Journal of Biomechanics

Upper Extremity Sling for Dynamic Rehabilitation of Traumatic Brachial Plexus Injury

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Abstract

The brachial plexus is a network of nerves that conducts signals to the shoulder, arm, and hand. When these nerves become damaged, loss of motor control and sensory perception can occur.[1] The goal was to design and construct a sling that will allow these patients to return to an active running lifestyle. The sling was made to support the shoulder and arm, and adapt to patients within different stages of rehabilitation. A prototype was constructed using a neoprene and nylon-polyester blend, and was tested for its efficacy using quantitative and qualitative methods. It was found through tensile loading that the neoprene material of the sling would not fail under the predefined factor of safety of two (a 100 N load). Additionally, from survey testing, user's agreed that the sling gave full support of the shoulder and arm, and was very comfortable to wear while running.

Introduction

The brachial plexus is a network of nerves that provide motor control and sensory perception to the shoulder, arm, and hand.[1] It originates from the lower four cervical nerves (C5 – C8) and the first thoracic nerve (T1). The five major nerves that make up the brachial plexus include the auxillary, median, musculocutaneous, radial, and ulnar nerves.[2] An anatomical diagram of the right brachial plexus in humans is shown in Figure 1.

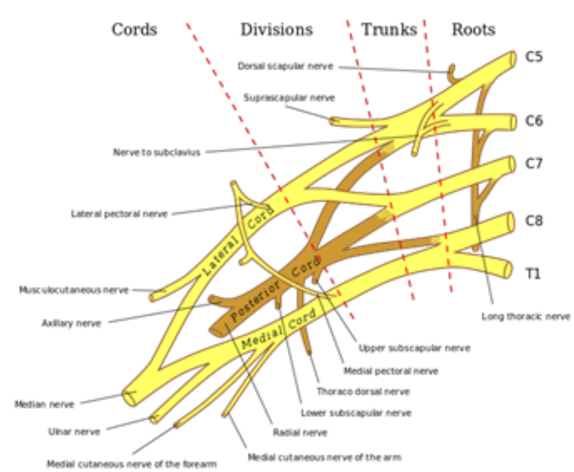

Figure 1: The anatomy of the brachial plexus. http://en.wikipedia.org/wiki/Brachial_plexus

An injury to the brachial plexus network typically results from substantial trauma either as a consequence of sporting or motor vehicle accidents. It is also common for newborns to sustain brachial plexus injuries during difficult child birthing sessions. Altogether, these types of impacts involve a force pushing the shoulder down, while the head is stretched in the opposite direction, causing a displacement of the spine relative to the shoulder and stretching or tearing of the brachial plexus nerves. The forces that result in overstretching are demonstrated in Figure 2.[1]

The severities of brachial plexus injuries range widely and typically result in symptoms such as paralysis, absent sensibility, and pain. These severities are grouped into three main classes that identify the degree of nerve damage: stretched, ruptured, or avulsed. In a case of an avulsion, the most severe of the three, the nerve root is torn completely from the spinal group.[3] Rupture and avulsion almost always require surgery whereas a stretch injury may be successfully treated with therapy.[1] The focus of our work is in the latter category.

Figure 2: Sagittal view of the sling includes shoulder strap, arm sleeve, bands, attachment points, belt loop holes, and forward facing adjustable arm bands.

Although various slings are available to treat brachial plexus injuries, none are capable of providing dynamic rehabilitation to facilitate the patient's return to an active lifestyle. The current slings on the market all keep the arm and shoulder in a locked and static position. They do so through many designs, and the most common method is by strapping the arm directly to the chest or side of the body. These slings do not allow for uses to run naturally, thus causing discomfort and poor body mechanics.

Methods

Design: The sling that was developed accomplishes the desired stability and mobility by being constructed from an anchoring vest that includes a shoulder cuff, and an arm support sleeve. Furthermore, the design utilized tension cables that were guided and placed in calculated positions to reduce the weight of the arm and provide added stability to the shoulder and elbow regions. The current prototype is being worn and displayed in Figure 2.

Testing: Various methods and approaches were used to examine the efficacy of our dynamic sling design. A preliminary static force analysis was first completed to examine the loads placed on the shoulder, and the information provided by this analysis was then used in SolidWorks modeling. In addition to these analyses, a tensile loading test and user surveys were conducted to further examine the device's efficacy. All methods used are discussed individually in the following sections.

Preliminary Dynamic Analysis

A preliminary dynamic analysis involved developing equations for the force due to angular acceleration of the shoulder. This calculation used a pendulum model to represent motion of the arm, rotating about a fixed point (the shoulder). The inputs to the equation are height, weight, and arm movement. The output is tension produced by the arm. The overall final calculation derived from the theoretical study is included in the Appendix.

SolidWorks Modeling

SolidWorks modeling was used to investigate the loads applied to the device and to determine if ripping or deformation of the material would result under normal conditions of use.

The preliminary dynamic analysis provided us with an expected maximum tension force of 50 N at the shoulder. It was also decided to incorporate a factor of safety of two. With the expected load and factor of safety determined, both loads were applied separately to areas of the sling that were most likely to fail, which included connection points on the shoulder and arm, the outer auxillary region, and the inner auxillary region. Six tests were conducted, including two tests on each region of failure potential. After completion of each test, the von Mises stresses, displacement, deformation, and factor of safety analysis were collected.

Tensile Load Testing

Tensile loading analysis of the neoprene constituent from the prototype design gave insight into the structural integrity and load under which the device fatigues. Following ASTM protocol D2240, linear tensile loading of a segment of neoprene was implemented in order to emulate an applied load from stretching the material, since a swinging load is difficult to test. The material was displaced at 5 mm increments, with the experienced load at each increment recorded. Through comparison to predicted loads experienced by the device that were determined in the preliminary dynamic analysis, the structural integrity of our device was assessed. The failure stress and strain was also calculated.

User Survey

A user survey was employed to determine the comfort and ease of device use. The survey, attached in the Appendix, was composed of questions designed to determine how the sling performed for individuals and how ergonomic the device was. Data regarding the user's past and current shoulder injuries was also collected to evaluate if the device had potential to be used for rehabilitation of other shoulder injuries. Ten individuals wore the sling for a one-mile run. After completing the exercise, each user filled out the survey to the best of their ability.

Results

Preliminary Dynamic Analysis

Using the derived equations form the dynamic analysis, it was found that a man of 90.72 kg (200 lbs) and 1.89 meters (6 foot, 2 inches) in height would induce a maximum force of 46.55 N when the elbow is directly in line with the body during the arm's swinging cycle.

SolidWorks Modeling

Based on the generated results from these tests it was found that our design would withstand the expected tensile forces in all three predicted regions of failure. Figure 3 displays the output von Mises stress for a 50 N load applied to the shoulder and arm portion of the sling. Although the inner auxillary region was determined to be the weakest under these tensions, it would take approximately 700 N of tensile force to cause failure. Stress concentrations were also found to never approach values that would exceed the design limitations. Safety factors for the six conducted tests were tabulated below. Form these values, our design ultimately led to an average factor of safety of 32, making our design

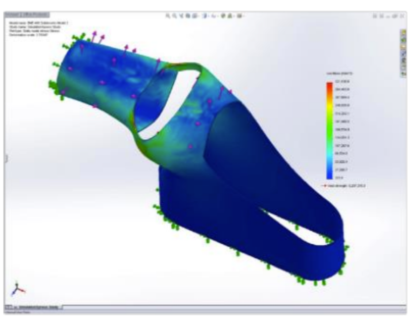

Figure 3: von Mises stress for the shoulder strap.

considerably more durable than initially anticipated. The overall final results outputted by SolidWorks testing can be found in Table 1 below.

Failure Area	Factor of Safety for 50 N Load	Factor of Safety for 100 N Load
Shoulder Strap	28	14
Outer Auxiliary	51	25
Inner Auxiliary	15	7

Table 1: Factor of safety outputs by SolidWorks for both testing loads.

Tensile Load Testing

To validate our SolidWorks model it was necessary to subject the prototype to relevant loads that would be imparted on the load-bearing neoprene. When we subjected a sample of neoprene to 5 mm increments and recorded the resulting force generation, the sample of neoprene failed at approximately 286 N of force. Based on our dynamic force analysis, which suggested the maximum theoretical force is 50 N, our failure load is vastly higher than any physically possible maximum load that could occur during use of the sling. Ultimately, our factor of safety is 5.7. The calculations for the stress versus strain relationship can be seen in the curve provided in Figure 4.

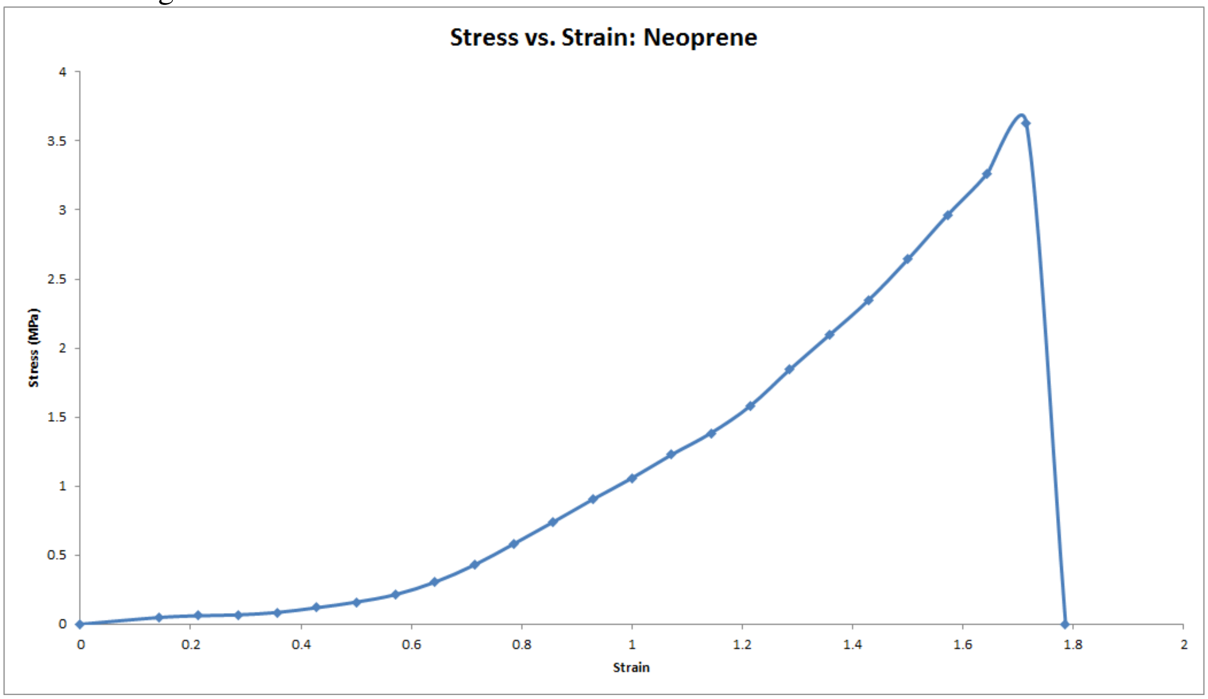

Figure 4. The stress-strain curve results from the tensile loading test.

User Survey

The user surveys completed by the ten participants revealed positive feedback for comfort, support, and usability of the sling. Among the participants, 90% of the subjects rated the sling to comfortable to very comfortable both at rest and while running. The sling was rated as providing complete support to the arm and shoulder by 100% and 90% of the subjects while running, whereas 70% felt complete support of the shoulder at rest. Additionally, 90% of subjects were willing to wear the sling again and for longer rungs. Among the minimal complaints received, the most common was that the thumbhole of the arm sleeve created unwanted pressure between the thumb and pointer finger. These complain was exclusively received from the male participants.

Discussion

Based on our results from previous and current work, our sling performed well in testing that measured its support, durability, and comfort. SolidWorks modeling insured that the sling would be able to support loads that the device experiences while being worn during a run. The tensile load testing insured that the neoprene skeleton of the device will not tear or deform during normal loads of the device and that the structural integrity of the neoprene is maintained through normal device used. Finally, user testing insured that the device was comfortable and effective. Our most common complaint was regarding the device, that the thumb hole is too constrictive, will be easily fixed with use of a different arm sleeve size and the use of neoprene material around the hole to distribute force more evenly. The efficacy of the sling insures its viability in the market and will offer dynamic support to patients who desire it.

Acknowledgments

We would like to acknowledge our client, Karen Blaschke, of UW Health and Clinics, for proposing the idea of the project. We would also like to thank our advisor, Mitchell Tyler, form the Biomedical Engineering Department at the University of Wisconsin – Madison.

References

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2. Functional Anatomy Blog. 2010. *Anatomy Review: The Brachial Plexus*. http://functionalanatomyblog.com/2010/03/16/anatomy-review-the-brachial-pexus/. Accessed March 5, 2013.
3. Hassan, S and Kay, S. 2003. *Brachial Plexus Injury*. Surgery (Oxford), 21 (10):262264.

Appendix

Preliminary Dynamic Analysis

Final calculation for the tension produced by the arm:

$$T_{arm} = \left(m_{arm}g\right)\left(\sqrt{1-\left(\frac{L_e}{L_{u-arm}}\right)^2}\right) + \frac{m_{arm}}{L_{u-arm}}\left(\frac{\left(v_{x-arm}\right)^2}{1-\left(\frac{L_e}{L_{u-arm}}\right)^2}\right)$$

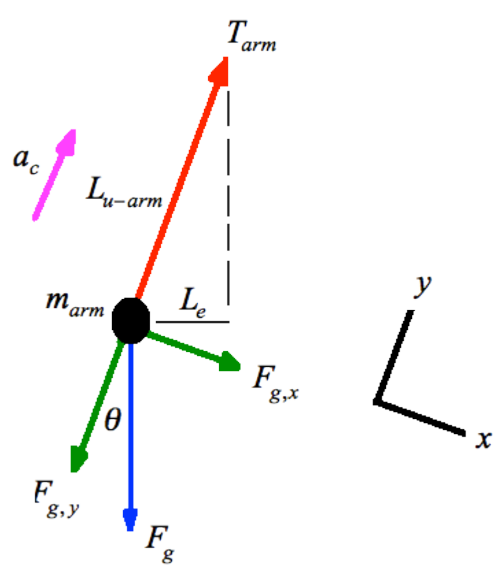

Figure 5: The free body diagram depicting the mass of the pendulum and corresponding forces at any given angle from the vertical to the mass.

User Survey Sample

BME 402, University of Wisconsin - Madison
"AlaTutella" Sling Survey

Name:

Gender:

Age:

Sling Size Used:

<u>Preliminary Questions</u>

- If you have never sustained a shoulder injury, please move to the next section -

Previous Shoulder Injuries (If Applicable):

How was/were the injury/injuries sustained?:

Were you required to undergo rehabilitation?:

If "yes":

- For how long?
- Under doctor supervision?
- What did the routine consist of?

- What were you prohibited from doing during this process (if anything) that you would have liked to do?

If "no", or you are currently undergoing rehabilitation:

- Discuss your rehabilitation phase for the injury:

- List activities prohibited from participating in that you would have liked to do:

Subjective Testing Responses:

1. Rate how easy/hard it was to put the sling on with one arm by circling the most applicable number:

1	2	3	4	5
Very Easy	Easy	Moderate	Difficult	Very Difficult

2. Rate your level of comfort while wearing the sling at rest by circling the most applicable number:

1	2	3	4	5
Very Comfortable	Comfortable	Moderate	UNcomfortable	Very UNcomfortable

3. Rate the level of support you can feel the sling providing to your shoulder at rest by circling the most applicable number:

1	2	3	4	5
Complete Support	Almost Complete Support	A Little Support	Very Little Support	No Support

4. Rate the level of support you can feel the sling providing to your arm at rest by circling the most applicable number:

1	2	3	4	5
Complete Support	Almost Complete Support	A Little Support	Very Little Support	No Support

5. Rate your level of comfort while wearing the sling during your run by circling the most applicable number:

1	2	3	4	5
Very Comfortable	Comfortable	Moderate	UNcomfortable	Very UNcomfortable

6. Rate the level of support you can feel the sling providing to your shoulder while running by circling the most applicable number:

1	2	3	4	5
Complete Support	Almost Complete Support	A Little Support	Very Little Support	No Support

7. Rate the level of support you can feel the sling providing to your arm while running by circling the most applicable number:

1	2	3	4	5
Complete Support	Almost Complete Support	A Little Support	Very Little Support	No Support

Additional Information:

1. If at any point you felt UNcomforable while wearing the sling, please explain:

2. After wearing this sling for a short run, could you see yourself wearing it again in the future, possibly for longer runs?

3. Can you provide any suggestions on how to improve the sling?

Thank you!!