Dynamic Sling to Support Upper Extremity Post Brachial Plexus Injury to Return to Active Lifestyle

Mid-Semester Report

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Table of Contents

Abstract	4
Problem Motivation	5
Client Description	6
Current Devices	6
Marketed Devices	6
Past Prototypes	8
Design Requirements	9
Design Alternatives	10
Backpack Design	10
Ring Design	11
One Strap Design	12
Design Matrix	13
Patient Comfort	14
Effectiveness	14
Ease of Use	15
Adjustability	15
Safety	15
Cost	15
Preliminary Analysis	16

Future Work 17

Timeline 17

Testing 17

Projected Costs 18

References 19

Appendix 20

Product Design Specifications 20

Free Body Diagram Analysis 23

Abstract

The brachial plexus is a network of nerves that can lead to varying levels of sensation and motor loss if damaged [1, 2]. Karen Blaschke is an occupational therapist with UW Hospitals and Clinics, and she works with patients that have experienced brachial plexus injury including our client, Margaret Overstake. Our design team was asked to create a dynamic sling that would allow someone with a brachial plexus injury to return to an active lifestyle. The sling should be adaptable for patients at different levels of rehabilitation. The final design we have chosen to pursue incorporates a chest strap with components that distribute the weight of the injured arm to the opposite shoulder.

Problem Motivation

The brachial plexus is a network of nerves that provides the arm and shoulder with sensory perception and motor control [1, 2]. It originates from the cervical region of the spine, then wraps around the back of the neck and down through the back of the shoulder [3]. Divisions in the plexus neurons form the ulnar, radial, and median nerves which receive and transmit signals from the arm and hand [3]. This complex anatomical feature is often modeled as a tree because of its branching characteristics through the upper back and shoulder, as shown in Figure 1.

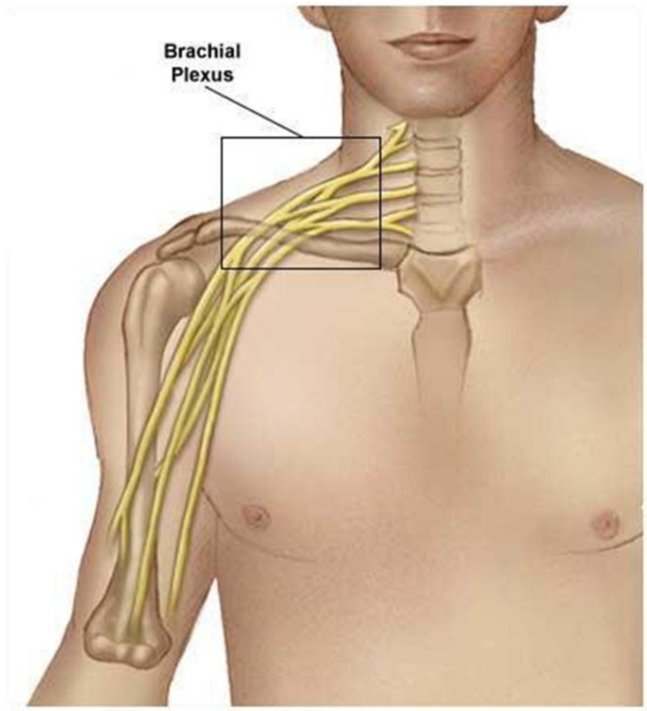

Figure 1: An anatomical depiction of the brachial plexus. This network of nerves originates at the spinal cord and branches through the shoulder and upper arm, innervating the entire limb [4].

Brachial plexus injury can result from various high-energy trauma accidents such as a long fall, sporting accident, or penetrating injury. The most common causes, however, are road traffic accidents during which the shoulder is intensely jarred, causing injury due to neural strain [3]. The four types of brachial plexus injury are categorized by the type of damage that has occurred [5,6]. Avulsion signifies the detachment of the nerve from the spinal cord and is the most severe case. Similarly, a rupture is a torn nerve, but not at the point where it attaches to the spinal cord. A neuroma refers to a torn nerve that has developed scar tissue, so it no longer functions normally. The final and most common type of brachial plexus injury is neuropraxia, which is stretching of the nerve [3, 5, 6]. Although neuropraxia still has a long recovery period, the probability for regaining function in the limb is greater than for the other three types.

Variation exists in the severity level of brachial plexus injuries, making each patient's recovery timeline unique [7]. The proximity of the injury to the spinal cord is also a factor that can affect rehabilitation and therapy regimes; if the injury is within the nerve root coming directly from the spinal cord, there is a lesser chance of recovery than if it were in the distal portion of the plexus [3]. In general, treatments from occupational and physical therapists are prescribed to gradually regain function in the limb. Initially, muscle movement is incredibly painful, but strength can slowly be regained over the course of two to five years [7, 8]. Some patients do make a full recovery, but the outcome is largely based on the individual [3].

Client Description

Karen Blaschke is a Registered Occupational Therapist in Rehabilitation Medicine with University of Wisconsin Hospitals and Clinics. Our other client, Margaret "Meg" Overstake, is a patient of Karen's that has suffered a brachial plexus injury. Meg is a working mother seeking to return to her normal exercise routine, which includes daily running. Both clients would like us to design a dynamic sling that would allow a patient with a brachial plexus injury to return to an active lifestyle. The sling will allow for activity at varying levels of rehabilitation while being able to develop with the patient as they gain strength and function during rehabilitation. Karen also envisions using the sling for other rehabilitation applications such as rotator cuff injuries.

Current Devices

Marketed Devices

Currently, a range of slings exists to support individuals experiencing brachial plexus injury. Again, recovery and rehabilitation regimes vary immensely, so device requirements will differ between patients. Immediately following the injury, the patient typically wears an immobilizing brace to prevent large movements of the shoulder and arm that may cause painful burning sensations [7,8]. The slings maintain a 90 degree angle at the elbow, and support the shoulder to prevent subluxation [3]. One example of an immobilizing sling is the *Rolyan Universal Sling & Swathe* produced by Patterson Medical (Figure 2) [9]. Another example that allows more movement is the *B-Cool Super Sling Plu*s, also distributed by Patterson Medical (Figure 3) [10].

Figure 2: The Rolyan Universal Sling & Swathe immobilizes the arm and shoulder immediately following a brachial plexus injury to decrease pain and prevent further injury [9].

Figure 3: The B-Cool Super Sling Plus maintains a constant elbow angle and allows for slightly more shoulder motion and use of the hand than the Rolyan model [10].

The *GivMohr Sling* was patented in 2005 and is the closest in function to the current design project (Figure 4) [11]. The *GivMohr Sling* is designed for patients reaching the end of rehabilitation, who wish to enhance their shoulder mobility. Its unique design allows dynamic motion in the shoulder while maintaining compression throughout the arm, reducing subluxation in the shoulder [11]. By supporting the shoulder, pain and discomfort is reduced and normal arm motion while walking is facilitated. One dissatisfying aspect of the *GivMohr Sling* is the plastic component that must be held in the user’s hand during wear. The piece is what provides the force to lift the shoulder, but it hinders the ability to use the hand [7]. Although the sling maintains normal arm motion during walking, it lacks the support necessary for running and other high-energy activities.

Figure 4: The GivMohr Sling is the standard dynamic sling available on the market. The placement of the straps allows for motion in the shoulder. Holding the plastic hand-piece creates a compressive force through the arm that opposes shoulder subluxation, but prevents the wearer from using their hand [11].

Past Prototypes

Because her sling options were few and posed many limitations on her ability to return to running, Meg initiated the design process on her own during her rehabilitation (Figure 5) [8]. Her design used a Thera-band as the main body and strapping material of the sling. She held both ends in her hand and the rest wrapped over her shoulder, weaved through the straps of her sports bra, and came back down her arm under her elbow. She incorporated a sleeve made of sock to keep the Thera-band aligned properly underneath her elbow.

Figure 5: Meg created her own sling for running while recovering from her brachial plexus injury. She wrapped a Thera-band around her hand and wove it through an elbow sleeve made from a sock. It then passed up through her sports bra straps and back down to her hand where she held it for the duration of her run [8].

Design Requirements

The design requirements seen in the Product Design Specifications in the Appendix are explained in more detail here. Requirements for this design fall into one of three major categories: safety requirements, client requirements, and patient comfort.

Because the device will be used during rehabilitation, safety requirements are critical in ensuring the sling will cause no harm to an already injured individual. The dynamic sling must fit snugly to the patient's arm but not so tight as to hinder blood flow in the arm. Since the wearer may have reduced skin surface sensitivity due to neural damage, the device should be designed to minimize the chance of pressure sores or chaffing. Also, the sling must not cause any additional damage to the shoulder and arm which may result from lack of proper support or undesired pressure on the injured shoulder. It should also be noted that if the product were to be marketed, it would require approval from the FDA.

In addition to safety requirements, the device must also function as required by the client. The client has specified that the sling must support the patient's arm during activities involving moderate shoulder motion, so none of its components should restrict movement of the shoulder joint. The device should also support the elbow at a user-adjustable angle while still permitting some flexion and extension of the arm. The sling will be an adult size, unisex fit and adjustable to offer support for a wide range of body types. During recovery, the device should allow varying levels of support for the user to choose from as arm strength increases. The device should maintain functionality throughout the entire course of recovery. Since full recovery is not always attainable, it would be ideal if the device lasts upwards of 10 years. It is also necessary that the sling function properly in both indoor and outdoor settings and be constructed from washable, water resistant materials.

Since the sling may be worn for extended periods of physical activity, care should also be taken in maximizing the comfort of the sling without compromising functionality. It is important that the sling can be put on and adjusted using only one arm. The device should be adjustable in size and support to fit the needs of the patient. To promote ease of use, the sling must be lightweight (not exceeding 1 kg) so that it can easily be carried with one arm and worn with little to no detectable weight imbalance. The materials used in the design should be breathable and should not cause any irritation or discomfort to the patient's skin. Because it will often be worn in public, the device should be aesthetically pleasing and simple in appearance.

Design Alternatives

The Backpack Design

This design as seen in Figure 6, is made up of two shoulder straps to be worn similarly to those found on a backpack. A short strip of elastic material connects the two straps across the back (a). Arm support is achieved by means of an adjustable and partially elastic band which is connected to a wrist brace at one end and the back side of the nearest shoulder strap at the other. The elasticity of the material is attained by layering slack, sturdy strap with a segment of elastic to give stretch with a stopping point (b). Another adjustable band runs from the wrist to an elbow cuff and then up the back of the arm to attach at the same point on the shoulder strap as the previous band. The elbow cuff is held in place by Velcro fasteners around the arm.

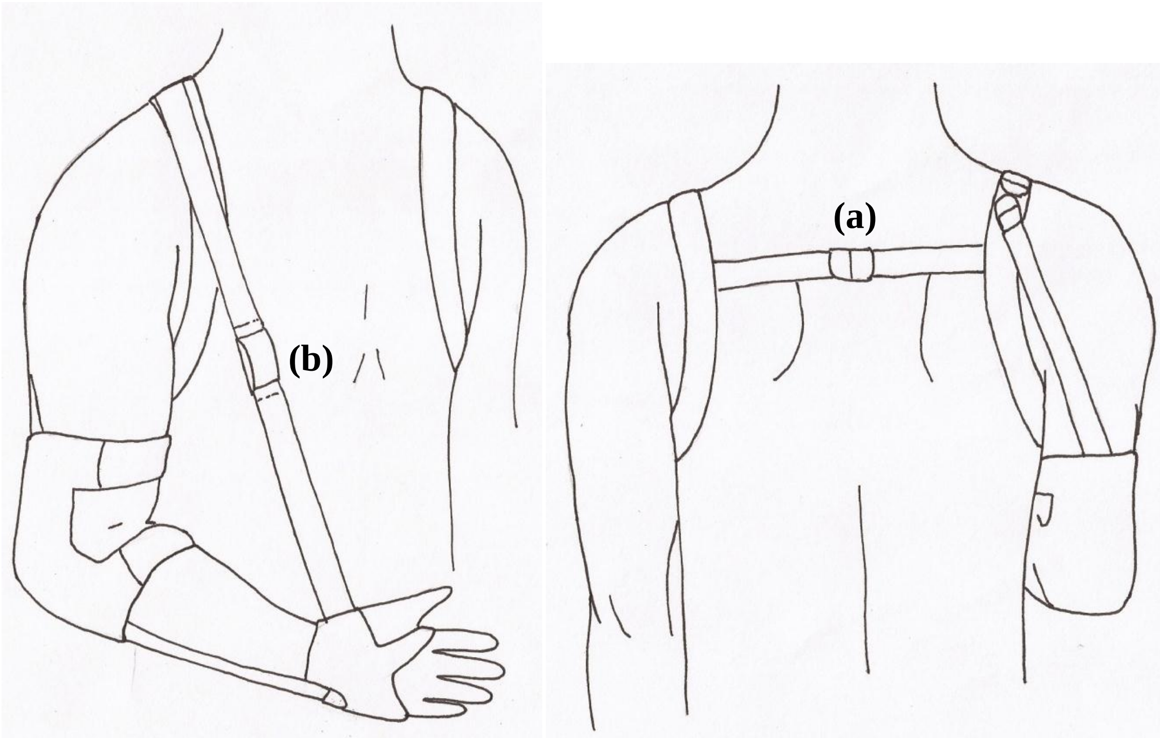

Figure 6: Front and back views of the backpack design. The design consists of two straps, an arm support between the injured shoulder and wrist, and a removable elbow component. Letters on the figure correspond to descriptions in the text. (a) Strap connection across the back. (b) Layer of strap over elastic segment to provide stopping point.

The Ring Design

The ring design in Figure 7 consists of two straps that slide onto the shoulders similar to the previous design, but are connected in an "X" shape across the back with a ring (a). Another strap runs across the upper chest, connecting the right and left shoulder straps. An arm support component is attached at the back upper shoulder strap, comes down under the elbow, attaches at the hand near the base of the thumb joint, and returns to attach at the shoulder. This strap contains a short elastic segment allowing for movement of the arm dynamically (b). A wrist brace provides both a connection for the strap and wrist support. A cup-style support fits under the elbow and has narrow Velcro or elastic fasteners across the top of the arm to keep the cup in place.

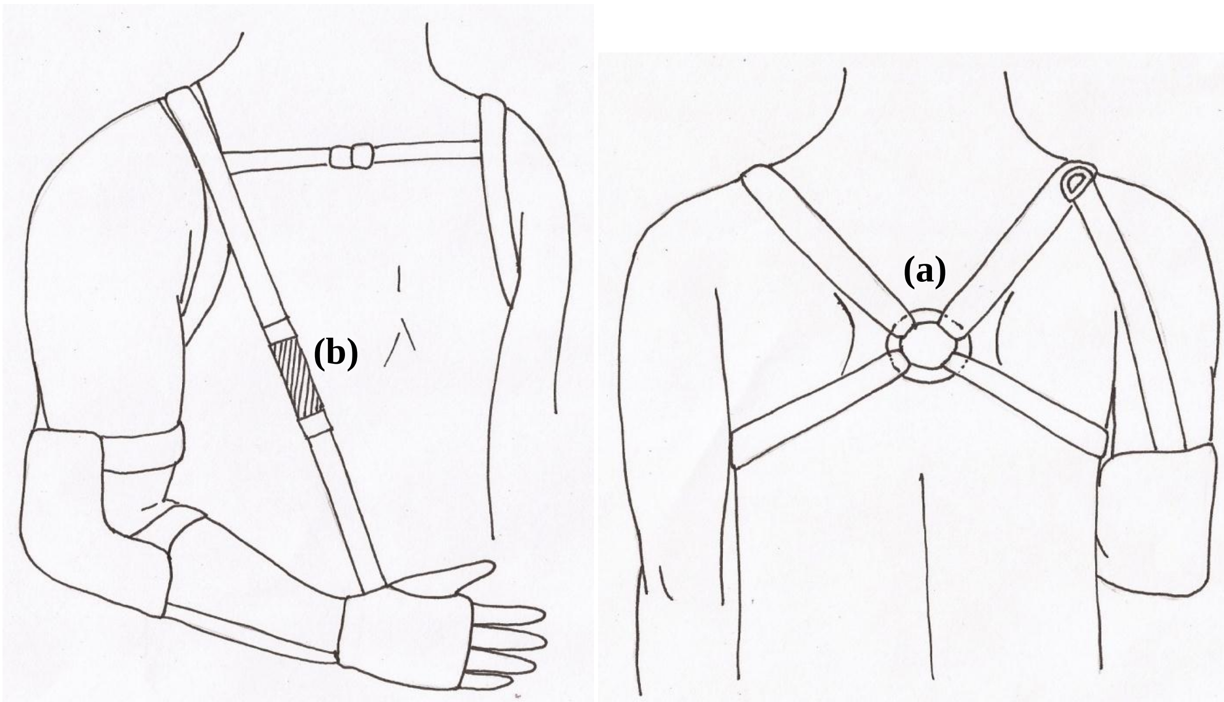

Figure 7: Front and back views of the ring design. The design consists of two straps connected by a ring, arm support, and a removable elbow component. Letters on figure correspond to descriptions in the text. (a) Ring connection on the back. (b) Elastic segment in strap that allows for movement of the arm.

The One-Strap Design

The one strap design can be seen in Figure 8. The main body of the sling is one continuous "Y" shaped piece (a). One end wraps adjustably around the chest, while the other branches off under the shoulder blade of the uninjured shoulder, wraps under the armpit and back over that shoulder. From this point it wraps to the back and over the injured shoulder where it attaches to a wrist brace on the injured arm. This attachment point allows adjustment of elbow angle. A sliding fabric strap in the back takes pressure off the back of the neck (b). An elbow strap attaches adjustably to the wrist brace and follows under the elbow, weaving through an elbow sleeve, and up the back of the arm. It weaves through a loop on the closest shoulder strap and clips into the far shoulder strap. The straps of the sling are made of a sturdy, yet stretchable material for support and comfort.

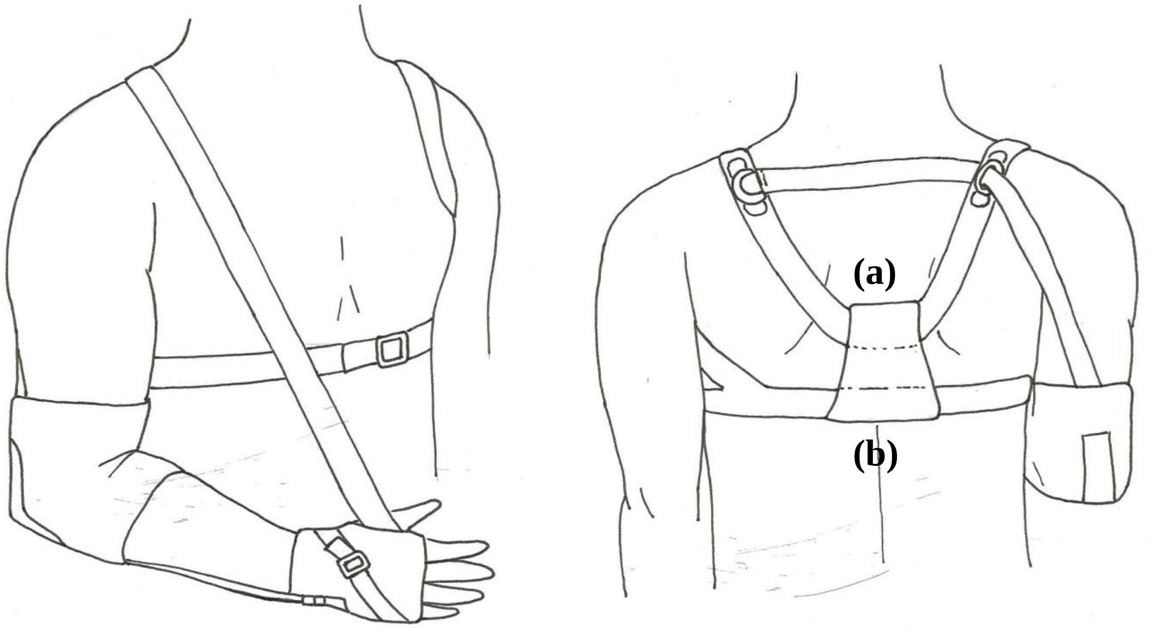

Figure 8: Front and back views of the one strap design. The design consists of one continuous strap of the same material, with a removable elbow component. Letters on the figure correspond to letters in the text. (a) “Y” shape configuration on the back. (b) Sliding fabric strap taking pressure off the neck.

Design Matrix

In order to evaluate each of the three designs, a design matrix was constructed. Each design alternative was evaluated on the criteria of patient comfort, effectiveness, ease of use, adjustability, safety, and cost. The complete scoring breakdown for each design alternative can be seen in Table 1. The one strap design scored the highest overall, and therefore will be the sling design that we pursue.

Weight	Criteria	One Strap	Backpack	Ring
25	Patient Comfort	22	18	20
20	Effectiveness	18	12	15
20	Ease of Use	13	17	16
15	Adjustability	13	9	11
10	Safety	8	6	7
10	Cost	7	8	6
100	**Total**	81	70	75

Table 1: The design matrix breaks down how well each design alternative follows the criteria that we see as important based on our design and client requirements. The maximum value for each criterion are on the left in the column labeled weight and each design was total to be given a score out of 100 which can be seen in the bottom row of the table.

Patient Comfort

Patient comfort was seen as the most important factor in the design and was therefore given the highest weight of 25 in the design matrix. It is important for the patient to be comfortable while using the sling because the design will be used specifically for rehabilitation purposes. The one strap design will be the most comfortable for the patient due to the location of strapping and was therefore given 22 points in the matrix. This was followed by the ring design with a value of 20. The ring design allows for a more comfortable strap fit across the back of the patient. The backpack design was given the lowest value of 18, with the belief that the horizontal strap across the back may cause discomfort.

Effectiveness

It is important that the sling be successful in maintaining support while remaining dynamic during activity. The ability of each design to distribute the weight of the injured arm to the opposite shoulder was also considered. For this reason effectiveness was weighted highly at 20 in the design matrix. All three designs would be successful in maintaining support for the patient during activity. However, the one strap design would allow the weight of the arm to be better distributed to both shoulders, due to the location of strapping, and was therefore assigned 18 in the matrix.

Ease of Use

Ease of use was also seen as a significant criterion, so it was also given a weight of 20 in the design matrix. The patient will need to be able to put on and adjust the sling with one arm, and the number of components should be minimal so that the sling is easy to use. The backpack design would be the easiest for the patient to put on by themselves and was for that reason given 17 in the design matrix. The one strap design would be more difficult to put on with the use of one arm due to the intricate strapping, so it was assigned a value of 13 in the matrix.

Adjustability

Adjustability is necessary in the design of the sling and was given a weight of 15 in the design matrix. Adjustability is important so that the design can fit varying body types and develop with the patient as they gain strength and mobility during rehabilitation. The one strap design would be adjustable both in fit and resistance. The design allows for adjustment around the ribs and movement of the strap on the back horizontally to better fit the patient. The design is also capable of adjusting the arm strap for elbow angle. For these reasons the one strap design was given the highest value of 13 in the matrix. This was followed next by the ring design with a value of 11, which allows adjustment of fit in the back but not as significantly as the one strap design. Finally the backpack design was given the lowest value of nine. The backpack would not allow for as great of an adjustment in fit as the other two designs.

Safety

Safety was given a value of 10 in the design matrix because there are few ways that the patient can be harmed with the use of the sling. However, safety is important because patients may have reduced skin sensitivity, so the sling should not cause pressure sores and should not further injure the shoulder. The backpack design was seen as the least safe due to the segment of limited elasticity. This may cause a jerking movement that could be harmful to the patient so the design was given a value of six. The one strap design was given a value of eight in the design matrix due to the fact that the materials used would be least likely to cause harm to the patient.

Cost

For the sling to be marketable once designed cost much be taken into account. Cost was seen as lower importance due to the simplicity of design materials needed, and was given a weight of 10 in the design matrix. However, it should also be affordable for varying incomes and be competitive with similar slings on the market. Components of the ring design, such as the hardware for the ring itself, were seen as more expensive in comparison to the other two designs and it was therefore given a value of six in the design matrix. Both the backpack and one strap designs would cost less to fabricate but the one strap design was given a higher value of eight in the matrix. The one strap design would be more cost effective because it would use a minimal amount of different materials throughout the entire design.

Preliminary Analysis

A free body diagram of the one strap design was used to analyze weight distribution across the device (Figure 9). For simplification, analysis was made without the removable elbow support, so the calculations are expected to represent the maximum weight to be carried by the injured shoulder. Due to this and the symmetric nature of the sling, the force on each shoulder was found to be equivalent in this configuration. By estimating angles, it was calculated that the weight on each shoulder equals 1.29 times the weight of the supported arm. For complete analysis and equations, see Appendix.

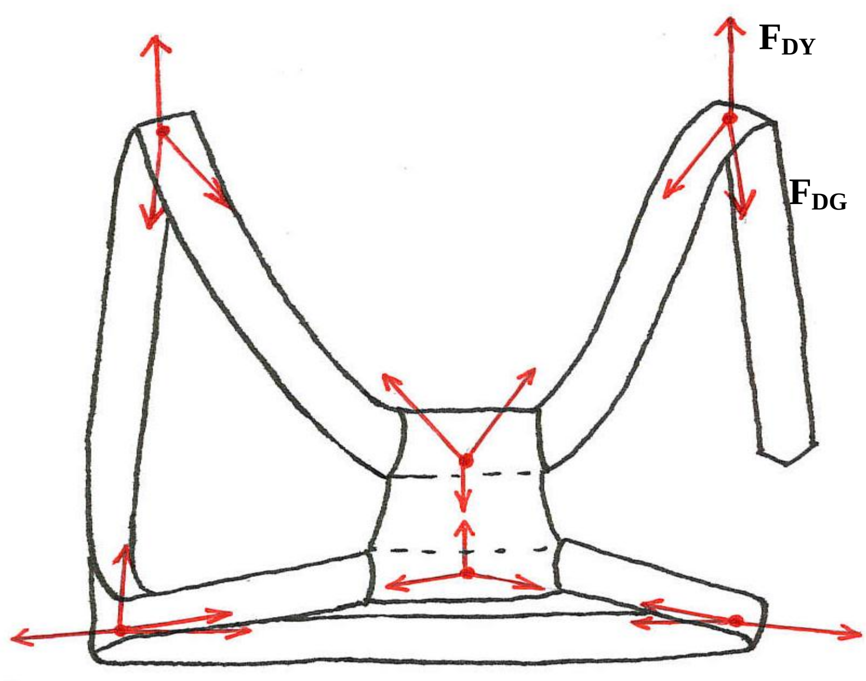

Figure 9: Free body diagram of the one strap design. F_{Dy} represents the force on the shoulder while F_{DG} represents the weight of the arm. Full calculations and equations can be found in the Appendix.

Future Work

Timeline

Table 2 outlines our goals for the semester and displays tasks that have been completed to date. Filled boxes represent our projected timeline and the checks are tasks that were worked on or completed.

Tasks	September			October				November					Dec
	14	**21**	**28**	**5**	**12**	**19**	**26**	**2**	**9**	**16**	**23**	**30**	**7**
Product Development													
Research	X		X										
Brainstorming		X	X		X	X							
Design Matrix			X	X	X								
Design Prototype													
Order Materials													
Fabricate Prototype													
Testing													
Meetings													
Advisor	X	X	X	X	X	X							
Client	X			X		X							
Team	X	X	X		X	X							
Deliverables													
Progress Reports	X	X	X	X	X	X							
PDS	X	X			X								
Mid Semester PPT					X	X							
Mid Semester Report			X	X	X	X							
Final Report													
Final Poster													
Website Updates	X	X	X	X	X	X							

Table 2: Our group's project schedule. Filled boxed represent our projected timeline and checks mean that the task was worked on or completed.

Testing

The sling will be evaluated by both obtaining feedback from the client and testing the components directly. A strength test will be used to determine how much weight can be supported by the materials in the device. Another test will involve sending a sling prototype to the client to be evaluated for comfort, functionality, and ease of use. A fair amount of comfort and functionality testing will also be carried out by group members using the sling themselves, both stationary and while running.

Projected Costs

Most of the materials for the design will be obtained through donations from the UW Health Orthotics Lab or Patterson Medical; therefore, there are no projected costs to report at this time [12]. It is worth mentioning that if marketed, the ideal cost of the device would be around $75.00 in order to be competitive with current slings on the market.

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Appendix

Dynamic Sling to Support Upper Extremity Post Brachial Plexus Injury to Return to Active Lifestyle – Running

Product Design Specifications
10/24/12

Group Members: Amy Martin, Lindy Couwenhoven, Stephen Monette, Clair Kurzynski

Advisor: Dr. John Puccinelli

Function:
The brachial plexus is the network of nerves that sends motor signals from the spinal cord to the shoulder, arm, and hand. Damage to these nerves results in various levels of control and sensation loss in the arm. The design of a dynamic sling will allow a patient with a brachial plexus injury to return to an active lifestyle. The sling will facilitate natural shoulder movement while maintaining elbow support during running. An adaptable resistance feature will be implemented, allowing the device to develop with the patient as they gain strength during rehabilitation.

Client Requirements:
- A device to support the arm during running or other physical activities
- Comfortable for long-term use (maximum three hours)
- Constructed from washable materials that are breathable and lightweight
- Adjustable in size and resistance to match level of rehabilitation
- Easy to put on quickly with one hand

Design Requirements:

1. Physical and Operational Characteristics

a. *Performance Requirements*: The sling should support the patient's arm while they engage in activities with moderate shoulder motion, so none of its components should restrict movement of the shoulder joint. Movement will be primarily in the sagittal plane during physical activity. The device should support an elbow angle set by the user while still allowing for flexion and extension. The sling will also be adjustable for varying body types.

b. *Safety*: A snug fit to the patient's arm is necessary but should not be so tight that blood flow is restricted. Additionally, users may have reduced skin surface sensitivity, so the device should not cause pressure sores. Precautions need to be taken when designing the sling to prevent the user from causing more damage to the shoulder.

c. *Reliability*: The sling should not slip or stretch beyond functional limits during usage.

d. *Life in Service*: Proper device function should be maintained throughout the entire course of recovery which is approximately 4 years. In the case that full recovery is unreachable, it would be ideal for it to last upwards of 10 years. During non-physical activity the sling may be worn for a maximum of eight hours.

e. *Operating Environment*: Although it will be used primarily during exercise both outdoors and indoors, the sling could have additional applications in the home or office.

f. *Ergonomics*: Functionality, comfort, and adjustability for patients of varying body compositions should be considered. It should also be easy to put on with the use of one arm and adjust for varying levels of patient arm strength during recovery.

g. *Size*: The sling will be an adult size, unisex fit and adjustable for further comfort and support. It will not be bulky so it can be easily worn with everyday clothing.

h. *Weight*: The device must be lightweight, a maximum of one kilogram, so that it can be easily lifted with one arm and worn with little to no detectable weight imbalance.

i. *Materials*: The sling will be fabricated from a washable, lightweight, and water resistant material. It will be in direct contact with the patient's skin during exercise, so precautions must be taken to prevent chaffing or discomfort.

j. *Aesthetics, Appearance, and Finish*: Because it will often be worn by patients in public, the device should be aesthetically pleasing. The design should therefore be relatively simple in appearance while still being functional.

2. Production Characteristics

a. *Quantity*: We are designing one sling with multiple, replaceable elements.

b. *Total Product Cost*: The target product cost is $75.

3. Miscellaneous

a. *Standards and Specifications*: If marketed, the product will require approval from the FDA.

b. *Customer*: The customer is any patient that has suffered a brachial plexus injury, with the design being particularly for those returning to an active lifestyle. The client also envisions the sling being helpful for other injuries such as bone fractures or rotator cuff injuries, and during post operational recovery.

c. *Competition*: Current slings on the market that are designed to support the arm and shoulder after a brachial plexus injury inhibit nearly all movement of the arm and shoulder joint. At the moment, there is no sling that allows natural arm movement during a run while still providing the necessary support.

Free Body Diagram Analysis

Letters correspond to how the figure is labeled following the equations.

At D:
$\Sigma F_x = 0$: $F_{DG} \cos(80°) - F_{DA} \cos(60°) = 0$
$\Sigma F_y = 0$: $F_{Dy} - F_{DG} \sin(80°) - F_{DA} \sin(60°) = 0$

$\rightarrow F_{DA} = F_{DG} [\cos(80°) / \cos(60°)]$
$\rightarrow F_{Dy} = F_{DA} \sin(60°) + F_{DG} \sin(80°)$

At A:
$\Sigma F_x = 0$: $F_{DA} \cos(60°) - F_{CA} \cos(60°) = 0$
$\Sigma F_y = 0$: $F_{DA} \sin(60°) + F_{CA} \sin(60°) - F_{AB} = 0$

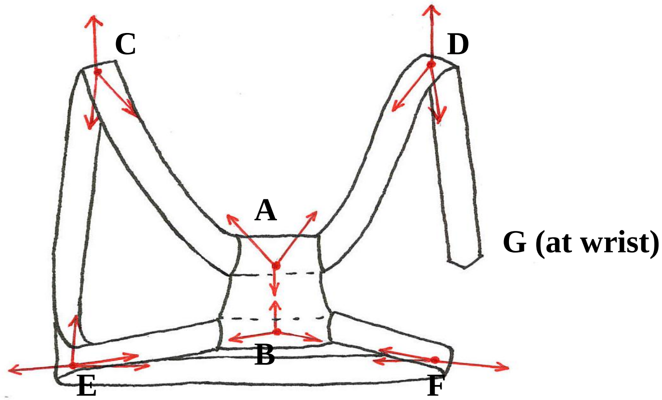
$\rightarrow F_{CA} = F_{DA}$
$\rightarrow F_{AB} = 2 F_{DA} \sin(60°)$
$\rightarrow$ Symmetry: $F_{Cy} = F_{Dy}$ and $F_{CE} = F_{DG}$

At E :
$\Sigma F_x = 0$: $F_{BE} \cos(15°) + F_{CE} \cos(80°) + F_{EF} - F_{Ex} = 0$
$\Sigma F_y = 0$: $F_{CE} \sin(80°) - F_{BE} \sin(15°) - F_{Ey} = 0$

At B :
$\Sigma F_x = 0$: $F_{BE} = F_{Ex}$
$\Sigma F_y = 0$: $F_{AB} - F_{BE} \sin(15°) - F_{BE} \sin(15°) = 0$

$\rightarrow F_{BE} = F_{Ex} / [2 \sin(15°)]$

At F:
$\Sigma F_x = 0$: $F_{Fx} - F_{EF} - F_{BF} \cos(15°) = 0$
$\Sigma F_y = 0$: $F_{BF} \sin(15°) - F_{Ey} = 0$


C
D
A
G (at wrist)
B
E
F