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Cover Page Footnote

NASA SD Space Grant Consortium "Project Innovation Grant" (#SA210033) Rushmore Tramway Adventures Mechanical Engineering, South Dakota State University Anamika Prasad Todd Letcher Cameron Fullerton Benjamin Larson Cody Greene

Full Body Harness Design Modifications and Evaluation: A Senior Design Project

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Abstract

Full-body harness (FBH) is critical for the safe operation of industrial and recreational activities, from installing and maintaining infrastructure such as wind turbines to ziplining and mountaintop adventures. However, harness design remains in the proprietary information of companies with limited technical information available for improvements or readjustments to specialized applications. As the outcome of the Capstone project, the paper focuses on multiple technical aspects and the engineering processes for designing FBH for ziplining recreational users, from selecting and testing materials for operation in cold weather to improvements in design and manufacturing for user comfort. The project is guided by technical input from local industry Rushmore Tramway Adventures (RTA), a ziplining and Rope Course company in the state. The contribution comes from technological design improvements such as a 12% reduced weight and redesign of contact points for increased user comfort and first-of-its-kind design documentation for FBH design.

Introduction

Harnesses are essential fall protection tools required in many industrial and recreational usage. The American National Standards Institute (ANSI) provides general guidance for harness design with ANSI Z359 guiding design FBH (*Safety Requirements for Full Body Harnesses*, 2011). The FBH falls under Class III harness classification and consists of harnesses along the upper legs, a suspender over the shoulders to provide full support throughout the body, and multiple D-rings as anchor points. Though these general features may be present in all FBH, the usage of harnesses has diversified to the point that a generic round harness design has become less viable for minimizing the risks of failures across different applications. This principle applies across all facets of the harness industry ranging from sport harnesses to industrial harnesses exposed to extreme environmental factors. Current harness designers create all-purpose harnesses while neglecting industry specialties. The issues lie in the sacrifices that must be made to the harness to make it compatible in general industry. Hence, an application-based design is needed for FBH to be most effective. Furthermore, since almost all harness design is company-specific knowledge, the design process and evaluation is not transparent.

The current paper focuses on FBH harness design for zipline adventure application where the use of harness is for short periods of expert guidance. The paper is an outcome of the Mechanical Engineering Capstone project at South Dakota State University. Further input for harness design needs and constraints came from collaboration with a zipline company in the region, Rushmore Tramway Adventures (RTA), a ziplining and Rope Course company based out of Keystone, South Dakota. RTA serves more than 300,000 customers yearly and full body harnesses are essential for their safe operation. Additionally, due to the region of operation, additional weather-related consideration for material was also considered. Finally, a balance between safety and cost of the final product was desired to address the large user base of operation.

Under the above design consideration, the project objective was twofold, (1) design and evaluate a specialized FBH harness for ziplining in the cold (2) present the design process and limitations transparently to guide future improvements. The paper first presents the design process, including design criteria, material selection, and the testing and simulation approaches. The outcome of the design is then evaluated per ANSI guidelines. Limited human testing was also conducted in the university after required clearance. The outcome is finally summarized, and key limitations are highlighted for future developments.

Design and testing methods

Figure 1 shows the various parts of the FBH harness referenced throughout this paper and as-worn condition. The design process involved discussing the design criteria, material selection, simulation, and testing. The company representatives were present during the design process to provide input. Testing included both hands-on tensile tests, computational simulation, and limited performance evaluation with human use. All these aspects are presented below.

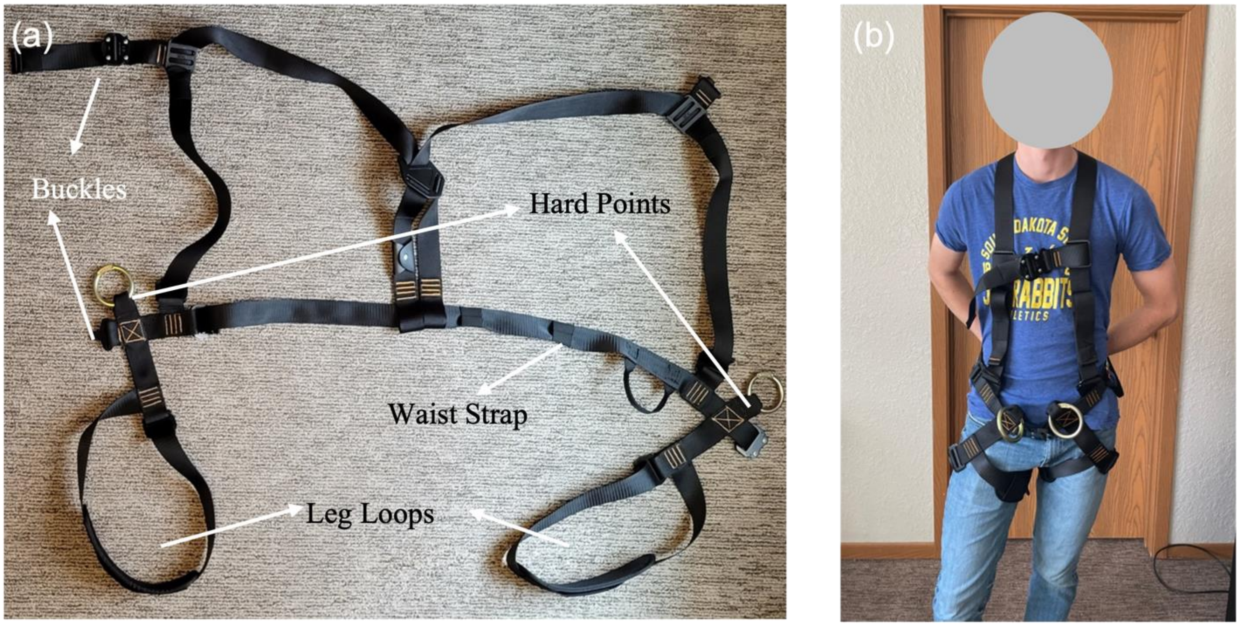


Figure 1: *Full Body Harness (FBH) (a) showing the different features and (as) in worn condition. The highlighted parts in (a) were targeted in the design modifications and included the material of the straps, changes in buckle and hardpoint design, and the overall dimension of the waist strap and leg loop.*

Design criteria

The design criteria were guided by several aspects including inputs from the company, safety standards from ANSI, and other considerations such as cost, material, and design weight. The company RTA desired several improvements in the harness redesigns, such as improving the ease of training, the efficiency of usage, better fitting over a large range of user weights, and increasing the life expectancy of the harness. The requirements set by ANSI included a feet-first dynamic test of 18 kN, hardpoint loading of 16 KN for one minute, and webbing withstanding 22 kN of tension (*Safety Requirements for Full Body Harnesses*, 2011). Other practical aspects considered by the team included a total harness weight of less than 5 lbs, a total cost target of $180 per harness, and improved suspension tolerance.

We primarily focused on addressing weight requirements to improve the ease of usage. The standard practice, which is not dictated by any authority, is fitting users between 160 to 310 lbs. This weight range for RTA customers typically included between 50 to 250 lbs. Hence, RTA used three different sized harnesses to cover its typical users, (1) 30 to 80 lbs for children, (2) 60 to 120 lbs for petite adults, and (3) 160 to 310 lbs for standard users. The above left a 40 lbs gap for its users between 120 to 160 lbs in which no harness properly fits. Also, the extra 60 lbs beyond 280 lbs were not in the traditional weight range of harness users of RTA. Hence, we targeted the weight range of adults from 120 to 280 lbs as a single group to eliminate multiple harnesses for different ranges while also addressing the weight gap.

Material choice

The most common material used in harness straps includes nylon (1050D Nylon also commonly called 1000D Nylon), high tensile polyester (HTP), and Dyneema® (*Harness Materials and Degradation*, 2013). While nylon is cheaper, lighter, and has better abrasion resistance, HTP provides higher strength and improved weather and tear resistance and hence is increasingly becoming more common. Dyneema® is a new entrant with superior properties. We selected the material for our design from these commonly available using a decision matrix that involved factors of cost, weight, strength, resistance (tear, abrasion, and weather), manufacturability, and lifetime performance. These performance criteria and strength parameters are presented later under Section 3 (see Tables 2, 4, and 5).

Tensile testing

The tensile test was performed using MTS 370 Landmark Tensile Tester (Instron, USA) housed on the campus (*MTS 370 Landmark*, n.d.). The tensile tester has a maximum displacement of 80 mm. We designed a special clamp to grip the fabric material preventing its slippage but not causing damage to the fabric. The clamp was machined out of aluminum. The face with which the material was in contact was sanded down using coarse grit sandpaper to increase the friction between the fabric and aluminum to prevent slippage. No teeth-like structure was designed, which is present in traditional holders since it could shred the fabric before failure. These grips proved vital for testing as they held the material firmly without letting the material slip enough to disrupt the test. Table 1 shows the grip dimension, and Figure 2 shows the grip in action.

The fabric polyester and nylon strips were tested vertically and measured 8 $inches$ from the tip of both grips, as shown in Figure 2b. The sample geometrical data (length, width, thickness) was recorded prior to testing. Once inserted, the machine pulled down on the fabric until failure. Data recorded on the MTS 370 Landmark included displacement, maximum strength, and maximum stress. The data was collected for each test specimen and recorded.

The materials were tested under multiple conditions. The polyester underwent a control, weathered, and baked test while nylon went through weathered and baked tests. The control test for polyester in its as-received condition. Weathered testing was conducted after two strips of polyester and two strips of nylon were placed outside for 5 months. This was meant to replicate the weather conditions that harness may be placed in the region of South Dakota. The average UV index over the 5 months was 2, the average humidity was 74.37%, and the average maximum and minimum temperatures were 46.71 °F and 26.51 °F, respectively. UV index played little factor since the material spent time outside in the Fall and Winter seasons. Baked testing included putting two strips of polyester and two strips of nylon in an oven at 50 °C over a period of 2.5 hours to replicate the extreme heat conditions the harness may face.

Pull Rate	5 mm/min
MTS Grip Size	19.05 mm
Alum. Grip Size	19.04 x 50.8 mm
Wedge Pressure	6894.76 kPa (1000 psi)

Table 1: *MTS 370 grip and material details*

Figure 2: *(a) Machining of the grip and (b)Grip in use during testing attached with the standard grip of the instrument with nylon material.*

Testing via computational analysis

The second phase of testing was completed through limited simulations. The harness model was made in SolidWorks (Dassault Systèmes, France) and finite element (FE) simulations were performed using the ANSYS student edition (Ansys, USA). Three simulations were performed for the three different material properties of HTP derived from the tensile test, specifically for control, baked, and the weathered HTP.

The model details are shown in Figure 3 along with a concentrated load applied of 23 kN, representing the maximum loading it should undergo in a fall. It must be noted that the harness will not undergo a force this extreme as the human body cannot handle that large of a force without dampening the force. The standards are set high as a factor of safety for the harness webbing losses strength to many factors including chemicals from sunscreen, UV light, abrasion, dirt, and more.

These simulations are idealized, and the idea is to quantify and show a proof of concept of the design approach under ideal geometry and under the constraints of ANSYS student edition number of element controls. For example, only half of the harness section was analyzed to account for symmetry. Also, only the bottom half of the harness was modeled as the majority of the load is focused in that area. The model was also significantly stiffer than the actual design based on fixed boundary constraints on the model. Full detailed analysis was outside the scope of this project.

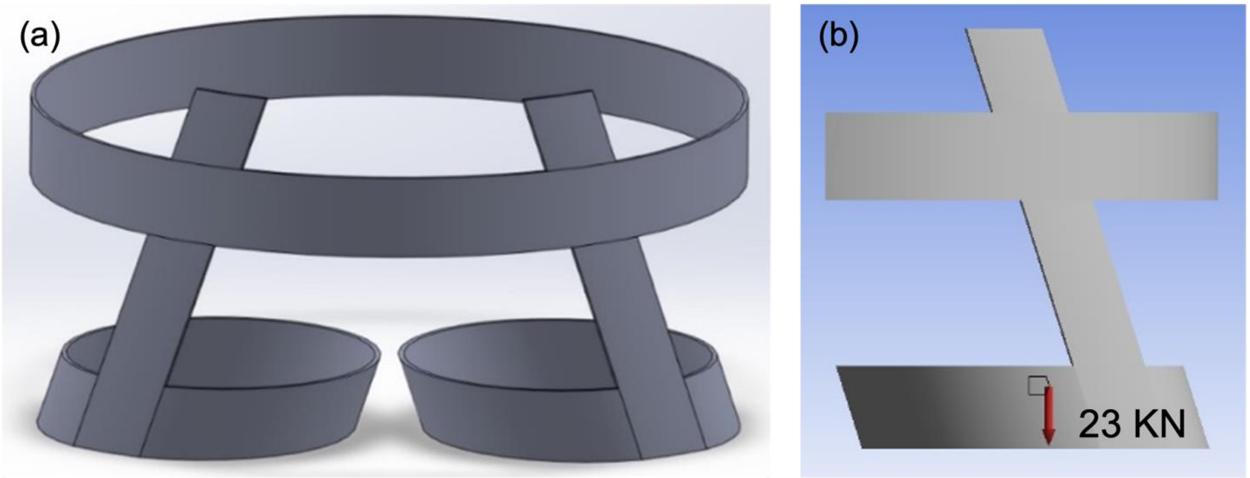


Figure 3*: Computational analysis showing (a) SolidWorks model and (b) section analyzed along with the location and direction of force applied on the model*

Human Comfort Analysis

Finally, limited human testing was also conducted at the South Dakota State University after required clearance from the Institutional Review Board (IRB) for human testing and completing training from the Collaborative Institute Training Initiative (CITI) Program guidelines to ensure the safety of all participants. Both members of the design team were certified by the CITI Program. The test was performed at the climbing wall inside the University Wellness Center.

Testing involved a pre-screening questionnaire to ensure all volunteers were in good health and matched the criteria for harness use. The data was gathered from eleven volunteers consisting of six males and five females. The average height and weight were 71.0 $inches$ and 173 lbs, respectively. The volunteers also had a wide range of experience in a harness, ranging from no experience to rock climbing to wind turbine technicians.

ANSI sets the standard for a “proper fit” which states at least 2 $inches$ of strap pulled with still being able to fit two fingers normal between the user and harness and no more than half the total diameter being pulled. Using these guidelines, the harness was put on the volunteers. The volunteers were then asked a series of qualitative assessment questions after the fit, which included (a) how does the harness feel, (b) are there any hotspots, and (c) is there anything limiting your range of motion? Following this, the volunteers were suspended no more than five feet above the ground and asked the same questions to assess the comfort of fit in suspended form. The users were assigned a grade of 1 to 10 based on comfort, freedom of motion, and pinch points. The data gathered was used to assess the fit of the design.

Harness redesign

General design changes

The harness was designed with a similar shape to the other harnesses previously used by RTA while addressing the new weight requirements. ANSI sets the standard for a “proper fit” as explained above. Additionally, the weight range guided the diameter of the waist strap and leg loop to address the proper fit. The waist strap diameter was set to 40 $inches$ with a proper fit going down to 24 $inches$, and leg loops as a diameter of 12 $inches$ with a proper fit going down to 6 $inches$.

The location of the buckles was the same as previous harnesses used by RTA. However, to make the harness faster to put on and take off, the mating buckles shown in Figure 4a were replaced with a tactical buckle shown in Figure 4b since the tactical buckles are easier to put on and take off and eliminate the time of undoing and connecting mated buckles. The change improved the effectiveness of use without additional training needed for employees on how to put on the harness.

***Figure 4**: The changes in the buckle design showing (left) the older design using the Mating Buckle and (right) the new design using the Tactical Buckle.*

Materials selection

A decision matrix was made to select one of the three material choices for RTA FBH. Table 2 shows the selection criterion, with the weight assigned based on their importance to the company. A rating was then given based on predetermined ranges, shown in Table 3. Dyneema® available to the team was of 1-$inch$ width instead of the 2-$inch$ width desired. Even with its strong attributes compared to Nylon and HTP in score with the set criterion, it was not used due to lack of required production. Disregarding Dyneema, HTP had the next highest score, so it was selected.

		Strap Materials					
		1050D Nylon		High Tensile Polyester		Dyneema®	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Cost	10%	4	0.4	3	0.3	1	0.1
Weight	5%	4	0.2	3	0.15	5	0.25
Strength	20%	3	0.6	4	0.8	5	1
Abrasion Resistance	15%	4	0.6	3	0.45	5	0.75
Weather Resistance	15%	2	0.3	3	0.45	3	0.45
Tear Resistance	15%	3	0.45	4	0.6	5	0.75
Manufacturability	5%	5	0.25	5	0.25	1	0.05
Lifetime	15%	3	0.45	3	0.45	4	0.6
Total **Score**		3.25		3.45		3.95	
Rank		3		2		1	
Continue?		No		Yes		No	

Table 2: Decision Matrix of Materials

Rating	**1**	**3**	**5**
Cost per yard	>$1	$0.40-0$.75	<$0.25
Weight (g/cm^3)	>2	1.25-1.75	<1
Strength (lbf)	<1000	2000-3000	>4000
Weather Resistance	No resistance	Will be affected	Never affected
Tear Resistance	No Resistance	Hard to Cut	Broke Seatbelt Cutter

***Table 3**: Score Determinate for Decision Matrix*

Design changes for improving life expectancy

Based on company experience, two spots were identified as the reason for the early retirement of harnesses. The first spot was the fabric hardpoints shown in Figure 4a, which is the point where a steel carabiner (coupling link used in rock climbing) is attached to the harness and is the only point of contact of fabric with the metal. The second was related to stitching direction and type of stitching. The choice of material HTP as detailed in Section 4.2, and the improvements described also targeted improving the abrasion performance and design life.

Hard point contact

The inside of the carabiner used by the RTA is not smooth due to the tri-locking mechanism. The constant loading and unloading of forces together with roughened inside caused localized wear of polymer material causing early retirement.

The change involved using steel O-rings shown in Figure 4b, which made direct contact with the metal carabiner and then transferred the load to the strap. While metal to fabric contact was still present via the O-ring, the smooth surface of steel O-rings reduced inner abrasion.

Previous harnesses used by RTA also had the hardpoint connected parallel to the waist strap, which caused the force to pull on the threads on their weak axis. Threads are strongly parallel to the direction sewn. Hence the changes were made in stitching direction and the type of stitching. Changing the direction of the connection to be normal to the waist strap means that the threads will be pulled on their strong axis, increasing the life of the harness.

Design changes in stitching

The team made design decisions on the stitch number and type since there was no clear indicator set by ANSI. The decision involved the type of threading, stitch pattern, and the number of stitches. A UV bonded nylon (V-138) was used, which is stronger and longer-lasting than the earlier used nylon thread (V-92). Two distinct types of stitching were used, including X bars and bar tacks. The X bars were used at the junction of the hardpoints and waist strap, as shown in Figure 4c, to make the stitching stronger in all directions since the junction between the hardpoints and waist strap gets pulled in different directions depending on what the user is doing. Bar tacks were used for the rest of the stitching as they are simple to sew and offer sufficient strength.

The strength of stitching can be determined with equation 1, which provides strength in lb/inch of sewing, taking into account the number of stitches per inch (SPI), thread strength, and a factor to account for the average loop strength of thread on a lockstitch sewing machine (*How to Sew Webbing Loops*, n.d.). Here the thread strength is taken as 22 kN or 4950 lbf and the factor was 1.5. The total seam strength per inch is guided by ANSI as 396 lb (*Safety Requirements for Full Body Harnesses*, 2011). Hence taking this as the target strength, we determined the SPI as 12.5. We used total stitching at each junction of 18.75 $inches$, giving a factor of safety of 1.5 in our design.

$$SPI \times thread\ strength \times factor = seam\ strength\ per\ inch$$

$$12 \times 22 \times 1.5 = 396\ lbs$$

$$\frac{4950}{396} = 12.5\ in$$

***Figure 5**: Design changes for improving life and performance of FBH showing (a) earlier fabric hardpoints connection to metal* (b) changes made to include steel O-ring at the hardpoints, (c) stitching design showing the X-bar. The details for the design were obtained through private communication (consultant from Fusion (*Fusion Climb*, 2022), private communication, Nov. 15, 2021)*

Tensile test results

As detailed earlier, the materials were tested under multiple conditions (as purchased, baked, and weathered). Table 4 shows data extracted from the tests. Table 5 shows the properties of nylon and polyester in the weathered condition, which represents the most real-life condition of the material used.

Materials	Max. Strength (N)	Max. Stress (MPa)	Distance Pulled (in)
Nylon-weathered	1729.9	30.3	3.1
Nylon – baked (test 1)	2003.8	35.1	3.1
Nylon – baked (test 2)	2125.4	37.2	3.1
Polyester- weathered	2085.5	36.5	2.4
Polyester-baked (test 1)	2466.3	43.3	2.5
Polyester-baked (test 2)	2576.0	45.1	2.5
Controlled Polyester	3219.5	56.4	2.5

***Table 4**: MTS 370 Landmark Material Testing Results*

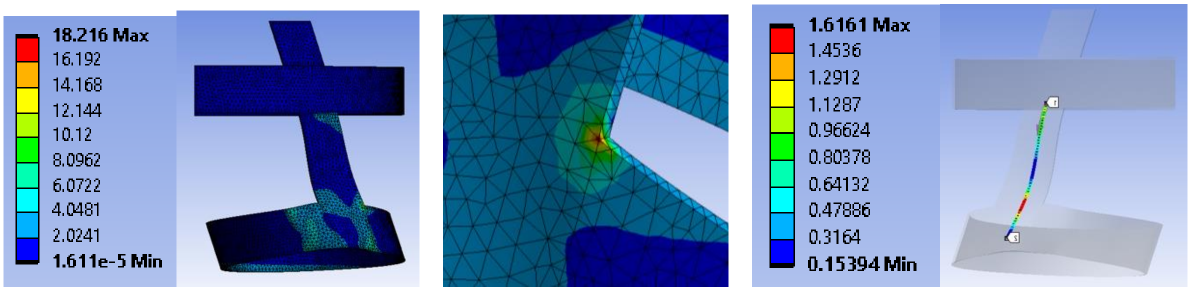
Properties	**Weathered Polyester**	**Weathered Nylon**
Poisson's Ratio	0.4 (*PROFESSIONAL PLASTICS, INC.*, n.d.)	0.39 (*PROFESSIONAL PLASTICS, INC.*, n.d.)
Young's Modulus (MPa)	57	40
Density (kg/m^3)	1400 (*Polyester Fiber - CAMEO*, n.d.)	1140 (*Polyamide - Nylon | Density, Strength, Melting Point, Thermal Conductivity*, 2021)
Bulk Modulus (Pa)	9.50E+07	5.76E+07
Shear Modulus (Pa)	2.04E+07	1.37E+07

***Table 5**: Material properties extracted from the tensile test for the weathered condition*

Simulation outcome

For the simulation, a force of 23 KN was applied to the leg loops of the harness, as shown earlier in Figure 3. Figure 6 shows the stress experiences for the control HTP materials, where the stress unit is MPa. The maximum stress experienced was approximately 6-8 MPa, shown as green-blue in Figure 6a, which is below the tensile yield strength of the material. There is a larger force shown in Figure 6a due to sharp corners used in the model leading to stress singularity in the model shown in Figure 6b. Figure 6c shows the stress inside of the model with a stress pathing.

Further improvements in the model are necessary to improve the outcome but were not taken at this stage due to time constraints. Hence the FE outcome is a proof of concept of its application to the design process. The simplified analysis illustrates that the harness will withstand the 23 KN force as required by ANSI.



(a) (b) (c)

Figure 6*: Finite element outcome for an as-received polyester sample showing (a) the force legend for Stress distribution plot, (b) location of stress singularity, and (c) Stress path*

Human comfort testing

The average “feel” of the harness on the ground on a scale of one to ten was 8.6 compared to 7.1 when the participants were in the air. Participants felt little to nothing “pinching” effect while standing on the ground. Participants did observe slight pinching around the lower rib/back area while suspended, which accounted for the lower score. It is worth noting that this issue was resolved towards the end of the testing by adjusting the fit of the harness around the participant waist. Overall, the outcome of human testing showed that the harness performed well.

Summary, limitations, and future work

We discussed the design and analysis of the FBH for a ziplining company in Keystone, South Dakota Rushmore Tramway Adventures. The harness had a final weight of 2.8 *lbs* which was 0.4 *lb* lighter than previous RTA harnesses. The weight reduction comes from the harness being slightly smaller to fit the optimal weight range for RTA. Assembling a harness also requires certification by ANSI, and our team could not acquire a certification since the certification agency does not deal with a single user. Hence a third-party company (Fusion, CA, USA) was contacted for certification, which increased the cost. Fusion is certified to manufacture harnesses under ANSI guidelines, which is needed for harnesses in the industry (*Fusion Climb*, 2022). The final design is slightly higher ($9) from the intended target of $180. However, the benefit came in the final certification for its use. The company will also restitch the harnesses once, which is normally $20 per harness. Restitching harnesses takes place as a harness is worn down and improves the life of a harness as stitching is the first place with signs of degradation. Inflation caused by COVID-19 also made the cost goal tough to satisfy.

Future work can be taken to improve the design process shown by addressing the limitation of simulation and additional material testing. Another aspect that can be analyzed is its performance under suspension trauma. An earlier work highlights that suspension tolerance can be increased by making the angle between the transverse plane and the leg loop 50° (Hsiao et al., 2012). Another observation made by the paper was that orthostatic angles below 40° and above 20° increased the time before the risk of suspension trauma. We expect that our design changes have doubled the expected time of suspension trauma. For example, with two-inch webbing strips and angles set on the harness and using analysis of the earlier work, we estimate the time before suspension trauma for the weight range of 160 to 310 $pounds$ to be 36.2 minutes. Previous harnesses had an estimated time of 17.7 minutes. Further evaluation and analysis can be taken for varying performance under suspension trauma.

Conclusion

In conclusion, the team successfully produced a redesigned harness to address the application-specific needs of the company RTA for their zip line operation. Product requirements were met as the harness weighed 2.8 pounds which was 12% lower than earlier and included key stitching/buckle changes and improvements in hard contact points for user comfort and fit for a wide range of body types. The testing completed consisted of tensile, simulation, and in-person testing. Third-party testing was completed by Fusion which was in addition to the material testing performed internally. In-person usage testing resulted in positive feedback that further proves the design changes.

The final outcome of the senior design team resulted in the successful purchase of the harness by the company, and they are planning on purchasing more with the aim to slowly integrate them as the main harness for their Aerial Adventure Park and Zipline. The failures and successes of this harness will be studied as RTA uses it and will be documented, and further improvements will be made based on issues brought up by them.

Overall, we have presented a detailed engineering process for designing an application-specific FBH, starting from materials selection and testing to a final product, user response, and its practical use in a company operation. Such detailed design and outcomes have not typically been publicly reported earlier as these processes are the manufacturer's confidential information. Hence our design provides detailed documentation and can find relevance in other application-specific harness designs.

Acknowledgements

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