Design, Prototyping and Preliminary Testing of an Elastic-Powered Climbing Exoskeleton

by

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SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL
FULLFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2011

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ABSTRACT

Human powered elastic mechanisms can be used to reduce work requirements of muscles, by storing and releasing energy to more evenly distribute work load. An exoskeleton was designed to delay human fatigue during rock climbing. This exoskeleton stores energy in the less intensive motion, extension while reaching upwards, and uses the stored energy in the more intensive motion, flexion during upwards ascent. A cuff 3D which will be printed by Objet Geometries Inc. utilizes Arthur Iberall's lines of non-extension to simultaneously maximize rigidity and comfort. Due to the inability of Objet's printed items to withstand the required high forces, a prototype climbing exoskeleton for the arm was fabricated from heat moldable plastic and latex springs. Pilot tests were conducted with the prototype and preliminary results were promising.

Thesis Supervisor: Hugh M. Herr
Title: Professor of Media Arts and Sciences

Acknowledgements

Special thanks to Professor Hugh Herr for providing the inspiration for the climbing exoskeleton and for advising me on this thesis.

Special thanks to Andy Marecki for his patience and guidance through the process of designing, testing and writing about the climbing exoskeleton. Thank you for teaching me more than you'll ever give yourself credit for.

Thanks to Grant Elliott for his inspiration and guidance in the field of exoskeletons.

Thanks to my friends at Metro Rock Climbing Gym for letting us distract their patrons with our silly looking arm attachments.

Thanks to Sarah Hunter for keeping me focused and making sure I clean up after myself.

Thanks to my mother for all of her worrying, and all of her not worrying when she finally believe me that my thesis was going to get done.

1. Introduction

Countless inventions each year attempt to enable humans to run faster, walk farther, jump higher, or fly. Humans are remarkably efficient, but the drive to achieve more will always be present. Few known devices have attempted to augment human climbing capabilities. Climbing is a whole body activity and its full augmentation would involve nearly every muscle in the body. An exoskeleton which augments human climbing capabilities would revolutionize the art of rock climbing and extend the limits of human exploration. In addition, such a device would help to better understand biomechanics assist in the treatment of muscle wasting diseases and other biological disabilities. This paper details an exoskeleton design which attempts to augment endurance in the arm muscles of a climber through the use of elastics.

1.1 Elastic Mechanisms

The quest to improve human capabilities through machine has been around since ancient times. The first human-powered elastic mechanisms came into use during the Neolithic Revolution between 13000 and 15000 B.C. During this era and since, elastic mechanisms have been used to amplify power, reduce muscle work and in opening and closing devices. In attempting to improve human capabilities though elastics, we attempt to utilize all of these functions.

Elastic mechanisms which amplify power work much like a bow and arrow. On our own power, we cannot throw an arrow quick enough to give it its piercing capabilities. The faster our muscles contract, the fewer fibers are able to generate power, and the less force the muscle is capable of generating (Herr). By using a bow, greater force can be generated upon release by bending the bow on a slow time scale and then imparting that higher force rapidly as the string is released. In this way, human power is amplified through the elastic bow and arrow.

The second function of elastics is reduce the work load applied to muscles. Particularly in application to cyclical motions, energy can be stored through elastics during an easy motion, such as falling on a trampoline, and released during the more difficult motion, the powering of a person upward. In this way, the elastic both reduces the muscle requirement in absorbing the impact of falling and assists the muscle input required to power the body off the ground. Especially in application to cyclic motions such as running, hopping or climbing, this type of elastic use may be particularly powerful in augmenting endurance by reducing required work output.

The third and final use of elastics is in opening or closing devices. An example is a simple spring loaded door. When the door is opened, a spring is stretched, which then powers the door closed. This type of elastic use is closely related to elastic use which reduces muscles. A planned motion is set with elastics such that one easy part of the motion is made slightly more difficult, while a second part of the cyclical motion is made easier, or in the case of the door, made to require no force at all.

Utilizing these three uses, passive human-powered elastic mechanisms can augment human capacities to output power and perform muscular tasks repetitively. Such a device could delay fatigue during physically challenging cyclical activities. In order to understand how to employ elastics to increase endurance, we first must understand the arrangement of the muscular system our body uses to generate power.

Skeletal muscles are arranged in agonist-antagonist pairs, one acting in extension, the other in flexion. Although this configuration allows for human adaptation to a variety of motions, it does not maximize the muscles' potential to perform any particular motion. For example, when a rock climber pulls himself up to a higher grip, only the flexion muscles can generate force, while the extension muscles look on passively , as shown in Figure 1, limiting both climbing power output and endurance. (Herr, 1993.)

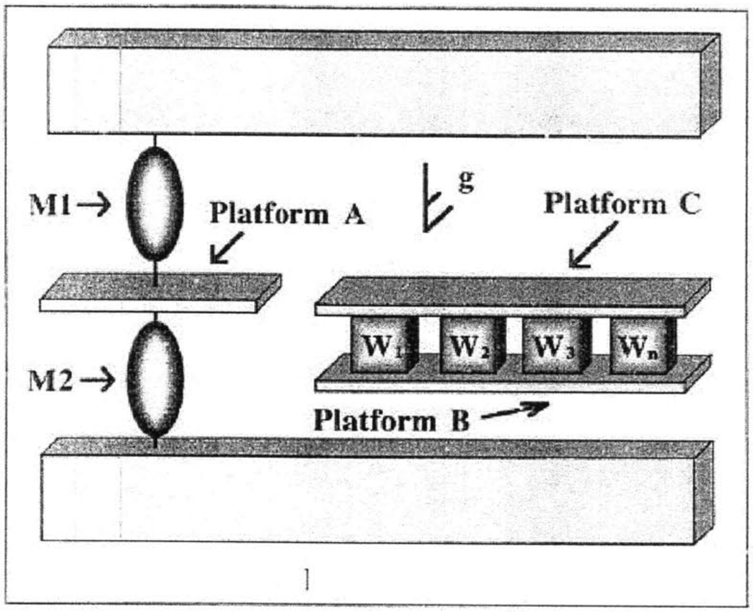


Figure 1. A simple muscular system lifting weight from B to C. M1 generates all of the force required while M2 looks on passively, since these muscles can only push and not pull.

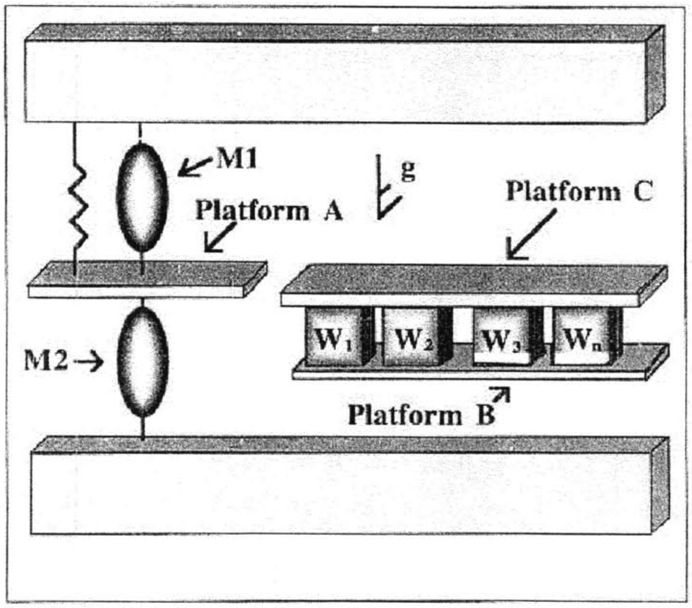


Figure 2. An elastic element in added in parallel to the M1 muscles. Now when weight is applied to the system, the spring is stretched and may then assist M1 in lifting the weights to platform C.

This thesis proposes the creation of an elastic climbing exoskeleton, which redistributes the workload between flexion and extension muscles in the arm. While the exoskeleton-wearing climber extends his arm to the next handhold, work will be done to stretch a synthetic rubber latex spring. The stretched spring can then assist in lifting the climber during the more fatiguing portion of the climb, the upward pull. Firstly, this elastic enhancement may enable the climber to pull upwards more quickly, enabling a high power output. In addition, while the net work done by the climber will not change, the work will be redistributed between flexion and extension muscles, decreasing work per unit volume of muscle. This work redistribution should delay muscle fatigue in the arm muscles, and thus enhance endurance.

The principle of work redistribution is illustrated by the diagram in Figure 2. When the M2 muscles, which represent the extensor muscles, contract, work is applied to the spring. While this motion is now more difficult for the extensor muscles with the added spring, the work required to extend the arm was previously negligible, so this slight addition does not increase the workload of the extensor muscles to a point which causes fatigue. Now, the added spring has been loaded in such a manner as to assist the M1 muscles. When the M1 muscles, representing the extensor muscles, contract to lift the weights on platform B to Platform C, the required force is greatly reduced due to the assistance of the preloaded spring. The spring both allows the M1 muscles to generate more power, and enables them to do less work. Throughout this extending and pulling cycle however, the net work done in the cycle has not been affected by the implementation of the spring. However, the work has been redistributed between the extension and flexion muscles, M1 and M2, in such a way that fatigue may occur much less rapidly.

1.2 Problem Statement

This investigation aims to explore the concept of a rock climbing suit to augment endurance. Rock climbing, especially in recent years, has become an anaerobic activity. Tremendous power requirements are necessary to propel the human body in large leaps to high handholds. The steepness of a rock climb can vary from 0 to 100 degrees off of vertical (Herr). A climber's goal is not to minimize time of ascent, but to reach the top without falling. Failed climbs are frequent and are generally the result of elbow flexor or finger flexor fatigue.

A device which employs elastics working against the extensor muscles and with the flexion muscles may assist the climber by the redistribution of work. This device, if properly tuned to the climber should delay the onset of elbow flexor fatigue and enable the climber to climb longer, tougher and steeper rock faces. The following section details the design of a tuned elastic mechanism, and the attachment of such a device to the body, in order to assist elbow flexion and increase climbing endurance.

2. Device Design

2.1 Human Interface

Likely the most important, and perhaps the most overlooked, factor in exoskeleton design is the attachment of a device to the body. Most mechanically assistive exoskeletons must be held rigidly against the body, while most natural rigid body structures, namely the skeleton, are hidden beneath protective sheathes of non-rigid fleshy muscle, fat and skin. The concepts behind employing elastics to assist rock climbing endurance is a matter of simple physics. However, these elastics, in order to function properly, must not slip relative to their original positions on the body, such that the maximum extension of the elastics can be utilized during the upward ascent. The largest challenge in the design of the elastic-powered exoskeleton to augment climbing endurance is the attachment of elastics rigidly, yet comfortably.

2.1.1 Iberall's Lines of Non-Extension

In November of 1964, Athur Iberall published an idea which was far ahead of his time. Iberall called for "The Use of Nonextension to Improve Mobility in Full-Pressure Suits." Iberall detailed in this paper lines across the human skin which essentially did not extend during movement. These lines, he thought, could therefore be constricted, without impairing the mobility of the subject wearing the suit. Iberall hoped to utilize this concept in the production of a full-pressure space suit, which concentrated its pressure on these lines rather than the entire body. Over a half century later, Iberall's lines of non-extension were employed in Dava Newman's "Bio-suit." Newman used Iberall's lines as a template for an inextensible mesh to which she applied mechanical loads to pressurize a suit. The suit allows full mobility, but is capable of restraining internal inflation in outer space (See Figure 3.) However, Iberall's lines of non-extension may be utilized for many other applications besides pressurized space suits. In the design of the cuffs which must hold our climbing exoskeleton in place, we followed Iberall's lines as a guide, hoping to more comfortably rigidly attach to the body, without impairing mobility.

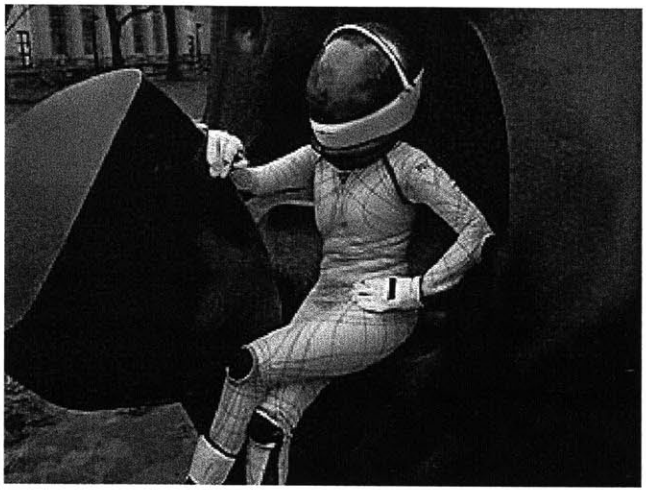


Figure 3. Dava Newman's novel pressurized space suit "The Bio-Suit" which utilizes Arthur Iberall's Lines of Non-Extension.

Iberall's paper first mapped out where on the body these lines of non-extension are located. He went about locating these lines in accordance with his theory which described why such lines should exist. The human body retains its form upon deformation, and tends to deform, "a small sphere of material…to nearly ellipsoidal shape. Since all points on an ellipse are derived from points on the undeformed circle, in general, there may be two diameters in the ellipse which are not stretched" (Iberall, 1). Iberall went about identifying these lines across the ellipse which did not stretch by stamping a one-inch ink circle on a subject's skin, and then watching the deformation as he/she moved. Deformations of small strains resulted in the identification of two unchanged diameters, which then became the lines of non-extension for that portion of the body. Generalization of deformation by one motion to deformation by all possible motions was made through the assumption that the human body consists on elastic parts mounted on a rigid skeletal frame. Since motion of the skin is limited by motion of the joints, lines on non extension for one deformation are essentially the same for all deformations. By continued mapping, Iberall was able to produce a network of lines of non-extension, as shown below in Figure 4.

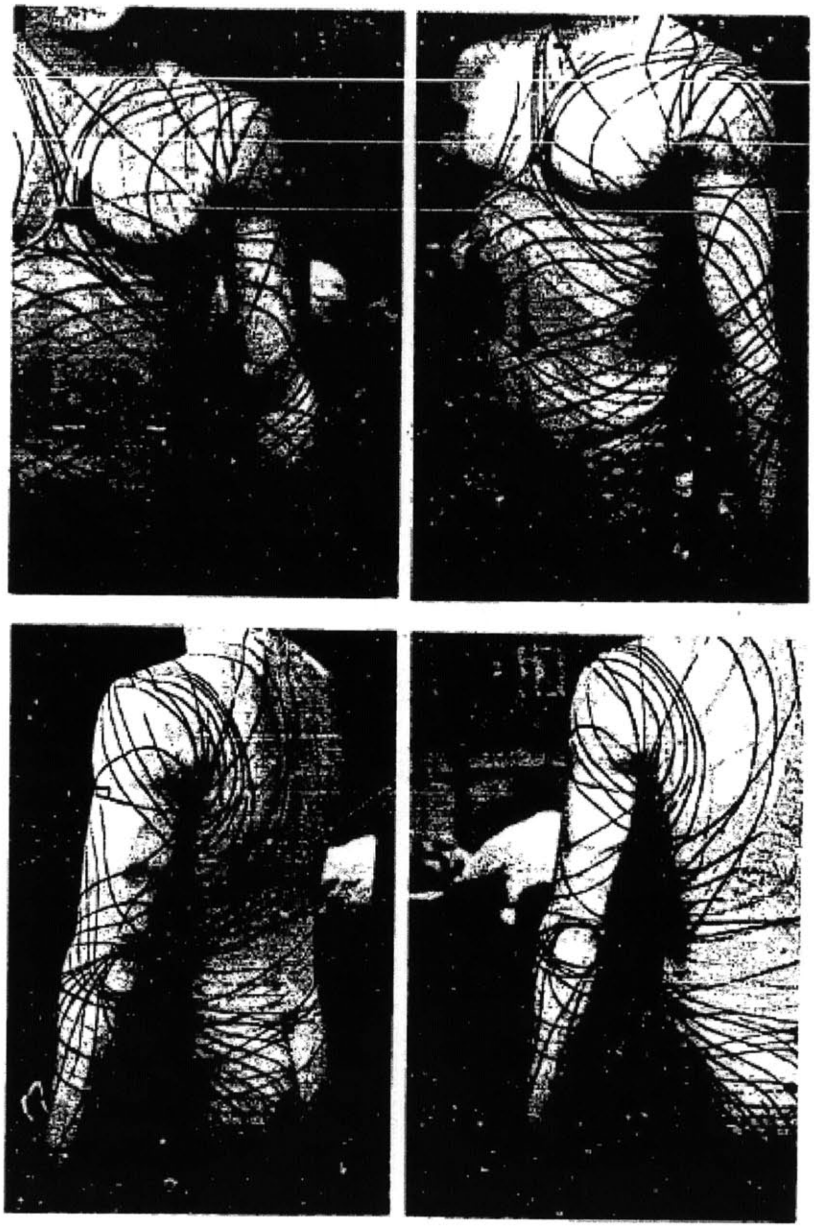
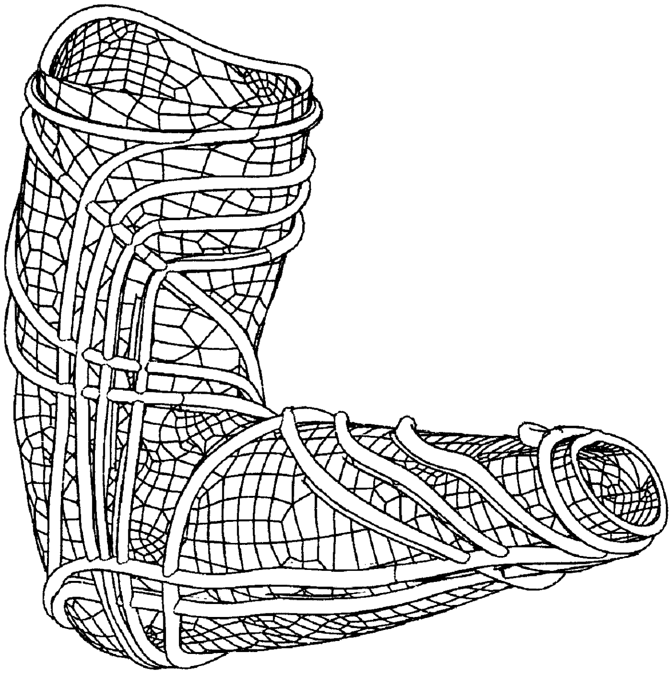


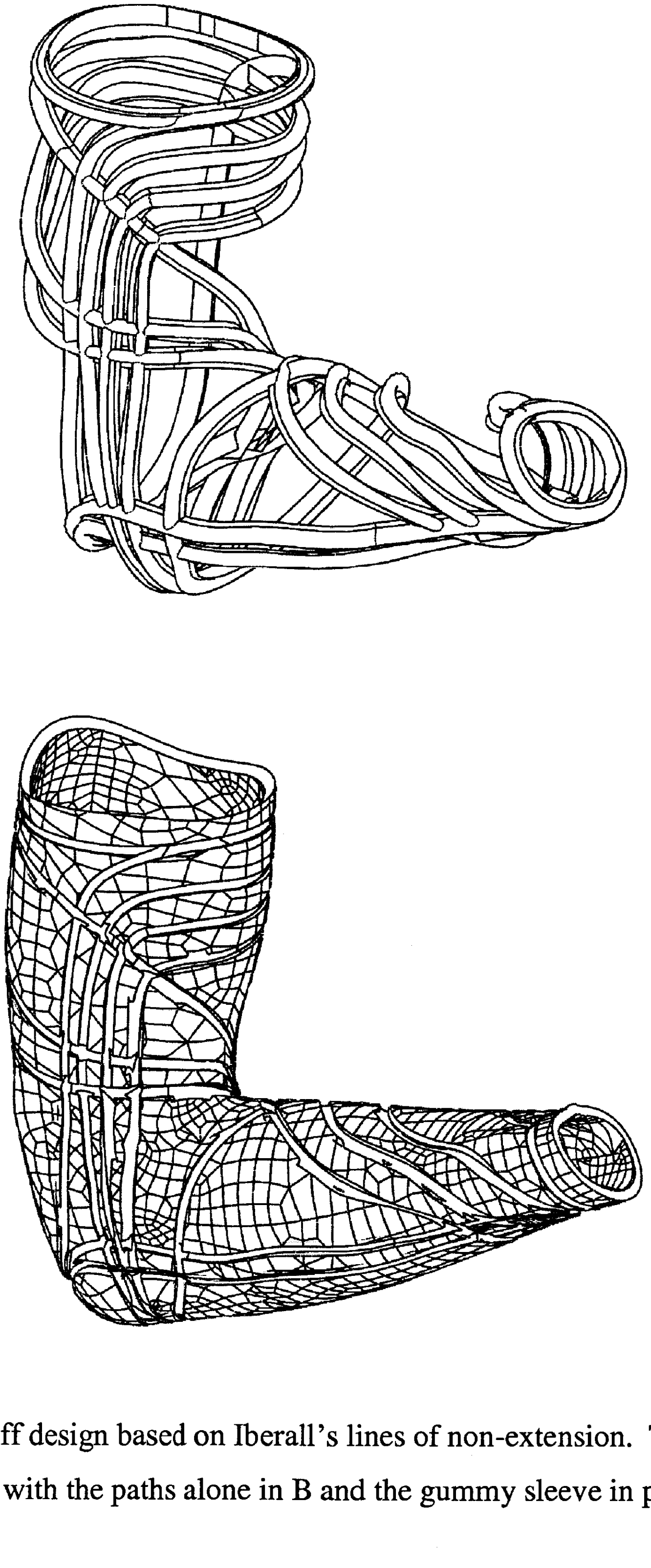
Figure 4. Iberall's lines of non-extension for the upper body.

To assess the deviation of his mapped lines to the actual non-extensive lines he wished to be determining, Iberall placed non-extensible string along his map of lines. The strings movement and tension was used to refine the precise locations of the various non-extensive lines.

Our goal in the utilization of these lines in exoskeleton design was to create a meshwork across the body to which we could attach latex elastics. In employing Iberall's lines of non-extension we both wished to supply this meshwork with rigidity and a lack of deformation upon movement, as well as provide the user with comfortable full range of motion while climbing in the suit. The chosen lines are imaged below (Figure 5A) in the original design of the climbing exoskeleton cuff. The paths in 5B represent rigidified lines on non extension imbedded in a soft gummy cuff, imaged in 5C, with paths carved for the harder portions. Design was carried out through Solidworks computer aided drawing technology, giving precise 3D dimensionality to our cuff concept. Our design, however, is too complex to be easily machined on standard equipment. For this reason, we turned to Objet's variable stiffness 3D printing technology. The next section details the capabilities and material properties produced by this process.

5A.





5B.

5C.

Figure 5. Arm extensor cuff design based on Iberall's lines of non-extension. The assembly of rigid paths are shown in A, with the paths alone in B and the gummy sleeve in part C.

2.1.2 Objet 3D printing

Objet's lineup of three dimensional printing systems offer high resolution and fine detail for virtually any rapid prototyping application. The company's PolyJet Matrix technology enables the fabrication of multi-material parts and assemblies where the mechanical and physical properties can vary significantly in a single build.

The Connex500 is Objet's largest and most capable multiple material 3D printer. Multiple material support in a single build means that the machine can simulate many of the complex aspects of part and assembly geometries. For example, intricate part mates and over molding in the injection molding process can both be simulated. Furthermore, Objet's digital materials mode supports the creation of composite materials from any two of its full cure materials in specific concentrations and structures. The digital materials capability significantly increases the flexibility and opportunities associated with the 3D printing process. Parts can now take on a range of Shore A values from around 27 to 95 with nearly high variability between these bounds. The Connex500 offers a net build size of 490 x 390 x 200 mm, which is larger than the bounding box of the climbing exoskeleton. The build resolution of this machine is 42 microns in the x and y axes in the plane of the machine's bed, and 16 microns in the z direction. The Connex500's accuracy is 0.004 to 0.010 inches, which varies depending on geometry, part orientation, and print size.

This two-material configuration is ideal for the proposed climbing exoskeleton architecture. One of the design for manufacturing features of the climbing exoskeleton sleeve is its ability to be 3D printed by Objet's machines. The prototype sleeve requires soft, compliant sleeve to act as a second skin to the user and provide adequate force distribution along the user's upper and lower arm. This rubbery sleeve will also help to keep the exoskeleton in place during climbing as it will be able to apply uniform shear forces along the surface of the arm, much like the silicon liner used with a traditional prosthetic socket. This sleeve will be covered by rigid bands along the arm's lines of non-extension. A stiff rubber is the ideal choice for this framework. These bands serve as connection between the rubber sleeve and the passive elastic elements of the exoskeletal system. The stiff structure will be interwoven with the sleeve and provide rigid attachment points for the latex springs.

The digital materials mode enables us to select the specific material properties, such as durometer and tear resistance to provide the best possible performance. Two materials, DM9885 and TangoPlus, are selected for this design. Table 1 lists the material properties of both these materials.

Property	TangoPlus	DM9885
Tensile strength (MPa)	1.455	6
Elongation at break (%)	218	55
Tensile tear resistance (N/mm)	3.47	26
Hardness Shore A	27	85

Table 1: Material properties for Objet materials used in climbing exoskeleton.

The TangoPlus material properties show that it is suitable for the sleeve, with its relatively low durometer and high maximum strain. The elastic modulus of the TangoPlus material is approximately 0.15 MPa. The material is soft, compliant, and has a high coefficient of friction with skin. Similarly, the DM9885 material has a significantly higher tensile strength, tear resistance, and hardness. It is stiff, but can still undergo significant strains to ensure that the user can put on and remove the exoskeletal sleeve. Despite being 3D printed, these materials are fairly durable. The same materials are used to create parts, such as living hinges, gaskets, and hoses that withstand significant deformation, including tension, bending, and torsion. The high maximum strains and good tear resistance indicate that the prototype sleeve should survive the rigors of climbing.

2.2 Optimal Spring Stiffness

In his 1990 paper, "Human-Powered Elastic Mechanisms," Hugh Herr outlines experiments conducted to approximate the optimal stiffness for an elbow flexion spring during an upward pulling motion, a pull up. In this way, Herr he determined an optimal division of work between the flexors and the extensors such that endurance was increased, in that the "climber" could perform more consecutive upward pulling motions. With latex tubing, the subject was asked to reach up, extending the latex, and then pull his or her chin entirely over the bar, then stand, lower themselves, and repeat the process to exhaustion. This process was repeated with several different springs of varying stiffness. While not perfect, this experiment mimics the action of a climber who reaches up (generally with one arm) to a higher handhold of a rock face, and pulls themselves upward. Thus the fatigue experienced by the subject doing pull-ups is similar to the fatigue which may be experienced by a climber wearing a similar, but more versatile elastic-powered device.

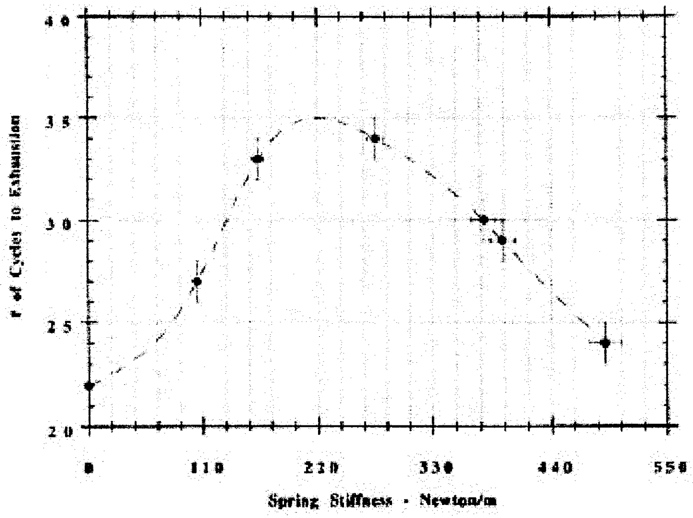


Figure 6. Number of cycles until exhaustion plotted versus spring stiffness.

Herr found that by using an optimal spring stiffness of 222±16 N/m, a subject could increase the number of pull up cycles until exhaustion by 59 ± 5 % of their unassisted number of cycles, as shown in Figure 6. Herr used as an estimate that the ratio of the forces done by the extensor and flexor muscles was approximately equal to the work done by the extensor and flexor muscles.

$$\frac{F_e}{F_f} = \frac{W_e}{W_f}$$

This force ratio of extension to flexion was estimated to be $F_e/F_f = 0.43 \pm 0.02$ using the weights and distances lifted and covered by the subject. The work done by the extensor muscles each cycle is easily computed as the energy stored in the spring.

$$W_e = \frac{1}{2}Kx^2$$

Where K is the spring stiffness and x is the distance the spring was extended before the pull up. Similarly, the work done by the flexor muscles each cycle can also be computed.

$$W_f = \frac{M}{2}gx - \frac{1}{2}Kx^2$$

Where M is the subjects mass and g is the gravitational constant. Note that the work done by a single arm is only lifting half the body's weight, since in the case of a pull up, both arms work at the same time to lift the body. Also note that these equations apply only when the climber reaches straight upwards to pull themselves because otherwise the distance x may be different from the spring extension length.

By combining the equations above, we find that

$$\frac{F_e}{F_f} = \frac{Kx}{Mg - Kx}$$

And that spring stiffness K,

$$K = \frac{Mg}{x}\left[\frac{\frac{F_e}{F_f}}{1+\frac{F_e}{F_f}}\right]$$

Using the values for the force ratio, the subjects' mass and the subjects' arm length, x, the theoretical optimal spring stiffness was calculated as 230 ± 16 N/m , aggressing closely with the experimentally determined value of 222 N/m.

If one wishes to estimate the stiffness required for a more severe climb, we need only go back to the work equation for the flexion muscles and divide body weight by a factor N instead of a factor of two. For climbs requiring more than half of the body weight to be lifted with one arm, N will be lower than two. Likewise, for climbs requiring the entire body weight to be lifted by one arm, N will be 1 and for climbs requiring less than half the body weight to be lifted, N will be more than 2. By making adjustments in this way for the extension and flexion work equations, the stiffness estimation can be adapted for different steepness climbs, different pulling geometries, and different weights being pulled.

Simple experiments like this one can be employed to make useful estimates for optimal stiffness necessary for elastic-powered human enhancing devices. Particularly in application to rock climbing, a few easy measurements determine an estimated optimal theoretical and measured stiffnesses which agree very closely, and give us confidence that our device will be close to optimized in stiffness upon its first trial. Although we may still test a small range of stiffnesses, the experiments by Herr greatly reduced the range of stiffnesses which needed to examined and gave us a good starting stiffness to begin our testing.

3. Prototype

Unfortunately, object technologies are not yet advanced to the levels of producing durable enough materials to withstand the abuses associated with rock climbing. For this reason, we chose to create a simple prototype to enable testing of extensor-augmenting elastics during rock climbing. This prototype was intended to me minimalist and was composed of heat-moldable plastic sheeting, Velcro, fasteners, neoprene rubber foam, weld nuts, shaft collars and wax thread.

The upper cuff is composed of a single ring of 1/8 inch plastic sheeting, varying from about 3 to about 5 inches in vertical thickness, purchased from North Coast Medical, Inc. The shape of the cuff was designed to fit directly underneath the indent caused by the end of the lower portion of deltoid muscle, yet avoid constriction of the triceps and the biceps. The net result is a thicker vertical portion in the armpit where no muscles are constricted. Velcro [WBC Industries] was sewn with wax thread onto the plastic cuff, and can be used to tighten the cuff around the arm. No padding (neoprene rubber foam) was needed on the upper cuff because it was deemed comfortable by two independent pilot subjects.

The lower cuff consists of an “X” shape of 1/16 in plastic sheeting wrapped about the wrist such that the center of the “X” is directly up the arm from the knuckle where the middle finger meets the hand. This “X” shape enables the avoidance of constricting directly to the protruding radial notch of the ulna. In addition, the “X” enables some twisting motion of the two strips relative to each other, which still allowing for the clamping of the device securely around the wrist. Velcro was sewn with wax thread to the “X” such that the two bottom leg segments could be tightened to each other as well as the two upper arms of the “X”. A layer of neoprene foam [McMaster #8570K19] rubber was added beneath the plastic X, both to increase traction of the plastic against the skin and to increase the comfort of clamping the wrist.

The weld nuts were inserted into the upper and lower cuffs by drilling out holes with a hand drill. Two were placed in the upper cuff and one in the center of the “X” in the lower cuff. The ¼” shaft collars [McMaster #6435K12] were then attached to the weld nuts, using 4-40 screws of ¾" length. Latex tubing of 3/8" diameter was threaded into each of the shaft collars starting on the upper cuff, so that two length of latex joined the two cuffs, with a loop around the bottom cuff.

The estimated stiffness of the two length of latex was determined through a force measurement experiment with a spring scale. The force strain curve in shown below in Figure 7.

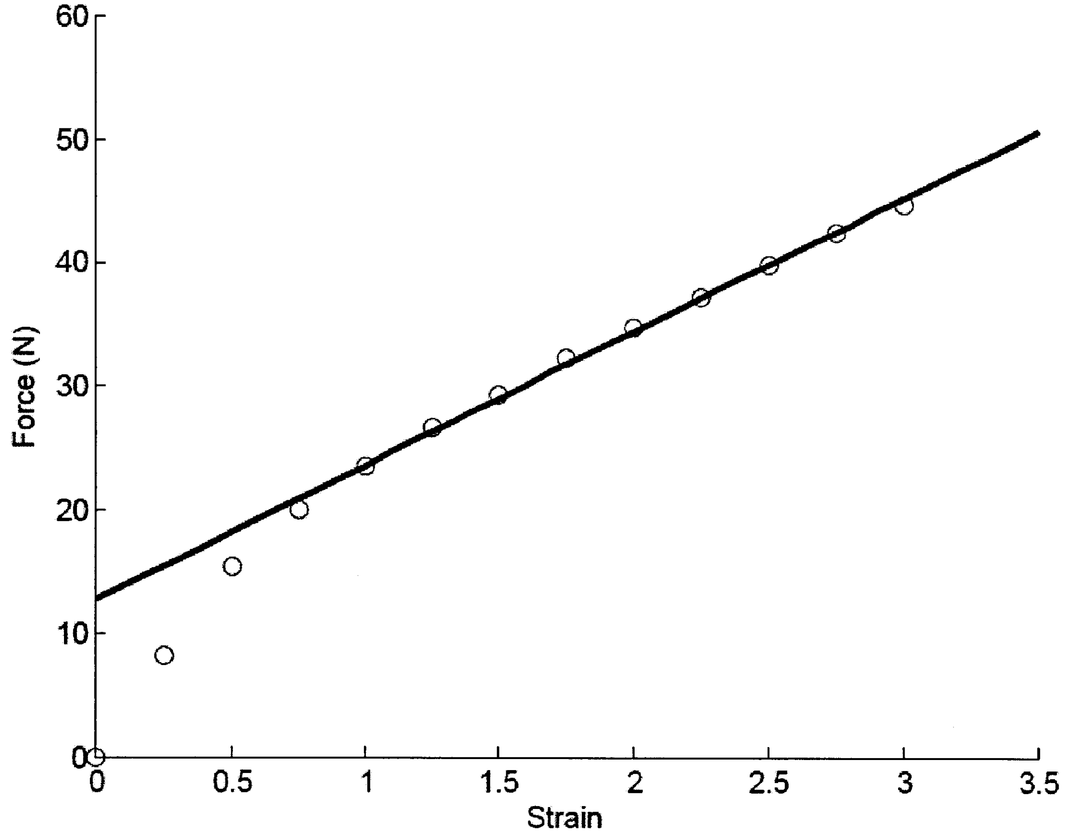


Figure 7. Force strain curve for latex rubber tubing.

The calculated stiffness of our exoskeleton, as predicted by a linear regression was 106 N/m, since it contained two lengths of the latex tubing, whose force-strain curve is pictured above. We believe that our stiffness was significantly lower than that seen in the Herr studies because our attachment was wrist to shoulder instead of wrist to hip. For this reason fewer muscles could be recruited to extend the latex springs before pulling upwards. We hope that augmentation of should and back muscles as well, our various elastic exoskeleton pieces will have stiffnesses which sum to roughly the optimal 200N/m seen in the Herr experiments.

4. Preliminary Results

Initial results for both the exoskeleton prototype and the printed cuff suggest that in the future a durable comfortable climbing exoskeleton may be achievable. It would appear that work redistribution between the extensor and flexor muscles in the arm does in fact increase the time before the onset on climbing fatigue. In addition, the wearability of the thermoformed cuff in indicative that the more accurate 3D printed cuff will offer increased comfort and better performance. Employing the lines of non-extension should increase the comfort and mobility of the exoskeleton significantly from the prototype to a finalized version.

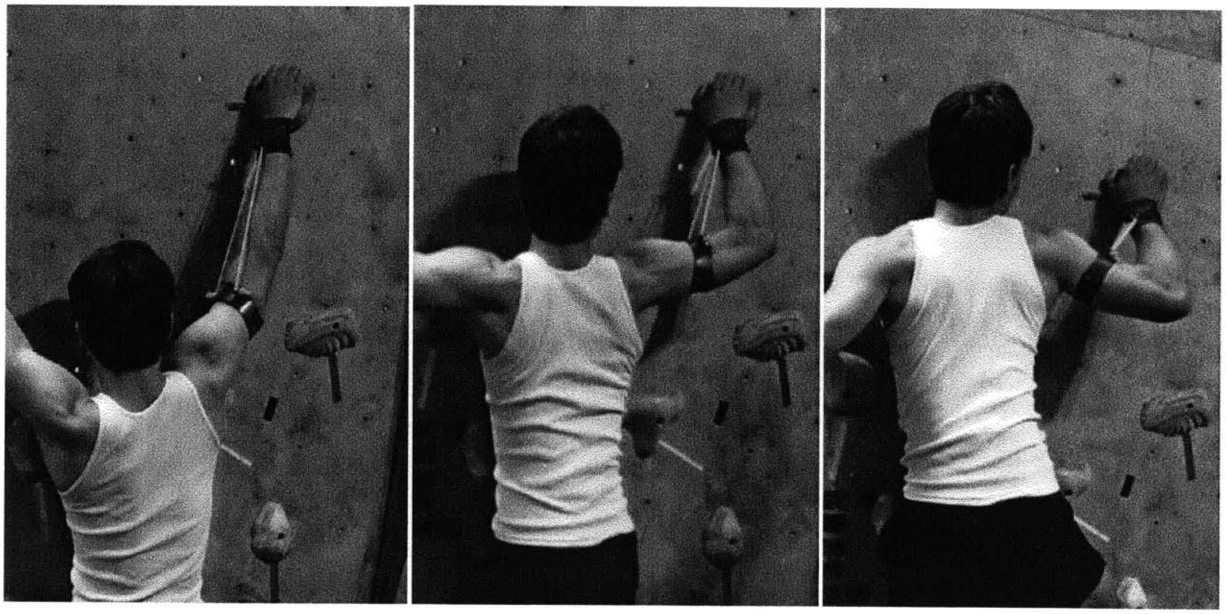


Figure 8. Subject climbing on a rock wall with the prototype exoskeleton in three steps: extension, mid-flexion and flexion.

4.1 Effect on Endurance

The prototype was tested at Metro Rock climbing gym in Everett, MA by two different subjects. One subject is imaged in Figure 8. Since the prototype is worn only on the right arm, the following test could be used to determine the prototype's effectiveness: does the right arm, assisted by the elastic-powered prototype, fatigue more slowly than the left arm. While this pilot test does not account for potential strength differences between the right and left arm, we feel justified in assuming its relevance, as most climbers develop strength in both arms equally, and use both arms equally during a long day of climbing at the gym.

While we had no quantitative measure of "fatigue," we had to rely on the subjects to report the varying levels of fatigue in each arm throughout an exhaustive afternoon of indoor rock climbing. Both subjects reported reduced fatigue in the flexor muscles of their right arm, and claimed they even began to favor taking high reaches primarily with their right hand due to the assistance. It would appear that the use of latex elastics in work redistribution indeed served its intended goal of reducing the onset of fatigue.

4.2 Future of our 3D Printed Cuff

The first model of the cuff based on Iberall's lines of non-extension will be printed by Objet starting on the week of May 9, 2011. The cuff will be printed with two different materials, TangoPlus for the gum-like soft portion and DM9885 for the stiffer lines of non-extension. The cuff was delivered to the MIT Media Lab Biomechatronics group on May 5, 2011.

However, our previous work with Objet has included a printed prosthetics socket for use with a trans-tibial amputee, designed by David Sengeh. Within the first minutes of use, the printed socket began to show signs of wear. Upon standing on the socket, the soft material ripped away from the harder material, and ripped up a seam rendering the socket unusable. This prosthetic socket was a first draft and not designed to support stresses in a wise way, but it illustrates the potential failures of Objet printed wearable devices such as our cuff.

One reason why the climbing exoskeleton cuff may fare better than the prosthetic cuff is that the stresses will be distributed along a meshwork of lines throughout the cuff instead on along a singly hard/soft interface. In addition, the paths of non-extension in the climbing cuff were made in a dovetail profile both to add strength by adding height to the profile of each of these paths since the bending stiffness of the path, K_B, goes as

$$K_B = EI$$

Where E is the Young's Modulus of a given material and I is the Moment of Inertia. I of a given geometry is equal to

$$I = \frac{1}{12}bh^3$$

Where b is the length of the base and h is the height perpendicular to the path and radially outward from the arm. In addition the dovetail may help to secure the stiffer portions of the cuff within its softer sleeve casing, preventing these paths from being able to pull out of the cuff.

While intelligent design can help to counter the weaknesses of the Object 3D printed devices, the device is essentially doomed by material constraints to be unusable for its intended application. Even if stress concentrations are distributed such that the printed cuff withstands the required forces, Objet materials degrade and become less stiff under UV light. The next section discusses future directions of Objet printing, and how material advances may help to make well designed cuffs such as this one usable for high load, and outdoors applications.

5. Conclusions

5.1 Promising Result for 3D Printing

The last years have shown the first applications of Object printed products into wearable items. In the past 3D printing has been used only as a prototyping device. Objet printers are currently used worldwide to print sneaker prototypes for Nike, and first drafts for many plastic part designs. However these devices can't stand up in the long term. If 3D printed items were made to withhold greater forces it would provide several advantages over comparative market technologies.

Firstly, 3D printing enables the production of parts similar to those currently produced by overmolded injection molding. For example rubber grips are over molded onto plastic injected molded handles of razors and other kitchen and bathroom appliances. With 3D printing, both the plastic and the rubber could be printed simultaneously, eliminating the need for extra molds and the exchange of materials from one mold to another. Objet is hopefully that soon metals will be capable of being printed, through sintering, side by side to plastics and rubbers as well.

Secondly, 3D printing enables interesting cuts as well as otherwise unmachinable features. Undercuts, the bane of injection molding and thermoplastic designs, are entirely within the capabilities of a 3D printer, with no added complexity. 3D printing also enables the production of captive parts which would be otherwise unmachinable.

Lastly, 3D printing enables the fast production of organic shapes, without casts or molds. Any body part can simply be scanned to a 3D model, modified to desired characteristics and printed. This feature makes 3D a promising manufacturing method for second-skin type applications, similar to the way it was employed in the production of the climbing exoskeleton cuff. Art and science alike have been fascinated since ancient times with the form of the human body. 3D printing enables the production of human-form models rapidly and easily. The coming years will likely show the growth and expansion of 3D printing technologies which enable the production of human-like forms.

5.2 Feasibility and Future Directions

Our prototype, in addition with the work of Hugh Herr in his paper "Human-powered Elastic Mechanisms" provide a strong argument for the possibility of an elastic-powered climbing exoskeleton. The principle of work-redistribution by elastics, utilizing the principles of elastic power enhancement and reduction of muscle work, appears to hold true in practice as well as in principle. There appears to exist an ideal stiffness for the extensor and flexor muscles of the arm which balances their work contributions to delay the onset of fatigue. Such a system of work redistribution can and should be applied to all of the muscle pairs associated with rock climbing for maximized endurance enhancement. In particular, the extensors and flexors of the fingers should be enhanced by work distribution as these are the other primary targets of fatigue by muscle climbing. Back muscle work distribution, particularly in the infraspinatus, teres major and teres minor muscles may also be helpful in delaying the onset of fatigue during climbing. Despite the many future improvements that should be made, we consider preliminary results for our elastic-powered human exoskeleton to be promising. Endurance enhancements were noticed by both of the subjects who wore the device, and improving human efficiency is no small feat, any day. We consider this a huge success for exoskeletons of all kinds.

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