Paper ID #24121

2018 ASEE Zone IV Conference: Boulder, Colorado Mar 25

Learning Assistive Device Design Through the Creation of 3D Printed Children's Prosthetics with Augmented Grip Diversity

Ryan Carroll, Canada College

Brian Carrozza, Canada College

Brian Carrozza is currently a sophomore at Cañada College in Redwood City, CA, majoring in Mechanical Engineering. He believes in improving the world with better design. His research interests include AI CAD for 3D drafting and super-insulated passive homes. He will pursue a career in research and design engineering where he will utilize his creativity to innovate and problem solve.

Yardley Ordonez, Canada College

Yardley Ordonez is currently a sophomore at Canada College working on transferring to a four year university. His plan is to become a Robotics Engineer and have his own consulting business in the future.

Mr. Edgar Sanchez, Canada College

Mr. Andres Lee, San Francisco State University

Recipient of a Bachelor's Degree in Mechanical Engineering with an emphasis in Robotics and Control Systems from San Francisco State University.

Dr. Amelito G Enriquez, Canada College

Amelito Enriquez is a professor of Engineering and Mathematics at Cañada College in Redwood City, CA. He received a BS in Geodetic Engineering from the University of the Philippines, his MS in Geodetic Science from the Ohio State University, and his PhD in Mechanical Engineering from the University of California, Irvine. His research interests include technology-enhanced instruction and increasing the representation of female, minority and other underrepresented groups in mathematics, science and engineering.

Dr. Wenshen Pong P.E., San Francisco State University

Wenshen Pong received his Ph.D. in Structural Engineering from the State University of New York at Buffalo. He joined the School of Engineering at San Francisco State University in 1998. He teaches courses in Civil/Structural Engineering.

Dr. Pong is a registered Professional Engineer in California. He is a member of the American Society of Civil Engineers and the Structural Engineers Association of California. He has published over fifty technical papers in the areas of Structural Control and Earthquake Engineering. Dr. Pong has been the Director of the School of Engineering at SFSU with 20 full-time faculty and over 25 part-time faculty since 2009.

Dr. Xiaorong Zhang, San Francisco State University

Xiaorong Zhang received the B.S. degree in computer science from Huazhong University of Science and Technology, China, in 2006, the M.S. and the Ph.D. degrees in computer engineering from University of Rhode Island, Kingston, in 2009 and 2013 respectively. She is currently an Assistant Professor in the School of Engineering at San Francisco State University. Her research interests include embedded systems, wearable technologies, neural-machine interface, and cyber-physical systems.

Hamid Mahmoodi, San Francisco State University

Hamid Mahmoodi received his Ph.D. degree in electrical and computer engineering from Purdue University, West Lafayette, IN, in 2005. He is currently a professor of electrical and computer engineering in the School of Engineering at San Francisco State University. His research interests include low-power, reliable, and high-performance circuit design in nano-electronic technologies. He has published more than one hundred technical papers in journals and conferences and holds five U.S. patents. He was a co-recipient of the 2008 SRC Inventor Recognition Award, the 2006 IEEE Circuits and Systems Society VLSI Transactions Best Paper Award, 2005 SRC Technical Excellence Award, and the Best Paper Award of the 2004 International Conference on Computer Design. He has served on technical program committees of Custom Integrated Circuits Conference, International Symposium on Low Power Electronics Design, and International Symposium on Quality Electronics Design.

Dr. Zhaoshuo Jiang P.E., San Francisco State University

Zhaoshuo Jiang graduated from the University of Connecticut with a Ph.D. degree in Civil Engineering.

Kwok Siong Teh received his B.S., M.S., Ph.D. degrees in Mechanical Engineering from the University of Illinois Urbana-Champaign, University of Michigan at Ann Arbor, and University of California at Berkeley in 1997, 2001, and 2004, respectively. He is currently a professor of mechanical engineering and the Associate Director of the School of Engineering at San Francisco State University. His primary research interests are in: (i) the synthesis, characterization, and applications of metal oxides, conductive polymer, and low dimensional carbon nanostructures for energy generation and storage; (ii) engineering design pedagogy that incorporates makerspace, case studies, and scenario-based learning.

Learning Assistive Device Design Through the Creation of 3D Printed Children's Prosthetics with Augmented Grip Diversity

Abstract

In this work, we document the ten-week summer research internship of a team of five community college mechanical engineering students, led by two mechanical engineering senior student mentors and a mechanical engineering faculty at a four-year college, in designing and prototyping an assistive device for children. The project began with the broad goal of designing/providing affordable prosthetics for children, which later was narrowed down to the significant problem of children suffering from congenital upper body limb deficiency or partial hand loss due to traumatic amputation. The research conducted for this paper focuses primarily on devices that have been fabricated for children with partial hand defects or amputations, specifically for those children whose wrists are still fully functional. This research seeks to bridge the gap between technologically advanced but expensive devices and low-cost mechanical prostheses that only perform basic single-grip functionality. This was done by designing a low-cost, 3D printable prosthetic hand with improved functionality. In order to enhance prosthetic functionality, increasing grip diversity was done by adding a mechanism that enables the ability to control fingers individually, thus allowing the user to handle smaller items with a more precise, two or three-finger grip. A grip lock has also been implemented in order to reduce fatigue during extended use. Multiple tests were devised in order to test the effectiveness of the design modifications made, with results showing marked improvements over a standard prosthetic in certain use cases. Our goal with these modifications is to increase the number of children with upper limb loss to be able to use 3D printed prosthetics and pass a series of tests to show the improvements. Based on post-internship surveys of the research students, noticeable and meaningful learnings and professional growth were reported. In particular, the summer research experience deepened the students' understanding of and readiness for demanding research, and kindled and/or reinforced the students' motivation to pursue a master's degree in a STEM field. Through working closely with student mentors and faculty, they gained valuable insights into how scientific workers work on real problems and the elements of the research process. Overall, the summer research internship has been a fulfilling and remarkable professional growth experience for all involved.

1. Introduction

For the past several years, institutions of higher education have devoted resources to increasing the number of engineering graduates and broadening participation of students from underrepresented groups. One of the strategies commonly employed in improving undergraduate STEM education is providing students access to research experiences. There are many studies documenting the benefits of research opportunities for undergraduate students including increased student engagement in their education [1-3], enhanced research and laboratory skills, improved academic performance [1-5], increased student self-efficacy [6,7], and increased understanding and interest for their discipline [1-4,8]. These studies also show that early and multiple exposures to undergraduate research experiences offer the greatest benefit. Developing successful research programs is particularly challenging in community colleges, most of which do not have on-going research programs. Establishing collaborations between research universities and community colleges is key to engaging students in research early in college.

In 2015, Cañada College, a federally designated community college in the San Francisco Bay Area collaborated with San Francisco State University, a comprehensive urban university, to develop and implement the *Accelerated STEM Pathways through Internships, Research, Engagement, and Support* (ASPIRES) project, which is funded by a three-year grant from the Department of Education Minority Science and Engineering Improvement Program (MSEIP). Among the main objectives of ASPIRES is to develop an internship program model that is suitable for community college students and provides multiple exposures to undergraduate research opportunities. For most undergraduate research internship positions, community college students are in competition with upper-division students who have taken more advanced courses, and have had access to research-quality laboratory facilities. Additionally, many of these community college students need to take classes during summer session to fulfill the transfer requirements. Since most summer research internship positions are full-time, community college students who are interested in participating in internship programs are often faced with the difficult choice between accepting a summer internship position or taking summer courses to ensure their timely transfer.

The ASPIRES Summer Group Research Internship Program is a ten-week program for freshmen and sophomore community college students who have no previous research experience and have at least one more year of courses to complete at Cañada College before transferring to a four-year university. In addition to allowing students to participate in the program as part-time interns, the group setting wherein students work with their peers and faculty they know will give students the supportive learning environment needed to succeed in their first internship experience. A collaborative learning environment has been shown to positively impact minority students—improving cognitive development [9] and reducing students' feeling of isolation [10]. The 2017 ASPIRES Group Research Internship program consists of six research groups.

This paper focuses on the work done by the ASPIRES Mechanical Engineering group consisting of 5 community college mechanical engineering students, led by two mechanical engineering senior student mentors and a mechanical engineering faculty. The project began with the broad goal of designing/providing affordable prosthetics for children, which later was narrowed down to the significant problem of children suffering from congenital upper body limb deficiency or partial hand loss due to traumatic amputation.

2. Overview of the Mechanical Engineering Group Project

In a study conducted by the Centers for Disease Control and Prevention (CDC), around 4 out of 10,000 births will suffer from upper body limb deficiency each year [11]. Upper body limb deficiency range from missing fingers to missing an arm. Traumatic hand amputations are another cause for upper body limb-related disability among young children. In a study of 2238 pediatric amputee patients performed by the National Traumatic Databank (NTDB), 54% involved amputation of fingers. The majority of amputations occurred in the age group of 0 to 5 years, many of which are caused by a caught between mechanism, followed by machinery, power lawn mower, motor vehicle collisions, and firearms [12]. From both studies, we recognized that children in the age group of 0 to 5 years had the highest risk of having the stump of the wrist with either a partial hand or no hand.

Through extensive research and several conversations with stakeholders, we came to realize that children who suffered a hand amputation or were born with a hand deficiency, have expensive options in hand prosthesis. It is reported that an electronically powered prosthetic hand will range in cost from $25,000 to $75,000 [13]. Body-powered prosthesis are a less expensive option, with costs ranging from $2,000 to $10,000 [14]. Observing the price ranges from both types of prosthesis, we recognized that body-powered prosthetics are the most reasonable choice for growing children. Among the key reasons are: (i) a body-powered prosthetic hand does not require a separate power source nor electronics, (ii) its simple structure means the cost of replacements are much lower, which is crucial for young children who generally experience higher growth rate than adults, (iii) it is generally lighter than its myoelectric counterpart, which reduces fatigue and enhances user comfort.

Some of the popular choices in body-powered prosthetic hand include having a body-powered hook or a wrist-actuated prosthetic, such as the M-fingers. M-fingers consists of wrist-driven, cable-actuated mechanical fingers with a multi-position thumb as an option. It is one of many wrist-actuated prosthetic hands that are available on the market. After extensive research on the prices of medically available prostheses, our group learned that annual prosthetic devices can range in cost from $500 to $3,000 [15]. Patients fitted with body-actuated prosthetics generally require less follow-up therapy than those with myoelectric prosthetics. In addition, body-powered prosthetics are more mechanically robust compared to the myoelectric ones, hence experiencing less wear and tear. The major replacement item for a body-powered prosthetic hand is the cables, which need to be changed out from time to time.

3. Mechanical Design and Prototyping

Figure 1 shows the mechanical design of our proposed prosthetic hand. The key design improvements proposed in this project are the incorporation of the Individual Finger Control (IFC) and the Grip Lock Mechanism. The IFC allows the user to articulate individual fingers while keeping the others stationary. Such individually addressable motion is achieved via the grip lock mechanism that allows for the tensioning and locking of individual cable attached to the fingers. We also chose to include an abducted thumb, instead of an adducted thumb.

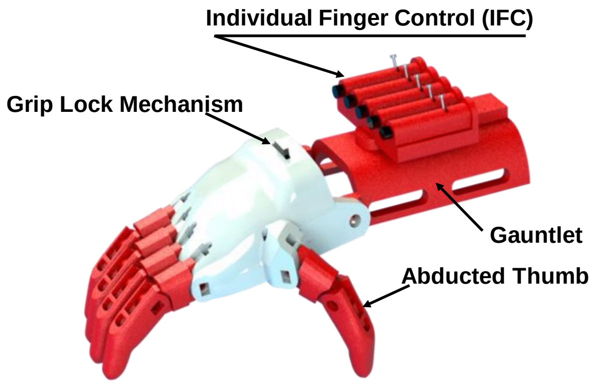

Figure 1. Child prosthetic hand designed and prototyped in this project. (Left) Three-dimensional SolidWorks rendering of the prosthetic hand. (Right) 3D-printed and assembled prosthetic hand.

3.1 Individual Finger Control (IFC)

Figure 2 shows the Individual Finger Control (IFC) mechanism with labeled parts of the design. The IFC raft and sleeve are both stationary parts to create tension on the string used for each finger tied with the string material. This design serves as a modified tensioner that most wrist actuated prosthetic hands use to anchor the string material and create tension. Observing Figure 2, we see each sleeve attached to the raft so they can be easily replaced individually instead of replacing the whole IFC mechanism. The rod our group designed implemented a switch feature that moved along the channel of the sleeve to create less tension on each string material used to implement the individual finger control, as we can see on the right side of the figure. The notch on the end of the rod is referred to as the anchor point, where we tie the end of a string that will create tension. As part of the IFC, it is important for features such as the rod, sleeve, and raft to be easily fixed or replaced.

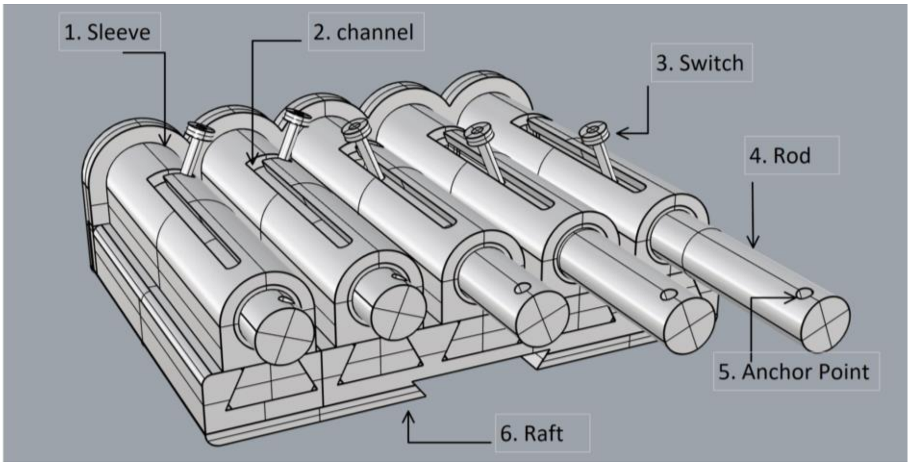

Figure 2: Individual Finger Control (IFC) Design.

Figures 3 shows the final IFC printed with polylactic acid (PLA). As shown in Figure 3, the modified tensioner is attached to the gauntlet portion of the prosthetic hand design. The gauntlet serves as an anchor for the whole prosthetic to strap onto the forearm portion of a human arm.

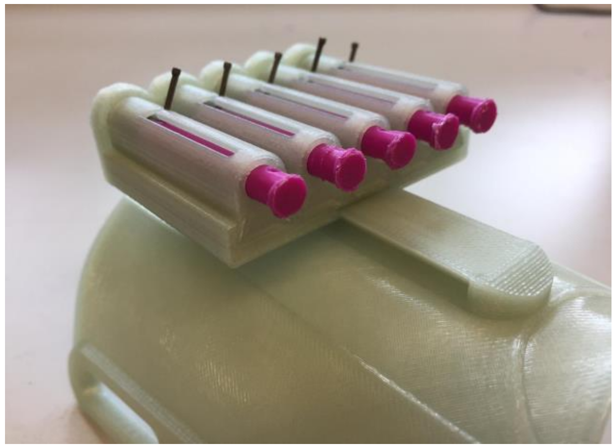

Figure 3: 3D printed IFC mechanism attached to gauntlet

3.2 Grip Locking Mechanism

Figure 4 shows the grip lock mechanism, which consists of three parts: the switch, the shim, and the bottom plate. Figures 5, 6, and 7 show the working of the locking mechanism. In the first stage (Figure 5), the locking mechanism is not active and we can see the channels where the string passes through are still visible. In the second stage (Figure 6), as we move the switch from the left (grip lock off position) to the right (grip lock on position), the bottom portion of the switch interacts with the shim and begins to clamp down. At this stage we can see that the channels are increasingly less visible. By the time we reach the last stage (Figure 7), we can see that the shim part is completely touching the bottom plate, hence clamping down on the string and creating a grip lock. This mechanism will help the user create a tight grip on an object that will be held for a long time instead of relying on the wrist movement to actuate.

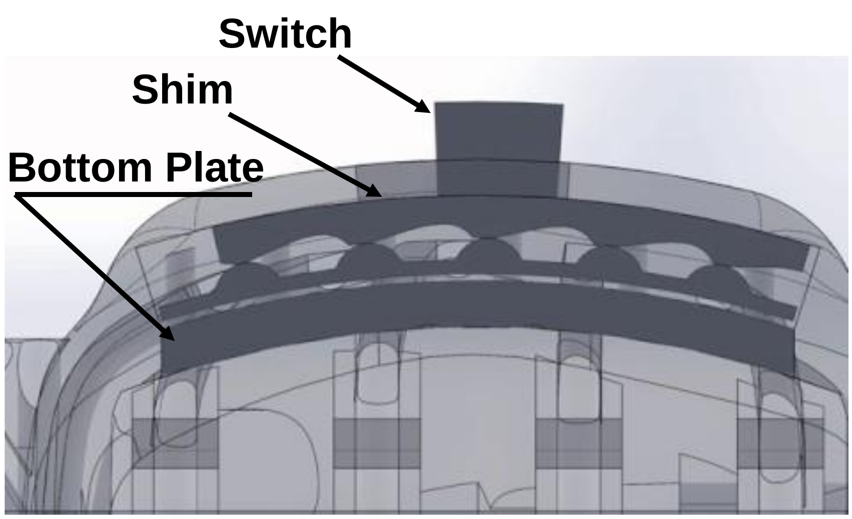

Figure 4: Grip lock mechanism

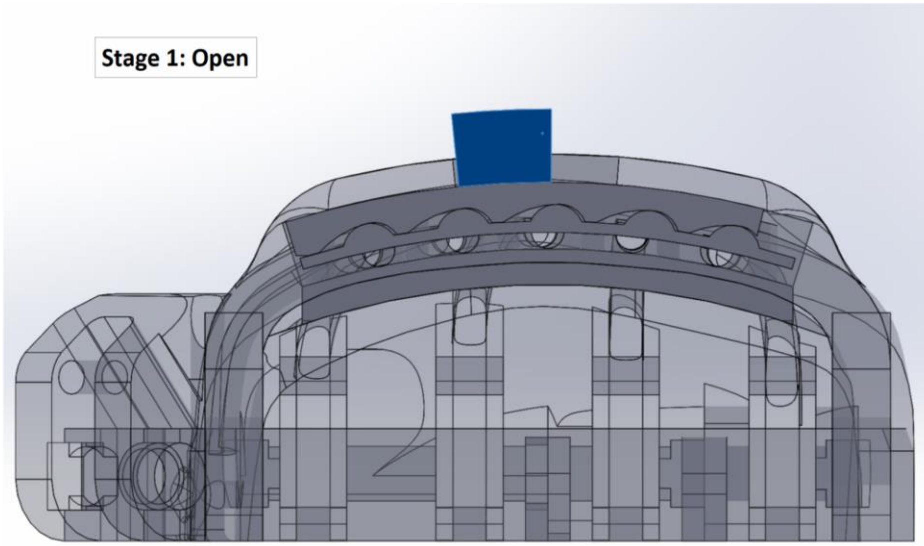

Figure 5: Grip Locking Mechanism open (unlocked)

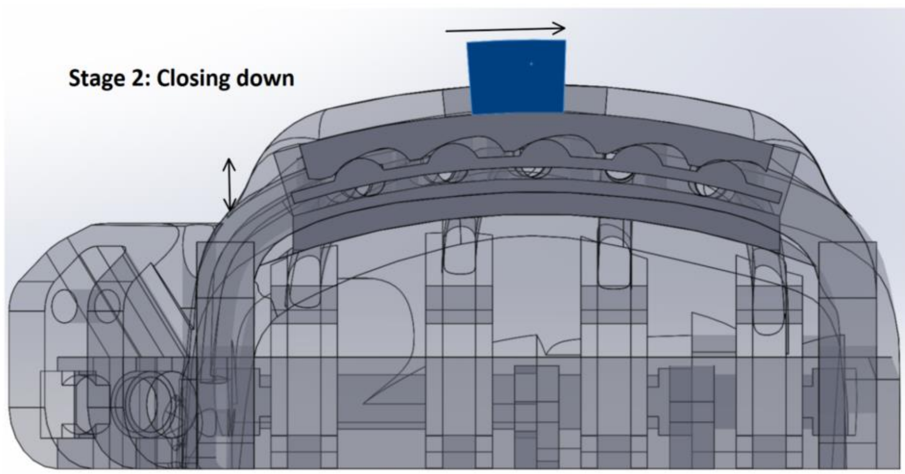

Figure 6: Grip locking mechanism in transition from unlocked to locked

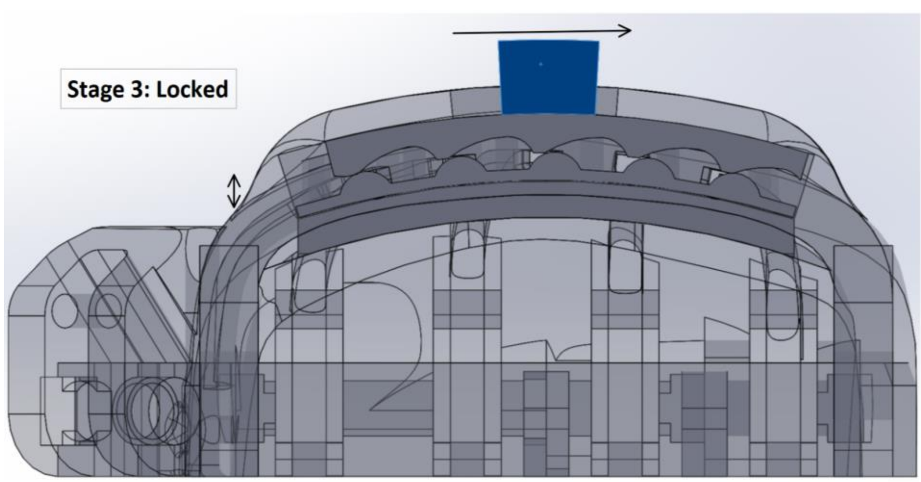

Figure 7: Grip locking mechanism locked

4. Results and Discussion

4.1 Design Testing and Discussion

Given the short duration (10 weeks) of this project, the team was not able to conduct user interviews nor feedback. Nevertheless, tests were conducted by team members using the specially-designed hand prosthetic meant to be worn by individual whose hand is intact. Three tests were devised and conducted: two separate precision tests, and a grip strength test. Each test was conducted using both a standard Reborn hand assembly as well as our modified Reborn hand with Individual finger control and grip lock. The first grip precision test is intended to evaluate the effectiveness of the individual finger control for tasks requiring a precise grip. This test consists of a pile of 15 washers (25.25mm Dia. x 1.25mm thick) which the tester picks up and places—one at a time—to form a second pile approximately 7 inches away. With the modified Reborn hand, the individual finger control is set to permit only the thumb and forefinger to perform the task. Each prosthetic was allowed 60 seconds to perform a trial. The second precision test is to evaluate both hands' ability to accurately make button selections, such as on a telephone or microwave oven. This test consists of a self-made four-button device assembled using a breadboard, Arduino, and four off-the-shelf push buttons attached to four multicolor LEDs. With the buttons numbered 1-4, a human tester was tasked with using each prosthetic to accurately push the buttons in a predetermined pattern at a fast pace. As they pressed the buttons, a second person watched the LEDs and recorded any incorrect button presses. The third and final test was designed to measure the advantage of a prosthetic having silicon fingertips installed, and the effect of this on the grip strength of the prosthetic. For this test, a length of fishing line was attached to the bottom of a one-inch diameter carbon fiber rod of negligible weight. Each prosthetic then held the rod as weight was hung from the bottom of the fishing line. Weight was added until the rod slipped from the hand's grip. The weight at which slippage occurred was then recorded.

Table 1: Grip Precision Test 1 - Stacking Washers
(Modified Prosthetic Hand [with thumb and index finger active])

	Washers moved from A to B	Washers Dropped	Washers failed to pick up
Trial 1	10	2	3
Trial 2	8	4	3
Trial 3	8	4	3
Trial 4	10	2	3
Trial 5	11	1	3

Table 2: Grip Precision Test 1 - Stacking Washers
(Standard Prosthetic Hand)

	Washers moved from A to B	Washers Dropped	Washers failed to pick up
Trial 1	9	3	3
Trial 2	10	2	3
Trial 3	10	2	3
Trial 4	9	3	3
Trial 5	8	4	3

Table 3: Grip Precision Test 2 - Patterned Button Pressing
(Standard Prosthetic Hand)

	Correct Input	Incorrect Input
Trial 1	3	11
Trial 2	6	8
Trial 3	4	10

Table 4: Grip Precision Test 2 - Patterned Button Pressing
(Modified Prosthetic Hand [with thumb and index finger active])

	Correct Input	Incorrect Input
Trial 1	13	1
Trial 2	14	0
Trial 3	14	0

Table 5: Grip strength Test - Weighted Rod
(Standard Prosthetic Hand, without silicone fingertips)

	Weight when slippage began	Weight when full slippage occurred
Trial 1	550 g	550 g
Trial 2	500 g	500 g
Trial 3	490 g	490 g
Trial 4	700 g	700 g
Trial 5	600 g	600 g

Table 6: Grip strength Test - Weighted Rod
(Modified Prosthetic Hand, with silicone fingertips)

	Weight when slippage began	Weight when full slippage occurred
Trial 1	1600 g	--
Trial 2	1464 g	--
Trial 3	1565 g	--
Trial 4	1500 g	--
Trial 5	1565 g	2240 g

4.2. Pre- and Post-Internship Student Survey

One of the key objectives of the summer research internship is to broaden the participation of minority students in research. To achieve this, priority was given to students from groups that are traditionally underrepresented in engineering. For the mechanical engineering group, four out of the five student interns were Hispanic and one was Caucasian. All of the students had at least one more year of community college coursework before transferring to a four-year institution to pursue their baccalaureate degree in mechanical engineering. All have completed the first semester physics courses but have varying preparations in engineering courses. All completed the freshmen level Engineering Graphics course, three have completed Circuits Analysis, and none has completed either Materials Science or Statics. To evaluate the success of the 10-week internship program in its goal of providing a successful group research experience for the students, pre- and post-internship surveys were conducted for each of the students as a cohort. A few insights were drawn from the surveys, which are summarized in Table 7.

Table 7. Students' Responses to Pre- and Post-Internship Questionnaires (1-Strongly Agree, 5-Strongly Agree.)

Question Prompt	*Post-Internship*	*Pre-Internship*	*Difference*	*% Increase*
I can imagine myself continuing after my BS to pursue a Master's Degree in a STEM field .	4.38	3.85	0.53	14%
I understand how scientists work on real problems.	4.13	3.7	0.43	12%
I am ready for more demanding research.	4.28	3.85	0.43	11%
I have skill in science writing.	4.16	3.76	0.4	11%
I understand the research process in my field.	3.81	3.42	0.39	11%
I have a clear understanding of the career opportunities in science.	4.28	3.97	0.31	8%
I have skill in how to give an effective oral presentation.	4.31	4	0.31	8%
I understand how knowledge is constructed.	4.03	3.76	0.27	7%
I understand how scientists think.	4.06	3.79	0.27	7%
I have the ability to integrate theory and practice.	4	3.76	0.24	6%
I can imagine myself continuing after my BS to pursue a Ph.d. in a STEM field/Medical School/other education beyond the Master's level.	3.72	3.48	0.23	7%
I have a clear career path.	4.16	3.94	0.22	6%

One of the most surprising insights that arises out of the summer research internship program was the fact that the biggest increase in students' responses is for the prompt "I can imagine myself continuing after my BS to pursue a Master's Degree in a STEM field." The average score increased from 3.85 to 4.38, a 14% improvement. Another similar prompt "I can imagine myself continuing after my BS to pursue a Ph.D. in a STEM field/Medical School/other education beyond the Master's level" also received an improvement of 7% comparing pre- and post-internship. As a background, all the community students who participated in the summer internship were either sophomores or early juniors, and hence some may not have figured a path toward completing 4 years of college, let alone graduate school when they started the internship program. The response to this prompt affirmed the value of the internship program in successfully planting the seed toward academic excellence. This is further supported by the positive responses to the other prompts "I am ready for more demanding research" and "I have skill in science writing" – both recorded a marked improvement (11%) from pre to post internship. Overall, the internship program has achieved its goal of creating strong awareness of STEM research as a career option, strengthening the learning of STEM subjects, and very importantly, giving participating students a boost in their interests and confidence in STEM.

Lastly, through this internship program, a few key lessons about what constitutes an effective internship program can be learned. As far as an effective internship program is concerned, students will need to be made the key stakeholders and content owners of the work, rather than just hired hands to run tests or to make things. And, the nature of the work should best be something that is perceived to be a “great cause” (adjustable child prosthetics in this case). For this particular project, the 5 students were given a rather ill-defined topic (related to child prosthetics), and were asked to brainstorm and define the topic. To this end, the students did an outstanding job of defining the problem, conceiving a solution, refining design procedures, and researching the background information necessary to support their proposed solution. In short, the students owned the problem and the solutions from start to finish, and they did so by overcoming many technical challenges as well as initial minor team dynamics issues. As a matter of fact, the most beneficial and critical aspect of this internship experience—aside from the eventual prototyping process—is the initial process of defining a real problem (through many trials and ideas being shot down) and coming up with well-researched and meaningful solutions to solve the problem. Finally, taking the risk of failure out of the internship is also an important element that the mentors need to stress at the beginning of the internship and repeatedly throughout the internship. Students were allowed the opportunities to try and fail without being judged, and through such trials and failures, learn the gist of design and prototyping. This is a great way to learn and is the only way to become a seasoned design engineer.

5. Conclusion

The collaborative partnership between Cañada College and San Francisco State University in developing a group summer research internship for community college students has been successful in creating opportunities for students, especially those from underrepresented minority groups, to engage in advanced academic work that develops research skills and applies concepts and theories learned from their classes to real-world problems. The program was successful in recruiting students from underrepresented minority groups as evidenced by the higher participation rate among Hispanic students compared to the overall engineering enrollments. The unique design of the program, i.e., group research internship that provides both half-time and full-time positions, has made these opportunities available to community college students who would otherwise not consider research and internship positions. The group setting wherein students work with their peers and faculty they know will give students the supportive learning environment needed to succeed in their first internship opportunity. The half-time positions were targeted towards students who have at least one more year of courses to complete at the community college before transferring to a four-year university to allow students to take summer courses they need for transfer as well as accommodate the work schedule of working students.

Results of the survey of program participants also showed that the program has helped students in solidifying their choice of major, improving preparation for transfer, enhancing student self-efficacy in pursuing careers in engineering, and acquiring knowledge and skills needed to succeed in a four-year engineering program. The humanitarian aspect of the project done by the mechanical engineering group in designing low-cost functional prosthetics for children proved to be particularly important in helping understand and appreciate the value of an engineering career. As a result of their research experience, the participants have also expressed that they are now more likely to apply for other internships and consider pursuing graduate degrees in engineering.

The collaboration between Cañada College and San Francisco State University, which has created opportunities for community college students to engage in research, has been mutually beneficial to both institutions. Research activities that were directly developed by the ASPIRES program participants enriched academic experiences of students at all institutions while enhancing the research capabilities of the university and strengthening the engineering transfer program at the community college. The success achieved through this partnership has contributed to promoting engineering education, led to an improvement the programs and services offered at both institutions, and can serve as a model of collaboration for improving engineering education at public institutions of higher education.

Acknowledgments

This summer research internship was supported by the US Department of Education through the Minority Science and Engineering Improvement Program (MSEIP), *"Accelerated STEM Pathways through Internships, Research, Engagement, and Support"* (ASPIRES**),** Grant No. P120A150014.

References

1. Lopatto, D. (2007). Undergraduate research experiences support science career decisions and active learning, *CBE Life Sciences Education* 6: 297-306.

2. Russell, S. H., M.P. Hancock, and J. McCullough. (2007). The pipeline. Benefits of undergraduate research experiences. *Science* 316(5824): 548-9.

3. Kinkel, D. H. and S. E. Henke. (2006). Impact of undergraduate research on academic performance, educational planning, and career development. *Journal of Natural Resources and Life Sciences Education* 35: 194-201.

4. Lanza, J. and G. C. Smith. (1988). Undergraduate research: A little experience goes a long way. *J. Coll. Sci Teach*. 18:118-120
5. Hunter, A-B., S. L. Laursen, and E. Seymour. (2007). Becoming a scientist: The role of undergraduate research in students' cognitive, personal, and professional development. *Science Education* 91: 36-74.

6. Nagda, B. A., S. R. Gregerman, J. Jonides, W. von Hippel, and J.S. Lerner. (1998). Undergraduate student-faculty research partnerships affect student retention. *The Review of Higher Education* 22: 55-72.

7. Hathaway, R., B.A. Nagda, and S. Gregerman. (2002). The relationship of undergraduate research participation to graduate and professional education pursuit: An empirical study. *Journal of College Student Development* 43(5): 614-631.

8. Guterman, L. (2007). What Good is Undergraduate Research, Anyway? *The Chronicle of Higher Education*, *53*(50) A12.

9. Cabrera, A., Crissman, J.., Bernal, E.., Nora, A., & Pascarella, E. (2002). Collaborative learning: Its impact on college students' development and diversity. *Journal of College Student Development*. 43(2), 20-34.

10. Swail, W. (1995). *The Development of a Conceptual Framework to Increase Student Retention in Science, Engineering, and Mathematics Programs at Minority Institutions of Higher Education*. Ed.D. dissertation, The George Washington University.

11. CDC. (2016, November 14). Birth Defects. Retrieved July 26, 2017, from https://www.cdc.gov/ncbddd/birthdefects/ul-limbreductiondefects.html

12. Borne, A., Porter, A., Recicar, J., Maxson, T., & Montgomery, C. (2017). Pediatric Traumatic Amputations in the United States. *Journal of Pediatric Orthopaedics, 37*(2). doi:10.1097/bpo.0000000000000693

13. Internet Medicine Admin. (December 13, 2014). *M-fingers* [Infographic]. Retrieved from:http://internetmedicine.com/2014/12/13/theres-a-new-touch-in-prosthetics-have-you-considered-silicone-lately/

14. Carey, S. L., Lura, D. J., & Highsmith, M. J. (2015). Differences in myoelectric and body-powered upper-limb prostheses: Systematic literature review. *Journal of Rehabilitation Research and Development, 52*(3), 247-262. doi:10.1682/jrrd.2014.08.0192

15. Resnik, L., Meucci, M. R., Lieberman-Klinger, S., Fantini, C., Kelty, D. L., Disla, R., & Sasson, N. (2012). Advanced Upper Limb Prosthetic Devices: Implications for Upper Limb Prosthetic Rehabilitation. *Archives of Physical Medicine and Rehabilitation, 93*(4), 710-717. doi:10.1016/j.apmr.2011.11.010