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Idea generation in biomedical engineering courses using Design Heuristics

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ABSTRACT
With increasing demand for improved medical equipment and healthcare, next-generation biomedical engineers need strong design skills. Equipping biomedical engineering students with tools for idea generation and development can increase student design success. Design Heuristics are an ideation tool developed through empirical studies of product designs. While identified in the mechanical engineering space, Design Heuristics may be applicable in biomedical engineering design. In our study, we implemented a Design Heuristics session during upper-level undergraduate and first-year graduate biomedical engineering design courses. We examined the applicability of Design Heuristics within individual and team concept generation contexts. The findings demonstrated that biomedical engineering students were able to use Design Heuristics to generate multiple concepts, and that initial concepts produced using Design Heuristics were carried over into final team design. The results support the applicability of Design Heuristics to student idea generation in biomedical engineering design.

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Word; biomedical engineering; design; Design Heuristics; idea generation

Introduction and background

With a growing focus on health care and aging issues, biomedical engineers are called upon to design innovative medical technologies (Bronzino 2014). Design is both a process and a skill, for which expertise can be developed (Cross 2008). In engineering, design involves devising a system, component or process to meet needs (ABET Board of Directors 2011), and its early phases include problem definition, requirements development, and concept generation and development (Allen et al. 2013; King 1999). Recent engineering education studies in biomedical engineering have focused on developing 'best design practices' to better educate biomedical engineering instructors and students about design (Allen et al. 2013; Goldberg and Pearlman 2013; King 1999; Lerner et al. 2006; Oden et al. 2010; Yazdi and Acharya 2013). This includes the important design activity of generating ideas, in which success entails the development of multiple creative and diverse concepts (Akin 1990; Atman et al. 1999; Brophy 2001; Cross 2001; Liu, Chakrabarti, and Bligh 2003). Best practices in idea generation, particularly using brainstorming, include deferring judgment, encouraging wild ideas, building on the ideas of others, generating a large quantity of ideas, and iterating on ideas (Osborn 1957). Biomedical engineering textbooks echo the importance of these practices, adding to sharing ideas between disciplines (Saltzman 2009; Yock et al. 2015).

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While the importance of idea generation has been emphasised, generating these multiple creative and diverse concepts can be challenging for students across all design domains (Ahmed, Wallace, and Blessing 2003; Ball, Evans, and Dennis 1994; Carlos and Badke-Schaub 2011; Cross 2011; Rowe 1987; Ullman, Dietterich, and Stauffer 1988), who often focus on limited solutions versus exploring diverse ideas (Daly, Yilmaz, et al. 2012; Jansson and Smith 1991; Youmans 2007). Currently, there is a lack of research focused specifically on instruction and tools to support idea generation in biomedical engineering education. Much of the research on idea generation in design has focused on mechanical engineering and industrial design settings (e.g. Hernandez, Schmidt, and Okudan 2013; Linsey, Markman, and Wood 2012). Two prominent biomedical engineering design textbooks emphasise the importance of brainstorming in idea generation (Webster and Pallas-Areny 2007; Yock et al. 2015) but may not provide their students with a systematic method of coming up with ideas. The lack of formal idea generation structure can leave students to come up with their own ideas and they often fail to employ specific design strategies to support their ideation.

Biomedical engineering design is different than other engineering disciplines. Biomedical engineering design artifacts often interface with the human body and impact human health, which is a unique feature of the field (Enderle and Bronzino 2012; King and Fries 2003). A design process in developing biomedical engineering devices may be embedded in another process to ensure that design is controlled (McDaniel et al. 2014). In the United States, where this study was conducted, medical environments involve complex regulations by the Food and Drug Administration that require rigorous validation and verification to test efficacy, safety and reliability of a product. A failure to account for the medical context early on could limit a team's ability to anticipate and adapt to challenges in development (Hagedorn, Grosse, and Krishnamurty 2015). Thus, biomedical environments can significantly restrict the viable engineering solutions and limit idea generation.

In additional to regulations, students in biomedical engineering programmes have distinct educational experiences from students in other design domains (Engineering in Medicine and Biology 2015; Gatchell and Linsenmeier 2005) and may engage in design processes uniquely from students of other fields. Research has shown design can be affected by domain knowledge and expertise; students' backgrounds may impact how they approach design projects, and some design process patterns exist based on disciplinary context (e.g. Blessing and Chakrabarti 2009; Dorst 2004; Perez, Johnson, and Emery 1995; Popovic 2004). Currently, biomedical engineering education exists in many institutions with varying emphasis (Stagg, Pearson, and Guda 2015). For example, biomedical engineering programmes at large, research-intensive universities may focus on training students toward research paths that align with the institution's research expertise (Krishnan 2014). Due to differing educational background and domain knowledge, biomedical engineering students may approach design differently and the usefulness of design strategies in biomedical engineering needs to be studied.

Design idea generation

Multiple design tools exist to support idea generation success broadly across disciplines including, for example, brainwriting (Geschka, Schaude, and Schlicksupp 1976), conceptual combination (Finke, Ward, and Smith 1996), Synectics (Gordon 1961), SCAMPER (Eberle 1995), brainstorming (Osborn 1957), TRIZ (Altshuller 1984, 1997), and Design Heuristics (Daly, Yilmaz, et al. 2012; Yilmaz, Daly, et al. 2016; Yilmaz, Seifert, et al. 2016). Ideation tools can help promote creativity and diversity of idea generation and transformation (Daly et al. 2016; Hernandez, Schmidt, and Okudan 2013).

One idea generation tool that has been empirically developed and evaluated in multiple contexts is Design Heuristics (designheuristics.com) (Daly et al. 2016; Daly, Yilmaz, et al. 2012; Yilmaz, Daly, et al. 2016). Design Heuristics are idea generation 'rules of thumb' designed to encourage exploration of a variety of ideas. Design Heuristics are meant to help engineering designers spark new ideas, guide them towards non-obvious ideas, and help them generate multiple concepts that are different from each other. Multiple designers using the same Design Heuristic can develop different ideas since a Design Heuristic card does not provide one right solution but rather a direction to consider possible solutions. The origin of Design Heuristics stems from cognitive psychology, where heuristics provide 'best guesses' and are common characteristics in expert performance (Klein 1999).

Design Heuristics were developed through studies of expert and advanced engineers and product designers, and from the analysis of award-winning products (Daly, Yilmaz, et al. 2012; Yilmaz, Daly, et al. 2016). From these studies, 77 heuristics were identified, and illustrated on a pack of cards for instructional use. Each heuristic is represented on a single card, with one side providing an illustrated graphic and written description, and the reverse side providing two illustrated examples of its application in existing products (Figure 1).

Design Heuristics were developed in the product design domain primarily with mechanical engineers and industrial designers. Empirical studies have demonstrated **their** usefulness for students and practitioners in some engineering disciplines to support the development of diverse, creative, elaborate, and practical concepts that contributed to final project designs (Christian et al. 2012; Daly, Christian, et al. 2012; Daly et al. 2016; Dawidow, Huff, and Leahy 2016; Kotys-Schwartz et al. 2014; Kramer, Daly, and Yilmaz 2014; Kramer et al. 2015; Sangelkar et al. 2015). However, few studies have explored idea generation in a biomedical engineering design context, and more specifically, Design Heuristics have not been studied in this context. Since 2012, Design Heuristics workshops at national conferences and various universities have included design educators from across engineering disciplines, and a question that has repeatedly emerged has been on the extent to which the design tool is transferable beyond mechanical engineering and industrial design domains (Daly 2012; Daly and Yilmaz 2013a, 2013b, 2014; Daly, Yilmaz, and Christian 2012; Daly, Yilmaz, and Gray 2015; Daly, Yilmaz, and Leahy 2016; Gray et al. 2015; Yilmaz, Daly, and Jablokow 2014).

Students' interpretation of the tool and educational background may impact their ability to apply the Design Heuristics tool to the biomedical engineering design domain. Some design projects in biomedical engineering likely have similar aspects as mechanical engineering design, such as being oriented to product artifacts. However, training biomedical engineers, including a focus on constraints and regulations related to biomedical engineering design, may limit students in their ability to use Design Heuristics. For example, if students interpreted the Design Heuristic, *Allow*

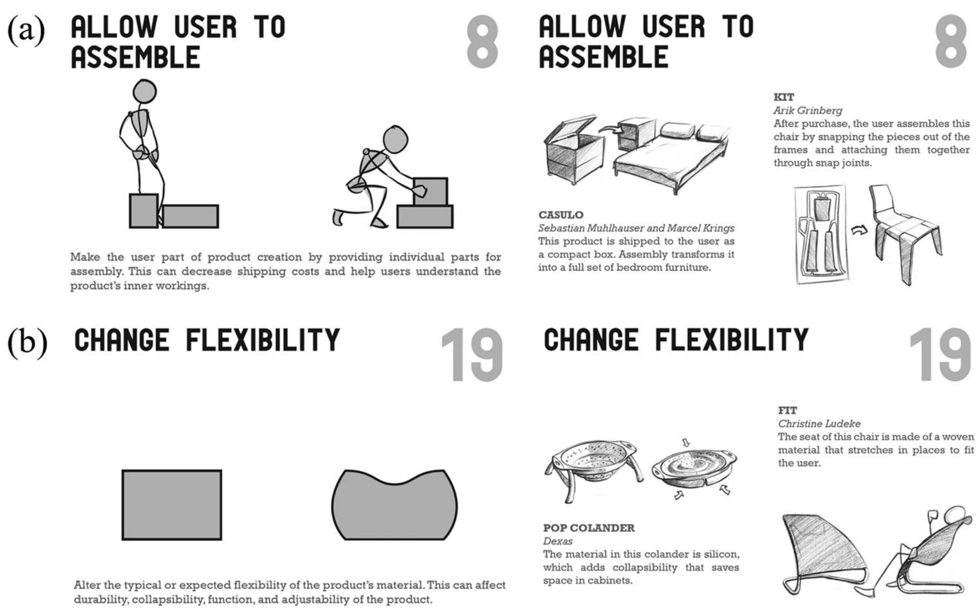

Figure 1. Design Heuristic cards (a) #8 Allow user to assemble, and (b) #19, Change flexibility.

user to assemble (Figure 1(a)) as introducing potential user errors and contamination into medical devices that require implantation or sterilisation (e.g. a bimanual vitreoretinal surgery product), they may not find that Design Heuristics are transferable to their domain. Design Heuristics can be interpreted in multiple ways to support idea generation, and the experiences and goals of the designer likely impact that interpretation.

Also, while some design tools are likely transferable to the biomedical engineering design setting because of similarities in some foci, scholars in biomedical engineering design have researched and called for the development and evaluation of design tools specifically in the biomedical engineering context (Hagedorn, Grosse, and Krishnamurty 2015; Lerner et al. 2006; McGoron et al. 2013; Mellodge and Deschenes 2009; Reuther, Cennamo, and Guo 2016; Schmedlen et al. 2016). Thus, we focused on Design Heuristics' usability in and transferability to the biomedical engineering design education domain as a first step to explore the potential use of the tool to support idea generation in biomedical engineering design projects.

Methods

Our work was guided by the following research questions:

(1) To what extent can biomedical engineering students use Design Heuristics in idea generation?
(2) To what extent are Design Heuristics applicable in biomedical engineering design problems?
(3) To what extent are heuristic-driven concepts evident in students' progression from individual to team to final project concepts?

To investigate these questions, we conducted a study in the context of two biomedical engineering courses in which students were engaged in biomedical engineering design projects. We asked students to generate ideas without and then with Design Heuristics, which allowed us to compare ideas generated. Our research methods were developed based on qualitative research standard practices (e.g. Creswell 2013; Patton 2001; Saldaña 2011) as well as other design studies that have leveraged design ideas as a primary data source (e.g. Linsey 2007; Linsey et al. 2011; Vasconcelos et al. 2017).

Because this study was conducted in an education setting during one course offering, having a control group without the instructional session was not possible. While other study designs could have been selected, such as a case study to follow a team in depth, or an analysis of ideas from prior course offerings to allow for comparison, these approaches either did not align with our goals or introduced additional variables, such as different course structures, instructors, and student populations across years. The classroom study type chosen is common in educational research (Allen et al. 2013; Baytiyeh and Naja 2017; Hoveskog, Halila, and Danilovic 2015; Shekhar and Borrego 2016), and the study methodology and analysis of the data was guided by these prior works of similar design.

As recommended for qualitative research, the researchers identified and recorded their biases regarding expectations of the results (Bickman and Rog 2008; Hill, Thompson, and Williams 1997; Saldaña 2011). Two of the researchers in study were part of the team that developed Design Heuristics, and based on experiences developing and studying the tool, we believed that Design Heuristics would support idea generation in biomedical engineering. Our research procedures were developed to control for our bias, such as by looking for patterns in the participants' reported data and being transparent by providing direct evidence from the data to support research claims.

Participants

Idea generation studies were conducted in a senior undergraduate capstone design course and a post-graduate biomedical engineering design course at a large university, located in the midwestern

United States. Both courses lasted two semesters (28 weeks) and emphasised designing, testing, and building medical devices for stakeholders, including university research labs, hospital clinicians, and medical companies. The senior capstone course included 36 students. Seven students declined to participate in the study, so 29 students working in 8 teams were included in the analysis. The graduate course was composed of 30 students. Two students opted out of the study, so 28 students' data across 6 teams were included in the analysis. All teams in both courses consisted of 4 or 5 students per team, and each pursued a different medical device design project (Table 1).

Data collection

After students refined their project goals and requirements, they participated in a single session (110 min) on idea generation. The sequence of the course session included:

A. Introduction on Idea Generation in Design
B. Individual Ideation
C. Design Heuristics Lesson
D. Individual Ideation with Design Heuristics
E. Team Concept Synthesis

The presentation began with a short introduction about the importance of idea generation in design, including principles such as producing multiple ideas and not evaluating ideas right away. Then, students were instructed to create 4 individual concepts during *Individual Ideation* using their own natural methods to come up with project design ideas independently. Students recorded each concept by sketching and writing a short description on a sheet of paper. This 20-minute stage documented their initial concepts when coming into the session.

Then, the facilitator provided a 20-minute lesson on Design Heuristics, including using a Design Heuristic card with a practice problem. The slides and lesson plan used came from the Design Heuristics website (Design Heuristics 2014). Next, during *Individual Ideation with Design Heuristics*, students used Design Heuristic cards to generate up to 4 more individual concepts for their projects in 20 min. Each member of a team was given the same set of 5 Design Heuristic cards, with two different sets in the study (see Table 2). In selecting cards to use for this study, we divided up the 77 Design Heuristic cards into two groups – product-centric (55 cards) and user/natural-centric (22 cards). Two cards from user/natural-centric and three cards from product-centric were selected at random for each set to create two sets of 5 Design Heuristic cards. Based on the previous work (Daly, Christian, et al. 2012; Daly et al. 2016), we considered this a manageable number of cards to read and apply in

Table 1. List of biomedical engineering students' design team projects.

	Team	Project
Senior level course	A	Portable Scalp-Cooling Device
	B	Instrumented Manipulandum to Train both Human and Nonhuman Primates
	C	ECLS Transport System
	D	Improvement of IVF Egg Retrieval Procedure
	E	Tremor Toothbrush/Oral Aids
	F	Retractor for Sacrospinous Ligament Suspension
	G	Bladder Irrigator
	H	Ergonomic Endoscopy Grip
Graduate course	I	Sudden Cardiac Arrest Alert
	J	Facial Treatment for Atopic Dermatitis in Infants
	K	Endoscopic Polyp Retrieval Device
	L	Method to Stabilise an Endoscope
	M	Percutaneous Endoscopic Gastrostomy Tube Dislodgement Prevention
	N	Bimanual Vitreoretinal Surgery Product

Table 2. Design Heuristics used in study.

	Design Heuristic Title	Description
Set 1	Adjust Functions for Specific Users	Design the functions of the product with target user characteristics in mind (e.g. age, gender, education, occupancy, ability).
	Create System	Identify the core product functions and define a multi-stage process to achieve the overall goal.
	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.
	Offer Optional Components	Provide extra components for the user to swap.
	Use Common Base to Hold Components	Align multiple components on the same base or railing system.
Set 2	Add to Existing Product	Use an existing item as part of the product's function.
	Mimic Natural Mechanisms	Imitate naturally occurring processes, mechanisms, or systems.
	Provide Sensory Feedback	Return perceptual (e.g. tactile, aural, visual) feedback to the user to guide use.
	Simplify	Remove unnecessary complexity from the product.
	Substitute Way of Achieving Function	Replace one or more components with other designs that can achieve the same function.

20 min. To record their concepts, students again created sketches, wrote descriptions, and noted which Design Heuristic(s) had inspired their concepts.

During *Team Concept Synthesis*, students shared their designs from the two individual stages with their teams. Each team of students was asked to generate up to 3 team concepts in 35 min. Students sketched their team concepts and wrote descriptions, and noted which individual concepts were related to their team concepts. Following the ideation session, students were encouraged to generate and develop more concepts outside of the courses. They progressed on their projects and documented the progression of their concepts in a final report.

Data used for the study were organised into 4 phases: (1) Concepts generated during individual ideation with students' own approaches, (2) Concepts generated during individual ideation with Design Heuristics, (3) Concepts developed by the teams through concept synthesis, and (4) Students submitted a final report at the end of the semester that included selected final design. In the undergraduate course, reports were collected at the end of the autumn and winter semesters, and only in the autumn for graduate students.

Data analysis

Concepts generated during each phase of the class session (individual natural ideation, individual Design Heuristics ideation, team ideation) as well as in teams' final design reports were organised. The individual and team Design Heuristics ideas were also matched with the specific Design Heuristics students indicated as contributing to each of their ideas. During these two sessions, students reported their Design Heuristic uses explicitly after generating each idea. We did not challenge students' reports of using the heuristics as one way to minimise study bias and because Design Heuristics can be interpreted in multiple ways. Analysis from all of the ideation data collected during the class session included frequency counts of ideas generated, and counts of Design Heuristics uses in individual and team ideation during the class session.

Analysis also consisted of comparing team concepts, including those synthesised during the class session as well as those included in students' final reports, to concepts from both individual stages to determine relationships between individual and team concepts. For the in-class team concepts, students were asked to explicitly state which individual ideas were used to synthesise into each team concept generated. If students indicated that individual ideas inspired by Design Heuristics were used to synthesise their team concepts, we accepted their self-reports that Design Heuristics influenced their team concepts. For the analysis of final concepts, we determined which ideas contributed by comparing the descriptions of the team concepts and final concept. In selecting the final concept, students used one of their team concepts. If students used one of the team concepts influenced by Design Heuristics as their final concept, we indicated that Design Heuristics influenced the progression of individual to team to final concepts.

This analysis of tracing influences from individual ideas (both natural and Design Heuristics inspired) to team ideas (both in-session and final projects) was used to investigate persistence of idea elements and the potential sources of these elements. Additionally, we assumed that teams included elements from individual concepts when they found them both useful and practical.

Results

Overall, 460 concepts were collected and analysed from 8 teams in the undergraduate and 5 teams in the post-graduate sections.

- 216 individual concepts (106 concepts in undergraduate and 110 concepts in graduate section) were generated with students' own approaches
- 191 individual concepts (92 concepts in undergraduate and 99 concepts in graduate section) were generated with Design Heuristics
- 40 team concepts were generated (22 concepts in undergraduate and 18 concepts in graduate course) during the in-class sessions
- 13 concepts from final reports generated by in final reports were examined

While the focus of our study was not to compare ideas generated with and without Design Heuristics, or to make claims about idea quantities in particular, we present the number of concepts generated by students for each of the individual in-class sessions in Table 3. Students generated more concepts during *Individual Initial Ideation* than *Individual Ideation with Design Heuristics*. This is similar to findings from other studies where ideation time is limited and reading and applying a design tool requires more time compared to simply documenting an idea that comes to mind (Belaziz, Bouras, and Brun 2000; Hernandez, Schmidt, and Okudan 2013; Linsey, Markman, and Wood 2012).

We describe the results of our analyses across individual and team concepts according to each research question in the following sections.

RQ1. To what extent can biomedical engineering students use Design Heuristics in idea generation?

We operationalised the extent to which students could use Design Heuristics in their ideation as their ability to generate and develop concepts for their projects using Design Heuristics.

All students were able to use Design Heuristics to generate multiple ideas, with the average being 3.4 concepts, ranging 1–4 concepts. Students used Design Heuristics to come up with new ideas as well as to develop ideas they had previously generated during *Individual Initial Ideation*. In addition, students applied Design Heuristics to build on their earlier concepts, further developing and elaborating on those ideas. We present examples of concepts generated by participants to demonstrate that students were able to use Design Heuristics to generate and develop ideas for their biomedical engineering projects.

As one example, Team A was designing a portable scalp-cooling device to alleviate brain inflammation. In *Individual Ideation*, one student generated a concept incorporating battery-powered peltier coolers inside a hat as a cooling mechanism (Figure 2.1). Next, he created a concept using

Table 3. Number of concepts generated during Individual Ideation with and without Design Heuristics.

Individual Ideation	Without *Design Heuristics*	With *Design Heuristics*
Generated 4 Different Concepts	49 (86%)	37 (65%)
Generated 3 or fewer	8	20
Average # generated	3.8	3.4
Total # of concepts generated	216	191

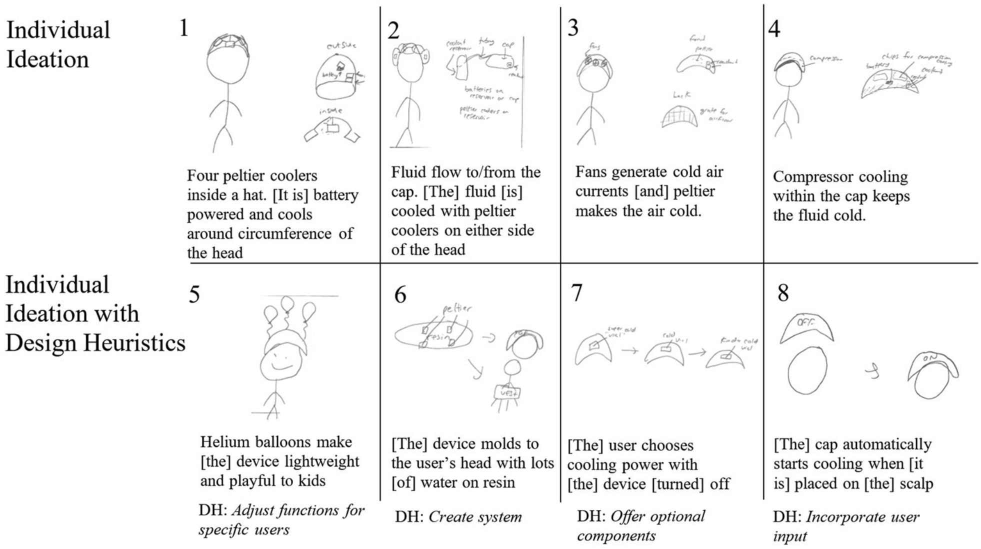

Figure 2. A single student's concepts in sequence, with 1–4 generated during Individual Ideation, and concepts 5–8 generated during Individual Ideation with Design Heuristics.

fluid flowing through the cap (Figure 2.2) cooled by peltiers. His third concept utilised peltiers to cool air and used fans to circulate it (Figure 2.3). Then, he designed a cap that would cool the head using a compressor (Figure 2.4).

Next, this student used Design Heuristics to generate ideas during *Individual Ideation with Design Heuristics*, where he created four more concepts and documented the Design Heuristics uses. Using the heuristic, *Adjust functions for specific users*, the student included helium balloons to make the device lightweight and playful for children (Figure 2.5). His next concept used the heuristic, *Create system*, to mould a cap to the user's head, and it can also be used as a vest to cool the rest of the body (Figure 2.6). Next, guided by the heuristic, *Offer optional components,* the student included inserts to change the cooling temperature when turned off (Figure 2.7). The final concept was a cap that automatically turned on when placed on the scalp, inspired by the *Incorporate user input* heuristic (Figure 2.8).

Concepts generated using Design Heuristics were often observed to build upon earlier concepts. For example, another student on Team A generated a concept using peltier coolers with surface temperature sensors and an adjustable headband (Figure 3.1). Using *Adjust function for specific user*, he created a concept with attachable and detachable cells to adjust for different sizes. A student on the Tremor Toothbrush/Oral Aids Team (Team E) started with a thick handle for grasping and a dampening mechanism to minimise tremors (Figure 3.2). He later added the heuristic, *Provide sensory feedback,* to design a device with a red light on unclean areas, and a green light when all the teeth were clean. A student on the Ergonomic Endoscopy Grip Team (Team H) design a powered grip to mechanically advance and rotate the shaft (Figure 3.3). Using the heuristic, *Provide sensory feedback*, he added a feedback mechanism to vibrate if too much force or pressure was applied. A student on Facial Treatment for Atopic Dermatitis in Infants Team (Team J) generated a concept with earmuffs to apply medication and moisturiser around the cheeks (Figure 3.4). Using multiple Design Heuristics (*Offer optional components*, *Use common base to hold component*, and *Adjust function for specific user)*, the student added an adhesive headpiece to treat the head eczema.

RQ2: To what extent are Design Heuristics applicable in biomedical engineering design problems?

We operationalised the extent to which Design Heuristics were applicable in biomedical engineering design contexts as: (1) the use of Design Heuristics across multiple projects and (2) frequencies of the use of each of the ten Design Heuristic cards provided in the study. Each of the biomedical

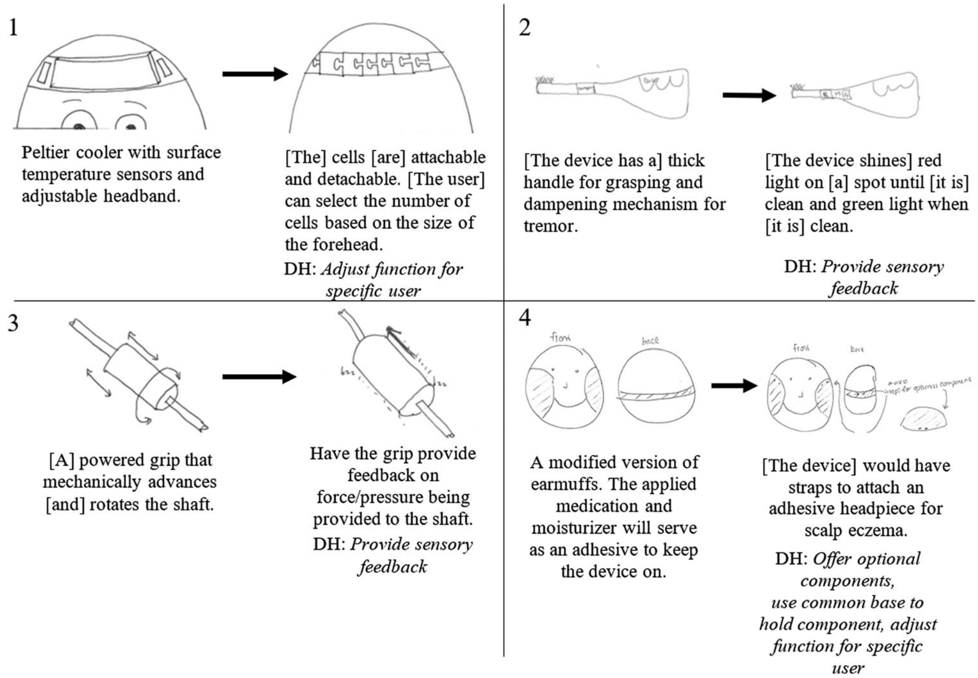

Figure 3. Examples of individual ideas generated using ideation and how those ideas were developed using Design Heuristics.

engineering problems in the courses was addressed by student concepts inspired by Design Heuristics (Figure 4). Students on the Tremor Toothbrush/Oral Aids Team (Team E) generated several concepts involving a mouth guard with tiny fans to clean teeth (Figure 4.1), inspired by *Add to existing product*, and a chewable toothbrush, inspired by *Substitute way of achieving function* (Figure 4.2). Students on the Ergonomic Endoscopy Grip Team (Team H) used the heuristic, *Provide sensory feedback,* to create concepts such as an endoscope with force sensors for color-changing light feedback (Figure 4.3). Another design, inspired by *Mimic natural mechanisms,* added small mobile legs to control movements (Figure 4.4). Students on Team N designed a new instrument for vitreoretinal surgery (retina repairs) to reduce glare caused by instrument reflections. A student used *Mimic natural mechanisms* and *Add to existing function* to create a concept for a luminescent-dye light source that would degrade or drain over time (Figure 4.5). Another student proposed a lens based on *Simplify* to focus light on specific areas of the eye (Figure 4.6). Team J proposed treating atopic dermatitis in infants with a ‘bear’ mask to make it playful (Figure 4.7), inspired by *Adjust functions for specific users.* Another student added a label to the forehead to indicate a time for mask removal (Figure 4.8), guided by *Incorporate user input*. Overall, Design Heuristics (represented by the set of ten heuristics from the 77 Design Heuristics) were applicable across a variety of problems in the biomedical engineering context.

Table 4. The number of Design Heuristic uses in guiding students’ idea generation.

	Heuristic Card	# of Uses
Set A ($N = 28$)	Adjust functions for specific users	22
	Create system	16
	Incorporate user input	18
	Offer optional components	24
	Use common base to hold components	20
Set B ($N = 29$)	Add to existing product	34
	Mimic natural mechanisms	24
	Provide sensory feedback	19
	Simplify	15
	Substitute way of achieving function	21

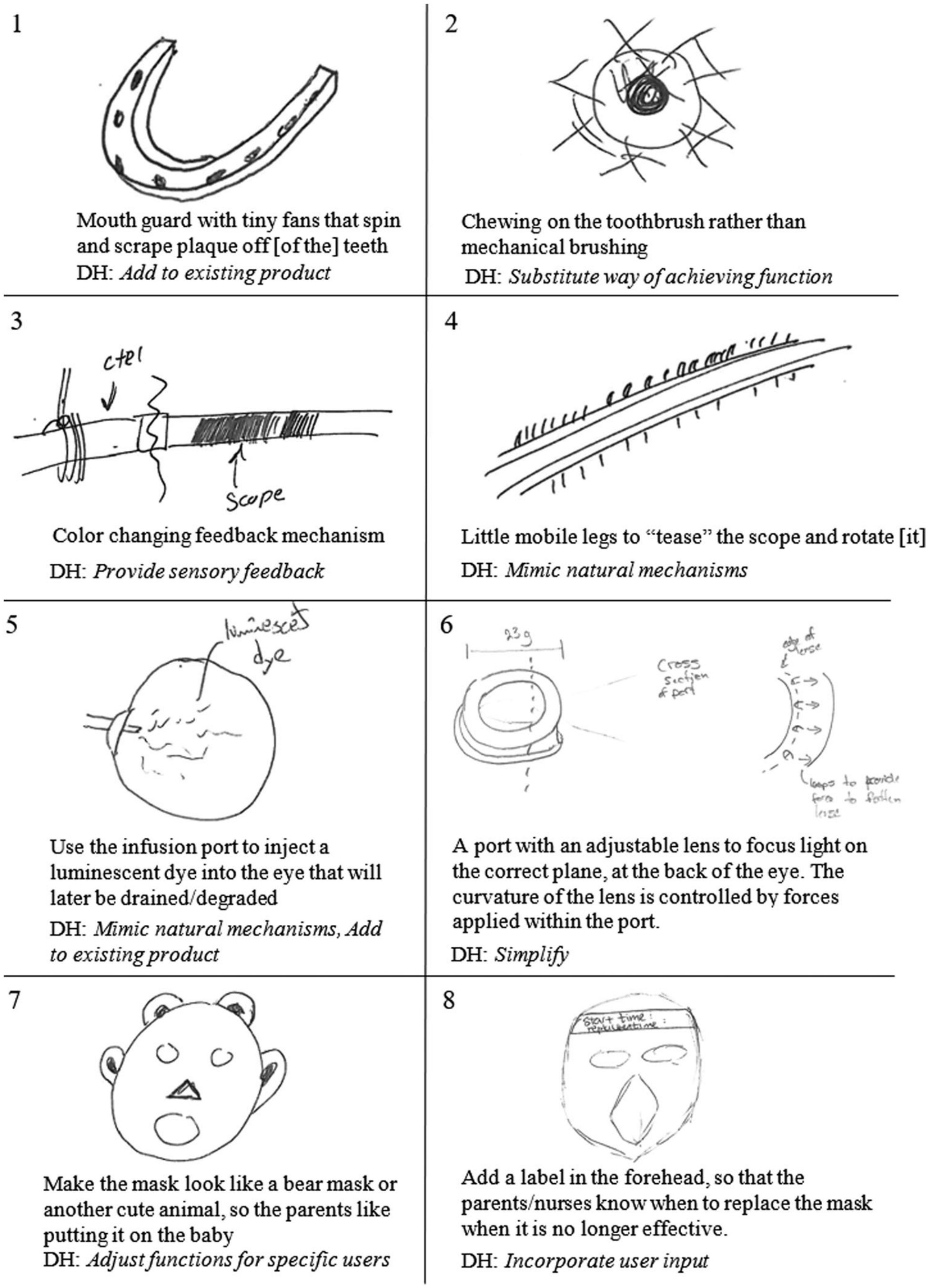

Figure 4. Example designs created by biomedical engineering students using Design Heuristics to guide them towards new concepts.

Each of the 10 Design Heuristics (from both sets) contributed numerous times to concepts created by multiple students (Table 4). The most frequently used Design Heuristics were *Add to existing product* and *Offer optional components*. However, even the least frequently used Design Heuristic, *Simplify,* was used over a dozen times. This demonstrates that all 10 Design Heuristics were applicable across the 14 biomedical engineering projects, establishing their applicability in the biomedical engineering design context.

RQ3: To what extent are heuristic-driven concepts evident in students' progression from individual to team to final project concepts?

During the *Team Concept Synthesis* portion of the in-class session, students worked in their teams to select up to 3 team concepts to pursue. Out of 14 teams, 12 teams incorporated concepts from *Individual Ideation with Design Heuristics* in their selected team concepts.

In students' final design reports, 8 out of the 13 teams included a concept inspired from *Individual Ideation with Design Heuristics* in their final report design (see Table 5).

For example, Team B designed an instrumented manipulandum, or device for tracking finger movement to correlate with neural signals for prosthetic limbs. Concepts 1b and 1c in Figure 6 show individual concepts created with Design Heuristics that led to the final design. Concept 1a (Figure 5.1(a)), using natural ideation, was a rigid manipulation device that is easy to wear and has bend sensors. Concept 1b (Figure 5.1(b)), inspired by the *Substitute way of achieving function* heuristic, used two bend sensors around the finger to track movement. Concept 1c (Figure 5.1(c)), using the *Simplify* heuristic, had slits to allow only 1 or 2 fingers to move. When the students came together to generate up to 3 team concepts, one (Figure 5.2) was a rigid system that incorporated concepts 1a, 1b and 1c, that would adjust to different neutral positions with bend sensors around the finger. Team B's final report design (Figure 5.3) maintained most of these elements. The final design incorporated piezo-resistive bend and force sensors into a stiff front plate design that tracked finger movements and constrained other fingers. Team B showed evidence of multiple heuristic-driven individual concepts carried over into their final design.

As a second example, four students on Team I, who were developing a device to detect sudden cardiac arrest and alert Emergency Medical Services, generated 12 concepts using Design Heuristics individually during *Individual Ideation with Design Heuristics*, and several heuristic-driven individual concepts were present in their *Team Concept Synthesis*, and in their final design. Concepts 1a, 1b and 1c in Figure 6 show initial individual concepts and heuristic-driven individual concepts. Concept 1a (Figure 6.1(a)), generated using natural ideation, measured pulse around the wrist with an alarm. Concept 1b (Figure 6.1(b)), inspired by the heuristic, *Use common base to hold components*, had components for detecting a pulse, alerting bystanders, and reading time. Concept 1c (Figure 6.1

Table 5. Presence of heuristic driven concepts in team and final concepts. Team C did not provide a final report for proprietary reasons.

Team	Project	# of team-selected concepts based on Design Heuristics (out of 3)	Final report designs based on Design Heuristics
A	Portable Scalp-Cooling Device	3	Yes
B	Instrumented Manipulandum to Train both Human and Nonhuman Primates	2	Yes
C	ECLS Transport System	1	N/A
D	Improvement of IVF Egg Retrieval Procedure	2	No
E	Tremor Toothbrush/Oral Aids	1	No
F	Retractor for Sacrospinous Ligament Suspension	0 (out of 1)	No
G	Bladder Irrigator	1	Yes
H	Ergonomic Endoscopy Grip	1	Yes
I	Sudden Cardiac Arrest Alert	2	Yes
J	Facial Treatment for Atopic Dermatitis in Infants	3	No
K	Endoscopic Polyp Retrieval Device	2	Yes
L	Method to Stabilise an Endoscope	2	Yes
M	Percutaneous Endoscopic Gastrostomy Tube Dislodgement Prevention	0	No
N	Bimanual Vitreoretinal Surgery Product	2	Yes
	Total:	55%	62%

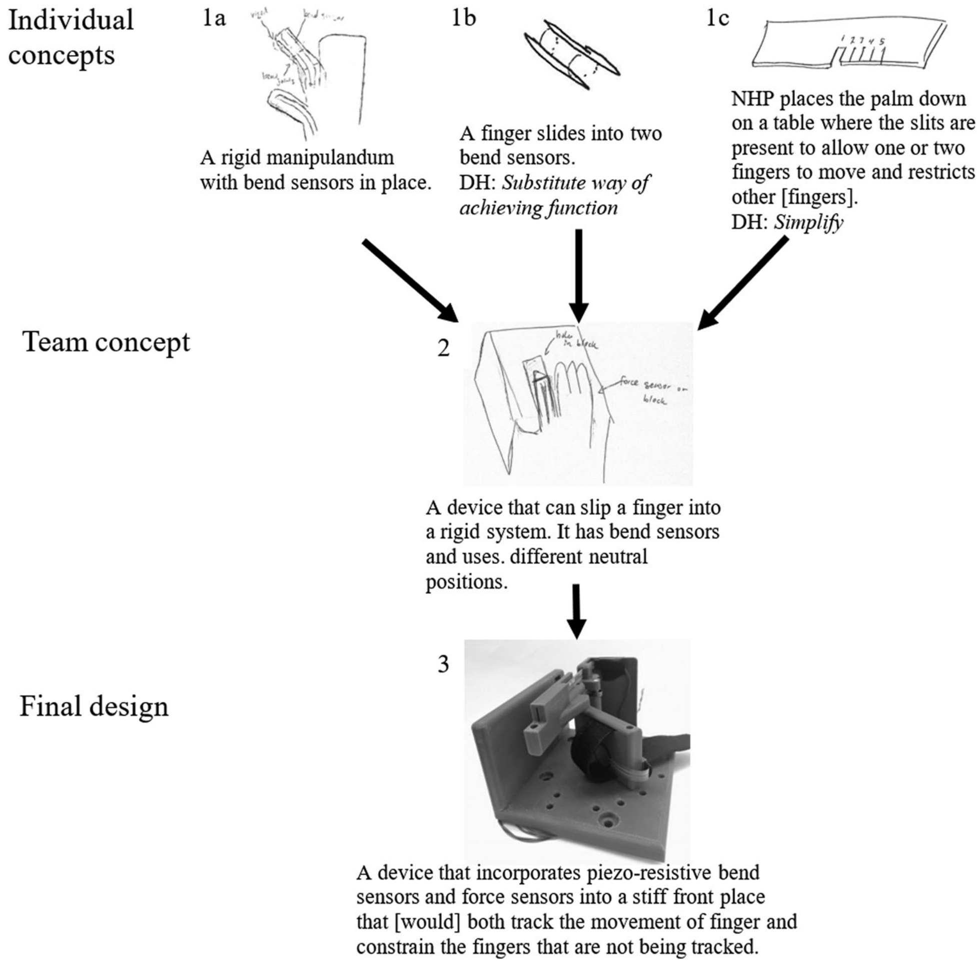

Figure 5. Team B's progression from their individual concepts to team concept to final design.

(c)), guided by *Incorporate user input*, used a button to cancel false alarms. When the students were asked to synthesise up to three team concepts, these three separate concepts (1a, 1b, 1c) were synthesised to form a team concept for a wristband with pulse monitoring, bystander alert (if the pulse was absent), and SOS button (Figure 6.2). This team concept became the prototype for the final design (Figure 6.3): A wristband that monitored the pulse, included a loud alarm when a pulse was absent, and a button to cancel false alarms.

Many heuristic-driven individual concepts persisted throughout the design process into the final designs, with 62% of final designs including heuristic-driven concepts. This suggests that students in both undergraduate and graduate biomedical engineering design courses considered heuristic-driven concepts to be useful and practical, because they decided to incorporate aspects of heuristic-driven concepts as they progressed to team concepts and final designs.

Discussion

Designing biomedical engineering devices involves complex regulations that can significantly restrict the viable solutions (Hagedorn, Grosse, and Krishnamurty 2015), which can also limit the use of design strategies in idea generation. Our results demonstrated that Design Heuristics are transferable

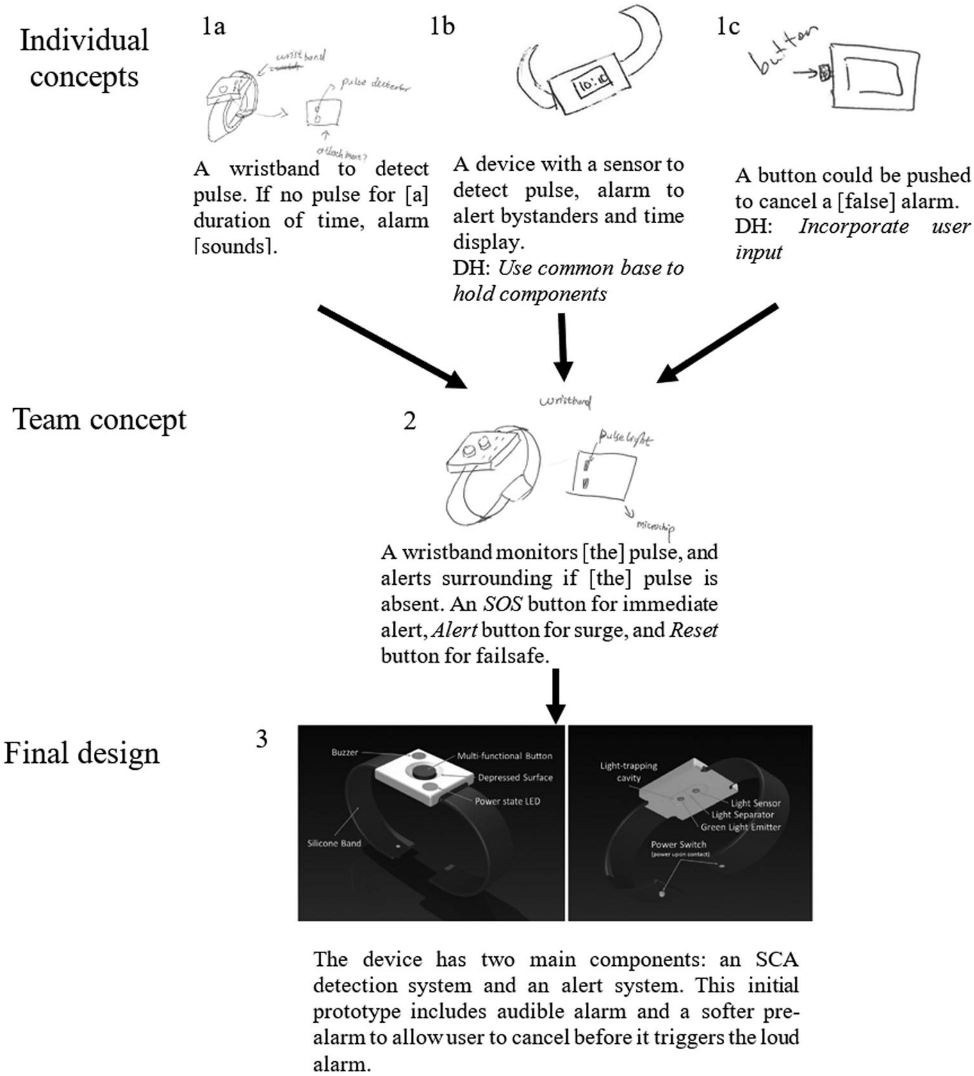

Figure 6. Team I's progression of concepts from individual concepts, to the team concept, and final report design.

to biomedical engineering design education and that students were able to use them to generate ideas. Students working on the same design problem used a variety of different Design Heuristics to generate multiple concepts, showing that many Design Heuristics were usable. Additionally, students working on the same problem generated different concepts using the same Design Heuristics, suggesting that biomedical engineering students used Design Heuristics as a tool to inspire ideas. For example, students on the ergonomic endoscopy grip team were inspired by *Provide sensory feedback* to generate multiple concepts. One student generated a concept that would provide vibrational feedback (Figure 3.3), while another student created a concept that would provide color-changing light feedback (Figure 4.3). Design Heuristic cards did not determine solutions as students' interpretations of the same Design Heuristic cards led to different solutions.

In addition to generating ideas, biomedical engineering students used Design Heuristics to refine initial concepts to further develop concepts, mirroring findings from other Design Heuristics studies (Christian et al. 2012). Other ideation techniques such as TRIZ have shown to be effective in multiple domains including mechanical engineering (Hernandez, Schmidt, and Okudan 2013), service design

(Zhang, Chai, and Tan 2005), and business development (Souchkov 2007). Furthermore, another ideation technique, biomimicry, has been used in industrial design (Louise and Casper 2012), architecture (Berkebile and McLennan 2004), and interior design (El-Zeiny 2012), demonstrating that design strategies can be used across multiple domains. Students in biomedical engineering have distinct educational experiences compared to other disciplines (Gatchell and Linsenmeier 2005) and may approach idea generation differently, which may not allow transferability of design strategies. This study demonstrated that Design Heuristics can be leveraged beyond mechanical engineering and industrial design, as they were shown to be transferable to biomedical engineering design for idea generation.

Students were able to use Design Heuristics to generate ideas in biomedical engineering, and within biomedical engineering. Design Heuristics were applicable across multiple design project contexts. Students used the same Design Heuristics across different problem contexts in the two design courses in our study, demonstrating that Design Heuristics were usable beyond a single or a few problem contexts in biomedical engineering. Similarly, the ideation tools such as TRIZ have been shown to be applicable to diverse problems within the scope of a single domain (Yamashina, Ito, and Kawada 2002; Zhang, Yang, and Liu 2014). In generating ideas using Design Heuristics, students may have been inspired to generate product-oriented solutions. For example, students who developed a sudden cardiac arrest alert could have generated ideas using principles from chemical engineering, electrical engineering, and computer science. However, they generated product-oriented ideas with tangible artifacts with Design Heuristics. Since Design Heuristics were developed from studying product designs, they may encourage generating ideas in the product domain. Further work is required to study how students use Design Heuristics in biomedical engineering. In our initial study of Design Heuristics in biomedical engineering, all 14 teams demonstrated that they were able to use Design Heuristics, showing the applicability of this tool in biomedical engineering design problems.

Finally, heuristic-driven individual concepts were evident in students' progression of ideas from individual to team to final concepts, demonstrating that students perceived heuristic-driven concepts to be practical, as they felt characteristics of concepts or whole concepts created with Design Heuristics were worthy of being their final design. Our findings align with previous studies of mechanical product design teams in developing design concepts with Design Heuristics, in that Design Heuristics inspired practical ideas that influenced later team concept development (Kramer, Daly, and Yilmaz 2014, 2015). In concept selection, individuals and teams must decide which ideas to drop and which ideas to further develop by assessing the potential to be a successful design (Florén and Frishammar 2012; Kim and Wilemon 2002). Prior studies show that students discard novel ideas during concept selection and choose conventional, practical concepts (Starkey, Toh, and Miller 2016; Toh and Miller 2016). Using Design Heuristics not only supported individual students in generating concepts, but also helped them to come up with practical concepts that advanced to their final team design. And, while in this study, we did not assess the creativity of final concepts, other research with Design Heuristics has shown that they support creative thinking as well (Daly et al. 2016; Yilmaz, Seifert, et al. 2016). Thus, it is possible that Design Heuristics could be supportive of both practical and novel ideas.

Implications for biomedical engineering education

Design Heuristics can be implemented in a single classroom session without providing extensive training to students. Biomedical design problems are often constrained by regulations and requirements, which could limit the exploration of possible solutions (Enderle and Bronzino 2012; Hagedorn, Grosse, and Krishnamurty 2015; Lerner et al. 2006). Design Heuristics can assist students in generating possible solutions to address design problems in biomedical engineering.

Also, Design Heuristics have been demonstrated to be useful in many institutions (Leahy et al. 2016) and this study demonstrated the transferability of Design Heuristics to another engineering discipline. In Europe, biomedical engineering programmes have expanded quickly (Nagel, Slaaf, and Barbenel 2007). Many biomedical engineering programmes in Europe have similar focuses as the U.S. programmes, such as concentrations in medical device, medical imaging, and biomaterial development (Educations 2018). Because of the similarities in biomedical engineering education, the usefulness of Design Heuristics may extend to the European engineering education context.

For instructors, Design Heuristics can be used to provide a structured idea generation lesson to help them teach their students about successful ideation. Design Heuristics could be used as a scaffolding tool (Wood, Bruner, and Gail 1976) to guide students in developing best practices in ideation in addition to brainstorming. Furthermore, biomedical engineering textbooks could integrate Design Heuristics as an idea generation method.

Limitations and future work

There were potential limitations based on the biases of the research team. Although the team attempted to set aside biases and expectations for this study's finding, the results may reflect some perspectives of the team.

As an initial study of using Design Heuristics in biomedical engineering, this study was conducted at a single institution with a small sample of courses, students, and design problems. Many of the projects in the two courses in this study were focused on product development, and other types of projects in biomedical engineering may show different results. The sample, then, limits a broader understanding of the application of the tool across diverse students, institutions, and project types. However, the study provides a detailed understanding of a small number of students and can provide information to guide future larger-scale studies.

Another limitation of our study was that we did not assess the qualities of ideas such as their creativity, diversity, and practicality or compare them to ideas generated without Design Heuristics. Due to having a small number of ideas per team, we could not analyse and compare the quality of ideas. As a first step, this study provides initial evidence about the utility of Design Heuristics in biomedical engineering.

As is common in qualitative research (Borrego, Douglas, and Amelink 2009; Creswell 2013; Patton 2001; Saldaña 2011), we focused on making claims in a specific context and we cannot generalise the usefulness of Design Heuristics in all contexts. Future work can expand the investigation of Design Heuristics into additional biomedical problems, and in other disciplines (Lee et al. 2018). For example, the possible role of Design Heuristics in biomedical engineering courses emphasising chemical and biochemical analysis is unknown. Design Heuristics could be tested in additional problem contexts to investigate their versatility.

Conclusion

This study demonstrated that Design Heuristics as an ideation tool can be used in biomedical engineering design classes to generate concepts. Students generated and developed multiple concepts for their projects using Design Heuristics, demonstrating transferability of Design Heuristics. Also, students in all 14 teams in this study were able to leverage Design Heuristics to generate ideas, showing that Design Heuristics can be used across multiple projects in biomedical engineering. Many of the heuristic-driven individual concepts persisted into students' team and final designs, which showed that the use of Design Heuristics led to concepts that the students considered to be useful and practical. Design Heuristics may be a useful tool for idea generation and development in biomedical engineering design courses.

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