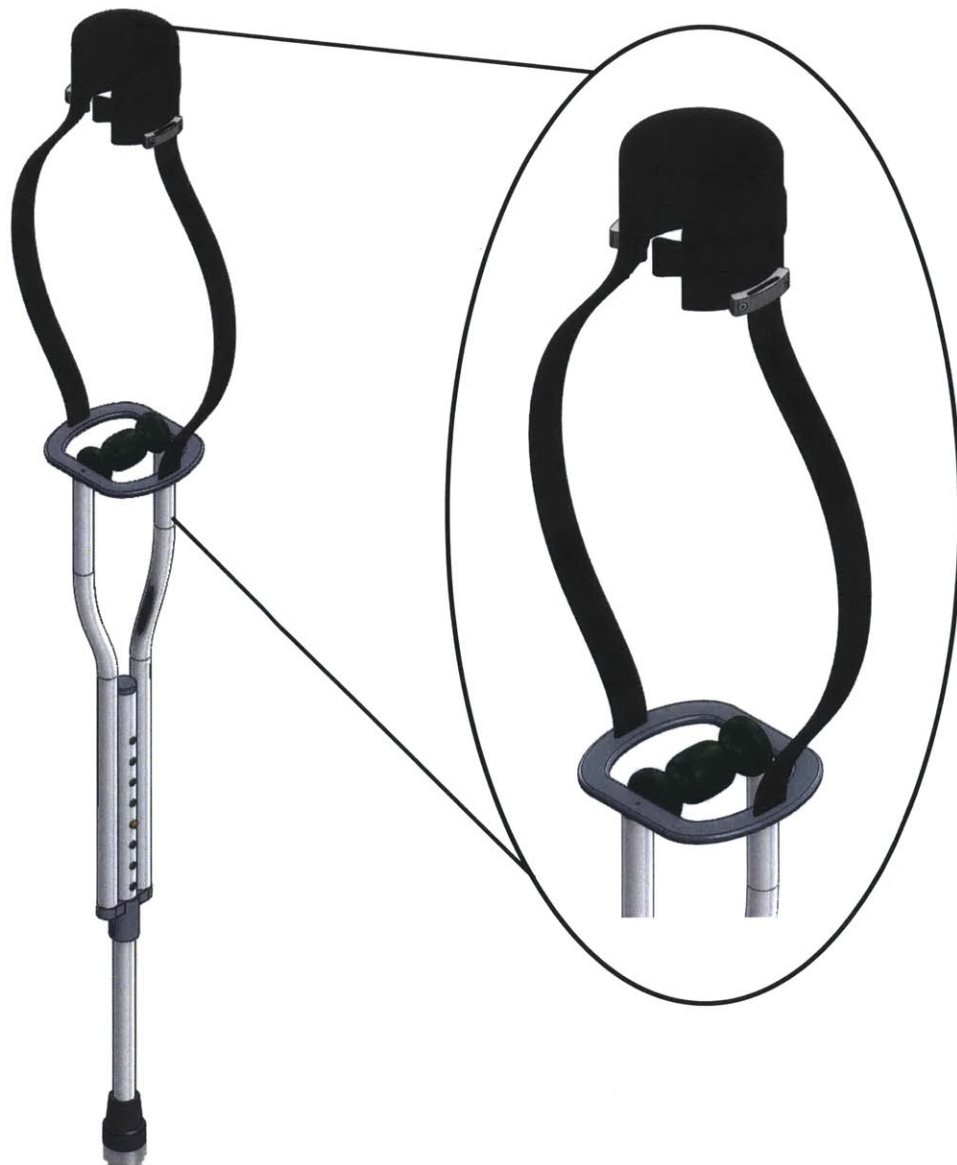


Figure 17: Computer rendering of a potential fully integrated crutch design. Note that the series elastic element is a compression spring inside the crutch tip.



Figure 18: Computer rendering of a second potential fully integrated crutch design. Note that the upper and lower carbon fiber leaf springs could be of different stiffness or different material. The handle could also rotate to change the alignment of the leaf springs with the body.

Alternatively, students in the MIT Materials Science and Engineering spring 2012 course 3.042: Materials Project Laboratory developed an S-shaped crutch similar to Figure 18. Each curve was formed of unidirectional fiberglass cloth wrapped over a polyurethane core. Although patients in short trials preferred the S

Crutch to a traditional axillary crutch, and were shown to expend 29% less energy in level-ground walking, the S Crutch rests against the axilla during use [16]. To avoid nerve damage and to add a parallel elastic element, the lower stanchion of the S Crutch could be incorporated with the upper arm cuff presented here.

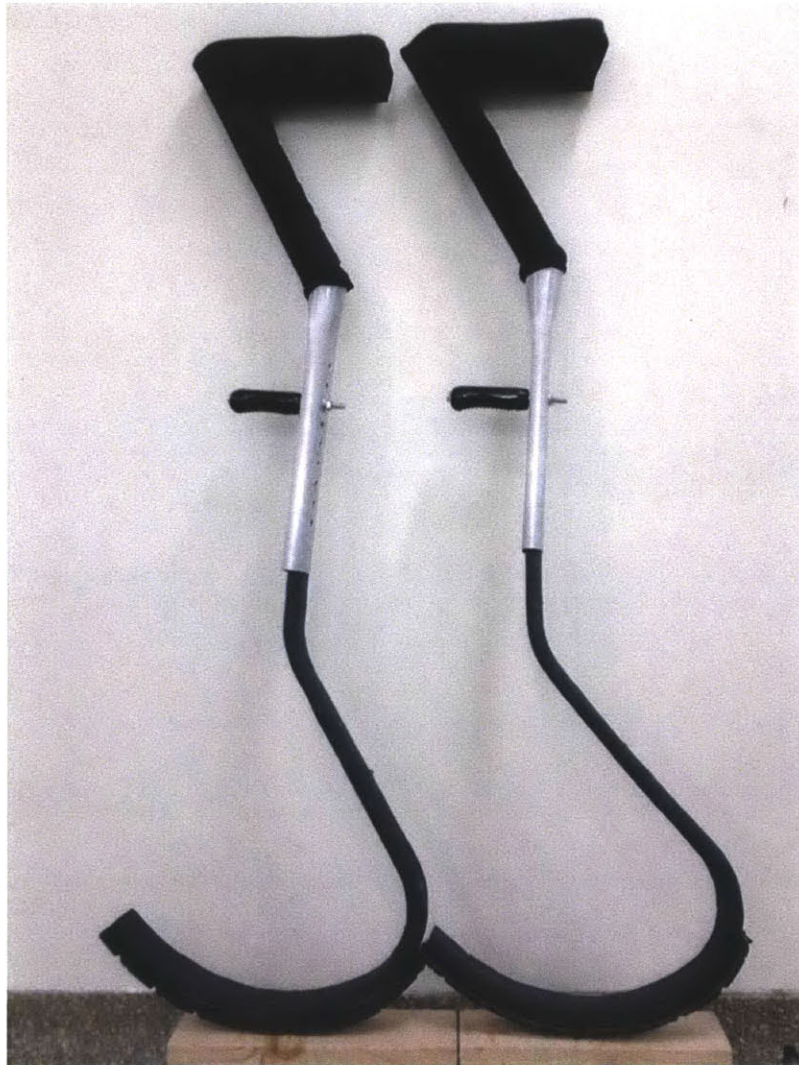


Figure 19: “S Crutch” designed and machined by students in 3.042 Spring 2012. Image courtesy of Vivian Dien, Anne Juan, Fei Pu, Ron Rosenberg, and Will Tashman.

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