Design in Biomedical Engineering: Student Applications of Design Heuristics as a Tool for Idea Generation

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Abstract
Creative concept generation is an important source of successful innovation; thus, techniques that support creative conceptual designs are imperative to instruction on engineering design processes. One ideation tool, Design Heuristics, was developed through empirical studies of designs by professional engineers and in award-winning products. While the Design Heuristics strategies were identified and validated in the product design space, their application in biomedical engineering spaces has not been examined. In our study, we implemented a Design Heuristics lesson during one session of a semester-long biomedical engineering design course for upper-level undergraduates. In this paper, we present an analysis of three design teams from the course to examine the applicability and impact of Design Heuristics within biomedical engineering design problems. Findings revealed that the biomedical engineering students successfully engaged in idea generation using Design Heuristics to build new biomedical engineering concepts. The findings suggest that Design Heuristics can support idea generation in biomedical engineering contexts, demonstrating the value of Design Heuristics outside of the previously-documented mechanical engineering and industrial design contexts.

Introduction

A primary goal of the undergraduate engineering curriculum is to support students' development of design skills, demonstrated by the ABET[1] requirement that students should be able to "design a system, component, or process to meet desired needs." ABET also emphasizes that these solutions will need to be innovative to address the complex problems in the world today[2]. Idea generation and development are important processes in design that lead to innovative outcomes and instruction using idea generation tools can increase the likelihood of students' success in these processes. One idea generation tool, called Design Heuristics, has been shown to be beneficial to student solution processes and outcomes in engineering design courses[3,4]. The focus of these studies has been on product design in mechanical and multi-disciplinary engineering and industrial design courses. However, there is potential for Design Heuristics to be applied to other engineering disciplines, such as biomedical engineering.

Biomedical engineering design courses focus on medical devices, and incorporate a wide variety of expertise and engineering disciplines, including mechanical, electrical, and chemical engineering[5]. The breadth of experience represented on a design team can help to generate innovative and diverse ideas. Biomedical engineering design courses focus on the processes of reverse engineering, problem definition and conceptualization, preliminary design, final design selection, prototyping, testing, and marketing, as well as addressing some unique biomedical focus areas such as medical device regulation[6,7]. Within the field of biomedical engineering design, there has been limited discussion of how to instruct students about the idea generation process. Instruction on idea generation appears in some biomedical engineering design textbooks with an emphasis on mindset, collaboration, and versatility in idea generation, along with guidelines for facilitation[8].

However, textbooks in biomedical engineering design provide minimal information about techniques for idea generation. Design Heuristics have been shown to be valuable in multiple product design contexts and biomedical engineering product design may also be a relevant application area. Biomedical engineering design includes device-oriented designs that require physical interactions with users, and so may benefit from generative heuristics gleaned from end-user products. In this research, we explored the extent to which biomedical engineering students were able to apply Design Heuristics during idea generation, and whether they selected Design Heuristics-driven concepts as practical concepts to take forward in their design projects.

Background

The consideration of multiple and diverse concepts during ideation can lead to innovative solutions[9,10]. Research indicates that diverse idea generation is difficult for students,[11–15] and that limited resources exist for engineering educators on how to generate innovative concepts[16–20]. Common teaching methods for engineering idea generation include "brainstorming" and morphological analysis; however there is little formal idea generation instruction or systematic approaches to idea generation[16–20]. Tools to facilitate idea generation include brainstorming[21], brainwriting[22], conceptual combination[23], Design Heuristics[24], IDEO Method Cards[25], lateral thinking[26], morphological analysis[6,27], Synectics[28], SCAMPER[29], and TRIZ[30,31]. Each of these tools has a unique approach to guiding idea generation, varying in their focus specificity, and usability[4]. For example, SCAMPER aids in idea generation by defining general prompts;[4] Synectics provides general theme suggestions to define the contextual meaning of product, and brainstorming sets rules to guide a team during idea generation sessions[21]. Design Heuristics provide "rules of thumb"[32] to introduce variation in design based on analyses of past products[33]. Because of the existing evidence of the applicability of Design Heuristics in product design contexts[4,34], we selected this tool for use in a biomedical engineering design course.

Design Heuristics are idea generation strategies to prompt designers to explore a wide variety of ideas during idea generation, leading to more diverse and creative design concepts[35–37]. Cognitive heuristics as defined in the field of psychology facilitate "best guesses" at potential solutions, and their use has been shown to support expert performance[38]. They are heuristics rather than algorithms because they provide a suggestion towards a possible solution rather than a deterministic outcome. A specific set of 77 cognitive heuristics for product design, called Design Heuristics, have been identified in studies of expert and advanced product designers and analysis of innovative products[24].

Each of the 77 Design Heuristics provides a different, specific prompt, and is illustrated with a graphic representation and examples of its use in specific products. The heuristics are printed on an index card that can be considered by designers to prompt ideas. On the front of each Design Heuristic card, there is a title of the strategy, a graphic image, and a description of the heuristic (Figure 1). The back of each card provides two example products where the heuristic is evident, demonstrating how the heuristic can be applied to multiple products. One of these example is always a seating device, and the other example is a consumer product, represented by a variety of products throughout the set of 77 cards.

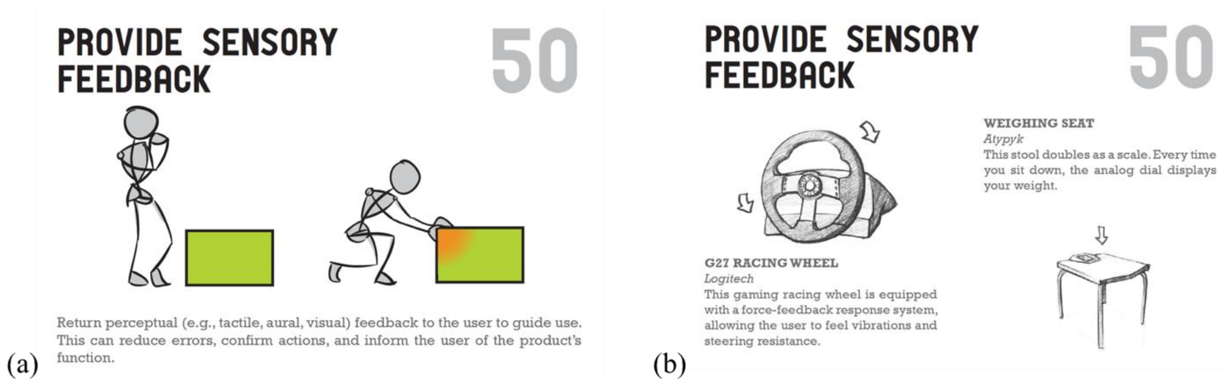

Figure 1. Design Heuristic card #50, Provide Sensory Feedback. (a) Front features the Design Heuristic strategy and description with image and text. (b) Back features two examples of how the heuristic can be applied.

For example, the Design Heuristic, *Provide sensory feedback,* prompts the designer to consider how to provide feedback to the user when they interact with the product. For example, in designing a prosthetic, this Design Heuristic could be applied by adding vibrating sensations for the user whenever their prosthetic touches a surface. By pushing the designer to consider aspects of designs noted by other designers, Design Heuristics can help novice engineers broaden their conceptions of the design space, consider non-obvious ideas, and generate multiple, diverse concepts[4].

In a series of studies, the Design Heuristics cards have been empirically validated as effective in helping students generate conceptual solutions to address design problems[39–41]. Designs developed with the cards were non-obvious and distinct, and led to diverse and creative ideas in later stages of the design process[3]. In studies with first-year mechanical engineering students[4,39], design concepts generated with Design Heuristics were more original than those generated without Design Heuristics, which were often replications of known ideas or simply minor changes to existing products[3]. Another study engaged first-year engineering students by teaching Design Heuristics as (1) a concept generation technique and (2) a concept transformation technique[42]. More variety of solution concepts was observed in design concepts generated with the Design Heuristics[43].

In a study with upper-level engineering students working in teams, concepts generated using Design Heuristics were observed as more practical, and were maintained from initial ideation through the final project design[3]. In this study of teams working on different design projects, Design Heuristics were found to be applicable across a diverse range of problems. In sum, Design Heuristics have been established as a beneficial tool to assist mechanical engineers in generating diverse and create ideas[3,4,41,42,44,45]. In the present study, we sought to determine whether this instructional method would also benefit students in the domain of biomedical engineering design.

Research Methods

Research Questions

The focus of this study was to investigate whether and how Design Heuristics may assist students in generating design ideas in the context of biomedical engineering problems. We were also interested in how students developed their initial ideas as they refined and developed their concepts. Our project was guided by the following research questions:

- How are Design Heuristics applied in concepts generated by biomedical engineering students?
- To what extent are heuristic-driven ideas present in concepts considered worthwhile and selected to take forward in the design processes?

Course Context and Participants

The goal of the biomedical engineering design course at a large Midwestern university was to design, test, and build medical devices for stakeholders such as university departments, clinicians, and industry. Skills developed through the course included problem definition, concept generation, detailed design, fabrication and evaluation, project management, and technical communication. Projects spanned from a wide range of topics including medical device creation, research equipment development, and usability of medical devices.

All students work in teams of four or five students as part of a year-long upper-level biomedical engineering course. Since we implemented a new pedagogical method in the class, we did not have a comparison group. For this study, coursework from three teams was examined to explore the application and practicality of the Design Heuristics-driven concepts. The three project teams selected represented a broad range of project types in the context of biomedical engineering product design:

Project Team A: Creating a New Device

The project team was composed of five students (three males and two females). One male student opted out of the study and was not included in the analysis. The instructor - defined problem was to "inhibit and reduce multiple sclerosis symptoms caused by inflammation and waste products in the brain by cooling the brain." The project focused on "creating a new device" for this application.

Project Team B: Research Application

The project team was composed of five students (three males and two females). One male student opted out of the study and his ideas were not included in the analysis. They were asked to develop "a research tool to measure and train non-human primates' finger position for hand manipulation." The device's purpose was solely for "research application."

Project Team C: Usability Focus

The project team was composed of four students (two males and two females). They were asked to create "user-friendly endoscopy equipment and technique to minimize musculoskeletal injuries in clinicians." The team's project definition had a "usability focus" on the clinician's interaction with equipment during the procedure.

Data Collection

Prior to the session, a Google forms survey was distributed to the students to gather background information on their experience in design and past projects. We then collected data during the idea generation phase of the course. Students spent one classroom session (110 minutes) learning and then applying Design Heuristics in a concept generation session for their project. Students were first asked to individually generate 4 concepts for their design problem in 20 minutes.

Then, they were given instruction on Design Heuristics as an idea generation technique and practice on an unrelated problem. The detailed instruction video can be found on www.designheuristics.com.Then, the students were asked to apply Design Heuristics to generate 4 new concepts in 20 minutes. Design Heuristic cards were divided before the session into two sets of 5 ("A" and "B") to include a variety but limited number of cards appropriate to the time limit (See Table 1). We selected several cards that encouraged user interactions and product modifications. Each team was given either set A or B to ensure that every member within the same group had the same set of cards.

Table 1. Selected *Design Heuristics*

	Design Heuristic Title	Description
Set A	6. Adjust Functions for Specific Users	Design the functions of the product with target user characteristics in mind (e.g. age, gender, education, occupancy, ability).
	29. Create System	Identify the core product functions and define a multi-stage process to achieve the overall goal.
	40. Incorporate User Input	Identify product functions that are adjustable and allow users to make those changes through an interface control, using buttons, sliders, levers, dials, touch screens, etc.
	49. Offer Optional Components	Provide extra components for the user to swap.
	68. Use Common Base to Hold Components	Align multiple components on the same base or railing system.
Set B	4. Add to Existing Product	Use an existing item as part of the product's function.
	46. Mimic Natural Mechanisms	Imitate naturally occurring processes, mechanisms, or systems.
	50. Provide Sensory Feedback	Return perceptual (e.g. tactile, aural, visual) feedback to the user to guide use.
	60. Simplify	Remove unnecessary complexity from the product.
	63. Substitute Way of Achieving Function	Replace one or more components with other designs that can achieve the same function.

On each concept sheet, students indicated their use of any Design Heuristics for each concept they generated during the idea generation session. After this individual idea generation session, students gathered with their teams and shared their design concepts. Finally, the teams synthesized their ideas for 35 minutes with the goal of determining their top three design concepts. Students documented their three selected design concepts in a team report.

<u>Data Analysis</u>

The design concepts were examined to identify the presence of Design Heuristics in individual design concepts and team design concepts[3]. Students indicated the title(s) of Design Heuristic(s) incorporated into their concepts during the idea generation session. For example, a direct application of Provide sensory feedback in a design concept would be to add lights to indicate how much force a doctor is exerting while using a medical device. For each individual concept, we documented students' reported use of heuristics as well as how they applied the heuristic(s) they reported.

Subsequently, we analyzed the extent to which heuristic-driven ideas from individuals were present in team-selected ideas. We used this measure as an indicator of practicality, as it meant that students teams considered these elements worthy of pursuit as they moved forward in their projects.

Findings

All twelve students across the three groups generated an initial set of four concepts on their own, and nine out of twelve students then generated four more concepts using Design Heuristics. All three teams generated three final team concepts by editing and/or merging the individual ideas generated. In some cases, students carried over desired characteristics from their heuristic-driven ideas in the synthesis of team ideas. In other cases, the heuristic idea was directly transferred over to the team concept. In this analysis, we present some examples of individual concepts generated using Design Heuristics, and how these concepts impacted the later team concepts. In the following subsections, we describe each of the three teams, their design contexts, ideas generated individually, and the team's combined ideas and the origin of these ideas.

<u>Team A: Portable Scalp-Cooling Device</u>

Team A was tasked with designing a portable scalp-cooling device and were given set A of the Design Heuristic cards. They generated sixteen ideas without Design Heuristics and fifteen ideas with the use of heuristics. Some examples of ideas generated using Design Heuristics are shown in Figure 2. The individual concept (Figure 2, I1) used the Design Heuristic *Adjust function for specific user* to generate a headband with a cooling mechanism that incorporates a small motor that automatically fits the band to the patient's head. The design concept addresses the need that some patients with multiple sclerosis may have difficulties adjusting the cooling band to the appropriate size for their head. The individual concept (I2) incorporates *Create system* that assisted in prompting ideas about functional steps and defining a multi-stage process to achieve the overall goal. A participant thought of interfacing the cooling system with a plate to provide the cooling mechanism that can be molded to the user's forehead which can be plugged into the side of the system. Individual concept (I3) also utilized the Design Heuristic *Create system* and generated a concept that uses peltier coolers, leveraging a thermoelectric effect to bring heat from one side of the plate to the other. The system generated from this idea includes coolers that are attached to a moldable resin with water, which can then be used as both a cooling vest and a cap that can be shaped according to the user's head.

When the students were asked to narrow down their individual ideas to three team ideas, individual ideas both with and without Design Heuritics were used to develop the team concepts. For example, individual concept 1 (I1), which was driven from the Design Heuristic, *Adjust function for specific user*, was not used in generating any of the team concept. However, other heuristic-driven ideas, were leveraged. For example, team concept 1 (T1) combined some characteristics of heuristics-driven individual concepts 2 (I2) and 3 (I3). Both concept I2 and concept I3 utilized the Design Heuristic, *Create system*. The team concept (T1) used optional forehead resin-moldable plate that is attachable and detachable and can provide additional cooling when needed. Ultimately, in Team A's group idea generation phase, all three of their team concepts incorporated Design Heuristic-driven ideas. Team A's T1 design concept demosntrates how the synthesis progressed with one of the three team concepts.

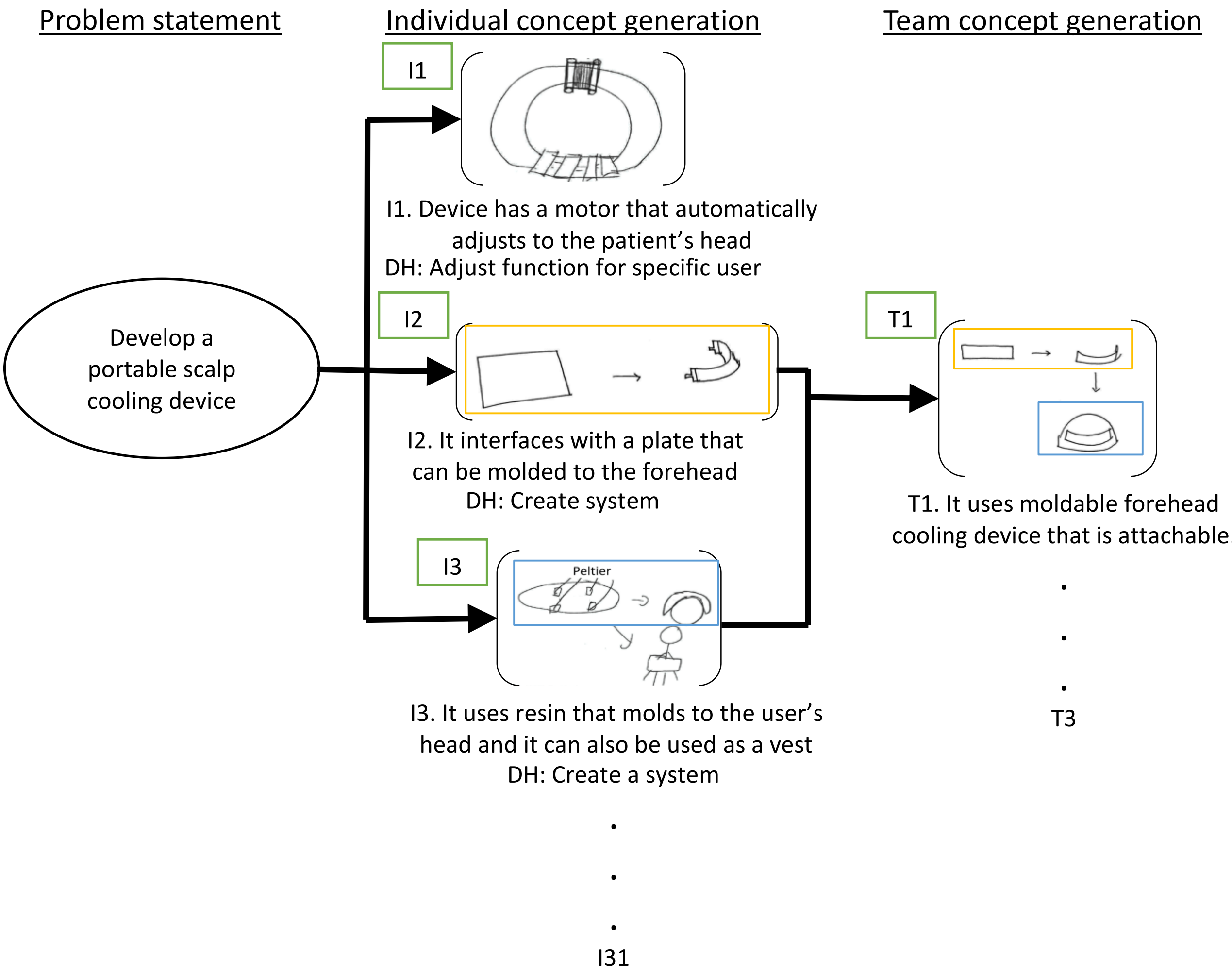

Figure 2. Team A – Three examples of individual concepts generated using Design Heuristics and one example of team concept.

Team B: Finger Manipulation Trainer

Team B was given a different set of 5 Design Heuristic cards (set B) than Team A and were able to leverage the heuristics to generate ideas as well. Their project consisted of designing an instrumented finger manipulation trainer for nonhuman primates. The students on this team were able to use a variety of *Design Heuristics* to generate ideas for their design problem. Using the Design Heuristic *Mimic natural mechanisms*, one student generated individual concept 1 (I1) to mimic a human finger to implement smooth joints that can bend instead of having rigid joints. Individual concepts 2 (I2) and 3 (I3) were inspired by the same Design Heuristic, *Provide sensory feedback*, but derived at two different ideas. Individual concept 2 (I2) used magnetic rings on the fingers to detect the bend relative to each other. When a finger is bent, the direction and the magnitude of the magnetic field would change. By detecting the bend relative to each other, it can provide a sensory feedback system from the magnetic force generated, which can be used to detect different finger positions. In the individual concept 3 (I3), a student generated a concept that measures bend changes using current measurements. When a desired finger position is detected, the trainer system would vibrate to provide a feedback mechanism.

Similar to Team A, heuristic-driven ideas were present in the next stage of the team design when they synthesized ideas from combining and building on the individual ideas. Two out of the three team concepts included individual ideas that were inspired by the use of Design Heuristics. One example of the team synthesizing individual ideas is team concept 1 (T1), which used electromagnetic technique to measure the finger position and the vibration mechanism provides the feedback mechanism. The electric field generated has a dual purpose of measuring the finger positions as well as powering the vibrator. The individual concept 1 (I1) was not used in the team ideation. The team idea derived from the individual concept 2 (I2), which used magnetic rings on the finger to detect the relative bend of the finger, directly transferred to the team concept. Also, the individual concept 3 (I3), which used the vibrating mechanism to provide a sensory feedback, is present.

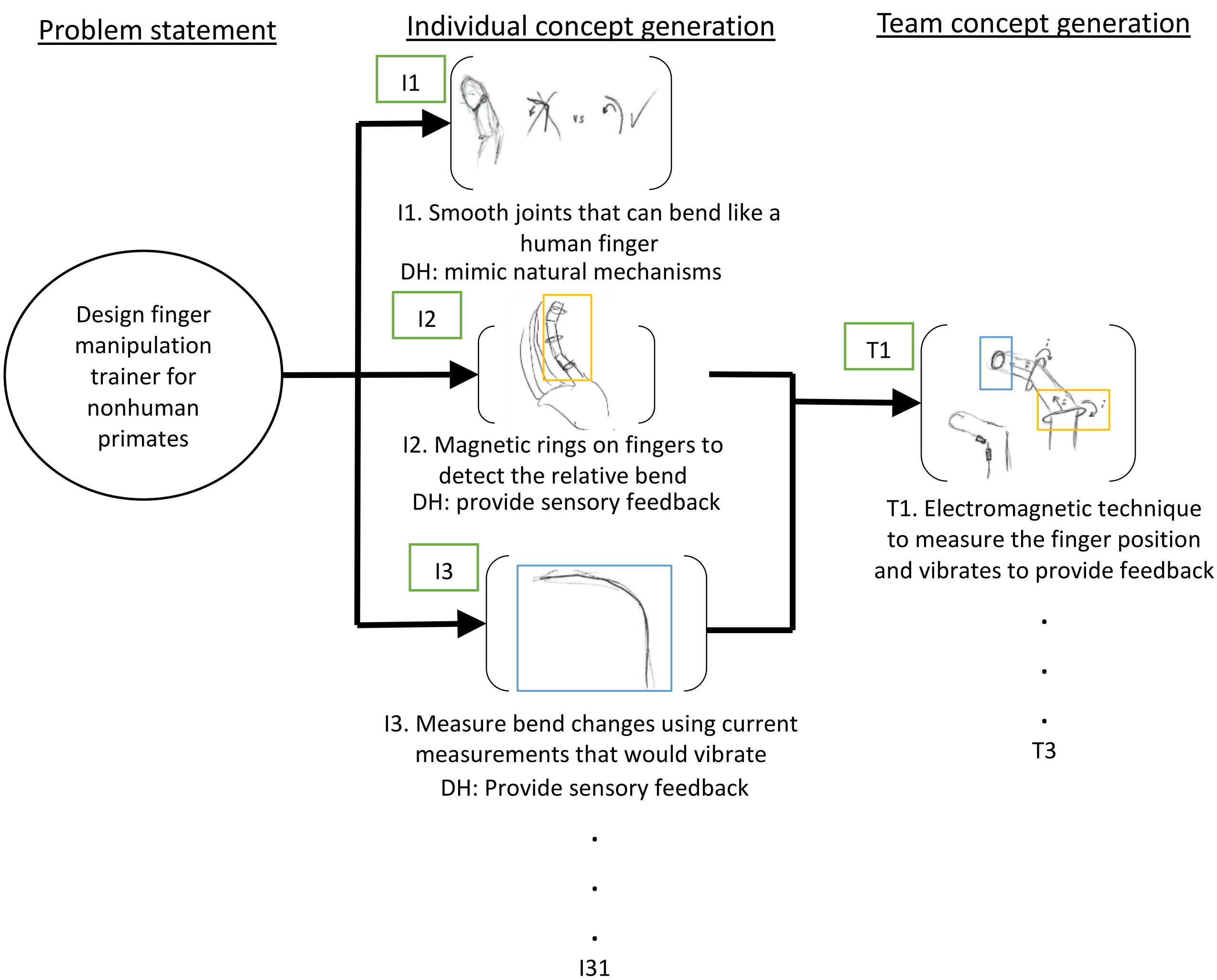

Figure 3. Team B – Three examples of individual concepts generated using Design Heuristics and one example of team concept.

Team C: Ergonomic endoscope

Team C was asked to design a device to make an endoscope more ergonomic for clinicians. During the ideation session, we provided them with a set B of the Design Heuristic cards. Similar to Teams A and B, the students used diverse Design Heuristic cards to generate multiple concepts. The individual concept 1 (I1) used *Add to existing product* heuristic and a student thought about incorporating a finger mechanism to the existing medical gloves to attach to an endoscope. This mechanism provided a tactile feedback and reduced the pinch force required to manipulate an endoscope. In individual concept 2 (I2), a student leveraged the heuristic *Provide sensory feedback* to generate an idea that used a color changing feedback mechanism. The visual feedback mechanism would alert a clinician on the amount of force applied to the endoscope to prevent an injury. Depending on the amount of force applied to the endoscope, the color would change and alert the user before a potential injury occurs. Another student generated the individual concept 3 (I3) that used the heuristic card *Substitute a way of achieving function.* A student developed an idea to manipulate an endoscope by providing a grip force in the radical direction, which allowed the user's natural hand movement to manipulate the endoscope.

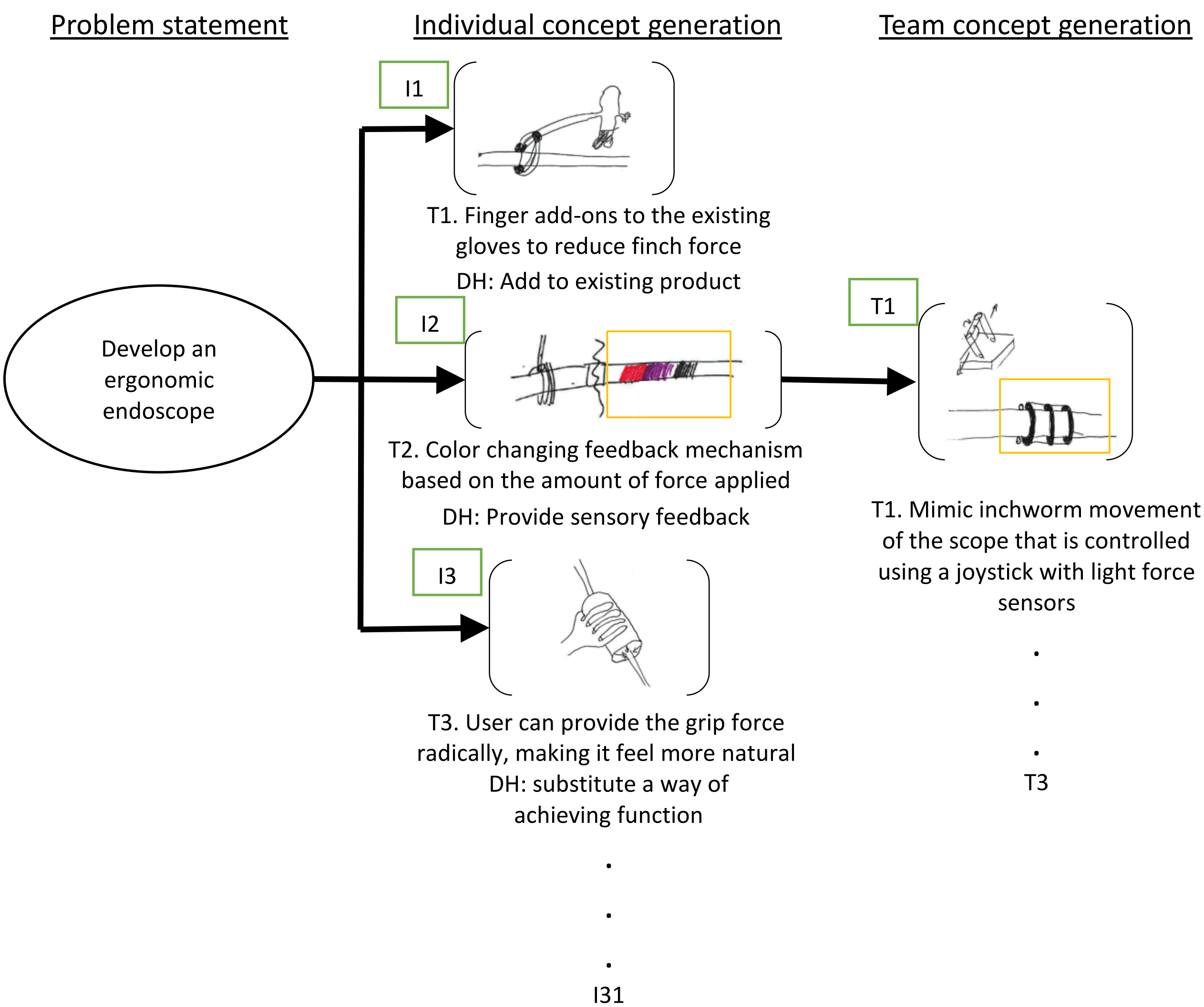

Figure 4. Team C – Three examples of individual concepts generated using Design Heuristics and one example of a team concept.

In the team idea generation stage, one out of the three team ideas incorporated a heuristic-driven concept. Many of the heuristic-driven ideas such as the individual concepts 1 (I1) and 3 (I3) were not used to synthesize the team concepts. The team concept 1 (T1) incorporated the heuristic-driven individual concept 2 (I2) that provided a visual feedback mechanism by changing its color based on the amount of force applied. Also, the team concept (T1) was inspired by non-heuristic driven ideas that mimicked the movement of an inchworm and used a joystick to control the endoscope's movement. The combination of these ideas yielded an endoscope that was joystick controlled to minimize the need for a clinician to manually maneuver the device and at the same time, it had a light force sensor that could change its color depending on the amount of force applied to ensure that the endoscope would not cause any injuries due to excessive forces.

Discussion

Ideas generated using *Design Heuristics* in biomedical engineering

Our analysis found that students were able to effectively use Design Heuristics to generate concepts for their design problems in biomedical engineering. Many of the Design Heuristics initially identified and tested in the product design space, such as *Create a system, Add to existing product, Provide sensory feedback,* and *Substitute a way of achieving function,* were demonstrated to be transferable and effective in idea generation in the biomedical engineering space. The students came up with multiple concepts for the same design problem using a variety of Design Heuristics, demonstrating that multiple heuristics could be applied in a variety of ways within the same problem context. Additionally, students were able to use the same Design Heuristic to generate different concepts, demonstrating that the heuristics guided but did not determine the solutions. In our post survey data, many students indicated that Design Heuristics were helpful. Students mentioned that Design Heuristics introduced ideas that they had not thought of before and helped them think outside the box.

This study aligns with previous findings that Design Heuristics aid in generating a variety of concepts in individual ideation sessions[4,41,46]. Also, these results demonstrate that Design Heuristics can support idea generation by students in the biomedical engineering design space, a new application area for Design Heuristics. Furthermore, since the three teams studied were working on different design problems, these findings validate that Design Heuristics can be implemented in a variety of biomedical engineering design contexts.

Presence of ideas generated using *Design Heuristics* in selected team concepts

The findings from the team idea generation session showed that many of the students decided to use their heuristic-driven individual ideas within their final team concepts. As they further developed their ideas, full detailed concepts or characteristics of concepts generated with Design Heuristics were selected for further development by the team, supporting their value as practical and useful for biomedical engineering projects.

These findings parallel previous studies of mechanical engineering design teams where evidence of heuristic use was apparent in the later stages of design[3,47]. The use of Design Heuristics not only aided individual designers in generating diverse ideas, but also created ideas that were practical and useful in designs, and so were carried forward in the teams' selected concepts. These findings suggest that students recognized desirable characteristics and values from the heuristic inspired ideas and felt their team concepts benefitted from heuristics-inspired concepts.

Implications for Biomedical Engineering Education

These findings suggest some benefits of using instruction on Design Heuristics to support idea generation in biomedical engineering design courses. Design Heuristics can be used at early stages of students' design processes to aid in generating a variety of design ideas to consider for future development and pursuit. Since biomedical engineering problems are often even more constrained by regulations and requirements, Design Heuristics can assist students in exploring the design space to identify innovative solutions.

For educators in biomedical engineering, instruction on Design Heuristics can be easily implemented in one classroom session. Because many students in biomedical engineering have limited past experience with design, Design Heuristics can be helpful in supporting students as they learn the value of considering multiple, diverse ideas in the early stages of design. Design Heuristics provide structured and effective strategies to promote idea generation in design classes. Materials for classroom use, videotapes of example sessions with students, and research evidence about Design Heuristics lessons are available on a public website (designheuristics.com). Design Heuristics also provide guidance for team sessions as they develop and synthesize their ideas[45]. Both instructors and students in biomedical engineering may benefit from the use of Design Heuristics in instruction on idea generation.

Conclusion

This study contributed to our understanding of how the Design Heuristics tool can be utilized in classroom instruction in a biomedical engineering design course. During initial ideation by individuals, as well as the subsequent team idea development, biomedical engineering students generated and adopted concepts using Design Heuristics. The results show that Design Heuristics are transferable from the product design context to biomedical engineering design problems, and students used Design Heuristics across diverse problem contexts. Using Design Heuristics led to generating far more ideas in additional to their natural ideation methods. Additionally, many of the individual ideas generated using the heuristics carried over to the team synthesis of concepts and were selected in their final choices, demonstrating that heuristic-driven ideas were practical and feasible. Design Heuristics can be a successful instructional component to support biomedical engineering design teams in creating diverse and practical concepts. By considering a variety of potential solutions, students learn the value of considering multiple concepts in early idea generation, and selecting favorable characteristics from their solutions in the concept development phase.

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References

1. Dym, C., Agogino, A., Eris, O., Frey, D. D., & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. *Journal of Engineering Education*, *94*(1), 103–120.

2. Shepherd, S., Colby, A., Macatangay, K., & Sullivan, W. (2006). What is engineering practice? *International Journal of Engineering Education*, *22*(3), 429–438.
3. Kramer, J. M., Daly, S. R., & Yilmaz, S. (2014). A case-study analysis of design heuristics in upper-level cross-disciplinary design course. Paper presented at the *Proceedings of the American Society for Engineering Education*. Indianapolis, IN, USA.
4. Daly, S. R., Christian, J. L., Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2012). Assessing Design Heuristics for Idea Generation in an Introductory Engineering Course. *International Journal of Engineering Education*, *28*(2), 1–11.
5. Enderle, J., & Bronzino, J. (2012). *Introduction to biomedical engineering* (3rd ed.). Academic Press.
6. Allen, M. (1962). *Morphological Creativity: The Miracle of Your Hidden Brain Power*. New Jersey: Prentice-Hall.
7. King, P. (1999). Design and biomedical engineering. *International Journal of Engineering Education*, *15*(4), 282–287.
8. Yock, P., Zenios, S., Makower, J., Brinton, T., Kumar, U., Watkins, J., … Kurihara, C. (2015). Ideation. In *Biodesign: the process of innovating medical technologies* (2nd ed., pp. 250–267). Cambridge University Press.
9. Brophy, D. R. (2001). Comparing the Attributes, Activities, and Performance of Divergent, Convergent, and Combination Thinkers. *Creativity Research Journal*, *13*(3–4), 439–455.
10. Liu, Y.-C., Chakrabarti, A., & Bligh, T. (2003). Towards an "ideal" approach for concept generation. *Design Studies*, *24*(4), 341–355.
11. Ahmed, S., Wallace, K. M., & Blessing, L. T. (2003). Understanding the differences between how novice and experienced designers approach design tasks. *Research in Engineering Design*, *14*(1), 1–11.
12. Ball, L. J., Evans, J., & Dennis, I. (1994). Cognitive processes in engineering design: A longitudinal study. *Ergonomics*, *37*(11), 1753–1786.
13. Cross, N. (2011). *Design Thinking*. Oxford: Berg.
14. Rowe, P. (1987). *Design thinking*. Cambridge, MA: The MIT Press.
15. Ullman, D. G., Dietterich, T. G., & Stauffer, L. A. (1988). A model of the mechanical design process based on empirical data. *Artificial Intelligence for Engineering, Design, Analysis and Manufacturing*, *2*(01), 33–52.
16. Grasso, D., Burkins, M. B., Helble, J. J., & Martinelli, D. (2008). Dispelling the myths of holistic engineering. *PE Magazine*.
17. Klukken, P. G., Parsons, J. R., & Columbus, P. J. (1997). The Creative Experience in Engineering Practice: Implications for Engineering Education. *Journal of Engineering Education*, *86*(2), 133–138.
18. Osborn, A. F. (1963). *Applied imagination: Principles and procedures of creative problem-solving* (3rd Rev Edition). Buffalo, NY: Scribner.
19. Pappas, J., & Pappas, E. (2003). Creative thinking, creative problem-solving, and inventive design in the engineering curriculum: A review. Paper presented at the *Proceedings of the 2003 American Society for Engineering Education Annual Conference*, Nashville, TN
20. Richards, L. G. (1998). Stimulating creativity: teaching engineers to be innovators. Paper presented at the *Frontiers in Education Conference, 1998. FIE'98. 28th Annual* (Vol. 3, pp. 1034–1039). IEEE.
21. Osborn, A. (1957). *Applied Imagination: Principles and Procedures of Creative Problem Solving New York*. Scribner.

22. Geschka, H., Schaude, G., & Schlicksupp, H. (1976). Modern techniques for solving problems. *International Studies of Management & Organization*, *6*(4), 45–63.
23. Finke, R. A., Ward, T. B., Smith, S. M., & more, & 1. (1996). *Creative Cognition: Theory, Research, and Applications*. Cambridge, Mass.: A Bradford Book.
24. Yilmaz, S., Daly, S. R., Seifert, C. M., & Gonzalez, R. (2016). Evidence-based design heuristics for idea generation. *Design Studies*, *46*, 95–124.
25. IDEO. (2002). *IDEO Method Cards: 51 Ways to Inspire Design*. Palo Alto: IDEO.
26. de Bono, E. (1968). *New think: The use of lateral thinking in the generation of new ideas*. New York: Basic Books.
27. Zwicky, F. (1969). *Discovery, invention, research through the morphological approach*. New York: Macmillan.
28. Gordon, W. J. J. (1961). *Synectics*. New York: Harper & Row.
29. Eberle, R. (1995). *SCAMPER*. Waco, TX: Prufrock.
30. Altshuller, G. (1984). *Creativity as an exact science*. New York: Gordon and Breach.
31. Altshuller, G. (1997). *40 principles: TRIZ keys to technical innovation*. Worcester, Mass.: Technical Innovation Center, Inc.
32. Nisbett, R. E. (1980). *Human inference: strategies and shortcomings of social judgment*. Englewood Cliffs, N.J: Prentice-Hall.
33. Yilmaz, S., Seifert, C., Daly, S., & Gonzalez, R. (2016). Design Heuristics in innovative products. *Journal of Mechanical Design*, *138*(7).
34. Daly, S. R., Seifert, C. M., Yilmaz, S., & Gonzalez, R. (2016). Comparing Ideation Techniques for Beginning Designers. *Journal of Mechanical Design*, *138*(10), 101108.
35. Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2010). Cognitive heuristics in design: Instructional strategies to increase creativity in idea generation. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, *24*(03), 335–355.
36. Yilmaz, S., & Seifert, C. M. (2011). Creativity through design heuristics: A case study of expert product design. *Design Studies*, *32*(4), 384–415.
37. Yilmaz, S., Daly, S. R., Seifert, C. M., & Gonzalez, R. (2011). A Comparison of Cognitive Heuristics Use between Engineers and Industrial Designers. In J. S. Gero (Ed.), *Design Computing and Cognition '10* (pp. 3–22). Dordrecht: Springer Netherlands.
38. Klein, G. A. (1999). *Sources of power how people make decisions*. Cambridge, Mass.: MIT Press.
39. Daly, S. R., Christian, J. L., Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2011). Teaching design ideation. Paper presented at the *2011 Annual Conference & Exposition*, Vancouver, Canada
40. Daly, S. R., Yilmaz, S., Christian, J. L., Seifert, C. M., & Gonzalez, R. (2012). Design Heuristics in Engineering Concept Generation. *Journal of Engineering Education*, *101*(4), 601–629.
41. Yilmaz, S., Christian, J. L., Daly, S. R., Seifert, C. M., & Gonzalez, R. (2012). How do Design Heuristics affect design outcomes in industrial design? Presented at the *International Design Conference*, Dubrovnik, Croatia.
42. Christian, J. L., Daly, S. R., Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2012). Design Heuristics to Support Two Modes of Idea Generation: Initiating Ideas and Transitioning Among Concepts. Presented at the *Annual Conference of American Society of Engineering Education*, San Antonio, Texas.

43. Shah, J. J., Vargas-Hernandez, N., & Smith, S. M. (2003). Metrics for measuring ideation effectiveness. *Design Studies*, *24*(2), 111–134.
44. Daly, S. R., Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2010). Cognitive Heuristics Use in Engineering Design Ideation. Paper presented at the *Proceedings of the American Society for Engineering Education (AC 2010-1032)*. Washington, DC.
45. Yilmaz, S., Daly, S. R., Christian, J. L., Seifert, C. M., & Gonzalez, R. (2013). Can experienced designers learn from new tools? A case study of idea generation in a professional engineering team. *International Journal of Design Creativity and Innovation*.
46. Yilmaz, S., Christian, J. L., Daly, S. R., Seifert, C. M., & Gonzalez, R. (2011). Idea generation in collaborative settings using design heuristics. Presented at the *International Conference on Engineering Design (ICED)*, Copenhagen, Denmark.
47. Kramer, J., Daly, S. R., Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2015). Investigating the Impacts of Design Heuristics on Idea Initiation and Development. *Advances in Engineering Education*, *4*(4), 1.