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Soft robotic glove for kinesthetic haptic feedback in virtual reality environments

Saurabh Jadhav [1], Vikas Kannanda[1], Bocheng Kang[1], Michael T. Tolley[1], Jurgen P. Schulze[2]
Department of Mechanical Engineering, University of California, San Diego, La Jolla, CA, USA[1]
California Institute of Telecommunication and Information Technology, University of California ,San Diego, La Jolla, CA, USA[2]

Abstract

Current virtual environments rely heavily on audio and visual feedback as a form of sensory feedback [1]. The degree of immersion can be increased by augmenting synthetic haptic feedback from the user interface. Most of the existing wearable haptic feedback systems use tactile stimulation by vibrating motors for haptic feedback which lack a compelling sense of immersion with force feedback[2][3].e.g. in the case of pressing a button. This research addresses this issue with hardware architecture for kinesthetic force feedback. This research focuses on the design of a wearable soft robotic haptic feedback glove for force feedback in virtual environments. The glove provides a force feedback to the fingers while clicking a button in virtual environments. The glove design includes a soft exoskeleton actuated by Mckibben muscles which are controlled using a custom fluidic control board [4]. The user's fingers are tracked using the infrared cameras. This tracking system provides the information for the position of the user's fingers. Based on this information, the soft glove is actuated to provide a haptic feedback. The Soft exoskeleton and actuation make the glove compliant, compact and unintimidating as compared to force feedback glove with rigid kinematic linkages. The glove design is inexpensive, mass-manufacturable and compatible to 90% of the U.S. population. The user could test the glove by playing the piano in virtual reality environment. The presence of audio, visual and haptic feedback makes the virtual reality environment highly immersive. The informal pilot study indicates that haptic glove improves the immersive experience of the virtual reality environments. Users in informal pilot study described the experience as "like nothing seen before", "mesmerizing" and "amazing".

***Keywords**: Haptics, Immersive Virtual Reality, Soft robotics, Kinesthetic feedback, 3D interaction.*

Introduction

A user interface is a gateway for communication between the user and virtual Environment. Since a large amount of neural processing power is devoted to the haptic stimulus received from our hands, synthetic haptic user interfaces greatly increase the degree of immersion in the virtual environments [5],[6].Hence we believe that providing haptic feedback while clicking a button in a virtual environment will greatly increase the human-computer interaction experience. Haptic stimuli can be broadly classified into tactile stimuli and kinesthetic stimuli. A tactile stimulus is felt by our skin like temperature and vibrations, while a kinesthetic stimulus is the sense of force and position of our fingers and hands. Most haptic interaction today provides tactile feedback where we feel a vibration sensation when we press a key. We believe that in applications like a virtual keyboard a kinesthetic haptic feedback can enhance the immersive experience for the user. Many user interfaces in virtual environments involve pressing a button or a key to type text or initiate some action. Since the button does not exist in the real world, as the user presses the button his finger just goes through the surface of the button which spoils the immersive experience in such environments. Previous work has attempted to address this experience issues with purely visual cues. M. Alger proposed the coloring and appearance of the button surfaces inspired by the surfaces in nature through which fingers can pass - water surface. Hence, aqua color was proposed for buttons in the virtual environments [7]. However, this experience is purely visual and lacks haptic feedback which is crucial to improving the immersive user experience in virtual environments. Some methods to address this issue include gloves with conductive pads on finger tips which provide inherent haptic feedback when a user presses their finger together (Pinch gloves) or a physical keyboard which the user can carry along (Twiddler) are used for user input and provide a haptic feedback [8][9].

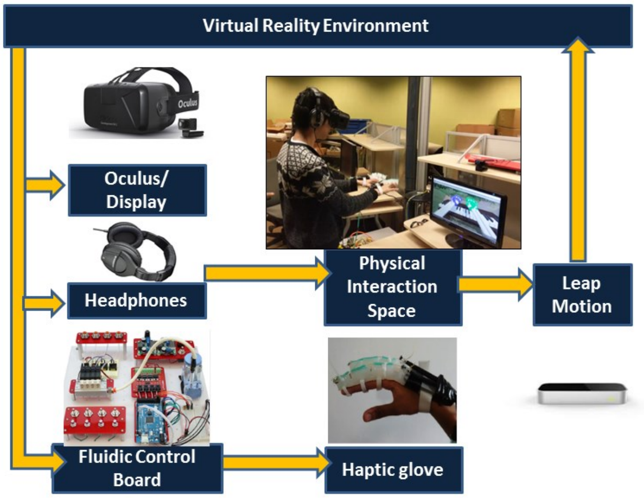

FIGURE 1: THE SCHEMATIC SHOWS THE USER WEARING THE HAPTIC GLOVE AND A HEAD-MOUNTED DISPLAY AND PLAYING THE PIANO IN VIRTUAL REALITY. THE FINGER POSITION IS SENSED BY AN OPTICAL TRACKING SYSTEM (LEAP MOTION).WHEN THE USER PRESSES THE VIRTUAL KEY A FEEDBACK IS PROVIDED TO THE GRAPHICS ENVIRONMENT AND A FLUIDIC CONTROL BOARD WHICH ACTUATES THE GLOVE TO PROVIDE A HAPTIC FEEDBACK TO THE USER.

The characteristics that can be perceived through haptics can be broadly classified as tactile (temperature, vibrations and texture), kinesthetic (inertia, shape, weight and deformation) and chemesthesis (reaction to certain chemicals on the skin). Due to challenges in achieving kinesthetic stimulus in a virtual environment, many applications have kinesthetic stimulus- force feedback and deformation substituted with tactile or visual feedback[7][10][11]. Examples of such applications are substituting the force feedback on clicking of a button in touch interface is by vibrations or the force applied to tighten the suture in remote surgery may be substituted by a visual display in which the color of the on screen marker corresponds to the amount of force applied. One of the main reasons for sensory substitution is presenting the feedback in its natural form is expensive or not technically feasible [1][5][12]. Y.Onai et al., presents the haptic rendering of 3-Dimensional objects by using ultrasound to render objects in virtual space which stimulate the tactile feedback to the skin [13]. However, this approach lacks to establish the compelling sense of immersion provided by kinesthetic force feedback in the real world.

Kinesthetic perception is usually provided robotics [1][14]. By manipulating an end effector on a robotic arm, a user can perceive the shape, deformation and mechanical properties of a virtual object through forces produced by actuators in the robotic arm in response to motion measured by position sensors. Single point contact is the most common form of kinesthetic feedback in which user interacts with a virtual environment using a probe connected to the end of the robot arm. The 3DS phantom robotic manipulator is an example of a single point contact displays [15]. However, these robotic arms need to be grounded somewhere in the virtual environment and thus constrain the user from moving about the virtual space [14].

Methods and Procedures

We propose to use a soft exoskeleton with soft actuation for the haptic glove which makes the glove compliant, compact and unintimidating to the user. We believe that the glove is a low-cost and robust alternative to the existing mobile haptic displays and rigid kinematic mechanisms and would prove to be sufficiently effective in simulating the kinesthetic haptic feedback. The haptic glove design was planned to have an exoskeleton which would resist the motion of fingers in certain directions to give force feedback.

Schematic of the system

The system consist of a virtual environment which gets the input for the position of the user's fingers using a desktop optical tracking system (Leap Motion) and depending on whether the finger collides with of the keys the virtual environment gives a feedback signal to a fluidic control board which in turn actuates the glove to provide haptic feedback to the user (Figure 1) [16]. This haptic feedback compliments the visual feedback provided by virtual reality headset (Oculus Rift) and audio feedback provided by headphones.

FIGURE 2: PIANO FOR INTERACTION IN VIRTUAL REALITY ENVIRONMENT

The application taken into consideration was a haptic feedback for interaction with the keyboard in a virtual environment. The application was developed using a gaming engine (Unity) for the virtual environment. It consists of a piano alongside a river to give a calm feeling to the user (Figure 2). The piano was chosen as a virtual object as playing piano involves continuous interaction with the keys which would give the user an opportunity to evaluate the haptic feedback system quickly for the user evaluation task. The application of playing piano can mimic experience in wide applications where a user needs to type some text or press a button in a virtual environment. The user will get a visual, audio and haptic feedback from the virtual environment and the effectiveness of haptic stimulus in enhancing the immersive experience can be tested by switching off the haptic stimuli.

Soft exoskeleton

A soft exoskeleton was chosen for the glove to make the glove compliant to the varying hand sizes. A rigid exoskeleton would make it necessary to have the hinge joints of the segments of the glove exactly over finger joints. This necessitates the glove to be customized for a particular hand size and thus unsuitable for varying hand sizes. A soft exoskeleton addresses this issue by reducing the thickness of the exoskeleton above the finger joints and thus assisting the exoskeleton in bending accurately above finger joints without using hinge joints. The soft glove can be molded from a single mold which makes it easier to manufacture and suitable for mass production. The glove actuation was carried by using a string pulling on the top of the exoskeleton to mimic a bell-crank lever mechanism. The soft actuation using Mckibben muscles was chosen over servo actuators because of their quick response, low force to weight ratio, low cost, and robustness. The spring-like response of the Mckibben muscle helps to adjust the position of the tip of the finger depending on the force applied by the finger which makes the actuation user friendly [4]. To keep the glove adjustable for varying hand size and also to have the first segment fit to the tip of their finger, we attached the glove to the hand by adjustable Velcro loops.

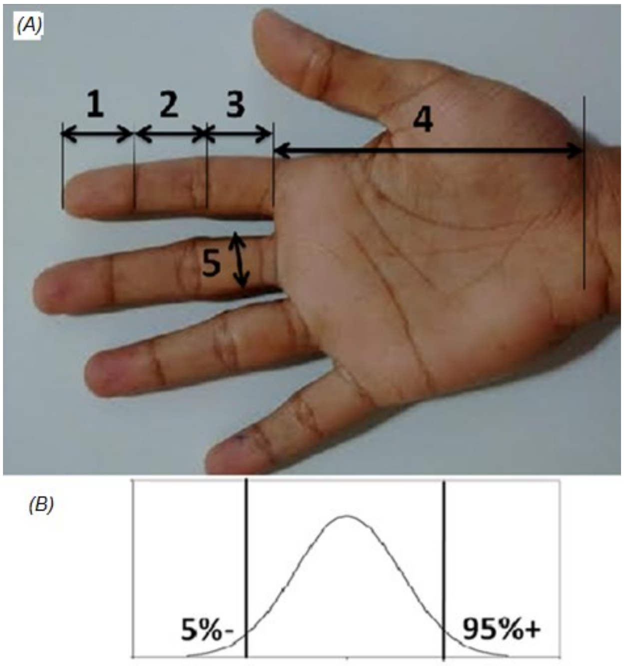

FIGURE 3: (A) DESCRIBES THE DIMENSIONS CONSIDERED FOR DESIGNING THE SEGMENTS OF THE SOFT EXOSKELETON TO ENSURE THAT THE GLOVE FITS 90% OF THE U.S. POPULATION. (B) DESCRIBES THE NORMAL DISTRIBUTION OBSERVED FOR U.S. ANTHROPOMETRIC DATA.

The glove was expected to be viable to the commercial market. Thus, the glove design should fit on hands of the most population in the U.S. According to anthropometric data [17], the distribution of the length of each phalanx, such as 1,2,3 shown in (figure 3), for U.S. Army personnel can be approximated as a standard normal distribution.

Since there are a few people who have extremely short phalanx (shorter than 5th percentile of the population) or extremely long phalanx (longer than 95th percentile of the population), the glove was designed to fit 90% of the population, which ranged from the 5th percentile length of phalanx (shortest) in the population to the 95th percentile length of phalanx (longest) in the population. Notches were designed between each segment of the fingers in order to make sure that the glove would be adaptable to different hand sizes (figure 4). The length of the notch was calculated as the difference between the lengths of 95th percentile's person's phalanx by the length of 5th percentile's person's phalanx so that the person wearing the glove would have the notch position on top of their finger joint between the first 2 segments of the glove designed. The same principle was applied to other finger's phalanx and joints. It was necessary to ensure that the exoskeleton is completely occluded by the user's hand to avoid any disturbance in optical tracking. Hence, for the width of the glove and the fingers of the exoskeleton, we considered the 5th percentile person's finger width.

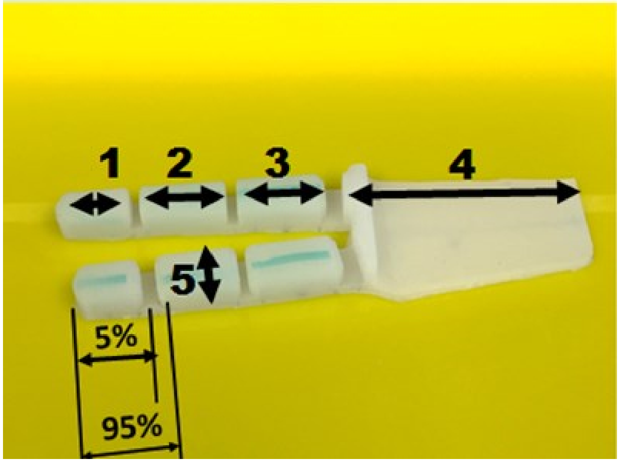

FIGURE 4: THE DIMENSIONS OF EXOSKELETON DESIGNED BASED ON ANTHROPOMETRIC DIMENSIONS FOR THE INDEX FINGER.

The soft exoskeleton was required to have some amount protruding thickness normal to the palm so that when the top face of the glove is pulled by a string, the protruding thickness would simulate a bell crank lever effect for pulling the fingertip and simulating the pressing of a key. The thickness of the protrusion for the glove was decided to be 1cm as a compromise between the force required to pull the string (more the thickness, lesser the force required) to simulate the key-pressing and the total weight of the soft exoskeleton. The final model of the exoskeleton of the glove was molded using platinum cured silicone rubber (Dragon Skin 30, Smooth-On inc). As the final product was required to be commercially feasible, molding was preferred over 3D printing considering the cost and time required for 3D printing.

Only four fingers (Middle and Index fingers on both the hands for the glove) were chosen to be actuated to be given the haptic feedback while playing the piano as we were limited by the number of output ports on the fluidic control board. However, the glove could be assembled to actuate all the fingers of both hands

Design of actuators -Mckibben muscle

While using the glove, the user's finger has to move up with joint movement coming from the knuckles. This requires a vertical force at the tip of the finger to simulate the action of pressing a button. The mechanism used in our glove is similar to a bell crank lever (figure 5), with the finger being one arm and the knuckle stub the other.

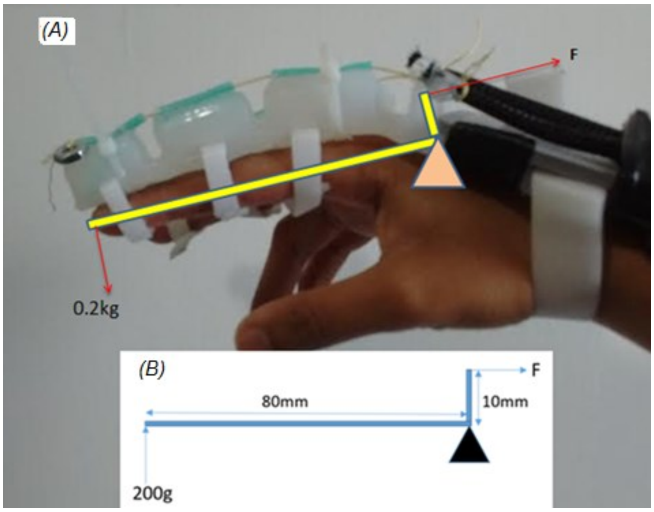

FIGURE 5: (A) DESCRIBES THE SOFT EXOSKELETON MIMICKING THE BELLCRANK LEVER MECHANISM: (B) DESCRIBES THE FREE BODY DIAGRAM OF THE MECHANISM. FORCE APPLIED BY FINGER IS APPROXIMATELY 2 N. HENCE, BASED ON MOMENT BALANCE WE CAN CALCULATE FORCE REQUIRED TO PULL THE STRING

Generally, the force required to press a button will vary depending on the design of the button. So to measure the force a general user would apply for a button is very tricky. To get an estimate of the force, we simulated pressing a keyboard button on a digital scale and recorded the peak force. From these tests, the mean value of force was found to be 200g-250g.

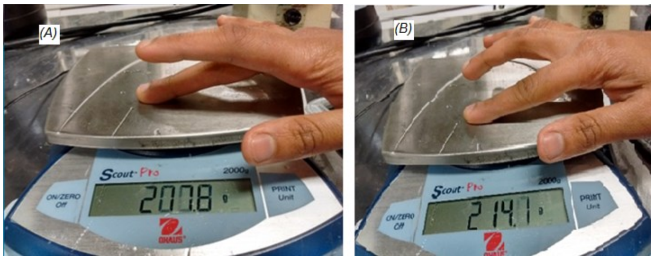

FIGURE 6: TESTING FOR ESTIMATING THE FORCE APPLIED BY THE MIDDLE FINGER (A) AND THE INDEX FINGER (B) WHILE PRESSING A BUTTON

From the anthropometric data, we get the maximum length of the middle and index fingers close to 95th percentile to be 80mm. The mechanism to actuate the soft exoskeleton mimics the bell crank lever mechanism. The force required to actuate the soft exoskeleton decreases with the increase in the height of the knuckle stub. The height of the knuckle stub was chosen to be 10mm as a compromise between the weight of the exoskeleton and the force required to actuate the soft exoskeleton. Using this data we can calculate the force the actuator needs to apply to simulate the button press. The force required is approximately 1.6kg. We found from a preliminary test that the length of contraction required by the muscle to simulate pressing of a key to be 1cm-1.5cm.

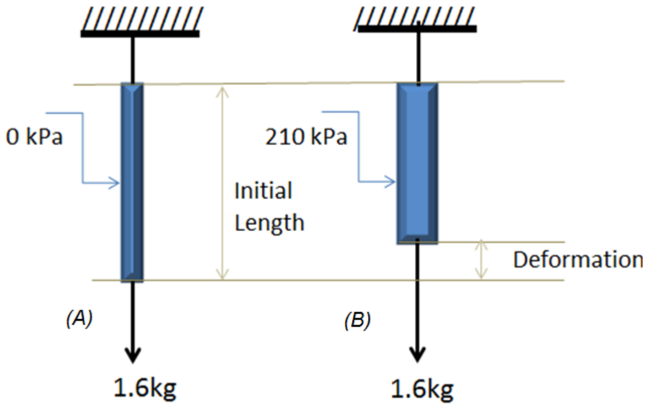

Figure 7: Schematic of testing setup for Mckibben muscle. (A) muscle in unactuated position suspended with 1.6 kg force stretched at it's initial length. (B) when the muscle is actuated by supplying compressed air at 210 kPa, the muscle contracts causing a deformation and thus lifting the weight.

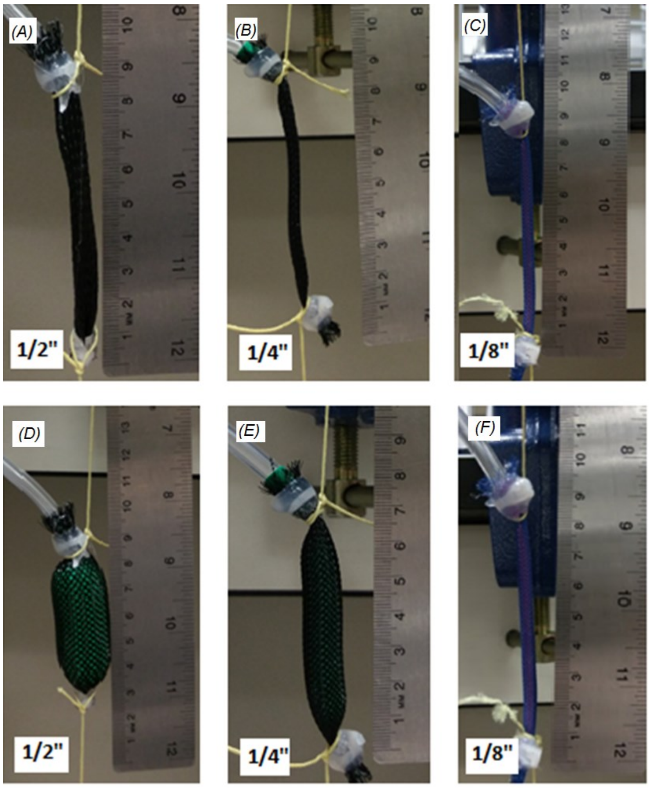

Figure 8: (A),(B),(C) show the length of Mckibben muscle in unactuated position for muscle made using 1/2",1/4" and 1/8" strap respectively.(D),(E), (F) describes the contraction in muscle length after actuation for muscle made using 1/2",1/4" and 1/8" braided strap respectively

Table 1: Test results Mckibben muscle for 30 psi actuation pressure (0.5", 0.25", 0.125" sleeve diameter) carrying 1.7kgf.

Sleeve Diameter (in)	Length (mm)	Contraction (mm)	Percentage Change
0.5"	75	20	26.66
0.25"	72	12	16.66
0.125"	76	4	5.26

Actuators were required to have a quick response to simulate pressing of a key without spoiling the immersive experience of the environment. Mckibben muscles were selected as an actuator to actuate the exoskeleton due to their quick responsiveness [4][18]. The muscles are made out of latex chambers inside braided fiber strap [19][20]. Three muscles of varying strap diameters available in the market were tested for a force of 16.66N to select the best fit for the glove. The pressure used to inflate them was approximately 210 kPa (30psi).The muscles were controlled using a custom fluidic control board.

$$F = 3\pi r^2 P\left(\frac{(1-\varepsilon^2)}{\tan(\alpha)^2} - \frac{1}{\sin(\alpha)^2}\right) \qquad (1)$$

The maximum length of the muscle we can fit over the wrist for a compact design was limited by the length of finger-wrist distance of the soft exoskeleton which is 85cm [17]. To fit the requirements of the design, the muscle with 85cm length was required to contract by 1-1.5cm (15-18% contraction) when actuated. Equation-[1] gives the mathematical model proposed by Zuglian F. for force (F) provided by Mckibben Muscle as a function of system pressure(P) used to actuate the muscle, braided shell radius r, strain value of the muscle (ε) and the initial angle between braided threads (α)[20]. The available system pressure (P) is 210Pa and the angle of braided strap(α) for all braided shells is 83º. For force value of 16.66N and the required strain of 0.166, the ideal shell diameter (2r) was found to be 0.58cm (0.23"). From experiments, the muscle constructed using a 0.25" diameter braided sleeve which produced a contraction of 16.66% was found to be ideal for our application and validated the theoretical calculation.

Fabrication and Assembly of the glove.

The molds were printed using ABS plastic on desktop fused deposition modeling 3D printers (Replicators, Makerbot Industries). The exoskeletons were cast using platinum cured silicone rubber (Dragon Skin 30, Smooth-On inc) which provides a good compromise between stiffness and flexibility. To connect the actuators to the finger tips fishing line was used which passed through tubes mounted on the exoskeleton. The tubes were embedded in the exoskeleton and secured by using zip ties.

The original concept was to fasten the exoskeleton onto a fabric glove, but that limits the adjustability of the haptic device. Instead, Velcro straps were embedded within the exoskeleton, and the glove was directly strapped onto the user's hands. The major advantage of using an adjustable glove was that glove was adaptable to all hand sizes.

For the pneumatic actuators, long latex balloons were found to be ideal to handle the high pressures. Zip-ties were used to seal the muscles, pneumatic tubes and hot glue to hold the zip-ties in place. The Mckibben muscles were tested for any leaks and the final assembly of the glove was fine tuned to accurately simulate the pressing of a key.

FIGURE 9: 3D PRINTED MOLDS FOR THE EXOSKELETON FOR LEFT AND RIGHT HAND

Results

The integrated graphics- fluidic control board system with assembled glove (Figure 12) was tested by our colleagues with and without any experience using virtual reality equipment. We created a virtual environment using a game engine (Unity) wherein the user can play the piano and also get the audio and haptic feedback while pressing the keys [21]. We conducted tests to get anecdotal feedback from them on the difference in immersive experience with and without haptic feedback and cost of the system they are willing to pay along with general comments.

FIGURE 10: FINAL OF THE GLOVE FOR INDEX AND THE MIDDLE FINGER OP LEFT AND RIGHT HAND: ASSEMBLY CONSISTS OF THE SOFT EXOSKELETON, EMBEDDED CHANNELS FOR PASSING THE STRING, MCKIBBEN MUSCLES, AND VELCRO STRAPS TO FASTEN THE GLOVE OVER THE HAND AND FINGERS.

The glove was tested by a group of 15 people including 2 virtual reality interface experts, 5 users with prior experience with some kind of virtual reality system and others with no prior virtual reality experience. The age group of the users varied between 23 to 40 years. All users agreed to the statement that the haptic glove increases the immersive experience and augments the graphics environment. 11 users agreed to the statement that the haptic glove accurately simulates the pressing of a button or a key. Downside according to some users was the time required for wearing the glove. Also, some users experienced a slight delay in fluidic control board and also suggested to miniaturize the entire control board to be portable. Users in the informal pilot study described the haptic feedback as “nothing like seen before”, “mesmerizing” and “amazing”.

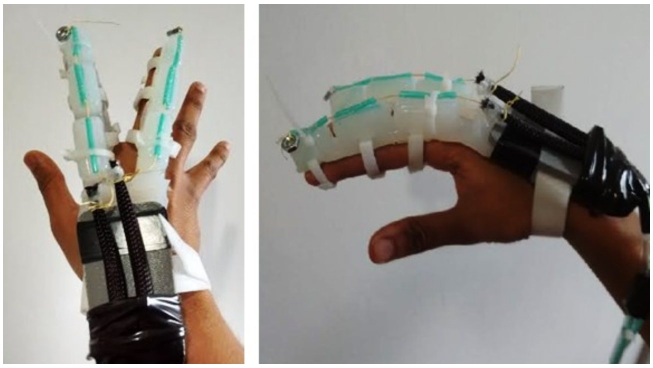

FIGURE 11: FINAL ASSEMBLED GLOVE FOR INDEX AND THE MIDDLE FINGER SECURED ON THE RIGHT HAND USING VELCROS.

The average cost that users were willing to pay ranged between 40-200 which makes this glove a good business case as the cost of making this glove considering the components required from the fluidic control board is around 65$ and could decrease if produced in mass quantity.

FIGURE 12: USER WEARING THE HAPTIC GLOVE AND OCULUS RIFT AND PLAYING THE PIANO IN VIRTUAL REALITY ENVIRONMENT WITH AUDIO AND HAPTIC FEEDBACK.

Conclusion and Future Work

With the advancement in virtual reality technology like accurately tracked head mounted displays, 3D spatial sound technology, visual realism, olfactory simulators and haptics technology, the question of design of systems to give a compelling immersive experience by rendering accurate synthetic stimuli to all human senses of the user arises. Current wearable haptics technology heavily relies upon tactile feedback by vibrating motors for substituting force feedback in virtual environments which lack a compelling sense of immersion. We believe that the prototype soft haptic glove described herein as a stepping stone for future wearable and user friendly kinesthetic haptic feedback technology.

The preliminary feedback from the users shows that the soft haptic glove sufficiently simulates the pressing of a button in virtual reality environment. The user can wear the glove described herein and naturally interact with user interfaces to perform activities like typing in space without spoiling the immersive experience in virtual environments. Using this glove radically different user interfaces can be developed wherein the user does not need to carry any controllers in his hand and interact with user interfaces naturally.

Improvements can be made in control of soft robotic board to reduce the lag in the fluidic control board, miniaturize the control board and introduce more degrees of freedom in the glove wherein the user can grasp and feel objects in the virtual environments. As the glove already uses soft material and pneumatic control board, tactile feedback can be introduced by in the glove using granular jamming on the surfaces in contact with the finger tips wherein the texture and the surface properties of the object can be simulated.

The glove could potentially be developed to accurately simulate both tactile and kinesthetic feedback in a single haptic device. The low cost, manufacturable and robust design of the glove can be mass-produced and hence can potentially become more common in the virtual reality developer community to improve the user experience.

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Author Biography

Saurabh Jadhav received his B.Tech in Mechanical Engineering from University of Mumbai (2014) and is a graduate student in Mechanical Engineering at the University of California, San Diego (2015-present). His work is focused on creating user interfaces for virtual reality applications.

Vikas Kannanda received his B.E in Mechanical Engineering from Visvesvaraya Technological University (2015) and is a graduate student in Mechanical Engineering at the University of California, San Diego (2015-present). His work is focused on feedback control systems.

Bocheng Kang received his BM.E from the University of Minnesota, Twin Cities (2015) and is a graduate student in Mechanical Engineering at the University of California, San Diego (2015-present). His work is focused on hardware design and manufacturing.

Dr. Jurgen P. Schulze is an Adjunct Professor in the computer science department and a Research Scientist at UC San Diego's Qualcomm Institute. He is the Director of Immersive Visualization Lab at the Qualcomm Institute and he teaches computer graphics and 3D user interfaces. His research is in scientific visualization, immersive virtual environments, human-computer interaction. He holds an M.S. degree from the University of Massachusetts and a Ph.D. from the University of Stuttgart, Germany.

Dr. Micheal T. Tolley is an Assistant Professor in the department of mechanical and aerospace engineering at UC San Diego. He is the director of the Bioinspired Robotics and Design Lab and his research focuses on approaches to the design of bioinspired robotic systems. He was a postdoctoral fellow at Harvard University's Wyss Institute for Biologically Inspired Engineering. He holds Ph.D. and master's degrees from Cornell University. He has a bachelor's degree from McGill University.