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HandiMate: Exploring a Modular Robotics Kit for Animating Crafted Toys

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ABSTRACT

Building from our previous work we explore *HandiMate*, a robotics kit which enables users to construct and animate their toys using everyday craft materials [32]. The kit contains eight joint modules, a tablet interface and a glove controller. Unlike popular kits, *HandiMate* does not rely on manufactured parts to construct the toy. Rather this open ended platform engages users to pursue interest driven activities using everyday objects, such as cardboard, construction paper, and spoons. These crafted parts are then fastened together using Velcro to the joint modules and animated using the glove as the controller. In this paper, we discuss the results from two user studies which were designed to understand the affinity of *HandiMate* among children. The first study reveals that children rated the HandiMate kit as gender-neutral, appealing equally to both female and male students. The second study discusses the benefits of engaging children in engineering design with HandiMate, which has been observed to bring out children's tacit physics-based engineering knowledge and facilitate learning.

Categories and Subject Descriptors

H.5.2 [**Information Interfaces and Presentation**]: User Interfaces; K.3.1 [**Computers and Education**]: Computer uses in Education

Keywords

Tangible User Interface; Children; Education Kit; Modular Robotics; Gender Neutral; Engineering Learning; Handicraft; Creativity.

1. INTRODUCTION

Right from a child's younger years, physical items such as building blocks, shape puzzles and jigsaws have been an integral part of their play. They have been encouraged to play with physical objects to learn a variety of skills [21]. Resnick extended the idea to define "digital manipulatives" as familiar physical items with added computational power which were aimed at enhancing children's learning [27]. These manipulatives such as modular robotic kits [4, 8], have traditionally attracted a predominant number of males [13]. These kits have manufactured building blocks based on which children construct. On the one hand they do encourage creativity but on the other, they do it in an instructive and constrained manner. Similarly, kits like e-textile where female participation is encouraged via sewing, crafting and decorating, do not cater to development of an electromechanical or robotic systems [23]. There exists a need for kits that encourages the kinds of engineering learning that is outlined in the Next Generation Science Standards [5] such as "Engineering Design" and "Forces and Interactions". As we do so, these kits should also encourage broad participation (i.e., are gender neutral) so as not to continue to reinforce existing inequities.

Figure 1: HandiMate is a modular robotics kit that supports learning in an open-ended design environment.(a) The HandiMate System, (b) Child fabricating the robotic toy, (c) Playing the toy with the glove controller, (d) User constructed robot.

By contrast, *HandiMate* aims to be both gender-neutral while also encouraging physics-based engineering play. The kit provides a construction platform which merges robotics with narrative play and crafting. This approach enables gender neutrality by emphasizing a broader range of play activities that are more open to divergent design possibilities. The kit itself is made up of 8 joint modules, where each joint module is packaged with an actuator, a wireless communication device and a micro-controller. This modularization makes quick electro-mechanical prototyping, a matter of pressing together Velcro. Animating these constructions is made intuitive and engaging by a glove-based gestural controller. We demonstrate that *HandiMate* attracts both genders to participate more ex-

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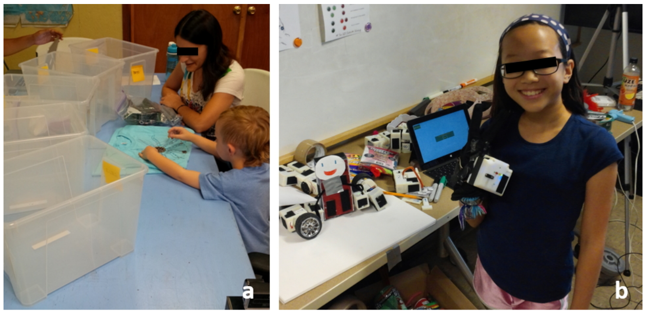


Figure 2: Two user studies designed for *HandiMate* (a) Gender Appropriateness, (b) Engineering Learning.

tensively and equally. We discuss the technical implementation of the kit and the studies conducted to access the compatibility among genders. We designed our studies to observe learning of broader engineering concepts among children. As a part of understanding the impact of this kit, we sought to conduct studies which were designed to answer the following research questions:

- Does changing the tools and the material, to craft the toys, affect the gender perception of the robotic kit?
- To what extent do children as the designer engage in general engineering concepts with *HandiMate*?

For this we conducted two studies among a total of 53 children over a span of two months. The first enrolled 32 children to better understand how youth perceived the gender of this toolkit and how they situate it among other toolkits. The second engaged 21 children in playing with *HandiMate* and conducted interviews to understand their design processes with learning outcomes. Apart from the above mentioned goals, this paper also contributes towards the design and implementation of a new animatornics kit, which enables users to craft and animate the toys.

2. RELATED WORKS

2.1 Gender Appropriateness

Robotic kits have been popularized in after-school informal educational settings for all genders. Even with efforts of neutralizing the gender perception on robotic kits, an imbalance of gender participation still exists where girl's participation rate is about 30% in a robotics program [19]. Previous works suggest a way to broaden the gender participation through merging art and technology in cross-disciplinary activities [11, 28]. Rather than fixating on a particular task-oriented application, girls exhibit interest towards designing motion path and clothing for robots which are regarded as creative activities [17]. Thus, girls should be considered as potential learners in robotics educational programs [14]. Efforts have been put to introduce toys and kits that are designed to attract female participation in engineering fields. Commercial kits like GoldieBlox [2] encourage building and rudimentary mechanical engineering concepts by their kit. Similarly Roominate [6] is targeted for girls to develop dynamic and electrical structures. These kits are aimed for smaller age group and are constrained by their manufactured material for usage. Thus they tend to be of a smaller scale and are less extensible. Meanwhile, work has been done with creditable research for the development of toy kits that support a more creative environment for STEM learning [10]. Our approach with *HandiMate* is to encourage craft materials and Velcro as constructing elements to provide an open-ended design environment for broadening the gender participation. Apart from the gender participation, *HandiMate* is aimed to appeal a boarder age group.

2.2 Learning Engineering Concepts

Piaget has argued that tangibles provide opportunities to reformulate our existing mental models [24], which has motivated a lot of research for developing pedagogical tools. Engineering concepts such as center of mass, friction, stability of structures, materials for construction and dynamic structure serves as important concepts to be taught to high school students [5]. These concepts would then serve as the foundation for design considerations in fabricating dynamic systems. Topobo is a system that supports children in exploring various physics concepts with manufactured primitives based on kinetic memory [26]. Similarly, Kinematics [22] allows children to assemble increasingly complex structures by recombing different predefined elements. This kit allows the children to learn via iterating and reassembling the constructed structure. EnergyBugs [29], a wearable energy-harvesting device for kids, made children to develop a tangible and emotional connection to energy. Schweikardt introduced roBlocks [31], a computational kit which enables the young users to explore complex ideas in science, technology, engineering and mathematics. The kit consist of manufactured sensor, actuators and logic modules to play with. By contrast, *HandiMate* encourages a more open ended design approach. We do not have any manufactured primitives, apart from the joint modules, for the users to build their toy. This kit enables the user to use everyday materials like cardboard, craft paper, and kitchenware in constructing the toy, thereby exploring various engineering concepts with materials and structures.

2.3 Modular Robotics Kit

Many researchers have explored different types of configurable robots for purposes such as smart machines capable of locomotion and transformation [20], educational tool kits that children can use to learn about programming [33], and simple toys [22]. These kits allow construction of robots using different materials like predefined plastic shapes [26], user manufactured plastic shapes [1], laser cut shapes [34] and a combination of craft and LEGO [28]. The control techniques in these kits generally use either a graphical programming system, autonomous control [20] or kinetic memory - the ability to record and playback physical motion [26]. This culture of building robots using pre-defined shapes has been widely commercialized via LEGO Mindstorms, Vex robotics and EZ-Robot [1].

These kits were typically designed to make systems with fewer (one to four) motor actuated joints. A majority of these prior works tend to restrict design freedom as they provide a set of predefined physical shapes that could only be assembled in specific ways. Crafting using everyday objects as primitives shapes provides more freedom in creative exploration. Also providing a glove as the controller shifts from the regular methods of control devices such as tablets and phones and potentially more active and embodied engagement.

3. HANDIMATE OVERVIEW

HandiMate is a platform which merges crafts and actuated joints. Designing the primitive blocks of this kit is open-ended, as the user fabricates them via crafting. We intended to develop a gender neutral kit, which takes the electronics and programming to the background and encourages users to build toys. Our design goals for developing this kit were:

- *Accessible*: The material used for constructing the objects should be easily accessible and be assembled quickly using simple and familiar techniques for everybody to use.
- *Engagement*: The kit should be engaging the user for interest driven play.
- *Safe and robust*: The kit is to be used by people of different age groups, the device should be safe and should work reliably.
- *Adequate & smooth movement*: The system should be able to recreate most motions (both fixed angle and continuous motion) smoothly to provide an enjoyable experience.
- *Expressive*: Encourage users to explore topics through a new form of storytelling medium.

3.1 Hardware

HandiMate is a kit that consists of eight joint modules, a tablet interface and a glove controller. Each module contains an XBee communication device that reads the information from the glove-based controller, a micro-controller (Arduino Nano) for interpreting this information, and Herkulex DRS-101 motors for motion. To allow the device to have both fixed angle and continuous rotation motions, inserts are used. These inserts are held in place with the help of magnets. The fixed angle insert allows for rotation from -90° to 90°. It snaps into the motor connector and locks the upper and lower halves of the module.

The glove-based controller is used to read the hand pose of the user and control the motion of the joint modules. It consists of an Arduino Nano (ATmega 328, clock speed 16MHz), flex sensors, MPU 6050 (IMU), and BlueSMiRF Silver (Baud rate 115200 bps) and XBee Series 1 (Baud rate 57600 bps). The Bluetooth device is used to receive the joint module and hand joint mapping from the tablet interface. Flex sensors are placed on the thumb (Interphalangeal, Metacarpophalangeal joints), index and middle fingers (Proximal Interphalangeal and Metacarpophalangeal joints) due to the greater dexterity of these fingers from the rest of the hand.

The seven flex sensors, are multiplexed by a 16-channel analog multiplexer. When the resistance of the flex sensor changes (34K to 67K ohms) by bending, the micro-controller picks up the voltage across the flex sensor based on a voltage divider circuit. These analog values are then converted into corresponding motor values. This mapping between the analog sensor value to the motor value is not directly based on the actual angle of the hand or finger, but is scaled to allow full rotation of the joint module within a comfortable range of motion of the hand or finger. In a similar manner the micro-controller also reads the angle values from the gyro-meter and accelerometer in the IMU device by I^2C communication and generates the motor values. The motor values are transmitted to the respective joint modules by a PAN network created by the XBee communication device.

A simple tablet application has been developed to understand the topology of constructions made and to effectively map them for gestural control. The interface is built using the Unity^{TM} game engine [7]. The application can be installed on any tablet or mobile device. A few basic families of constructions are made available with predefined control mappings where the user has to select the position and direction of motion of the joint modules. The interface also allows the user to create objects that are different from these predefined families and to assign their own user-defined mapping to the object being constructed. Once defined, these mappings are transferred to the glove-based controller using Bluetooth communication. This operation has to be done only once each time the user constructs a new object.

3.2 Animation Actions

The action library was inspired from sock-puppetry (Puppet Shaped Constructions) and gestures used from daily life activities (Global & Construction Gestures). The actions from the glove can be classified as two according to the functionalities associated with them - (a) Global Command and (b) Construction Control. The global actions enables the user to initiate or terminate the process of control by two commands respectively: *Shake* and *Closed fist* (Figure 4(a)). After shaking the hand, the user is expected to keep their hand flat for 100 milli-seconds. Whenever the latter gesture is performed in any orientation of the hand, the system comes to a complete standstill. The shake gesture is then required to restart the system. The construction control gestures are used for animating the construction. The toys made by the user can be of the following three main categories.

3.2.1 Articulated

The constructions of these types have a fixed angle of rotation motion. They are further sub divided as: *Puppet Shaped Constructions*: For controlling this type, the user makes use of the thumb, index and middle finger (Figure 4(b)). *Robotic Arm*: The index finger and orientation of the hand controls the robot arm. Three joints of the finger are mapped to each DOF of the robot arm (Figure 4(c)).

3.2.2 Vehicular

These types of constructions consist of 2, 3 and 4 wheeled robots. The speed is mapped based on the principle of a joystick where the speed is proportional to the angular displacement of the hand from the relaxed (flat) position (Figure 4(d)). The direction of tilt decides the steering direction of the car. In these types of construction, the user is given the option of adding the different articulated constructions mentioned above, over the vehicle.

3.2.3 Custom Robots

The previous two categories had predefined mappings for the control technique. This category does not have any fixed mapping. On the contrary, this feature allows the user to explore and experiment with different mapping techniques, and select one which they feel is more natural. The user is given the option of choosing the modules which are being used and their desired motion like fixed angle clock wise (CW), fixed angle counter clock wise (CCW), continuous rotation CW, or continuous rotation CCW. Once they select the modules, they have the option of choosing the hand joint number and mapping the hand joint to the respective joint module

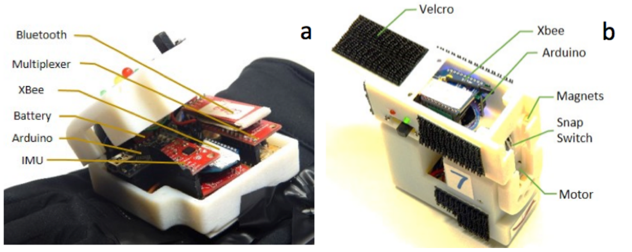


Figure 3: Hardware components of the kit (a)the glove and (b)the joint module

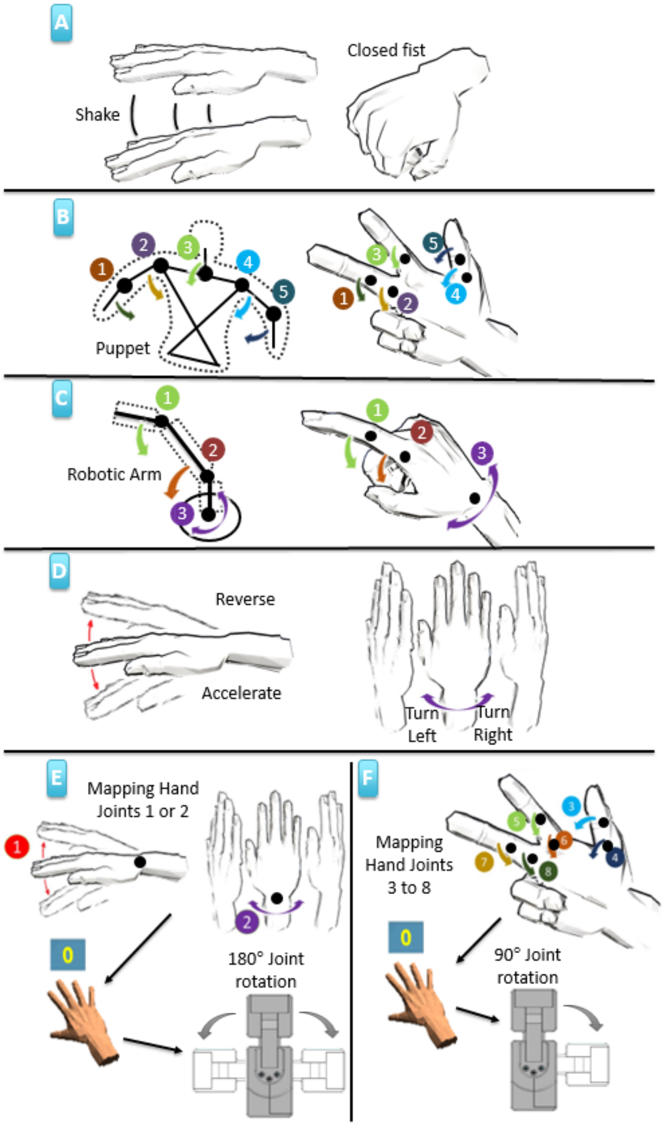


Figure 4: Interaction methods: (a) Global Gestures; Gestures for (b) Puppet Shaped Constructions (c) Robotic Arm shaped constructions (d) Vehicular constructions; User Defined gesture mapping for custom robots (e) Hand joints 1 or 2 (f) Hand joints 3 to 8

(Figure 4(e,f)). The user has the option of mapping multiple joint modules with the same hand joint. To avoid inconsistency and confusion, the option of mapping multiple hand joints to the same joint module is not made available.

As hand joints 1 and 2 allow a 180° angle hand rotation, the joint modules controlled by these joints move from -90° to 90° when in fixed angle mode. Since joints 3 to 8 are finger controlled, the joint modules mapped to them can rotate from 0° to 90° or -90°. When the joint module is in continuous rotation mode, the user can control the speed of the joint module rotation based on the deflection from the relaxed (flat) hand position. Joints 1 and 2 allow bi-directional speed control whereas joints 3 to 8 allow unidirectional speed control.

Kit	Included Materials	Image	Gender Hypothesis
HandiMate	Cardboard, Craft Materials, Velcro, Joint Module, Glove		Neutral
VEX Clawbot	Steel Chassis, Gear Sets, Shaft, Screws, Bearings, Motors, Remote Joystick		Masculine
LEGO Mindstorms EV3	Lego Blocks, LEGO Servo Motors, Remote Control		Masculine

Figure 5: Summary of the selected robotics kits

4. EVALUATION WITH CHILDREN

Children lately have been exposed to complex modular robotic kits like Lego Mindstroms and Vex Robotics. In general, robotics has been known to attract disproportionate numbers of boys. We argue that this is largely due to the kinds of more masculine materials used and construction practices privileged that has disproportionately attracted males to robotics historically. In short, by diversifying the tools and materials, we think we can radically impact the persistent STEM pipeline issues in computing and engineering fields. *HandiMate* aims for broadening of participation from both the genders by drawing on more gender neutral materials and privileging a wider range of construction practices in the design process. We designed our studies to understand how can crafting, when coupled with modular robotics, attract both the sexes. Also how this kit via its construction exercise, will leverage creativity and help develop intuitions for engineering concepts among children. We conduct two such studies for this purpose. The first study evaluates a comparison of *HandiMate* with other commercial robotic kits. Quantitative data was collected from these sorting tasks. The second study had qualitative interviews which were held after a 90 minute session with the kit.

4.1 Gender Appropriateness Study

The goal of proposed study is to evaluate the gender perception of *HandiMate* by children as well as how this kit compares to others on the existing market. We modified the gender sorting methods of Campenni and Raag [12, 25]. Instead of using surveys, we showed users actual components and kits to make their decisions. Throughout the study, we could observe impacts of components on gender perception of kits. In order to empirically study the gender appropriateness, we gathered users with various ages and genders.

4.1.1 Participants

The user study took place at a local Boys and Girls Club. A total of 32 children of ages between 6-15 years participated in the user study. The children were involved in the study during their extra-curricular hours. We randomly picked a single user from play area to conduct the study. Among 32 children, 15 were girls (μ_{age}=9.29) and 17 were boys (μ_{age}=9.47).

4.1.2 Materials and Procedure

We prepared three robotics kits including *HandiMate* (Figure 5) and seven component groups (Figure 6) for the sorting task. These include following: 1) *HandiMate*, 2) Vex Clawbot, 3) LEGO Mindstorms EV3, 4) Lego blocks, 5) Wheels, 6) Electrical components,

Figure 6: Summary of selected components shown in most masculine (left) to most feminine (right) order based on gender sorting rating task. Selected components include (a) Lego blocks, (b) Wheels, (c) Electrical components such as battery, breakout board (d) Velcro, (e) Cardboard, (f) Textile kit, and (g) Craft kit. In addition, three robotics kits were also tested.

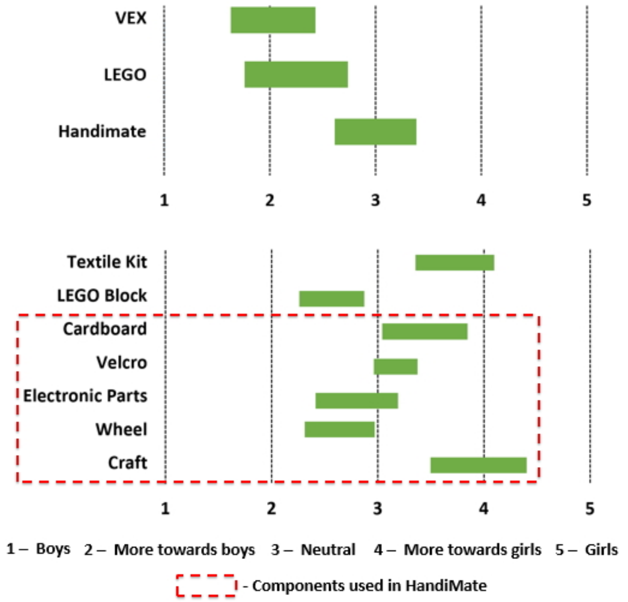
7) Velcro, 8) Cardboard, 9) Textile kit, and 10) Craft kit. These examples were placed in transparent baggies to explicitly show contents and to limit play.

The gender sorting task began with five clear plastic bins, identified with a labeled sticky note. The bin on the far left was labeled “boys", the bin on the far right was labeled “girls", and the bin in the middle was labeled “both boys and girls" (Figure 2(a)). We explained the contents of each baggie and allowed participants to explore them. They were asked whether the material or kit in question seemed to be more appealing to boys, girls, both equally, or somewhere in between. Then, they placed baggies in the bin of their choice and researchers moved on to next baggies for same purpose.

4.1.3 Results

Based on five level Likert-like scaled data, we conducted two post-hoc analysis: Bonferroni post-hoc analysis with one-way analysis of variance (ANOVA) and two-way ANOVA. Bonferroni method was adopted to reduce errors during multiple comparisons. One-way ANOVA showed that the gender perception among different kits ($F_{(2,93)}$=11.46, $p<0.05$) and components ($F_{(6,210)}$=17.22, $p<0.05$) were significant. A Bonferroni showed that VEX (μ=2.05, SD=0.83) and LEGO Mindstorm (μ=2.25, SD=0.98) showed similar (masculine) perception ($p>0.05$), the *HandiMate* exhibited a different (neutral) perception (μ=3.03, SD=0.78, $p<0.05$). Components sorting results dissected into three groups based on their perception: masculine (Wheel, Electronic parts & LEGO block), feminine (Craft material & Textile kit), and neutral (Velcro & Cardboard). With these results, we present interesting findings on the relationship among gender, kit, and the components.

By combining crafting and construction activities and not having a predefined form or structure to both the toy or play pattern, we expected to see a neutral gender perception on *HandiMate*. Figure 7 clearly illustrates the result as expected. To verify the effect of merging different activities, we looked into evaluations of individual components. In *HandiMate*, the following items were utilized as components: Craft material (μ=3.81), wheel (μ=2.44), electronic part (μ=2.61), Velcro (μ=3.00), and Cardboard (μ=3.32). The average rating of these materials came out to be 3.04 which aligned with an overall kit rating. This implies that merging feminine (crafting) and masculine (constructing) activities neutralized the perception of a whole kit.



Gender	HandiMate	LEGO Mindstorm	VEX	Average
Male	2.76 (0.75)	2.47 (1.07)	2.03 (0.87)	2.42
Female	3.42 (0.79)	1.75 (0.75)	2 (0.85)	2.39

Figure 7: Gender sorting result for different kits (Top) and components (Middle). Gender sorting result for each gender (Bottom).

We performed a two-way ANOVA on different genders and kits to make sure whether one-way ANOVA result fairly represents overall genders' opinion. Although there was no significant difference on each gender's view on all kits, we observed that participants exhibit significant difference ($F_{(1,56)}$=4.49, $p<0.05$) on the gender perception between *Handimate* (μ_{female}=3.42, μ_{male}=2.77) and LEGO Mindstorm (μ_{female}=1.75, μ_{male}=2.47). A gender rating on LEGO Mindstorm was more towards “boys". In figure 7, we observed that girls expressed LEGO Mindstorm as a kit for boys whereas boys rated it more towards for both boys and girls. The user interview contexts supported these rating trends. More than half of girls mentioned “LEGO is for boys, not for us" and some girls said “I like crafting more than constructing". Boys mostly said that “everyone likes LEGO". Moreover, component evaluation on LEGO Block showed the lowest ratings (most masculine) among all other components. Another interesting finding was that both male and female participants expressed *HandiMate* as a kit for their own genders. This indicates that the proposed kit lowers a gender barrier which was not observed in LEGO Mindstorm or VEX. Findings from this study indicates that the engineering learning study should not be biased by different genders and sets the stage for more equitable participation. They all exhibit similar level of interest towards *HandiMate* and hence are equally motivated to create their toys.

4.2 Engineering Learning Study

We also explore *HandiMate*, as an engineering learning platform for children where they are encouraged to apply tacit engineering understanding to construct dynamic structures. The learning is made possible by the ability to iterate with craft materials to assemble and fabricate their toy via the eight joint modules. Due to the open-ended nature of using the craft material as the building blocks, we observed a broad span of engineering concepts in-herently implemented by them. This study was structured towards a systematic artifacts analysis method to build a coding scheme for relating mechanical engineering constructs to childhood play. This resulted in the hierarchical chart of mechanical engineering taxonomies (Figure 9). Units of analysis were the final artifacts in the context of the workshop, created by the single user. The artifacts were examined and coded using the key mechanical engineering concepts from Dynamics, Mechanics, Materials, and Design.

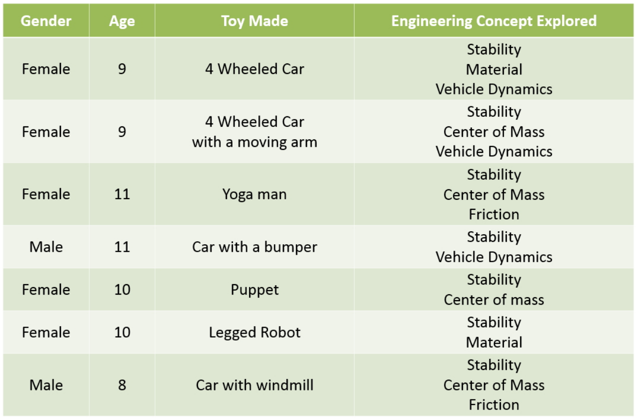
4.2.1 Participants

During our second study, users showed a similar level of motivation for playing with *HandiMate*. This unbiased perception ensured us to conducted a follow-up study on children's learning behavior. We recruited 21 children from ages between 8-13 years, by distributing user study fliers in libraries and community centers. Out of the 21 children, 12 were girls and 9 were boys. A compensation for participation included 10 dollars and the option to take home the crafted structures without the joint modules.

4.2.2 Materials and Procedure

This study was conducted in a closed environment where each participant worked with a researcher in one session at a time. We provided raw materials such as spoons, fork, and pans, craft material like cardboard, matboard, construction paper, multi-colored thread, colored craft sticks, assorted feather collection, crayons, markers, tape, glue gun, knifes, googly eyes, scissor and foam core board to work with. For quick prototyping, precut basic 2D and 3D shapes of foam core board like rectangles, circles, triangles, hexagon, cubes, rectangular prisms, and triangular prisms were also provided. The user was also given the option to cut any specific shape from the raw materials provided. Before starting the study, a pre-task interview was conducted where we asked questions regarding their school curriculum to probe their understanding of engineering concepts. These questions were designed with reference to the current state school curriculum [3].

The study with each participant lasted for 60 to 90 minutes. The participant was initially made aware of the *HandiMate* framework. We explained to the participant the physical structure of the joint modules, tablet interface and gestural control methods of the glove-based controller. The participant was then asked to build their own desired construction using the raw materials and eight joint modules provided. They were allowed to sketch their idea first and then build in steps, test each step and proceed or directly complete the whole fabrication and play with the system. The researchers observed the design iterations while they were constructing the toy. Later the participants were interviewed on their design decisions for the toy. These interview questions were open-ended to elicit maximum input from the children. The interview script consisted of questions like "What did you try to build here?", "We observed that while making the toy, you changed this. Why did you change that?", "What will you do to make the toy work better?" and "What did you learn here today, that you will apply while you construct your own toy/robot later?". During the study, researchers carefully monitored word choice to avoid influencing the children's vocabulary. A primary coder with advanced engineering training, coded the transcripts of audio interviews and videotaped observations, noting if any of the targeted engineering concepts was present in the data. Each of these cases was compiled and further analyzed for the purposes of this study.



Gender	Age	Toy Made	Engineering Concept Explored
Female	9	4 Wheeled Car	Stability Material Vehicle Dynamics
Female	9	4 Wheeled Car with a moving arm	Stability Center of Mass Vehicle Dynamics
Female	11	Yoga man	Stability Center of Mass Friction
Male	11	Car with a bumper	Stability Vehicle Dynamics
Female	10	Puppet	Stability Center of mass
Female	10	Legged Robot	Stability Material
Male	8	Car with windmill	Stability Center of Mass Friction

Figure 8: Examples of engineering concept explored by children during user study.

4.2.3 Results

The results of this second study indicated that boys and girls tended to engage in a different design process with the kit. Universally, all 12 girls enjoyed and came up with interesting crafted toys, dividing their alloted time in three activities : designing, fabricating and decorating the toy. Whereas the boys were very task oriented and wanted to build more functional prototypes. We also noticed that boys would iterate over their toys more, to make the robot perform their intended task more efficiently. However, despite these differences in the goals and process of activity, both the genders explored engineering concepts while constructing their toy in their own manner (Figure 8). The major domains of knowledge explored by the participants are highlighted here.

Materials: From an engineering point, material selection is based on the functionality of the component. Engineers make calculated decisions on what material to use, so that the component as well as the assembly does not fail. Since for the process of crafting, the children were given a lot of materials to construct their toys with. We observed some intuition in them for selecting material based on strength, by the end of the study. While some used cardboard as they defined it was "more flexible" than other materials, other learned that Styrofoam shells are flimsy material for the purpose of a dynamic system. Most of them opted to use Velcro over other temporary fasteners like duct-tape, hot-glue gun as they felt Velcro was "stronger" than others.

Center Of Mass: For dynamic structures the center of mass is a key design factor. The stability of the system, in dynamic conditions, is heavily influenced by the position of the center of mass for that structure. We observed young participants implementing design changes to alter the center of mass of their toy. An 11 year old

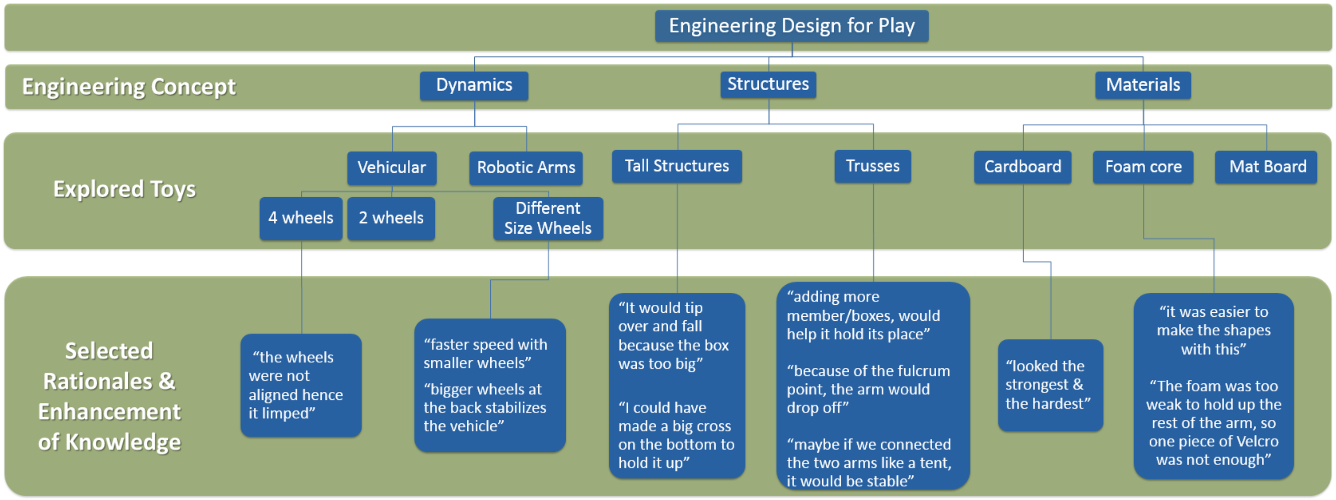


Figure 9: Exploring Engineering Design for play (a) Engineering Concepts - The broad classification of concepts implemented by children in their toys. (b) Explored Toys - The various types of toys fabricated by the children. (c) Rationales and Enhancement of Knowledge - Quotes from studies on understanding the failure mode in the process of iterative design to find out solutions.

girl made a “Yoga-Man" toy, where she would constantly iterate her design as it would fail. She finally resorted on shortening the height of the toy and adding wheels at the bottom. In her interview she justified this decision by saying “Because it was heavy and big on the top, and there is gravity. So big objects, if they are heavy, are hard to stand up."Similarly, we also observed some students shortening the height of their crafted toy so that it could perform a task with stability. On asking, they would say that their toy would “fall off" so they made it short as an improvisation.

Friction: The materials used by the participants were crafted boxes and structures. This lead to rather flimsy designs. Many a time, while the toy was in motion, the components would interact with each or with ground to create friction hindrances. This was observed by a large group of participants and they worked their way out to reduce these frictional losses.

Stability of the Structure: In engineering context, "Structures" is an application oriented field of study which explores design of trusses and machine. During our study, we observed a lot of examples where participants showcased intuition towards making the static structure stable. A 9 year old girl, who wanted to make a robotic arm on top of a 4 wheeled toy, ended up designing a triangular truss member in the middle to make the system stable. “So there would be some weight in the middle and some on the side, and if it wanted to tip over, it would be balanced on the other side and would not fall as easily." Another 11 year old male, made a similar toy of a robot arm on top of a wheeled toy. The arm would keep hitting the body of robot and would fall off. He recognized the problem: “ I think so that the point where it was hedging off was responsible for it. It hits there and it has enough momentum to break off and keep on falling." He successfully understood the concept of fulcrum by seeing it in action and improvised his design by making the arm offset from the body. The common solution implemented by children was to make the base of the structure bigger and wider. This gave them more stability to their dynamic toy. Some of them even added more weight to the bottom structure of the toy, so that it stays more firmly on the ground.

Dynamics: The participants made various types of toys which had 2, 3 and 4 wheels. While constructing the toy, they would fail and improvise their designs. Motivated by the popular concept of ‘Hot-Rods’ one 9 year old girl, used different sets of wheel for the front and the back. In the interview she said “The back wheels should be bigger because they are heavier so they put more weight on the front wheels, it would go faster." Another 9 year old female, made a wheeled toy that was limping, when it moved forward. She then improved the wheel alignment so that the wheels aligned in the same axis of rotation. On asking why she did that, she replied “It goes slower, because if the wheels are not straight, it’s not going straight". There were some intuitive solutions for wheel selection like “bigger wheels will lift up the middle". An 8 year old boy, changed from making a 4 wheeled toy to 2 wheels. In the interview he replied “ when I test drove it, it was slow and everything was breaking so I thought about a 2 wheeler.....it is lighter than a 4 wheeler. So less weight there is, it would go faster."

4.2.4 Engagement

HandiMate also provided motivational benefits to the child, as they had a sense of autonomy over the creation of the toy. When the child wanted to realize his/her toy, he/she would put their best effort to make it as close to their imagination as they can. Since they are using craft material, they had to fabricate every detail from their imagination. Some children wanted to fabricate toys from popular fantasy stories like “Dobby from Harry Potter" or “a Pirate Captain". They define their own tasks and thus are engaged to bring their creation to life . The added advantage of controlling the toy via a glove made a alot of children excited. They felt it was “very cool" to operate the toy with the glove via hand and finger movements. We also noted that, because of the glove the child was more dynamically involved with the toy, as they were immersed in controlling the toy via their hand. It was interesting to note, that while controlling the toy with the glove, they would not look at the hand for gestures. Rather they were constantly watching the toy’s motion and controlling it seamlessly with the hand motions. They thus exhibited a very good case for proprioceptive control. This may suggest that the glove, because of it proprioceptive abilities, is an ergonomic controller. The glove also contributed to the emotional responses exhibited by the children.

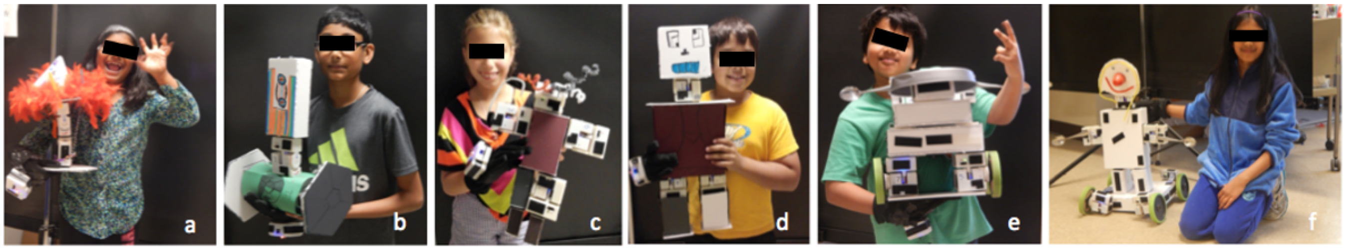


Figure 10: Display of tacit concept via toys : (a) & (b) Stability of Structure (c) & (d) Center of Mass (e) & (f) Dynamics.

Emotional Responses: We did not carry any designed experiment to record their emotional response while building and playing with their toy, but we made observations on their reactions (Figure 11). Their fabricated toy was a realization of their imagination, be it an anthropomorphic character or a wheeled super-vehicle. So when they controlled the toy, they were very excited to see the toy come to life. They responded emotionally by excitement and surprise. Some children were completely engrossed in crafting the details of the toy, while building it. This eventually built up their curiosity to see their toy in action. During fabrication, they were emotionally attached to the toy and many of the children ended up taking the crafted components home. “I will give it to my teacher", replied an 8 year old girl who made a doll. This seemed to indicate the glove’s importance in the designs.

Figure 11: Emotional Response and Engagement: The child becomes excited and amazed to see their fabricated toy come to life. They also control the toy purely on the proprioceptive abilities of the glove.

4.2.5 Designing for Play

The study involved the children to first sketch their toys on a paper and then fabricate it. The freedom provided to fabricate primitives from materials made them iterate their design, when a prototype failed. This design process of actively constructing the toy develops deeper understanding of the engineering concept, based on their design iteration experiences [30]. Later after the study, we would ask them “If you were to make this same toy 2 years from now again, what will you change in your drawing? How will you make it better?" They would then acknowledge the mode of failure in their existing design. They suggested on thinking about the failure mode at the sketching phase, the next time they made a similar toy. They were able to showcase learning of engineering concepts via designing and fabricating their toy. Through the iterative design process they enhanced their knowledge towards physics based engineering concepts (Figure 9).

5. DISCUSSION

The results of the gender sorting task revealed that merging constructing and crafting activities increases interest from both the genders. As proven in our gender appropriateness study, each gender favors *HandiMate* as toy for themselves, where the children can be actively involved in playing with the kit. Margolis [18] mentioned that toys will affect student’s comfort, confidence, and willingness to enter engineering educational programs. Unlike previous robotic kits where major users were male students, introducing craft-based activities into such kits can attract more girls to be active users. The platform designed with both feminine and masculine activities can shorten the gender gap in the Science, Technology, Engineering, and Math (STEM) learning field.

The gender perception study with components showed that traditional primitive blocks (such as LEGO , Vex) tend to exhibit masculine perception due to naturally embedded activity like construction. Current robotic kits using these primitive blocks might cause girls to think of it as toy for boys, not for them. The issues of gender imbalance in toy kits has been highlighted in recent articles [9, 16]. Utilizing various materials to fabricate those primitive blocks supports creativity through craft activities among children. Such kits that support an open-ended design environment, leads children to explore broad engineering concepts such as material selection and stability of structures. It was evident that both genders benefited from using such kit, where girls were equally engaged as much as the boys.

While designing and fabricating the toy, we observed that children change their understanding of engineering concepts. In early design stages, they did not expect and understand the behavior of their toy in the first trial of testing their toy. This notion of accommodating the external modal into their mental modal, supports the constructivist theory championed by Piaget [24]. At the same time these iterative activities enhances the child’s conceptual understanding. Throughout the redesigning process, children could embed several engineering concepts to their toy such as, adding a fixture to improve the stability. We observed tacit knowledge being put to use such as “it would drag the other end and it would not be able to move", where the children enhanced their understanding of friction from the playing experience with *HandiMate*. This use of tacit knowledge implies that educational kits that introduces the iterative design processes can enhance the learning in children.

Studies with *HandiMate* encouraged participants to be involved in further robotic workshops. To better understand, we surveyed briefly after each study if users would like to take part in further engineering learning activities and whether they were engaged in constructing the toy given their previous robotic experiences. 85% of participants mentioned that they will opt in for such future workshops after the *Handimate* user study. Engagement was higher in subjects with prior robotics experiences by 21% than participants without experience. These results indicate that children's first exposure to a robotic workshop is a basis to form their involvement and willingness in further workshops. Thereby suggesting that educational toys can encourage broad participation especially for girls towards STEM learning by introducing gender-neutral activities.

6. FUTURE WORK

Based on our observations, we are making improvements to the system. We plan to expand the capability of our joints by adding various sensing modalities including light, sound and ultrasonics. The present system has modules to perform rotary actuations. We are working on embedding capabilities of linear motion in our modules. It was interesting to note, that many users would perceive the gestures as a control mechanism in different ways. This opens up some research questions pertaining to the gesture mapping done for the toys. In the future, we will evaluate various gestures for controlling these tangible toys and develop a rationale for mapping them to toy actions.

We are also preparing to conduct user studies where we assess how multiple users engage in collaborative activities to make various types of toys. In addition, we plan on embedding craft as a part of the play value with the play pyramid [15]. More specifically, we are interested in finding out craft's value in children's play involving design and construction as well as its role in a standard curriculum. We are currently working with professionals and researchers in the educational field to design appropriate studies to bring out craft's role in play involving engineering design. Also the promising results from this study has motivated us to plan longitudinal evaluations about the kit's effect in educational curriculum.

7. CONCLUSION

Recent modular robotic kits attract predominately boys. But by introducing crafting into these kits, our research demonstrated that such kits attracted both the genders of children. *HandiMate* encourages girls and boys to fabricate the primitive blocks for their toy from craft materials. Because of the open-endedness of the primitives and imaginations to build from, it encourages a broad participation among children. Such ideas of merging construction with craft activities can effectively channelize and further help increase female participation in the STEM learning activities.

We also studied the constructive learning using this kit. In our study with 21 children, we observed iterative design process of the users. The iterations resulted in a conceptual change and better understanding of how things work. The ability to embed ones own design ideas and iterate on aspects of it in an open play environment, leads to broad engineering learning in children such as stability of materials, center of mass, structures, friction, and dynamics. By incorporating such open-ended gender-neutral design environments, next generation education tools [5] may help scaffold more students to learn STEM fields.

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