# Adaptive Component Design
# Leads to Rethinking the Design Research Process: Experiential Learning in Undergraduate Research

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**Abstract**

**Background**: Experiential-learning provides students the opportunity to apply their knowledge of the new product design and development (NPD) process and extend their understanding of how NPD is accomplished. These opportunities are varied and may require flexibility in implementation by faculty mentors and students.

**Purpose:** This project drew on the faculty mentors' professional experience and engagement with design engineering projects and explored how we can engage students in a very individualized and customized application of the NPD processes. Our initial research question included: 'Could we develop adaptive devices to enable a 10 year-old with unique physical challenges to ride a bicycle?' Our client has primary use of one leg and one arm and we were uncertain if this design challenge could be achieved.

**Design/Method:** Our project involved working directly with a child and his parents which required training in 'Research involving Human Subjects' and an Institutional Review Board (IRB) application and approval. This IRB training helped us stay focused on the needs of our client through our design process. We primarily used Human Factors observational and interview methods for our data gathering. Through concurrent data gathering, design, and analysis an iterative processes of designing, fabrication, and testing of bicycle configurations and adaptive attachments led to our successful proof-of-concept prototype. Our client with his prosthetic leg and a short arm is now able to ride a bicycle with his friends.

**Results:** The required pre-project training in the Belmont Principles and 'research involving human subjects' created a shift in how we designed our data gathering processes resulting in a more engaged client, a revised design process and better results. This type of high-stakes project motivates and engages students with its condensed timeline (the students were graduating at the end of the spring semester), a real client and real design requirements.

**Conclusions:** This undergraduate research, design and build project provided the opportunity for college seniors to apply their skills in an engaging way where results were very uncertain but at the same time highly desired and valued by their client. Our team reimagined our design research and testing processes to adapt to the specific clients' ways of engaging with the project.

## "Can you make something that would allow my son to be able to ride a bike?"

**Background**: We were approached by an academic colleague with a question, "Can you make something that would allow my son to be able to ride a bike?" His son is a very active, 10 year old missing the forearm bones in his left arm and has a prosthetic leg adapted to fit his thigh on the right. When we met him, he was quite adept at pushing himself around on a small, human-powered, RazorA-type scooter. We were intrigued on many levels. Our students have designed and built many new product concepts in their courses in our product design program. We have excellent prototyping and manufacturing labs including additive manufacturing equipment. Some of our students are interested in careers in the adaptive technology and prosthetics industry. The faculty mentors have experience with building, maintaining, and competitively riding bicycles. We set our design question as: 'Is it possible to design and build adaptive devices and modify a bicycle to a allow our client to ride?' We did not want to assume it was possible due to the high level of unknowns, including our client's abilities and strength and the adaptability of bicycle configurations.

In a product design educational program students build their competencies in the new product design process through learning many methodologies in design research and analysis, defining design requirements, ideation, evaluation, modeling, prototyping and testing. The product design and development structure typically starts with identifying and defining a need, using various design research methods, data collection, analysis and defining design requirements. The process moves on to concept generation, concept evaluation, implementing designs, testing prototypes, and eventually communication of the design details to production. Product design and mechanical design textbooks by Ulrich and Eppinger (1995,) Ullman (2003,) and Cross (2008) discuss many of these NPD methodologies. Kelly (2001) in *The Art of Innovation* describes his methods in terms of the "Understanding, Observing, Visualizing, Evaluating and Refining, and Implementing." Koberg & Bagnall (1974) and Cross (2008) add to describing the NPD processes and emphasize feedback loops where the design process involves learning about the design challenge and this learning may require reexamining earlier design stages. For students, as novice designers, to grasp this cyclical/spiral-like process will help them move beyond solution fixation. From the data gathering and conceptual stages to the detail design stages, there are challenges that need solutions and this process is used repetitively.

In our product design-oriented program, our students gain experience moving through these new product design and development processes, gathering data and working towards solutions. They use project planning methods like Gantt charts and tools for organizing and analyzing their design research, design requirements and solutions including a modification of the 'house of quality' Quality Functional Deployment (QFD) diagram (Ullman, 2003 pg 143-

170). Design research methods including observations and interviewing help to capture the 'voice of the customer' and the QFD helps to keep these requirements visible and centrally located during the design process (Cross, 2008, Ullman 2003). Generally once the design research is completed, analyzed and the design requirements formed, the designers move on to the concept generating, visualizing, prototyping and testing phases. Sometimes, for students, the testing phases include their proposed 'customers' but often the testing does not reach outside of the course labs and participants.

**Purpose:** This experiential-learning opportunity provided us a framework to have a few students engage in a design engineering challenge with unknown outcomes. This type of project is new for the students and is much 'higher-stakes' with real clients, a real timeline (their graduation) and with real results that will affect real people. Instead of a classroom scenario, we were, in a sense, a design firm with real challenges needing to be solved and with an uncertainty of success. We would use our new product design and development methodologies to design the process for carrying out our research and the students would be key team players. Our client had very specific size, strength and coordination attributes that needed to be identified. The very real risk for the project was disappointment. We were unsure if riding a bicycle was possible for our client so we were very clear in the beginning that this was an exploration with unknown outcomes. Our client and his parents were very willing to try since they had already tried unsuccessfully to ride a bicycle and imagined that if the sizes and adaptions were different it might work. They came to the project with a very positive willingness to try.

Bicycles contain many mechanical and functional design nuances that would provide great teaching and learning opportunities for the students. We would consider center of gravity effects on balance and safety, power ratios and mechanical advantage, mechanical fitment, connection design, and strength of materials. Building testing fixtures and adaptive devices would have the faculty mentors and students sharing knowledge on CAD drawings, machining, measurement and other manufacturing methods.

This type of experiential-learning can provide the novice designer with the opportunity for primary research using direct observation of the human/object interface. This type of 'action research' (Johnson, 2008) is unpredictable and allows the faculty mentors to model observation techniques, open-mindedness and inductive reasoning moving from observed phenomenon to making connections with previous knowledge to incremental design decisions. This type of authentic problem-solving builds creative and critical thinking skills expected of a college graduate. (Doyle, 2008)

**Design/Method:** <u>Pre-project planning and client relations</u>: Unlike many of the student design projects, we would be working physically close with our client who is a minor. This situation required us to have our project approved by our Institutional Review Board (IRB). Before submitting our project proposal the faculty mentors and the students were required to engage in the online training related to 'research involving human subjects.' Like many institutions, ours uses the Collaborative Institutional Training Initiative (CITI) courses. One of the project's faculty mentors had done this training before and was aware of the beneficial learning and framework it provides. We selected two topic courses *Biomedical Responsible Conduct in Research* and *Responsible Conduct of Research for Engineers*. The Biomedical course included units on The Belmont Report, history and ethics, IRB regulations and process, informed consent and conflicts of interest. The Engineering course also included units on Research involving Human Subjects and several other ethical research topics (CITI). This training helped provide greater societal support for the ethical principles we, as instructors, try to impart to our students. Many of the nuances around protection of privacy, informed consent, and working with the developmental levels of minors were illuminated by the information in the training courses. Our students were made aware of the importance of proper ethical practices in our research and its implications in their careers.

This pre-project training on ‘research involving human subjects’ set a framework for how we thought about creating our research process and how we tested our designs and prototypes. The Belmont Report (1979) gives a simple way to remember:

> “The Basic Ethical Principles,
> 1. Respect for Persons,
> 2. Beneficence
> 3. Justice.”

‘Respect for Persons’ had us thinking about and communicating our process. We informed our client and his parents that they can stop their participation at any time. Their right to privacy was considered in the way we would protect their identity in our documentation processes including non-identifiable photographs and keeping our data from getting into a public realm. Any publicity of the project identifying the clients would need their permission. In planning our bi-weekly interactions with the client, we wanted to make sure he was having a positive experience. We were meeting with him and his parents after his school day so we had to be very aware of his energy and interest levels, be flexible and adjust our progress accordingly.

Our communications with our client let him know that ‘he was the boss’ and could stop any activity at any time if he felt uncomfortable or did not want to do it. Discovery by all of us was part of every meeting. At one meeting we had created a conceptual mock-up in professional model-making clay for him to grab with his fingers in his short arm to help with balancing on the handlebars. He did not like the feeling of the clay so we found another way to prototype the adaptive device. We found that respecting the client's needs and comfort levels was paramount to maintaining his engagement with the project.

'Beneficence' had us thinking about making sure we did no harm. We thought about the consequences of failure in each design decision and test. In the informed consent agreement we asked that our client always wear a bicycle helmet and to not take the training wheels off until an agreement was made with his parents. As we went through the design and prototyping processes we thought about how to make this process easy, enjoyable and safe for our client. While planning our meetings with our client we thought through how to make all the adjustments, made sure all the tools were handy, and we had a plan for keeping our client either engaged or had something to do while we did our work. For example, we discovered through our discussions that our client was very interested in CAD software. Several times, we had CAD models pulled up on the computers so one of the students could show our client their virtual 3D models of the adaptive components we were planning to build or images of him on the bicycle created in CAD by our students. At other times we brought our client into the lab and had him help with the tools as we made adjustments. Our thoughtfulness around engaging our client so he would have a positive experience created an atmosphere of 'designing with' instead of 'designing for.'

'Justice' had us thinking about the reasons we were engaged in this project. Our client would directly benefit from this project if it was successful, by being able to ride with his friends, who at age 10 were pedaling around their neighborhood, testing their independence. If this goal was not achieved we would have helped him and his family move closer to understanding their other options, like a tricycle version. The knowledge we gained from this project may enable us to help others with physical challenges.

Project Progress: The students helped develop a plan for the project, creating a Gantt chart that was updated several times as we tracked our progress, assigned tasks and further defined the detailed design. We needed to design methods and build devices to capture ergonomic data. First was a way to hold the testing bicycles stationary while our client pedaled. We needed to find a source of bicycles and parts. We needed to purchase materials and specific tools our lab did not have, for example a 9/16-20 tap to thread new holes for pedal adaptions. We planned to use technologies available to us including video cameras, computers with CAD and CAM software, a Fused Deposition Modeler (FDM) additive manufacturing machine (commonly referred to as a 3D Printer), and a prototyping and metal machining laboratory.

We were able to find a collaborative source for bicycle parts. Bicycles are very common and part of life for most young people and active adults in our region. As children grow and change their riding preferences, there have become a large number of discarded bicycles. In our community there are a few organizations that have dedicated themselves to refurbishing older bicycles and making them affordably available. Through community outreach we were able to contact the Bellows Falls Community Bicycle Project, a non-profit organization with a plethora of used bicycles and parts. They let us borrow many bicycle parts and frames in different sizes to help us with capturing ergonomic data, testing and fitment. Using as many existing components as we could helped us determine the fitment to our client much faster than if we had to design and build a frame. Our process of multiple, iterative prototypes reflected the IDEO motto of "Fail often, to succeed sooner" (Kelly, 2001.)

Our initial plan was to capture the dimensions and abilities of our client during our first meeting and then proceed with our design work. Our Human Factors data collecting focused on observations with most importantly documenting the sequence of activities and the spatial movements (Stanton, 2005). We also used informal interviewing as we solicited continuous feedback directly from our client. Our first observations became a pilot observation leading to redesign of the data collection process. Each discovery would lead to new information, design redirection, adaptations and revisions. During our first meeting we observed that our client, while using his human-powered scooter, could only create power with his prosthetic leg when it was in straight alignment with his body. With feedback from our client, we also observed that he had to be in a more upright position to reduce pressure on an attachment pinch- point of is prosthetic leg. Keeping the Belmont principle of 'Respect for Persons' in mind, this was all that we could accomplish at our first meeting. We revised our plan to one of concurrent data gathering and design work. After each meeting we debriefed, answering the question of 'What did we learn?', and planned our next steps with 'What can we do with what we learned in terms of the design?' and 'What data do we need to gather next?' Our methods evolved as each discovery helped move the project in an incremental way, based on the rhythm and needs of the client, during our client interactions. We found that in order to keep the client engaged the client's needs had to lead the pace and the schedule of our work.

The design and engineering challenges of adapting a bicycle for our client's specific needs soon proved to be beyond tradition bicycle fitment and design parameters. We needed to prioritize the data gathering and design as each solution would allow us to discover new information about the next design priority.

1. Balance and upper body position,
2. Getting on and off the bicycle
3. Creating power for propulsion
4. Steering and control
5. Shifting and Braking, only one hand can be used
6. Pedal staying horizontal, toe up with adaptive device always on top
7. Prosthetic foot removal from pedal (emergency stops)
8. Details of steering

The first bike frame we tried proved to be too small. We had to adjust the seat so high that our client's high center of gravity and the short wheel base would have proven unsafe on anything but flat surfaces. Going up a hill may have put his center of gravity behind the axle of the rear wheel. One of the first big discoveries was foot (pedal) brakes would not work. Only one of our client's legs had enough strength to push backwards for stopping and if it was in the front two quadrants of rotation he would not be able to stop. Also when getting on the bicycle the pedal for his prosthetic foot needed to be in the upper front quadrant of the pedal rotation. Getting on and off the bicycle required the pedals to freewheel backwards for alignment. The pedals on a foot brake system cannot be rotated without rolling the bicycle or picking up the back tire, neither being acceptable operations.

**Figure 1. First bicycle for testing with stand**

With a larger frame for our next meeting we adjusted the seat height so his good leg could power the crank. We discovered that his prosthetic leg was mostly 'along for the ride' but helped with a little power in the lower, forward quadrant of the pedal rotation. The larger-frame bicycle had 5-speed gearing on the rear wheel which is not conducive to mounting training wheels. We needed


**Figure 2. Posture on the bicycle as a design challenge**

**Figure 3. Hip position and arm length variations as design challenges**

to make custom training-wheel attachments so our client could learn to ride. To give our client enough range of power to get the bicycle started and to go up hills we needed the 5-speed rear axle gearing and had to custom-machine a smaller front gear for the crank set. After several meetings testing various configurations, it also became apparent that our client had the dexterity to use a toe clip on the pedal of his strong leg. We added the toe clip which increased the power he could deliver to the pedals through the entire pedal rotation.

Figure 4. Gathering more data on the prosthetic foot to pedal alignment

The prosthetic foot needed to be secured to the pedal and not slip out while riding. We observed that there was very little articulation between the lower leg tube and the foot of our client's prosthetic. After we made our first adaptive 'slipper' and had our client test it, revisions were needed to the location of the prosthetic foot's engagement with the pedal. We found that the power transmitted through the joints in his prosthetic leg resolved primarily vertically under the shaft where the lower tube connected to the foot. With the prosthetic leg and foot always at forward angles while pedaling, the 'slipper' needed to be move aft to keep the leg tube located vertically over the pedal axle while in the front quadrant, for our client to be able to exert power through his prosthetic leg and keep balanced over the pedal. The 'slipper' needed a shallow toe cup to keep his foot on the pedal and needed to be angled outward slightly to keep his leg with


Figure 5. Testing and documenting revised 'slipper' designs to accommodate the prosthetic leg and foot angled positions to improve balance and power.

Figure 6. 'Slipper' design with toe cup to hold in the foot, an open side for quick release, and toe-out angle for better tracking

the prosthetic tracking correctly and comfortable as he pedaled. Each meeting led to discovering new information. Our client was also learning about himself and his own capabilities. This incremental, slowed-down process respected the available time our client could spend with us and most importantly made his engagement and feedback a very important part of our design effort. We were able to keep reassessing what worked and what did not work which ultimately led to a successful outcome.

**Figure 7. Client testing with training wheels**

Our client became more and more comfortable as he was able to sit and pedal the bicycle on our stationary fixtures for longer periods of time. We needed to custom-design and weld a stem to raise the handle bars. An upright body position was needed for steering control with his full-length arm and with the prosthetic leg being more in-line with the body he had better power and comfort. His shorter arm needed to contact the handlebars for balance and control without twisting or leaning forward. The seat needed to be angled slightly to prevent interference with the top of his prosthetic leg. After the adjustments to achieve comfortable and effective positions for his torso, legs and feet, we were able to capture the correct geometric and dimensional data for locating the adaptive hand-hold for his shorter arm.

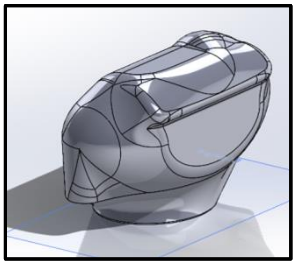

**Figure 8. CAD model of a hand grip adaption. One of many ready for 3D printing**

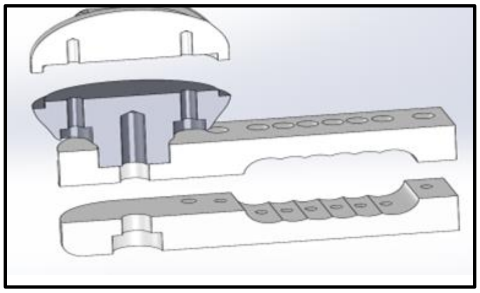

**Figure 9. Offset Hand support CAD assembly with designed-in adjustability**

Our designs for the adaptive hand and foot devices included designing-in adjustability to help us easily find the most comfortable and effective positions. This made the best use of our short meeting times with our client. Once a comfortable position was identified we were able to redesign and simplify the adaptive devices. We still included some adjustability in the proof-of-concept prototype that our client would use over the summer. As he improved his riding skills he and his parents could make some adjustments.

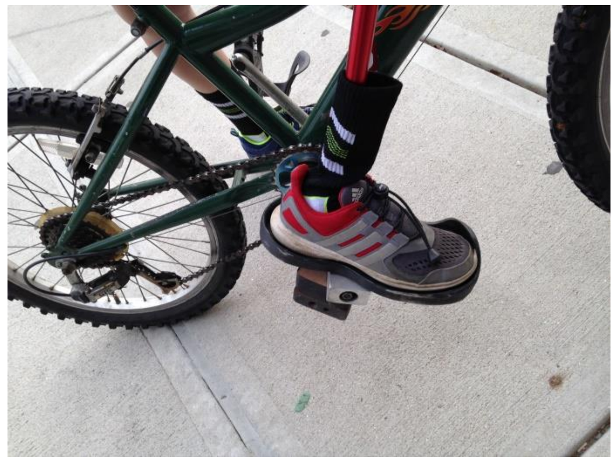

**Figure 10. Bicycle frame repainted green and ready for the client. Note: this photo was taken after he had learned to ride with the training wheels off**

The two senior students who worked on the project in the academic year 2014-15 completed their preparation in the fall semester and implementation in the spring semester. By the end of the spring semester, we were able to achieve a functional and field-testable proof-of-concept prototype. Before handing this prototype over to our client for the summer, we tore the bicycle apart, cleaned and painted the frame from purple to green, our client's favorite color. The bicycle was greased and reassembled ready for extended use. Our client rode the bicycle all summer quickly gaining skills and balance. He and his father were able to take the training wheels off within 2 weeks.


**Figure 11. Our client riding with his friends**

During the implementation semester, the students took on more and more management responsibilities. Using the planning process and their Gantt chart they resolved their own conflicts over time commitments, and self-assigned tasks and job titles. They asked for and accepted faculty mentorship and assistance. We were glad to answer our research question in the affirmative and were indeed able to create an adapted bicycle that our client was able to ride and ride exceedingly well.

Opportunity for Redesign: Our client rode with his family and friends all summer and through the fall season. They came back to us with feedback about how the proof-of-concept prototype worked. Some parts had shown signs of wear and some of the adjustable components had loosened and needed tightening from time to time. Some features of the hand-adaptive device were not used very much. As expected our client has grown with increases in his shoe size and prosthetic leg length. We have another opportunity for students to get engaged in redesigning the components and improve their functionality.

This year we have two new seniors taking on the project and are well into the design process. They went through the IRB process and training and have planned to resize the adaptive foot pedal piece and redesign it for future adjustability. They are planning to redesign the pedal counterweight system, and create a fairing for the foot pedal adaptive device to protect the mechanical components from impact with an aesthetic message of fleetness. We are using what we learned about incremental, concurrent data collecting and design as we plan each meeting with our client.

**Results:** The principles conveyed in the pre-project training led to rethinking how we, students and faculty mentors, developed our data gathering and testing plan that focused on the unique needs of the client. Our initial research question included: Could we develop adaptive devices to enable a 10 year-old with unique physical challenges to ride a bicycle? As our plan developed, our methods evolved as each discovery helped move the project in an incremental way, based on the rhythm and needs of the client. In order to keep the client engaged, we found that our client's needs had to lead the pace and schedule of our work. The pre-project training on 'research involving human subjects' set a framework for how we planned, revised and implemented our research process and how we tested our designs and prototypes.

Our project involved reconfiguring and remaking many bicycle components, many times. Our community outreach to obtain bicycle components created very positive relationships between the college and our surrounding communities. A multitude of technologies were used to gather data, including building a bicycle testing stand, using photography and video, designing and creating dimensioning devices, creating CAD drawings, creating parts with additive-manufacturing technologies, and machining and fabricating parts. As the students found the need to design devices to capture dimensions, they developed their skills related to prosthetic design. These skills are transferable to areas like fixture design, product design and quality assurance. Our prototypes needed to be designed and built with a multitude of adjustability. We needed to accommodate adjustments while the client was learning to ride the bicycle and maximize the amount of information attainable during each meeting with the client.

**Conclusion:** The project resulted in the students being able to apply the skills they have learned during their college education and show how the product design process and creative problem-solving can create an enriched experience for both themselves and for someone needing adaptive devices. Typically in product design and development there are more 'knowns' and less 'unknowns.' This project had unforeseen outcomes that took us beyond the norms and protocols of bicycle design. This project exemplifies the value of undergraduate research experiences to build student's capabilities and confidence while engaging them in a very rewarding activity.

The success of the project was, in large part, due to the client-focused approach inspired by the pre-project IRB training. This approach helped to build the client's ability to engage with us, to become part of the design team, and provide valuable feedback. The resulting custom-built bicycle with custom adaptations enabled the client to learn to ride very quickly. He is now, like other children his age, riding his bicycle to school, riding around with his friends and going on long rides with his parents, a very happy (and growing) customer.

The faculty mentors gained knowledge about how to mentor students through this type of custom design engineering project. Custom bicycle design and prototyping is a workable design/ build platform for undergraduate students. The incremental, concurrent data-gathering and design process increases engagement with the client and helps spread out the design challenges into scaffolded steps that are more manageable for undergraduate students. The process has provided guidelines for implementing this type of project with future students.

The student learning outcomes have included project management, ergonomic research, and incremental design planning. They have applied their CAD and prototyping skills and learned to design and implement tests to gather data. They have gained the social skills needed to engage with a client. This process is similar to new product design and development when a new functionality and technology are being explored. In an undergraduate setting, product design projects, even if open-ended, rarely provide the opportunity for this extensively iterative process and the motivation to make it work.

Special thanks to our first set of students, Alex Delcore '15 and Peter Solek'15 and our current set of seniors, Ryan Murray and Mackenzie Burton-Williams. We are very grateful to

our client and his family for their enthusiasm and engagement and for giving us the opportunity to use our design and engineering skills to improve their lives and the lives of others.

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