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]. Karen Blaschke, an occupational therapist with UW Hospitals and Clinics, works with patients suffering from brachial plexus injury and has requested a sling that will allow these patients to return to an active lifestyle, mainly running. As an engineering team, we aim to create a sling that will adapt to patients at differing levels of rehabilitation. Three designs for the arm portion and two designs for the body anchor were created and evaluated. An arm and anchor design were selected and integrated to create a sling that offered support and allowed proper movement of the arm while running. The prototype was constructed using cotton and foam materials, while incorporating bands at specific locations for support. Testing revealed that the sling did not inhibit motion of running ($p<0.05$) and force on shoulder was reduced more than 80%. To improve our design in the future we wish to perform testing on human subjects with brachial plexus injury, perform more thorough force distribution testing on the vest, prove the sling facilitates proper running mechanics, and use a more breathable material.

Background

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 auxiliary, median, musculocutaneous, radial, and the ulna[2]. The anatomy of the brachial plexus is shown in **Figure 1** below.

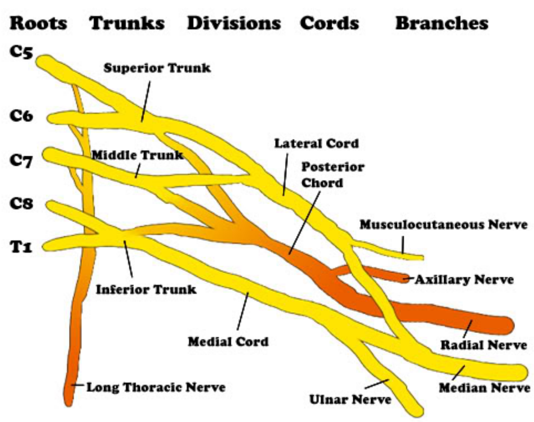


Figure 1: The anatomy of the brachial plexus nerve[1].

An injury to the brachial plexus often results from substantial trauma from sporting or motor vehicle accident injuries. It is also common for newborns to sustain brachial plexus injuries during difficult childbirth sessions. These types of impact injuries result from 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 resulting in stretching or tearing of the brachial plexus nerve network. The forces that result in overstretching are demonstrated in **Figure 2** below[1]. Infectious inflammation and tumors can also result in brachial plexus related pain and disability[7].

The severity of the brachial plexus injury ranges widely. There are three main classes that identify the severity of nerve damage in which it may be stretched, ruptured, or avulsed. In a case of avulsion 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].

There are also different types of brachial plexus injuries, which are categorized as open and closed. An open injury is due to a laceration often caused by a gunshot or blade wound. A closed type injury is caused by traction or crushing of the nerve network. Overall, common symptoms of a brachial plexus injury include paralysis, absent sensibility, and pain[3].

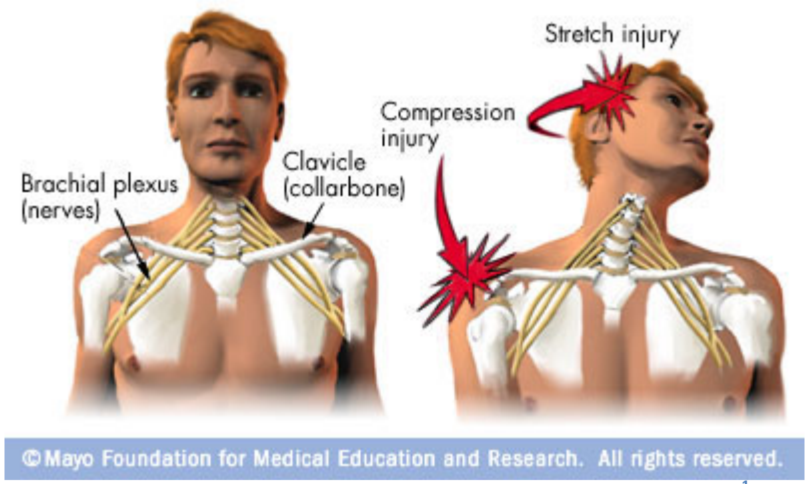


Figure 2: Image depicts a stretch injury. Compressive force to the head and shoulder[1].

Several treatment options are available to aid in reducing the symptoms of brachial plexus injuries. The nerve can either be repaired or reconstructed through surgical procedures. For reconstruction, the damaged part of the brachial plexus is removed and replaced with sections of nerves taken from other parts of the body. In an avulsion case, a similar procedure is conducted by transferring a less significant nerve that is still attached to the spinal cord and reattaching it to the nerve that has avulsed. Lastly if the arm muscle has deteriorated, a surgical muscle transfer may be performed which involves the removal of a less significant muscle or tendon from another part the body and transferring it to the injured arm.

Recovery from a brachial plexus injury is variable[1]. Regardless of the necessity for surgical intervention, the rehabilitation process generally requires a full immobilization phase followed by a slow progression through dynamic exercises with an increased resistance over time[3]. This allows for a stabilized healing time followed by regrowth and reactivation of atrophied muscle groups.[9]

Preliminary Force Analysis

Preliminary static and dynamic analyses of the arm were conducted to more completely understand the forces acting on the shoulder. The static analysis involved the use of anthropometric tables to determine the location and force at the center of mass for each section of the arm (hand, forearm, and upper arm). A moment calculation about the shoulder and elbow was then done to determine the forces acting about those points when the elbow was at a 90 degree angle. The second stage of this process involved developing equations for the force due to angular acceleration of the shoulder. This calculation involved treating the arm as a rigid body rotating about a fixed point at the shoulder. Since these equations are variable due to height, weight, and arm movement, they were left in variable form. The force from angular acceleration will be determined by testing rather than numerical calculation. These overall calculations are included in the Appendix.

Problem Motivation

Currently, few dynamic slings exist on the market, and none aid in the motion of running. A dynamic sling that could support the shoulder during the motion of jogging would not only benefit individuals with brachial plexus injury but it would also impact other injuries of different degrees that affect the shoulder, such as rotator cuff injuries. This sling would function to allow for variable support of the full upper extremity while remaining comfortable and easy to use. Ideally, the design will be breathable, lightweight, and withstand washing. The design must facilitate proper running form and arm swing mechanics while distributing the weight of the affected shoulder onto healthy areas of the body.

Current Devices

There are various sling designs on the market to support patients of a brachial plexus injury. These current methods focus primarily on preventing subluxation of the affected shoulder and do not show a potential to be used in dynamic situations like during running or exercise.

Figure 3: Patient wearing the GivMohr sling[5].

One device, the GivMohr sling, leads the field in its support of the affected shoulder.[5] This design consists of a figure-8 strap of webbing that loops around the anterior of the unaffected shoulder to focus on correct anatomic alignment and emphasize proper movement and function. Testing results have concluded that this device successfully reduces vertical subluxation without over-correcting vertically or horizontally. Results also concluded that the sling provides little horizontal support[5]. On another note, the patient's hand is secured in a non-function position by holding onto a plastic handle. Even though this device properly supports the shoulder, a patient running while wearing the GivMohr sling will feel uncomfortable in this extended arm position. Because of these features, this device is recommended for static use only in late recovery periods of therapy, and is therefore lacking in the dynamics support our team seeks. Specific aspects of this design, however, can be replicated in our teams sling including the locations of attachment points and materials used.

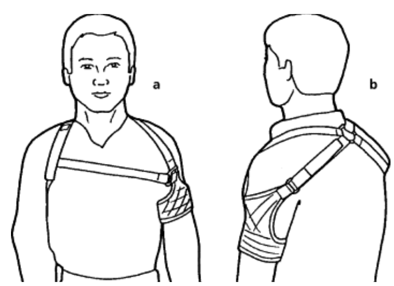


Figure 4:Drawing of Rolyan humerus cuff, posterior view[6].

Another device, the Rolyan humerus cuff, incorporates other design aspects to accommodate different anatomical support mechanisms. Its construction consists of an anterior and posterior strap connected from the humerus cuff to the uninjured shoulder straps. Through testing, this sling was successful at reducing vertical asymmetry of the injured shoulder, but was unsuccessful at reducing vertical subluxation and often led to restriction of circulation in the upper arm[6]. Once again by observing this other design our team has sought after replicating the anchoring mechanism, consisting of under-the-arm straps that connect in the back, by an O-ring.

Previous Design

In the fall semester, a dynamic sling to support brachial plexus injuries consisting of several straps was first introduced. The first is a two inch wide strap that circled the chest and was connected by Velcro. The second strap ran from the chest of the uninjured shoulder, looped around a metal ring, and then crossed over the injured shoulder. Two Thera-bands of specific length and resistance were chosen to meet the necessities of the injury. One band ran from the injured elbow, up the posterior portion of the upper arm, and around the back to the uninjured shoulder. The other attached from the wrist to the strap hanging over the injured shoulder. Through the team's testing, conclusions stated that this design successfully redistributed the weight from the injured to uninjured shoulder. Their design met the specifications they sought after, but noticeable modifications can be made. The sling proved to not be very breathable because of the tight and thick cuff mechanism in place. Also, the device was difficult to assemble and adjust due to the clipping method being implemented. Finally, the design was catered to one specific person and their body size. For all of these reasons, the team hopes to design an improved universal sling that can be used in dynamic exercises, that will support multiple injuries, and that will have different attachment sites for personal adjustments or preferences.

Design Specifications

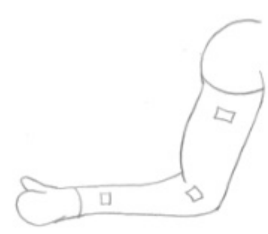
The dynamic sling has specific aspects crucial to developing a successful device. The main focus of the design will be to stabilize the shoulder in an anatomically correct position throughout the running motion. Proper arm swing, shoulder rotation, elbow angle and orientation are critical to mimic normal running patterns. Aesthetically, the design must be visually appealing, breathable, washable, and not cause abrasions, chaffing, or restriction of blood flow. Recovery from a brachial plexus injury may take multiple years, so the device should last the entirety of the patient's therapy. The sling must be able to be worn with lightweight clothing without being ungainly or causing uncomfortable pressure points. Adjustability in tensile supports will be available to accommodate different body types and degrees of disability. Ease of assembly is critical because the patient must be able to put on the sling by themselves after receiving simple instructions or a written outline. Our design aims to produce one finished sling product while staying under a budget of $150.

Design Alternatives

An upper extremity sling is generally composed of multiple parts: a large anchoring and weight distributing part across the chest area, components around the affected arm for support, and tensile elements reducing or eliminating the load of the injured arm. When determining the design for our device, we found it was necessary to break our design down into separate anchoring and arm sections. We then explored possible alternatives for each section, and combined the best parts into the final design. Each section acts independent of each other to provide support and facilitate proper running mechanics, but as a whole they combine to accommodate proper running mechanics. For this reason, we decided to grade the separate sections on the same criteria when developing our final design.

Designs for Arm Section of the Sling

Sleeve



The arm portion of the design considered was a full-length sleeve, with anchoring attachment points sewn on at designated areas. These attachment points will be placed at optimal positions to create the best arm stability and promote proper arm mechanics throughout the entire running motion. Yet, given the fact that these attachment points might tend to pull on the sleeve material when strapped to the anchoring system, their amount must be limited in order not to ruin the construction of the sleeve overtime.

Cuffs

Multiple cuffs that incorporated attachment points to the anchoring system were explored as well. These cuffs would strap onto the patient at designated areas to promote proper arm alignment and arm swing mechanics while running. In addition, they would be made of Velcro, and could become easily adjustable upon desire. Overall, the cuffs allow for a greater amount of attachment points, and easy variability from one patient to the next based on differing arm sizes. The downfall to the cuff concept is that there are multiple parts that have to be attached, which may create confusion when assembling. It also has the possibility of sliding up and down the arm more easily, which could lead to mechanical failure.

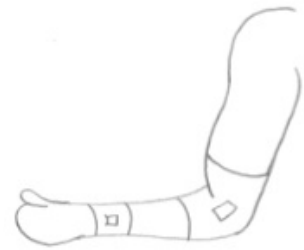
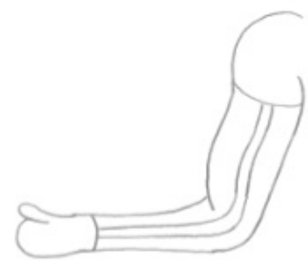


Figure 7: Illustration of the cuff design.

Hybrid

A cross between the cuff and sleeve design was the last option contemplated. This design consists of a full-length sleeve with support running through the fabric, as well as denser cuffs integrated into the sleeve to serve as attachment points. This denser portion of the sleeve would reduce material displacement, and the cuff sections would serve as a location for multiple attachment points for tensile elements. This design lends itself well to promoting proper arm mechanics throughout the running motion and

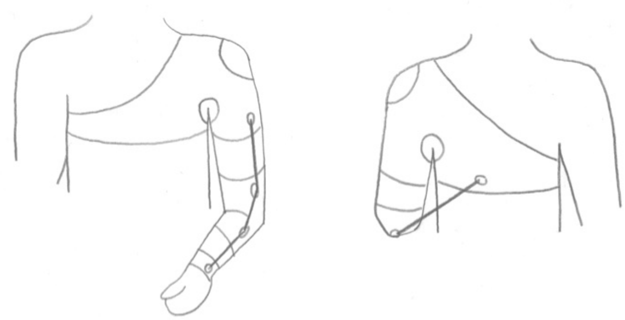


eliminating the potential for movement and tearing from the attachment points as seen in the plain sleeve design. The single piece design also makes this easy to put on and easy to use.

Design Options for Anchoring Section of the Sling

Vest

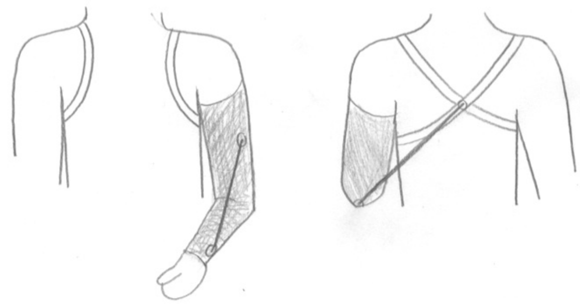
One anchoring system considered was a vest design. It is appealing because it functions as a shoulder cuff by securing to the injured shoulder through a strap that eventually distributes the shoulder weight to the opposite side of the body along the chest. In addition, a large surface area makes it optimal for multiple attachment points that connect from the arm portion of the sling.



The vest design could also be constructed out of two parts, a chest region and a back region, that connect through Velcro. With these two regions separated, the sling can adapt to a wider range of body sizes, can be easy to put on, and can cater to multiple different body types.

Strap

The second design alternative reviewed for the anchoring system of the sling was a strap system. The straps will be sewn into a figure eight like approach, and the patient will place each arm inside either gap. Then, the mechanism can be tightened in order to pull the shoulders back, and the overall result will reduce loading of the shoulder and promote more natural posture. Since this anchoring system is only made of straps, its surface area is greatly reduced, which limits the amount of space for attachment points that connect from the arm portion of the sling. The amount of straps also will make the design far more confusing to put on.



Design Matrices

Both portions of the design make significant contributions to achieve a universal goal, so they were weighed and graded based on the same criteria and scale. The mechanics category was given the highest weight, due to the fact that the slings overall purpose is to facilitate proper arm swing and running mechanics. Second, the ergonomics of the sling was given a high priority because it must be comfortable and user friendly in order for the patients to actually want to exercise in it. Next, universality, ease of use, and ease of manufacturing all received a lower weight. Universality was weighted lower because it is an easier conceptual point to modify/add in later prototyping. Ease of use and ease of manufacturing also received a lower weight because these categories have a lower impact on the success of the initial design, and can again be modified and worked into later prototypes. Cost received the lowest weight because material usage throughout the designs is largely universal, so there is not a large difference between the material costs of any design.

Arm Section Matrix

Category	**Weight**	**Full Sleeve**	**Cuffs**	**Hybrid**
Cost	10%	7	8	7
Ease of Manufacturing	15%	6	7	5
Ease of Use	15%	5	4	8
Universality	15%	4	7	8
Mechanics	25%	5	7	8
Ergonomics	20%	7	4	8
	Total Out of 10	5.6	6.05	7.3

As seen above, the hybrid design scored highest in this design matrix. Its ability to incorporate many attachment points led to its high scores in mechanics and universality, while its sleeve portion gave it a higher ranking in terms of comfort and ease of use for the patient. However, it could become difficult to assemble when sewing the denser material into the sleeve for the attachment points, and its overall cost might be more than if the team were to have used cuffs.

The cuff design scored low in both the ease of use category, and the ergonomics category, because the team predicted that it could eventually cause chafing and the assembly of the cuffs could easily become confusing with their amount and placement. For the same reason as the hybrid, it scores high in both the mechanics and universality sections of the matrix.

Lastly, the full sleeve design lost points in the mechanics and universality area because the material displacement associated with the sleeve leads to a reduction in available attachment points. It also scores low in the ease of use section, because its sleeve structure could make it difficult to correctly define the orientation of the sleeve for proper use due to twisting and pulling of the fabric. This sleeve aspect does give the design higher scores in terms of ergonomics and comfort, and cost efficiency.

Anchoring Section Matrix

Category	Weight	Strap	Vest
Cost	10%	8	5
Ease of Manufacturing	15%	7	5
Ease of Use	15%	4	7
Universality	15%	6	8
Mechanics	25%	6	8
Ergonomics	20%	6	8
	Total Out of 10	6.05	7.1

From the final anchoring section matrix, the vest design won overall. Its large surface area permits for a variable amount of attachment points, and its shoulder cuff character gives it large scores in the mechanics, ergonomics, and universality categories. In addition, the vest design will be easier for the patient to put on. However, its complicated infrastructure and contorted curves that allow it to fit comfortably around the body will make it difficult to manufacture, and possibly more expensive.

The vests competitor, the strap mechanism, came in second because it lacked the ability to provide as much mechanical, ergonomics, and universal support. The mechanical and universality category suffered due to the fact that it provides a limited amount of space for multiple, variable attachment points. This factor could lead to a reduced ability to cater toward a wider range of disabilities as well as a lowered capacity to facilitate proper arm swing. In addition, the figure eight strap structure could be easy to confuse and assemble onto the patient along with causing chafing and abrasions to the skin. This strap structure does work in the designs favor, nevertheless, when considering the simplicity of its manufacturing and cost.

Final Design

The final design for the sling will incorporate a vest like chest anchoring system coupled with a hybrid sling and cuff system for the arm support. The expected prototype is pictured below in **Figure 11**.

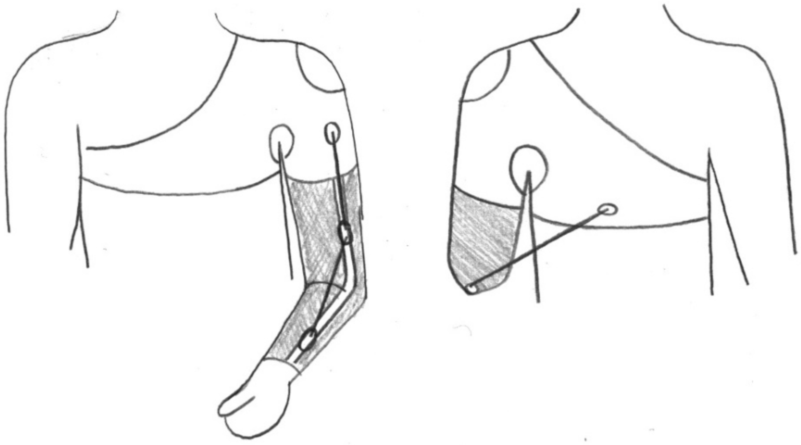


Figure 11: Shows a preliminary sketch of the final design.

The anchoring system was made out of a foam layer with cotton sewn around it to provide a solid anchoring base for the tensile support elements. These elements ran from under the elbow up to the shoulder, where they were split by a guide system to provide forces in the direction of shoulder muscle groups. This significantly decreased loading of the arm while providing force at the shoulder muscles to facilitate full arm swing. In addition, this vest is solidly secured, and results in reducing the risk of mechanical failure due to material displacement. The large surface area represented also allows for more attachment points to be added if more tensile elements are deemed necessary. Along the same lines, the larger area distributes loading across the material to eliminate uncomfortable pressure points that could be apparent in other designs. Finally, the vest design reduces the difficulty to put the device on for an injured patient because it is less confusing than a design containing multiple straps.

The arm support sleeve is currently made of cotton for proof of concept, with plans for moisture wicking fabric technology that contains anchoring elements incorporated into the fabric in the future. This design enhances the ease of putting the device on because it is one continuous element. The sleeve includes tensile support attachments around the forearm near the elbow, to support the weight of the arm, as well as on the back of the upper arm, to support cables that run from the wrist to the back of the arm allowing the maintenance of a 90 degree elbow angle. These force carried by these tensile elements can currently be set based on disability by a physician, but there are plans to make more elements that are fully adjustable by the user to accommodate differing degrees of disability.

Figure 12: Visual of our final design in front view (left), back view (middle) and side view (right). Parts easily observed are the shoulder strap, arm sleeve, blue and green bands for tensile support, and belt holes for distribution of forces.

Fabrication

In order to start making the prototype, materials had to be purchased. From the fabric store called JoAnne's Fabrics, the team purchased approximately two yards of black cotton, five yards of utility fabric, and one yard of a denser cotton for the inside lining of the prototype. Although neoprene was previously the fabric of choice, utility fabric was selected as the next best alternative since it was much less expensive and still would provided some support in response to tension due to its rigid structure.

The fabrication process then began by cutting the vest pattern out of an unused t-shirt to determine the proper dimensions and fitting of the future vest. From there, the t-shirt had components added and subtracted from it to produce what would be expected as an optimal outline for the vest. Next, a total of eight pieces were cut in comparison to the t-shirt outline, four out of the black cotton and four out of the thicker utility fabric. It is common practice within sewing to combine layers of fabric so that they are facing inside-out, followed by sewing along the sides, and then turning the material back over to right-side-in. This same concept was performed when making both the front and back regions of the vest. For example, the first step when making the front piece of the vest was to combine the layers in order of the utility fabric, followed by two layers of cotton, and then the utility fabric again. Then, after sewing along all the edges except for one, the updated piece was turned right-side-out through the unsown region so that only the cotton portions of the vest were now exposed and the utility fabric was on the inside. The fabric along the resulting hole from which the piece was turned through was then pinched inward and sewn again along its border to close off the remainder of this half of the vest.

To complete and combine the vest together as a whole the common hook-and-loop fastener fabric, known as Velcro, was employed to areas where the front and back portions of the vest would come together. These areas of the vest included the shoulder strap position along with the two locations that connect the front and back pieces around the chest and the arm. Half of these regions also received more hook-and-loop fastener fabric than the next in order to account for varying sizes of individuals who may use the vest. These few steps completed the main fabrication process of the vest.

Next, the making of the sleeve portion of the prototype followed in a similar manner. Tracing from the outline of an arm, and leaving holes for the thumb and fingers in the pattern, four pieces were cut from the black cotton material appropriately. Two pieces from each cut were sewn together inside out, flipped, and then their holes were pinched and sewn shut. Lastly, the resulting flipped two pieces were sewn together in similar fashion to produce a sleeve with a thumb slot, finger slots, and an arm insertion slot.

Combining the vest and sleeve elements of the design meant using elastic cables for connections and added support. In order for this concept to be possible, the team devised the strategy of placing belt loops made of the black cotton material onto various places of the vest and sleeve. These belt loops would either act as guides for the tension cables, or as points for them to clip onto. After some research and trials, the team thought it would be best to fabricate belt loops and place them along the top section of the vest on both the back and front sides. In addition, more were placed at the top of the shoulder strap, underneath the sleeve near the elbow, and toward the lower back upper arm of the vest.

As a final precaution, additional small units of the vest were made in order to act as size variance pieces for the arm and chest regions. Some individuals with larger body types might require this extra amount of fabric in order to fit into the vest. These pieces were made just like the vest prototype, match the vest prototype, and strap onto the arm and chest regions appropriately through the same hook-and-loop fabric mechanism.

Testing

Meg's Running Test

Before the team had created and tested its prototype, performance testing was completed on last semester's sling design. The team accompanied our clients, Karen Blaschke and Margaret (Meg) Overstake, along with Jenny Kempf, a physical therapist specializing in leg running mechanics, to the Runner's Clinic in Research Park where the testing was conducted. Kempf used simple tools to conduct the testing including a high speed camera, high definition television, and basic treadmill. Videos were taken from each side to view arm motion of the healthy and injured arm, as well as from behind to observe lower body mechanics.

To begin the entire process, Meg was asked to run without the sling so a controlled observation of her upper and lower body running mechanics could be analyzed. She ran for approximately 2 minutes at 5 mph while video data was collected.

The second phase of testing called for Meg to fatigue her arm using a 5 lb dumbbell by doing continuous arm curls for 1 minute. This mimicked the fatigue she would experience after running for extended periods of time. She was then asked to run at 5 mph for approximately 2 minutes to gather video data. From this running trial, it was noted that Meg was frequently stretching her forearm and wrist due to tightness and stiffness that developed from the fatigued.

Finally, Meg put on the sling designed by the previous semester's team. Again, she ran at the same speed while video data from the different orientations was gathered.

Kinect Motion Capture

After creation of the team's design was complete, testing was necessary to determine if the sling facilitated in mimicking proper running mechanics. Since high quality video capture was inaccessible, the team sought after a cheaper alternative. The team was introduced to Microsoft's Kinect hardware and software by Professor Thelen, and decided on this option because of its ease of use and acceptable accuracy of data collection. The Kinect system uses infrared lasers that act as depth sensors to capture a full three dimensional image, and it is very successful at capturing joint locations to outline an entire human body. For our purposes, we placed the Kinect system about 7 feet off the ground facing the front and side of our running test subject so that the device could accurately capture the right arm while running.

The program used to collect the data, known as SkeletalViewer, is free software that can be downloaded from Microsoft's website. The software has a simple interface allowing one to see the infrared image processed by the Kinect, which appears as a stick figure depiction of the significant landmarks and joints being recorded, and a full, real-life video of the patient. The program was modified to allow the joint location data to be outputted into a text file for easy computation.

To interpret and analyze the data, a MATLAB program was necessary. The basis code was obtained from Thelen's Neuromuscular Biomechanics Lab. The team modified the code to be able to calculate the angle between a vector from the right shoulder to right elbow and a vector from the right shoulder to the right hip. MATLAB would then plot these angles over time for easy recognition of the arm swing's maximums and minimums angles.

To begin testing, the test subject was placed on a treadmill and asked to run at 4.5 mph for 15 seconds without the sling. After their run, the text file from the SkeletalViewer was inputted into MATLAB and then analyzed by the program. A team member used the cursor in plot viewer to identify a smooth, noise-free area of the run for accurate results. The max and min angles were then recorded for future statistical analysis. All 4 team members ran once without the sling and once with the sling.

Newton Spring Scale Testing

An alternative test was completed to determine if the sling effectively supported the arm while in use. A Newton scale was used to measure the force the arm was supplying to the test subject. Three locations were used to measure the force; these included the elbow, middle forearm, and hand. Each team member was measured at these three locations once while wearing the fully assembled sling and once with just wearing the sleeve. To measure the force, the hook on the scale was inserted into the fabric of the sleeve. Wearing the sleeve did not have a significant effect on the force observed.

Results

Video Analysis

The videos of Meg running were analyzed quantitatively using ImageJ to determine what areas of her running mechanics needed to be correct. During testing, qualitative assessments were also made.

The angle at the elbow was measured by marking the shoulder, elbow and wrist based on color content as collection points in the video. The angle was then recorded and averaged throughout the video. This average can be seen in **Table 1**. From this analysis, the healthy arm angle at the elbow is near 90 degrees. The injured arm has decreased load bearing ability, and thus the optimal 90 degree angle is not able to be maintained. After Meg's arm was fatigued, her elbow angle increased to an even larger angle during running. The past semesters sling did well in correcting this elbow angle. The second piece of data that was recorded was the max arm angle of shoulder flexion and extension relative to the

vertical. This was angle was measured from a vector running from the elbow to the shoulder compared to a vertical vector shown in **Figure 12**. A total of 5 maximums and 5 minimums were found for each condition and averaged. This showed that her healthy arm had longer shoulder swing, while her injured arm had a decreased capacity for proper arm swing. The data from this test is shown in **Table 1**.

Meg was also asked to qualitatively describe the performance of the sling. She described the waistband as being stretchy and loose. The strap on her right hand was making an uncomfortable pressure point. She also disapproved of the hand piece; she would prefer a glove with cut off fingers. After observing her run, it was noticed that the orange band that goes behind the right arm would go slack when she extended her arm, then slap the back of her arm while becoming tense and impede motion as her arm moved forward.

	Angle (Degrees)							
Trial	Healthy Arm Min	Healthy Arm Max	Injured Control Forward	Injured Control Back	Fatigued No Sling Forward	Fatigued No Sling Back	With Sling Forward	With Sling Backwards
1	12.14	40.81	0.42	45	6.05	42.08	5.06	41.89
2	14.38	38.78	0.7	44.86	-1.14	41.98	-2.39	39.78
3	9.09	38.66	6.43	29.76	-1.72	38.8	2.73	38.95
4	6.44	39.97	3.72	46.17	4.7	39.17	4.6	42.22
5	13.99	41.72	-4.04	47.43	-3.55	43.72	7.33	41.49
Average	**11.208**	**39.988**	**1.446**	**42.644**	**0.868**	**41.15**	**3.466**	**40.866**

Table 1: Comparison of healthy arm sling to injured arm swing.

In conclusion of this testing, specific modifications must be made to improve the sling design. After having to use the old design team's poster to assemble the sling, it was determined that the sling must be simple enough to put on without lengthy instructions. The sling must not have movable parts that have direct skin contact because even after 5 minutes of Meg's run, she felt discomfort. Finally, the bands must not be able to go slack through any of the running motion.

Table 2: Results for minimum and maximum angle with and without sling for each team member. Averages and standard deviations are also noted.

	Kelly	Colin	Tony	Marie
No Sling				
Min (Degrees)				
1	26.68	25.24	15.53	23.3
2	30.01	25.07	17.9	23.1
3	35.67	29.28	19.07	26.68
4	29.66	31.59	18.26	25.05
5	35.06	35.02	19.31	27.76
Avg	31.416	29.24	18.014	25.178
SD	3.8362	4.252099	1.503207	2.048419
Max (Degrees)				
1	86.58	72.29	75.34	75.45
2	85.27	69.7	73.81	78.89
3	88.48	70.68	76.32	73.85
4	93.44	70.5	75.92	69.42
5	88.05	71.86	77.66	69.67
Avg	88.364	71.006	75.81	73.456
SD	3.1078	1.054268	1.406734	4.008825

	Kelly	Colin	Tony	Marie
Sling				
Min (Degrees)				
	23.78	18.44	22.5	18.17
	24.21	17.99	21.8	19.21
	25.96	24.39	22.8	19.38
	29.62	25.71	23.11	20.22
	30.58	25.22	22.06	20.86
Avg	26.83	22.35	22.454	19.568
SD	3.113294	3.80742	0.53271	1.026192
Max (Degrees)				
	85.87	76.15	76.42	72.66
	85.6	75.24	76.52	74.79
	86.41	78.18	78.39	68.92
	83.44	73.6	76.14	69.24
	84.44	76.44	75.67	69.03
Avg	85.152	75.922	76.628	70.928
SD	1.197568	1.678964	1.038687	2.664521

Kinect Motion Capture and Spring Scale

The results from the Kinect motion capture and Newton Spring scale testing were consistent and enforced the efficacy of our sling. From the results it is noted that the sling did not inhibit arm swing motion and effectively relieved the shoulder of force generated from the arm. The full results can be noted below in **Table 3**.

Statistical Analysis

To analyze the significance of our data and the efficacy of our sling, statistical analyses were performed. Determining if the minimum and maximum angles with and without the sling were the same required the production of a paired, two sample t-test for variable means. The null hypothesis stated that the average angles were more than ten degrees different from the other, and ten degrees was used because it was the allowed accepted error of the Kinect system. This test was performed on the minimum and maximum averages of each team member with and without the sling.

The statistical test results of each team member can be found in **Table 3** below. As noted in **Table 3**, the p-values for all team member's running trials for both the minimum and maximum angles was <0.05. Therefore, we can reject the null hypotheses and confidently conclude that the angles are statistically the same. Also, as noted in **Table 3**, the variance was lower in the trials with the sling in almost all the cases. This may also suggest that the sling encouraged a more consistent running form and aid in the motion of running. A graph was constructed using one of the team member's data and can be seen in **Figure 14** below.

Table 3: Statistical results for each team member. Averages, variances and p-values given.

	Average Angle with Sling	Average Angle without Sling	Variance With Sling	Variance without Sling	P-Value
Kelly Minimum	31.416	26.83	14.72	9.69	0.014
Kelly Maximum	88.36	85.152	9.66	1.43	0.01
Colin Minimum	29.24	22.35	18.08	14.5	0.009
Colin Maximum	71.01	75.92	1.111	3.34	0.0002
Tony Minimum	18.014	22.454	2.259	0.283	0.000177
Tony Maximum	75.81	76.628	1.9789	1.07887	0.0000955
Marie Minimum	25.178	19.568	4.196	1.053	0.001
Marie Maximum	73.456	70.928	16.07	7.09	0.0006

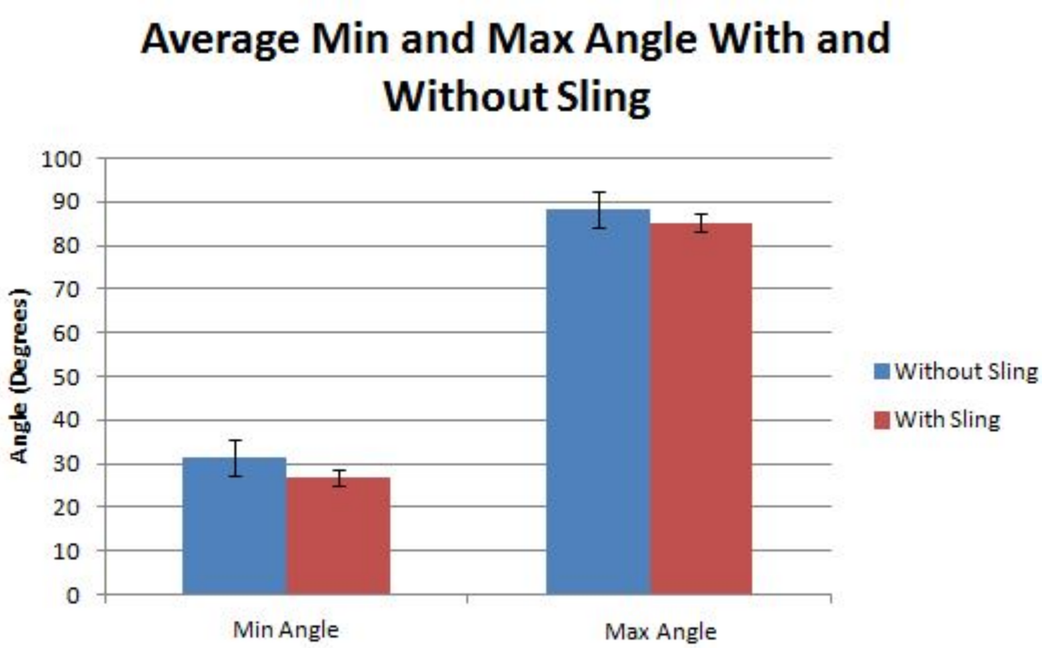


Figure 14: Graph showing average min and max values with and without sling for one of the team members.

For the force analysis, the percent of reduction of force was used. The results are below in **Table 4**. The sling significantly decreased the force. A graph representing the reduction of force can be noted in **Figure 15**.

Table 4: Results from force testing, percent decrease in force is provided.

Force without Sling (N)	Force with Sling (N)	% Difference
Elbow	Elbow	
21.89	3.614	83.49
Mid-Arm	Mid-Arm	
16.125	2.78	82.76
Hand	Hand	
7.506	0.5556	93

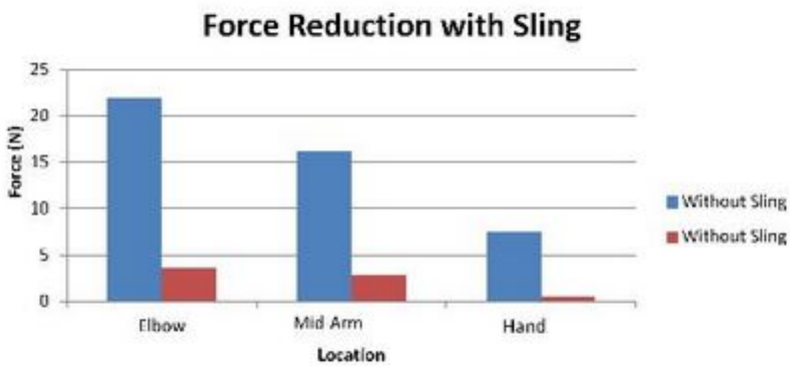


Figure 15: Graph showing the reduction in force at specified locations of arm.

Future Work

To further improve the quality and functionality of the design, testing the prototype on a subject in the near future who has a brachial plexus, rotator cuff, or other type of injury that harms the strength and condition of an individual's shoulder is desired. In addition, to encompass a better understanding of the sling's mechanical properties, a more sophisticated and dynamic analysis of the sling in three dimensional space would be preferred.

While the sling felt comfortable to wear and run in for less than a minute, the team also feels that it would be beneficial to test the ergonomics of the prototype. The future of the sling's use and wear depends on this aspect, which is why the ergonomics of the prototype should be highly considered with more time in the future. Ideas for more analysis in this subject include setting up a user manual and having subject's attempt to use the sling with no prior knowledge and some form of reduced arm or shoulder mobility. Also, it would be best if volunteers could try to run with the sling for variable distances and provide feedback about their running experience with the device.

Lastly, some changes to the concept need to be done. One change includes the incorporation of a variable tension support system for those who have different arm, chest, and shoulder dimensions. If the team could also devise a way to universalize the sling's sizing, this would be beneficial and reach out to a larger market of people. One final transformation to the design would be to manufacture the prototype using athletic and more breathable material. This adjustment would once again provide a stronger user friendly experience while running in the vest.

Conclusion

Brachial plexus injuries cause a moderate to severe loss of function of the upper extremity in patients who have experienced a traumatic injury. Currently, full immobilizers are offered for patients who have recently suffered an injury or completed an operation. However, there are no slings that can offer support during the extremely important dynamic phase of rehabilitation. A preliminary design containing a vest and sleeve hybrid element has been created to offer comfort and support during this dynamic phase by. One way in which it was expected to satisfy this hypothesis was by designing the overall system to mimic the support offered by a healthy arm and shoulder through variable tensile elements.

A theoretical force analysis was conducted to help conclude that the final design concept could function to support the shoulder in a static environment. Two physical tests were also conducted to try and prove the designs outcomes on shoulder support while running. The first was comparing the force created by the weight of the arm by using a Newton scale in two cases, one without the use of the sling and one with the use of the sling. The second physical test was conducted using Microsoft Kinect and MathWorks MATLAB software to determine if the sling has any negative or positive effects on the stability of the shoulder by measuring the angle that the shoulder makes throughout the running arm swing motion. Conclusions for statistical analysis of the data collected from these two tests show that the sling reduces the force produced by the arm, providing support to the shoulder, as well as stabilizing the motion at the shoulder during running. Overall, the team expects that the sling design will allow for patients to enter a dynamic section of rehabilitation with the end goal of promoting healing to regain full active function of the upper extremity.

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Appendix

Product Design Specifications

Function:

The purpose of this design will be to create a shoulder sling to aid in rehabilitation and functionality of patients suffering from traumatic brachial plexus injuries. The device must have tensile support of major muscle groups throughout the upper extremity with the ability to vary the amount of support as well as types of support given due to the varying degrees of disability in patients with brachial plexus. In order to aid in the dynamic rehabilitation, the device must contain design elements that allow for a guided and supported natural running motion while having ergonomic specifications that keep the device comfortable during extended periods of exercise.

Client Requirements:

- A sling will be designed to give anterior and posterior support to the shoulder, especially in order to prevent slouching as to create proper body alignment while running.
- Adjustable for different body types and degrees of disability.
- Comfortable structure that does not cause abrasion or chaffing.
- Easy to assemble and secures properly to the body.
- Materials should be easy to clean and light in weight.
- If the user so chooses to exercise in the sling on average of four days a week, the sling should be able to last for three to five years.

Design Requirements:

1. Operational and Physical Characteristics

a. *Performance Requirements*: The support system should be focused on stabilizing the shoulder and keeping the arm in its proper place throughout the running motion. This includes keeping the arm directly at the side of the body, bending the elbow in a ninety degree angle, and creating arm movement from the shoulder.

b. *Safety*: The sling will be designed so that it will not restrict blood flow, cause abrasions, contain sharp parts, cause asphyxiation, or facilitate poor running mechanics.

c. *Reliability*: The sling should function properly throughout operation, and stay secured in its appropriate location.

d. *Life in Service*: The sling will be designed to last throughout a patient's recovery period. This varies depending on injury, but overall, this time span should be approximately three to five years, if the user so chooses to exercise in the sling about four times a week.

e. *Operating Environment*: The device should be able to withstand the outdoors while in use during exercising, including all types of weather conditions. In addition, the sling will be functional inside different indoor environments of the home, office, or gymnasium.

f. *Ergonomics*: The sling will not interfering with lightweight clothing, and will be adjustable and comfortable for patients of a medium to strong build (roughly 50 - 75 kg for women, and 70 to 100 kg for men). Also, the design will make it easy for patients to place properly on themselves without assistance.

g. *Size*: The size will be adjustable and made for adults of both sexes. This range covers chest circumferences of approximately 75 to 100 cm, and arm diameters of 22 to 40 cm.

h. *Weight*: The sling should not cause slouching or weigh down the arm due to an increased load. The target goal for the weight of the design is approximately 1.5 kg.

i. *Materials*: The material that makes up the design should be hypoallergenic, washable and easy to clean, and weather resistant. In addition, the sling should be relatively soft in places that it come into contact with the skin.
j. *Aesthetics, Appearance, and Finish*: The sling will be designed to look sleek and trim since patients will be wearing the device in public.

2. Production Characteristics

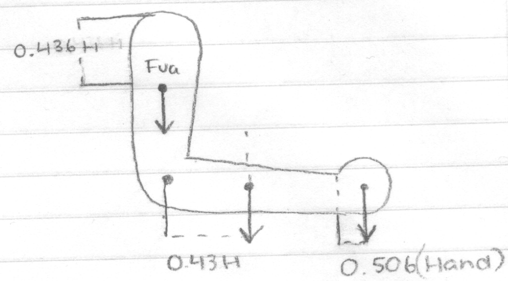
a. *Quantity:* There will be one finished sling product, that will have multiple replaceable components.
b. *Total Project Budget Cost*: The intended cost for the sling will range at approximately $150.

3. Miscellaneous

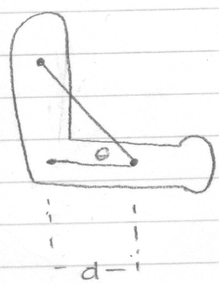
a. *Accessories*: The design of the sling will incorporate a utility pocket that will allow for the placement and security of mp3 players, keys, and or other small personal belongings.
b. *Market Approval:* If the sling is successful and reaches market potential, approval by the FDA is required.
c. *Competition:* The current design for a sling on the market that allows for a full arm swing throughout the running motion does not appear to exist.

$$\text{Arm Total} = g(0.5\, m_b)$$

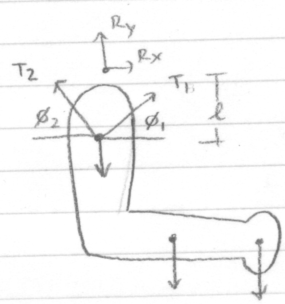
$$F_{fa} = g(0.016\, m_b)$$
$$F_{ua} = g(0.028\, m_b)$$
$$F_h = g(0.006\, m_b)$$



$$\text{Moment}_{elbow} = (0.06278\, H)(F_{fa}) + (0.2006\, H)\, F_H$$



$$d(-2T\sin\theta) + M_e = 0$$



$$l(T_1 \cos\phi_1 - T_2 \cos\phi_2) - M_e = 0$$

MATLAB code

```
function []= animate(JC)
% Animates a skeleton based on joint center kinematic data collected with
% kinect system

    X=zeros(7,5,size(JC.HipR,1));
    Y=zeros(7,5,size(JC.HipR,1));
    % right leg
    X(1,1,:)=JC.HipR(:,1);
    X(2,1,:)=JC.KneeR(:,1);
    X(3,1,:)=JC.AnkleR(:,1);
    X(4,1,:)=JC.AnkleR(:,1);
    X(5,1,:)=JC.AnkleR(:,1);
    X(6,1,:)=JC.AnkleR(:,1);
    X(7,1,:)=JC.AnkleR(:,1);

    Y(1,1,:)=JC.HipR(:,2);
    Y(2,1,:)=JC.KneeR(:,2);
    Y(3,1,:)=JC.AnkleR(:,2);
    Y(4,1,:)=JC.AnkleR(:,2);
    Y(5,1,:)=JC.AnkleR(:,2);
    Y(6,1,:)=JC.AnkleR(:,2);
    Y(7,1,:)=JC.AnkleR(:,2);

    Z(1,1,:)=JC.HipR(:,3);
    Z(2,1,:)=JC.KneeR(:,3);
    Z(3,1,:)=JC.AnkleR(:,3);
    Z(4,1,:)=JC.AnkleR(:,3);
    Z(5,1,:)=JC.AnkleR(:,3);
    Z(6,1,:)=JC.AnkleR(:,3);
    Z(7,1,:)=JC.AnkleR(:,3);

    % left leg
    X(1,2,:)=JC.HipL(:,1);
    X(2,2,:)=JC.KneeL(:,1);
    X(3,2,:)=JC.AnkleL(:,1);
    X(3,2,:)=JC.AnkleL(:,1);
    X(4,2,:)=JC.AnkleL(:,1);
    X(5,2,:)=JC.AnkleL(:,1);
    X(6,2,:)=JC.AnkleL(:,1);
    X(7,2,:)=JC.AnkleL(:,1);

    Y(1,2,:)=JC.HipL(:,2);
    Y(2,2,:)=JC.KneeL(:,2);
    Y(3,2,:)=JC.AnkleL(:,2);
    Y(4,2,:)=JC.AnkleL(:,2);
    Y(5,2,:)=JC.AnkleL(:,2);
    Y(6,2,:)=JC.AnkleL(:,2);
    Y(7,2,:)=JC.AnkleL(:,2);

    Z(1,2,:)=JC.HipL(:,3);
    Z(2,2,:)=JC.KneeL(:,3);
    Z(3,2,:)=JC.AnkleL(:,3);
    Z(4,2,:)=JC.AnkleL(:,3);
    Z(5,2,:)=JC.AnkleL(:,3);
```

```
Z(6,2,:)=JC.AnkleL(:,3);
Z(7,2,:)=JC.AnkleL(:,3);

% right arm
X(1,3,:)=JC.SR(:,1);
X(2,3,:)=JC.ER(:,1);
X(3,3,:)=JC.WR(:,1);
X(4,3,:)=JC.WR(:,1);
X(5,3,:)=JC.WR(:,1);
X(6,3,:)=JC.WR(:,1);
X(7,3,:)=JC.WR(:,1);

Y(1,3,:)=JC.SR(:,2);
Y(2,3,:)=JC.ER(:,2);
Y(3,3,:)=JC.WR(:,2);
Y(4,3,:)=JC.WR(:,2);
Y(5,3,:)=JC.WR(:,2);
Y(6,3,:)=JC.WR(:,2);
Y(7,3,:)=JC.WR(:,2);

Z(1,3,:)=JC.SR(:,3);
Z(2,3,:)=JC.ER(:,3);
Z(3,3,:)=JC.WR(:,3);
Z(4,3,:)=JC.WR(:,3);
Z(5,3,:)=JC.WR(:,3);
Z(6,3,:)=JC.WR(:,3);
Z(7,3,:)=JC.WR(:,3);

% left arm
X(1,4,:)=JC.SL(:,1);
X(2,4,:)=JC.EL(:,1);
X(3,4,:)=JC.WL(:,1);
X(4,4,:)=JC.WL(:,1);
X(5,4,:)=JC.WL(:,1);
X(6,4,:)=JC.WL(:,1);
X(7,4,:)=JC.WL(:,1);

Y(1,4,:)=JC.SL(:,2);
Y(2,4,:)=JC.EL(:,2);
Y(3,4,:)=JC.WL(:,2);
Y(4,4,:)=JC.WL(:,2);
Y(5,4,:)=JC.WL(:,2);
Y(6,4,:)=JC.WL(:,2);
Y(7,4,:)=JC.WL(:,2);

Z(1,4,:)=JC.SL(:,3);
Z(2,4,:)=JC.EL(:,3);
Z(3,4,:)=JC.WL(:,3);
Z(4,4,:)=JC.WL(:,3);
Z(5,4,:)=JC.WL(:,3);
Z(6,4,:)=JC.WL(:,3);
Z(7,4,:)=JC.WL(:,3);

% torso
X(1,5,:)=JC.HEAD(:,1);
X(2,5,:)=JC.SC(:,1);
X(3,5,:)=JC.SR(:,1);
X(4,5,:)=JC.HipR(:,1);
```

```
    X(5,5,:)=JC.HipL(:,1);
    X(6,5,:)=JC.SL(:,1);
    X(7,5,:)=JC.SC(:,1);

    Y(1,5,:)=JC.HEAD(:,2);
    Y(2,5,:)=JC.SC(:,2);
    Y(3,5,:)=JC.SR(:,2);
    Y(4,5,:)=JC.HipR(:,2);
    Y(5,5,:)=JC.HipL(:,2);
    Y(6,5,:)=JC.SL(:,2);
    Y(7,5,:)=JC.SC(:,2);

    Z(1,5,:)=JC.HEAD(:,3);
    Z(2,5,:)=JC.SC(:,3);
    Z(3,5,:)=JC.SR(:,3);
    Z(4,5,:)=JC.HipR(:,3);
    Z(5,5,:)=JC.HipL(:,3);
    Z(6,5,:)=JC.SL(:,3);
    Z(7,5,:)=JC.SC(:,3);


    % Create two views of animated motion
    animator(X,Y,'axis','equal','xlabel','x(m)','ylabel','y(m)');
    animator(Z,Y,'axis','equal','xlabel','z(m)','ylabel','y(m)');

function [hLine, hAxes] = animator(varargin)
%ANIMATOR  Convenience function for animatorApp
%   This is a convenience wrapper function around "animatorApp". You call
%   them exactly the same as with "animatorApp", but you don't get any
%   objects returned.
%
%   ANIMATOR() opens up the animation viewer.
%
%   ANIMATOR(X, Y) animates the data. The data has to be in one of the
%   following formats. The general form is a 3-D array. 1st dimension is
%   the number of elements in a signal (m). 2nd dimension is the number of
%   lines (n). 3rd dimension is the number of frames (p).
%     1. X can be either an m by 1 (2D) array or an m by n by p (3D) array.
%        If 2D, all frames will use the same X vector
%
%     2. X - m by 1
%        Y - m by n by p
%          (This is for animating n lines, with a single X vector for ALL of
%          p frames)
%
%     3. X - m by 1 by p  OR  m by n by p
%        Y - m by n by p
%          (This is for animating n lines, with a fixed X vector for EACH
%          of the p frames OR X-Y pairs per frame)
%
%     4. X - [] (empty)
%        Y - m by n by p
%          (Y will be animated against it's index 1:m)
%
%   ANIMATOR(X, Y, PARAM1, VALUE1, ...) accepts additional arguments:
%     'axis'     : {'auto'}, 'equal
%     'xlim'     : 'auto', [XMIN, XMAX]. Default uses the full range
%     'ylim'     : 'auto', [YMIN, YMAX]. Default uses the full range
```

```
%    'title'    : <title text>
%    'xlabel'   : <xlabel text>
%    'ylabel'   : <ylabel text>
%    'smooth'   : {'off'}, 'on'. Anti-aliasing
%    'frame'    : {1}. Starting frame number
%    'speed'    : {9}. Integer between -10 and 10. 10 is fastest, -10 is
%                 fastest in the reverse direction.
%    'framerate': {1}, 2, 3, 5, 10. Animate every # frames.
%
%   [hLine, hAxes] = ANIMATOR(...) returns the handles for the lines and
%   the axes. This allows for customizing of the objects.
%
% GUI Features:
%   The controls allows you to speed up and slow down (or reverse) the
%   playback. You can pause at any time. You can also drag the time line
%   bar to go to arbitrary frames. Also, use the arrow keys to move between
%   frames (left or right) or change the speed (up or down). Spacebar
%   pauses/starts the animation. In addition to the animation speed, the
%   animation frame interval rate can be set from the menu.
%
%   The graphics properties can be customized via a context menu on the
%   objects. Right-click on the plotted lines to bring up the context menu.
%
%   The animation can be exported to an AVI (R2010b or newer) or an
%   Animated GIF. The Animated GIF option requires the Image Processing
%   Toolbox (if R2008b or older), for converting RGB to Indexed data.
%
%  Example 1:
%    x = (0:.01:10)';
%    y = nan(length(x), 2, 400);
%    for idx = 1:400;
%      y(:, 1, idx) = sin(2*x) + cos(0.25*sqrt(idx)*x);
%      y(:, 2, idx) = -cos(0.7*x) + sin(0.4*sqrt(idx)*x);
%    end
%    ANIMATOR(x, y);
%
%  Example 2:
%    load animatorSampleData;
%
%    % Vibrating string
%    [hL] = ANIMATOR(X1,Y1,'ylim',[-.7 .7],'title','Vibrating String','smooth','on');
%    set(hL, 'marker', 'o');
%
%    % Two double-pendulum
%    [hL, hAx] = ANIMATOR(X2,Y2,'axis','equal','title','Double Double-Pendulum');
%    set(hL, 'LineWidth', 3, 'Marker', '.', 'MarkerSize', 20);
%    set(hAx, 'XGrid', 'on', 'YGrid', 'on');
%
% See also animatorApp.

% Versions:
%   v1.0 - Original version (Aug, 2007)
%   v1.1 - Added option for specifying initial frame and animation speed
%   v2.0 - Added exporting option (AVI or Animated GIF) (Nov, 2007)
%   v2.1 - Added settings dialog for AVI and Animated GIF (Nov, 2007)
%   v2.3 - Refactor functions (Nov, 2007)
%   v2.4 - Changed graphics to Painters. Some graphics card has problems (Oct 2008)
%   v2.5 - Changed back to OpenGL.
```

```
%   v3.0 - Converted to object oriented code and added the ability to load
%        different data sets (Aug 2012)
%
%   Jiro Doke
%   Copyright 2007-2012 The MathWorks, Inc.

app = animatorApp(varargin{:});

error(nargoutchk(0, 2, nargout, 'struct')); %#ok<NCHKE>   % for backwards compatibility

if nargout > 0
   hLine = app.hLine;
end
if nargout > 1
   hAxes = app.hAxes;
end

end

function u=unitvec(v)
% given a matrix v, normalizes the vector in each row of v to have unit 1
% length
vm=sqrt((sum((v.*v)'))');
u=v./(vm*ones(1,size(v,2)));

% Close figures and clear out other variables that have been assigned
close all;
clear all;
% Load a Kinect data file
[JC,time]=load_kinect;
% %JC represents a data structure with the following variables, each of which is
% an nx3 matrix, where n is the number of points and the columns represent the
% x, y and z coordinates
% HC hip center
% SP spine
% SC shoulder center
% HEAD head center
% SL shoulder, left
% EL elbow, left
% WL wrist, left
% HL hand, left
% SR shoulder,right
% ER elbow,right
% WR wrist,right
% HR hand,right
% HipL hip, left
% KneeL knee, left
% AnkleL ankle, left
% FL foot, left
% HipR hip,right
% KneeR knee,right
% AnkleR ankle,right
% FR foot,right
% % You can animate the motion using a routine provided to you. This routine
% contains playback controls so that you can control the speed, skip frames,
% pause the action and even save *.avi movie files
% animate(JC);
% You can define the thigh vector as pointing from the right knee to the hip
```

```
rarm = JC.SR-JC.ER;
larm = JC.SL-JC.EL;
% It is convenient to compute unit vectors (vector of length 1) that point
% from the knee to the hip
urarm=unitvec(rarm);
ularm=unitvec(larm);
% Repeat this for the shank, which points from right ankle to the knee
torso=JC.SC-JC.HC;
utorso=unitvec(torso);
rtorso=JC.SR-JC.SP;
rutorso=unitvec(rtorso);
ltorso=JC.SL-JC.SP;
lutorso=unitvec(ltorso);
% You now want to implement code to compute the knee angle, defined as the
% angle between the thigh and shank (hint: it is useful to use the dot product;
% see help dot to learn how to use this function in Matlab). Your plot of knee
% angle should like a repeating version of the knee flexion data shown in Fig.
% 9
% % To measure maximum knee flexion angles during stance on successive strides
% in your plots, it is convenient to use the ginput command, which will return
% a series of digitized points from your plot. After digitizing points, compute
% % the mean and standard deviation of your measure
% armext=ginput(10);
% % For computing the knee separation distance, one can create a vector
% pointing from left to right knee and compute the magnitude of the vector at
% each time frame

rangle = acosd(dot(urarm,rutorso,2));
langle = acosd(dot(ularm,lutorso,2));

plot(langle);
```