Using Electroactive Polymers to Simulate the Sense of Light Touch and Vibration in a Virtual Reality Environment

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***Abstract*—Virtual reality simulators seek to immerse users in realistic interactive environments. However, at present, while several provide kinesthetic feedback, most lack tactile feedback. Current means of tactile feedback do not generate enough force to the digits, deliver a non-intuitive sense of feedback and are too large or heavy to be used in hand-worn configurations. The tactile feedback system developed herein uses electroactive polymers to create light touch and vibratory sensation to the fingertips, and DC motors to constrict the distal digit. In essence, when current is passed through the electroactive polymer in the shape of a cantilever (7 mm long by 19 mm wide), it bends on its long axis, providing a forces of 25 mN. Vibratory feedback is created by varying input voltage with a sinusoidal waveform. To generate fingertip constriction, two DC motors cinch a wire attached to a rubber thimble. These hardware components are controlled by a computer running X3D software, an ISO standard for representing 3D graphics, which affords a virtual environment for the tracking of one's hand. Upon contact with a virtual object, the actuators generate prescribed forces or vibrations. With this setup, a series of human-subjects experiments will be conducted whereby the task is to contact and differentiate virtual spheres of differing stiffness. Experiment 1 will test the electroactive polymers to determine the threshold for recognizing light touch, Experiment 2 will test vibrational discrimination, and Experiment 3 will test the ability of the user to differentiate constriction forces.**

I. INTRODUCTION

ACCORDING to a national study of medical errors in U.S. hospitals, errors in surgical procedures contribute to 50,000-100,000 unnecessary deaths, and over a million serious injuries annually [1]. These error-related deaths are related to variations in the training and experience of health care providers. Medical simulation can help address this problem by allowing medical professionals to practice high risk procedures in low risk virtual environments.

Of the medical simulators on the market, such as the GI Mentor, and LAP Mentor, all are specialized to certain types of procedural interactions, such as endoscopic procedures or laparoscopic surgeries. There are currently very few medical simulators that incorporate tactile feedback on the market, which we believe is an essential part of increasing immersion within the virtual environment. In order to improve upon current simulators, the team will design a haptic glove that incorporates accurate position sensing, tactile feedback, and hand representation that will increase the user's sense of presence within the training environment. This will lead to a more intuitive and effective simulation that has the potential to improve training procedures if incorporated into medical curricula.

II. BACKGROUND & PAST RESEARCH

Unfortunately, providing haptic feedback in VR simulations is difficult because of requirements to be low cost, lightweight, have a fast response time (~1.5 kHz) and deliver a large range of forces over small and large spatial areas alike. There are several commercial systems available now. For example, video game systems (e.g., Nintendo Wii, Xbox Kinect, and PlayStation Move) can accurately track arm and body movement, but do not deliver force feedback that might convey a user contacting a baseball bat with a ball for example. Hand held video game controllers on the other hand, can provide vibration feedback, but do not free the hand to perform a wide range of arm and hand movement.

In contrast, various haptic gloves have been built to provide both kinesthetic and tactile feedback in addition to tracking the movements of the hands. Kinesthetic feedback relates to the sensation of joint movement and muscle tension [2]. This sensory system detects contact forces of large magnitude and weight being held at a distance. One of the earliest kinesthetic feedback devices is a DC motor, cable, and pulley system that pull back on the fingers to restrict movement like the third party Cyber Grasp glove [3]. Some other kinesthetic feedback haptic glove designs(MR Brake glove among others) incorporate fluids that can dynamically change viscosity in the use of friction braking systems [4]. This design uses MR fluid cylinders to give passive force feedback via bar linkages. The passive system

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restricts movement with brakes rather than actively applying forces, but is a heavier design, which uses high tolerances making it difficult to build. Winter's design of MR brakes uses small linear cylinder actuators filled with MR fluid making it more lightweight, but diminishing the maximum force output [5]. For the light weight and compactness, however, it has a decent amount of feedback. Another design consists of a pneumatic piston design that pushes compressed air into small pistons through an endoskeleton, in-the-palm design. It is lightweight, has a quick response time, and low static force with IR and Hall Effect sensors on the inside. The inner hand design does not allow for full fist closure though, and it is difficult to control the position of the pistons [6].

Haptic gloves are further divided into active feedback gloves, in which actuators move independent of the user's intentions, and passive feedback gloves, in which the actuators just provide resistance to the user's intended movements [7]. Passive feedback is considered safer because they act as dampeners and cannot forcibly exert the finger past its natural limit. The final division in haptic gloves occurs in the placement of the actuators. Exoskeleton gloves place actuators on the back of the hand to preserve motion at the sacrifice of weight and complexity (Micro Hydraulic System [8], and Cybergrasp [3]). Endoskeleton gloves place actuators within the palm of the hand which restricts maximum allowable motion, yet makes the device more compact(Rutgers Master II glove [6]).

Tactile, or cutaneous skin, feedback relies on the input of millions of tiny mechanoreceptors on the skin to detect forces at the skin's surface [9]. This sensory system is responsible for resolving initial skin contact with an object, temperature, surface roughness, and viscosity. There are vibro-tactile designs, which use small vibration motors at the fingertips and palm to provide cheap simple tactile feedback [10]. Another type of tactile feedback design uses an electrical stimulation of the fingertips to give the sensation of touch. This has no moving parts, but it is difficult to stimulate a single receptor on a finger and to physically construct. A third type uses a dielectric polymer, much like one of the kinesthetic devices but on a much smaller scale. This incorporates a polymer grid that acts as a soft actuator that surrounds the fingertip [11]. Research has been tried on electroactive polymers which change shape when subjected to an electric charge. They have a high strain response and a fast response rate as well as being lightweight and allowing for a full range of motion They are however very experimental, and difficult to manufacture. A wearable hydraulic device has also been built. With this design, there is muscle like cable motion which shrinks and expands as an actuator. It has exoskeleton design that allows for free movement, but the water creates a slow response time [12]. Also, a pneumatic tactile device was used for robotic assisted surgery uses an array of tiny balloons embedded in a silicone display that is strapped to the fingertip. The balloons can be inflated individually and with different inflation intervals to give the user a variable sense of object collision with the fingers.

This project will focus on Electroactive polymers (EAPs). These are a novel type of actuator that has shown considerable promise in past years. EAPs demonstrate large strain when subjected to an electric field, and show many advantages for use as a mechanical actuator. Notably, their softness and flexibility allow them to mold to the contours of the human frame, and their simple, lightweight construction reduces the user's awareness of the actuator. Major disadvantages of EAPs include a high activation voltage (up to 500 volts in some uses) and relatively low actuation forces. We will use a type of EAP, called a dielectric elastomer (DEs), which converts electrical energy into mechanical work. A DE actuator is composed of a flexible capacitor sandwiched between two compliant electrodes. By applying a voltage across the electrodes, electrostatic pressure squeezes down on the elastomer film, compressing its thickness. As a result, the film is forced to expand in the planar direction. The elastomer returns to its original shape when the charge is removed. When constrained to one side, uniaxial bending is observed in the dielectric film; this setup is known as a unimorph dielectric elastomer. The advantages of DE actuators are their high elastic energy density, lightness, high response speed, low current, and resilience. The actuators can also be formed into any shape, allowing them to fit on multiple parts of the body. Furthermore, their unique bending characteristics allow them to emulate biological movements of the muscles and limbs.

III. REQUIREMENTS & OBJECTIVES

Several requirements were setup for the devices. After consulting the National Area Medical Simulation Center, we have identified a strong need for an ultra-lightweight glove that can deliver tactile perception to the user, be portable, be easily integrated into other simulations, have good ergonomics, and not inhibit regular motion.

1. The force feedback shall have a delay time of less than one half second
2. The system shall be displayed the 3D virtual environment
2.a. The monitor shall display the 3D virtual environment at a refresh rate of at least 60 Hz
2.b. The monitor shall display the 3D virtual environment at a refresh rate of at least 60 Hz
3. The glove shall interact with the virtual environment
3.a. The glove shall have collision detection
3.a.i. The glove shall have tactile feedback upon collision with virtual objects
3.a.i.1. The force feedback shall generate a load pressure of at least 0.2 N/cm2; the minimum that a human finger can sense
3.a.i.2. The force feedback shall generate a bandwidth of at least 20-30Hz; the minimum frequency by which tactile cues are sensed by the user
3.b. The virtual environment shall change as a result of contact with the glove

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3.b.i. Virtual objects shall move when properly contacted at velocities over 1 m/s and accelerate based on the appropriate mass

3.b.ii. Virtual objects shall deform when properly contacted

4. The glove shall be able to move comfortably

4.a. The glove shall weigh less than 5 lbs

4.b. The glove shall not inhibit the user's natural motion

5. The virtual reality system shall cost less than $7500 U.S. dollars

6. The glove shall be safe for the user

6.a. The glove shall not shock the user

6.b. The glove shall not cut the user

6.c. The glove shall not crush the user's body parts

6.c.i. The glove shall not place more than 50 Newtons of force on the users appendages

7. The glove shall not place more than 50 Newtons of force on the users appendages

7.a. The glove shall be able to fit a small hand size to a large hand size

7.b. The glove shall not have to fit a extra large hand size

The many haptic feedback requirements were carefully considered when defining an objective for a haptic glove. Our haptic glove focuses on creating a tactile contact actuator at the fingertip to offer touch cues in virtual reality training and operating environments.

IV. METHODS

Our virtual reality system is composed of inputs in the form of flex sensors, to track relative position, and magnetic field sensors, to track absolute positioning of the hand. We used flex sensors to determine the positions of each finger to relay to the simulation software and provided absolute tracking and three dimensional rotation by using a magnetic field sensor called Flock of Birds. In order to simulate our virtual reality glove on the display we used H3D, a 3D simulation tool. The simulated glove interacts with the H3D virtual environment and the computer provides collision detection within it. For haptic feedback, we used a vibration and indentation electroactive polymers from Strategic Polymer Sciences. To control the electroactive polymers, the high voltage power supply (TREK model 2210) and a function generator were linked to the polymers. Low level Data communication was achieved by compiling all inputs into C++ and Python code and feeding the inputs into H3D.

A. Strategic Polymers

To suit our light touch and vibration requirements, we desired an Electroactive Polymer that generates a large actuation force (Fig. 1.). To accomplish this, we took a commercially available design and customized it to suit our needs. This design was originally long and slender, which creates a large strain, but a low actuation force. We shortened the polymer to add a mechanical advantage, and made the actuator much thicker by adding layers of polymer, giving an added stiffness. Ultimately, the samples were given 10 layers of film at about 6 micrometers per layer, and were decreased in length to about 19mm; a perfect length for the fingertip. This shorter and stiffer actuator can now deliver about 2.5 grams of force, which is enough to elicit tactile perception on the skin. An issue with our design, however, was the large activation voltage and its proximity to human skin. To remedy this, the samples were encased in a thin silicon coating that ensures safety without sacrificing actuation force. By applying a voltage from 0-500V across the actuator we were able to vary the level of sensation of touch on the fingertip. Also, by using a sinusoidal wave input, we are able to elicit vibrational, or pulsatile, pressures to the user. Strategic Polymer Sciences, Inc. was consulted for the fabrication of the customized, multi-layer polymer actuators. A wearable tactile feedback glove was designed to hold the polymer and provide tactile stimulation to the skin. The design allows the polymer to rest on a cantilever that is attached to a ring-like device worn on the distal phalanx of the index finger. Sitting directly below the fingertip, the polymer is able to deflect into the skin when the user encounters a virtual object. A long, slender flex sensor bridges the connection between the ring. This tethers the polymer to the base of the glove resting on the back of the user's hand, while also tracking bending of the finger. The plastic parts were designed in Autodesk Inventor and printed using "uPrint" rapid prototyping machines.

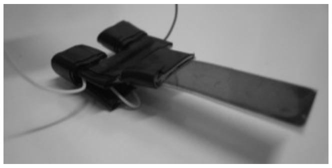


Fig. 1. An Electroactive Polymer Actuator

B. Constriction Motors

Another actuator design was investigated in addition to the electroactive polymer concept. The final design incorporates two micro metal gear motors that rest directly above the fingertip, side-by-side. A ring fits on the distal phalanx of the index finger that extends to house the two motors. A strong, metallic thread was attached to a spindle on each motor's rotating shaft. The spindle wove underneath the fingertip through an elastomeric support material. Thus, when the two motors are set to rotate in opposite directions, the thread pulls up on the finger and delivers a constricting force to the fingertip. By varying the speed of the motors, different forces can be experienced.

These specific motors were chosen based on their highly compact size and large torque output. A micro gearbox with a gear ratio of 30:1 rests within the motor. By applying the maximum voltage of 5V, a speed of 440 RPM can be reached, with a torque of 4 oz-inches. A free-body-diagram of the assembly was constructed to determine the amount of reaction force felt at the fingertip based on two motors delivering equal 4 oz-inches of torque(Fig. 2.). The plastic parts were designed in Autodesk Inventor and printed using "uPrint" rapid prototyping machines.

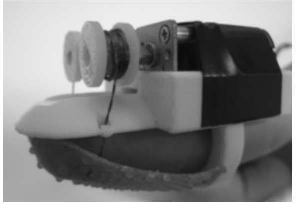


Fig. 2. DC Constriction Motor mounted to the glove prototype.

C. *Virtual Environment Visualization*

There are many haptics software development platforms out there that can display visual 3D figures in a virtual environment (VE) and interact with user through force feedbacks (e.g., OpenHaptics, GHOST, CHAI 3D, and MHaptic). The platform used here is H3DAPI, an open source haptics platform that uses OpenGL and X3D, two popular graphic standards, for rendering 3D figures. H3DAPI is device independent, supporting many devices that are available in the market, such as SensAble PHANTOM device, Force Dimension Omega device, and Novint Falcon [13] as well as custom made devices. Its device independency is one of main reasons we use it instead of other haptics software platforms such as OpenHaptics, which can only be used for SenseAble devices.

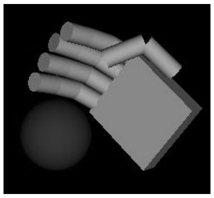
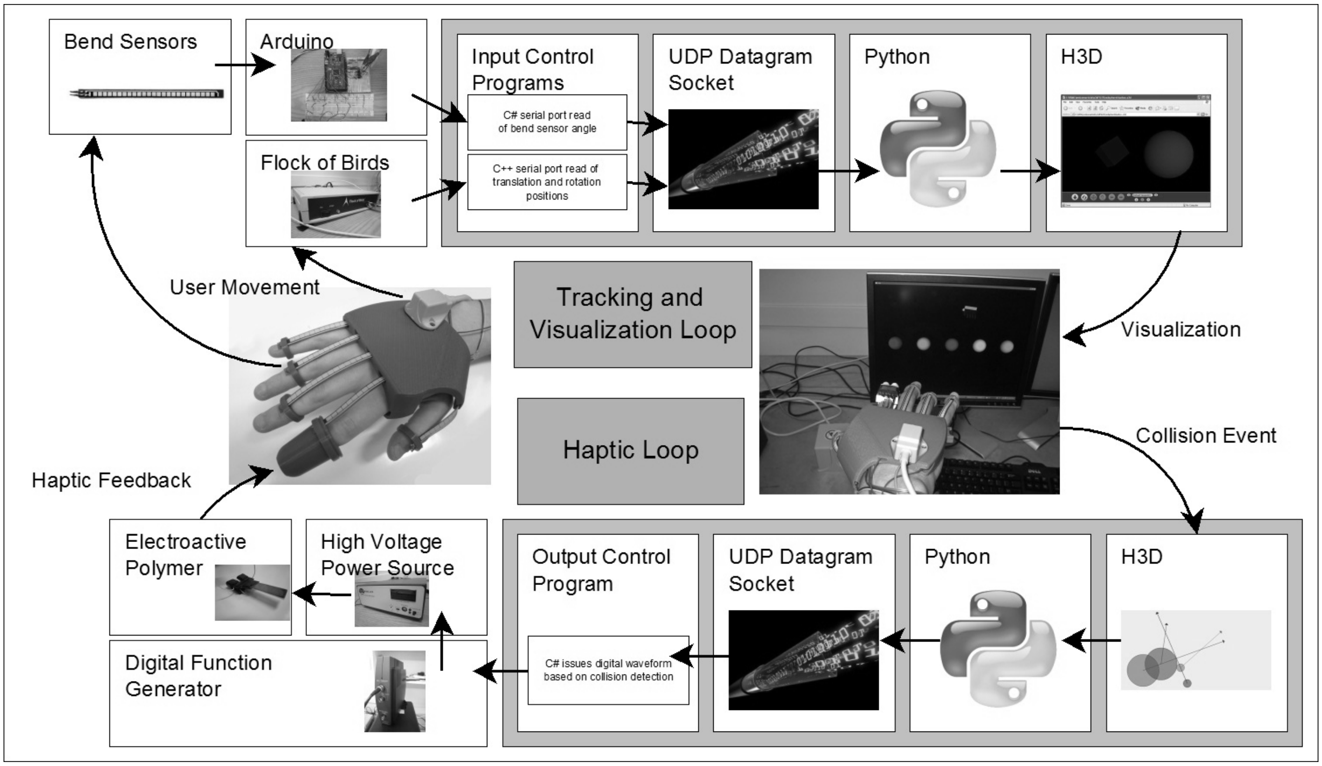


Fig. 3. A model of the hand in the virtual environment

Using H3DAPI, we created a model of the hand by combining a box and fourteen cylinders (Fig. 3.). Each finger of the hand model is composed of two to three cylinders, where each cylinder represents a segment of the finger. The box has the dimensions of 2.5 inches × 2.5 inches × 0.625 inch, and the cylinders have the radiuses of 0.2875 inch and the heights of 0.8125 inch to 1.25 inches. In order to simulate a moving hand, the box and the cylinders need to move at exactly the same time, and are never disjointed. The bending of each finger is simulated as rotations of each cylinder and group of cylinders with the point of rotation at the bottom of each cylinder.

H3DAPI is written in C++ programming language, and programmers use the X3D modeling language and Python scripting language to develop new software applications. Our graphics component used X3D and Python We used X3D and Python to create our graphics component where we created basic shapes such as the box and the cylinders mentioned above in an X3D file. Each of these shapes is represented as a node with defined colors, sizes, positions, and rotations in this file. A Python script was written to complete most of the processing needed for the VE and communicates with various devices through User Datagram Protocol sockets. It also performed all of calculations needed to map the values received from these devices to the values that can be used for the displaying these shapes in the VE. This Python script is represented as a node in the X3D file as well. It is linked with the basic shapes in the VE to affect their attributes such as position and rotation, which are needed for the virtual hand model to move, rotate, and bend fingers. With H3DAPI we could create and control visual 3D

Fig. 4. Full map of the data communication in the virtual reality system. The upper half consists of tracking, while the lower half consists of the haptics loop.



figures quickly in the VE.

D. *Data Communication*

A data transfer module was built to serve as communication between the programs running the virtual environment, including Python and H3D, and the haptic control programs written in C# (Fig 4.). The concept employed to facilitate this communication is what is known as a datagram socket. Sockets are abstract concepts that represent some universally designated memory location for a stream of data. Datagram sockets can be used for local transfer of information. Using the same port number, port #1989, in our programs written in Python and C# pass a stream of bytes to and from each other in real-time. Below are descriptions of each of the peripheral devices and the programs that control the input signals for tracking and visualization in the virtual environment.

Communication between Polymer Actuation and X3D

In order to discretely control the actuation of the polymers at high voltage, two devices were used. The first is a computer-controlled, digital function generator by Vellman Instruments (PCGM1000). It can deliver multiple functions, at frequencies ranging from 0.01Hz to 2MHz, and voltages ranging from -5V to 5V. This generator allows for control from the H3D virtual environment through a C# program. The output signal from this generator is then amplified by a TREK Model 2210 high voltage power supply, which can deliver up to 500V to activate the electroactive polymers.

Communication between Flock of Birds and X3D

The Flock of Birds' input signal is received through a predetermined set of functions developed for it in C++. The C++ program pulls the absolute position of the hand in Cartesian coordinates and the rotation of the hand in rotational matrices from the Flock of Birds device before delivering three values and three matrices to a datagram socket.

Communication between Arduino and the Datagram Socket

The constriction motors were controlled using an Arduino ATMega1280. Arduino is an open-source, single-board microcontroller used to power small electronics and send information through the serial port. When connected through the USB port of a computer, the Arduino draws its power directly from the host computer. Ideally, we would use the Arduino Bluetooth Board to communicate with the computer wirelessly and create a totally wireless haptic system. An L293D chip was used to drive the motors. This chip operates as an H-Bridge circuit; by allowing the current to flow in two directions, the directional rotation of the motors can change. The Arduino is able to adjust the speed of the motors through pulse width modulation; by adjusting the duty cycle, or the time the enable pin of the L293D chip is left on, the voltage delivered to the motors is able to vary from 0-5 Volts, thus controlling the speed directly. The Arduino code is not only able to adjust the constriction force of the motors, but can also deliver pulsatile feedback by quickly rotating the motors backwards and forwards. This opens up capabilities ranging from surgeries involving a constricted artery to taking pulses on a virtual patient.

The Arduino chip delivers the signal value through a serial port where it is interpreted by a C# program. This program deciphers the value into the associated components, and delivers the values as an array to a datagram socket where it can be streamed to the virtual environment.

Communication between Python and the Datagram Socket

On the Python side of the data transfer, a listener is setup in order to input the values from the various socket channels that have been established. Each algorithm is triggered by the presence of a new value or set of values over any of the channels and changes the representation of the hand based on the purpose of the associated device.

V. EXPERIMENTS

Human-subject psychophysical experiments will be performed to evaluate the simulation of three types of tactile sensations [14]. The first experiment will test the EAPs' delivery of light touch to fingertip skin. The second experiment will test the representation of vibrational forces provided by the EAPs. The third experiment will test the representation of pressure using a constriction motor device.

A. *Setup*

The experimental setups consisting of geometric objects coded in the X3D language will be displayed in the virtual environment. Each subject will be given a warm-up time prior to the experimental trial to familiarize with the EAPs, constriction motors and interactions with virtual objects.

Experiment #1: Determination of light touch sensation

The voltage delivered to the EAPs will be adjusted incrementally to determine the threshold at which the subject is able to feel light touch on their fingertips. The voltage values that will be used to experiment with the EAPs are: 0, 50, 100, 200, 300, 400, 425, 450 and 500 Volts.

Experiment #2: Comparing vibrational forces

During the warm-up time, only a constant feedback will be provided. A vibration of 1 Hz is presented if the object is touched. In the experimental trials, there will be various amount of vibrational forces delivered via EAPs(as seen in Table I and Fig. 5).

Fig. 5. Screen shot of the experimental setup. Five identically sized spheres (radius = 1.25 inches) labeled A-E are placed in random order of vibrational force feedback. Various vibrational frequencies delivered by the spheres' surfaces. The voltage source will be set to output 400 V.

Table I

Sphere	Vibrational Frequency [Hz]
B	1
D	5
A	10
E	50
C	100

Experiment #3: Comparing pressures

The experimental setup is similar to that of Experiment #2. In this case, the feedback will be provided by a constriction motor device that will deliver pressure to the fingertip. During the warm-up, only a constant feedback will be provided by setting the motor's torque to 0.0155 Nm; the motor will be able to produce a pressure if the spheres were to be touched. In the experiment, several levels of constriction will be used shown in Table II.

Table II

Sphere	Constriction Level	Motor's Torque (Nm)
B	1	0.0155
D	2	0.0243
A	3	0.0332
E	4	0.0442
C	5	0.0564

B. Procedures

In the first experiment, the threshold voltage value corresponding to a subject's ability to sense light touch via EAPs will be determined. This will be done by increasing the voltage output and allowing the subjects to sense the indentation of the EAPs on their fingertips.

In the second experiment, the effectiveness of the vibro-tactile feedback mechanism will be determined by allowing subjects to judge the various amounts of vibrational forces that will be delivered by five identical spheres individually. The subjects will run their fingertips over the surfaces of the spheres in order to receive vibro-tactile feedback. The vibrations will be delivered through the EAP to the subject's fingertip that will be in contact with the sphere's surface. The subjects will be asked to sort the spheres by the strength of the vibrational force delivered to them. The sphere that will deliver the most force will be placed to the far left and thereafter the spheres with less force will be placed in descending order. The metrics that will be used to evaluate the subjects' performance will be limited to the completion time and number of transpositions (the number of interchanged objects in a sorted list).

In the third experiment, the subjects will compare different pressures delivered to their fingertips via the constriction device. They will also be asked to determine the order of the spheres based on pressure delivery. The sphere that will delivers the most pressure will be placed to the far left and thereafter spheres with less pressure delivery will be placed in descending order. The time that will be taken to determine the correct order will be recorded. In addition, the number of transpositions will be recorded.

C. Participants

Subjects who will be asked to participate in these future experiments will be engineering students at UVa. There will be an even representation of female and male subjects between the ages of 20-22 years. All of them will be right hand dominant. Also, they will not be familiar with the vibrational and constriction feedback mechanisms that will be used in the experiments.

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