Abstract—Over the past few decades, various haptic gloves have been developed for use in virtual environments. The actuating systems for most existing haptic gloves require lots of external auxiliary equipment. Because of this, the motion of the user is restricted by the length of the electric wires or pneumatic tubes attached to this equipment. A compact actuation system, including related equipment, is thus indispensable for a wearable haptic glove to be truly effective. To resolve the problem of hampered motion and reach, a micro hydraulic actuating system was developed in this research. It was composed of a slim, flexible artificial muscle, a compact hydraulic module for actuating the muscle, and a micro pressure sensor for measuring without flux loss. The characteristics of the muscle were investigated for their control capacity. The step and sinusoidal responses were analyzed to evaluate the performance of the micro hydraulic system. Once these analyses were completed, a lightweight and compact actuation system was built incorporating a wearable haptic glove. By virtue of the developed micro hydraulic system, the wearable haptic glove was able to operate independently of any external equipment, and movement was completely free of any restrictions from wires or tubes.

I. INTRODUCTION

OVER the past few decades, different types of haptic gloves have been developed for applications in virtual environments, rehabilitation, and teleoperation of robots [1-6]. Most of these gloves have been integrated with associated equipment on a desk. In addition to the glove, the desk has generally included a PC for simulating virtual environments, a monitor for showing 3D graphics, and other equipment needed for successful operation. A user sits at the desk and operates the glove while viewing the monitor, and consequently, workspace has been limited to the vicinity of the desk. Since the user sits in front of the desk, it has been convenient to locate the controller or power source on the desk, connected to related equipment by lines and tubes. Attention has only been paid to the mechanism on the hand, not to the other related equipment.

Recently, immersive virtual spaces and ubiquitous environments have become the latest trends in virtual environments [7-10]. In these systems, a user has a high degree of mobility and interaction with the space. Therefore, a haptic glove for these systems should allow unrestricted movement. To make such a wearable haptic glove, a lightweight and compact mechanism must first be considered. The main issue in reducing size and weight involves the actuation mechanism which includes an actuator and a force transmission mechanism. Because this mechanism is so critical, the compact actuation system was selected as the focus of this research.

Ohashi et al. developed a haptic glove known as the Sensor Glove II (SG II) [4]. To reduce the amount of bulk and weight on the hand, they designed a wire-driven mechanism to transmit force from the hand to a distant point. The feedback force to the finger was transmitted via a wire in a tube so that the actuator could be located separately from the hand. As a result, the wire-driven mechanism reduced the weight of the mechanism on the hand significantly by removing the mass of the actuators. However, the outer tube of the wire-driven mechanism interfered with the inner wire during force transmission, and friction degraded the performance of the actuator. The mass on the hand was reduced, but it still existed, albeit in another place connected by wires. Consequently, the motion of the hand continued to be restricted in the length of the wire, and the longer wire contributed to a greater loss of transmitted force.

Choi et al. tried another approach to achieve wearable size and weight in designing their haptic glove, SKKH [5]. Instead of transmitting the driving force through wires, they attached small actuators directly to the exoskeletal links on the finger. They used an ultrasonic motor as the direct attached actuator because it could provide high torque with small size in contrast to a typical electrical motor. However, in this case, the entire mass of the device was concentrated on the fingers. Moreover, an ultrasonic motor requires a high voltage motor driver which is comparatively bulky and heavy. Even more problematic, a rotary actuator, like an ultrasonic motor, requires a complicated mechanism consisting of pulleys and
A linear actuator was adopted to develop a haptic glove by Mouzit et al. [6]. They focused on a simple structure to reduce the weight and size of the mechanism on the hand. They successfully removed most of the exoskeleton on the hand by using a linear actuator. The haptic glove developed from their work was named the Rutger Master and operated via a simple and compact mechanism. The Rutger Master could generate a large force since it was actuated by pneumatic power. Great improvements to the haptic glove have been achieved through previous research, but these improvements have generally been limited to the hand mechanism. Even though the glove itself has been made more compact and light, its workspace is still restricted by the power or communication lines connected to external equipment, e.g., pressure sources for pneumatic systems, batteries for directly attached actuators, and wire-driven systems for force transmission. In many cases, this external equipment has remained bulky and heavy. A complete wearable system, including not only the glove but also auxiliary equipment, has still not been developed.

To resolve this problem, a compact and lightweight actuation system was proposed in this research. The proposed actuation system consisted of an artificial muscle, a small hydraulic module to actuate the muscle, and a micro pressure sensor for feedback control. As the artificial muscle is slim and flexible, it looks similar to cable for power transmission, and thus it could be bent and attached to skin contours. However, the difference between them is that the artificial muscle can actively shrink as an actuator not like the passive cable. The linear actuation of the muscle enabled the development of a simple structure for the exoskeleton mechanism. The small hydraulic module was designed to actuate the muscle by using a piston-cylinder mechanism. Though compact and lightweight, the hydraulic module provided pressure high enough to allow flexion of the finger. The micro pressure sensor was designed to measure the pressure of the muscle for feedback control. As a result, the micro hydraulic system could be integrated with the wearable haptic glove, as shown in Fig. 1. By virtue of the micro hydraulic system, a wearable haptic glove, including a wearable controller and battery, was developed in this research. Because all equipment necessary for operation was included in the glove, the user could move freely without restriction from any lines.

II. MICRO HYDRAULIC SYSTEM

The main challenge in developing a wearable haptic glove was how to design an actuation system small enough to wear. In this research, a micro hydraulic system small enough to mount on the forearm was developed for actuation. The micro hydraulic system was composed of three parts: a slim artificial muscle, a hydraulic actuating module and a micro pressure sensor, as shown in Fig. 2.

A. Slim and flexible artificial muscle

Previous research has shown that a linear actuator, rather than a rotary actuator, is best for designing a simple hand mechanism [6]. Flexibility of an actuator is also important when a device is attached to the human body. The McKibben artificial muscle was adopted to this research because it is flexible and also linearly actuated. The McKibben artificial muscle, which was invented in the 1950's by Joseph L. McKibben, consists of an expandable elastic tube wrapped in
a braided veil [11]. The inner tube is filled with working fluid so that the volume and pressure of the tube can be controlled. When the inner tube is pressurized, it expands in a balloon-like manner against the braided veil, and the veil prevents the inner tube from expanding while maintaining the volume with a geometric constraint of the braided veil. As a result, the expansion of the inner tube makes the artificial muscle shrink, as shown in Fig. 2. In other words, the artificial muscle is shortened when pressure in the inner tube is high, whereas it relaxes at low pressure.

In this research, the artificial muscle was specially designed as shown in Fig. 3. Its design was slim and compact as suitable for a wearable haptic glove. Even though the outer radius of the artificial muscle was less than 2mm, it could exert over 5N of tension force, which is enough to reflect kinesthetic feeling to a finger.

B. Hydraulic actuating module

The Mckibben artificial muscle can be actuated with both pneumatic and hydraulic working fluid. Gas moves faster than liquid in the elastic tube because of its low viscosity, and therefore, a pneumatic system has a faster response than a hydraulic system. However, it is difficult to control position with a pneumatic system due to the compressibility of the gas. Moreover, a pneumatic system requires other equipment to provide a high pressure air source, such as a compressor, regulator or reservoir. The auxiliary equipment is often too heavy and bulky to make it wearable. By contrast, a hydraulic system allows precision control, and it is relatively easy to achieve high pressure with a compact module.

Considering these factors, water was selected as the working fluid for this research. A compact hydraulic actuating module was designed to control the slim artificial muscle, as shown Fig. 2 and 4. A nozzle on the hydraulic module was connected to the muscle, and a motor rotated a screw which slid a piston, thereby injecting water from the cylinder into the muscle. The actual module, illustrated in Fig. 1, had a radius of 16mm, a length of 170mm, and a weight of 120g.

C. Micro pressure sensor

A pressure sensor was indispensable for controlling the proposed micro hydraulic system. Existing industrial sensors are fairly accurate; however, they generally consume a large amount of flux to measure the pressure. Because the developed muscle operated with only a few cubic centimeters of flux, significant loss for measuring was not acceptable. A micro pressure sensor was developed to operate with a small amount of flux, as shown in Fig. 5.

![Fig. 3. Slim and flexible artificial muscle with diameter of 2mm.](image)

![Fig. 4. Compact hydraulic actuator module for the slim artificial muscle.](image)

![Fig. 5. Micro pressure sensor.](image)

![Fig. 3. Slim and flexible artificial muscle with diameter of 2mm.](image)

![Fig. 4. Compact hydraulic actuator module for the slim artificial muscle.](image)

![Fig. 5. Micro pressure sensor.](image)
III. CONTROL OF THE MICRO HYDRAULIC SYSTEM

In order to control the micro hydraulic actuation system, characteristics of the developed muscle were examined. The characteristics were described as a simple equation for convenience of control. The contraction force was successfully controlled with the equation, regulating the pressure of the muscle with the developed micro pressure sensor.

A. Characteristics of the developed muscle

To examine the characteristics of the developed artificial muscle, the relationship between pressure, length, and force was empirically investigated. Fig. 6 shows the contraction of the muscle and exerting force with respect to pressure. Larger contractions resulted from higher pressure, whereas smaller contractions occurred in proportion to exerting force. The force-contraction graph moved upward for higher pressure. Note that the maximum force, measured at equal pressure, occurred at minimum contraction. Similarly, contractions increased as force decreased at the same pressure. Muscle shrinkage peaked when no more force could be generated at the maximum contraction point. To measure the exact contraction length of the artificial muscle, a small amount of tensile force was maintained on the flexible artificial muscle so it remained straight. The length of the artificial muscle for this experiment was 230mm. When the artificial muscle was operated with 0.55MPa, it generated about 4N contraction at its full relaxed length.

A theoretical model of the McKibben artificial muscle has been well proved [11-13], but an actual system shows somewhat different behaviors. For control of the artificial muscle, the regression of empirical data is more practical than the calibrated theoretical model. The relationship between pressure, contraction, and force becomes a multiple linear regression problem. In this research, the empirical raw data was fitted to a quadratic form as

\[ P = 0.0002F^2 + 0.0113\varepsilon^2 + 0.0027\varepsilon \cdot F + 0.0075F + 0.0485\varepsilon + 0.1758 \]  

(1)

where \( P \) is the pressure of the artificial muscle, \( \varepsilon \) is the contraction of the length, and \( F \) denotes the exerting force. The regression equation (1) is represented compared with raw data, as shown in Fig. 7.

The gray colored mesh reflects the raw data while the unfilled mesh represents the regression equation. Since relationships are clear and strong in the raw data, the regression is well matched. The root mean square error between Eqn. (1) and the raw data was calculated to be 0.0191 Mpa. The regression equation was used in the actual operation of the micro hydraulic actuation system for convenient control.

B. Control of the hydraulic system

The contraction force of the muscle can be controlled by regulating pressure with respect to its length. To control a desired force with the micro hydraulic system, a reference pressure needed to be calculated from the desired force. This was easily done from the prescribed Eqn. (1). The micro pressure sensor observed the pressure in the muscle, and the measured data was fed back to a motor controller. The motor controller controlled the piston of the micro hydraulic module and regulated the pressure in the muscle as the reference value. In this way, the desired force was generated by the micro hydraulic system.

IV. EXPERIMENTAL RESULTS

To evaluate the performance of the developed system, bandwidth was examined with respect to step and sinusoidal excitations. All the results shown the mechanical bandwidths, and the control bandwidth was much faster than it.

Fig. 8 shows the step response. The macroscopic response reveals that the system was very damped because of the effect of a viscous flow, and no overshoot occurred due to the damped characteristic of the system. Small fluctuations continued to occur following the reference step because pressure waves traveled rapidly in the tubes with natural frequency. However, the magnitude of remaining pressure
waves was too low to be recognized by human operator. The time constant of the system was measured at about 125 milliseconds following the step reference. To evaluate the system response, sinusoidal references were excited, as shown in Fig. 9.

Fig. 9 shows sinusoidal responses at two different frequencies. The system successfully followed the reference for 2 Hz excitation. However, the system marginally chased about 0.707 times the magnitude when it followed a 4 Hz reference. These findings reveal that the mechanical bandwidth of the system was about 4 Hz. The response in this research was lower than other pneumatic actuation systems for haptic gloves [6, 12-13]. One reason for this difference was that the viscosity of the working fluid in this study was higher than air. Much more, the performance of the installed motor in the integrated system was not enough to guarantee high bandwidth (refer the specification in Table I). The bandwidth of the first prototype was traded for the weight/volume requirements in this research, and all the results shown in Fig. 8 and 9 were brought by a small 2.7-watt motor. The performance could be improved by changing the motor in the actuating module.

V. APPLICATION TO A WEARABLE HAPTIC GLOVE

A. Integration of a wearable haptic glove

The developed micro hydraulic system was integrated into a wearable haptic glove for three fingers, as shown in Fig. 1 (b). The user wore a skinny exoskeleton on the back of his fingers and hand. The articulated exoskeleton allowed the user to flex and extend the fingers freely. The artificial muscle originated on each fingertip and continued down the forearm. For enough force, each finger was coupled by three artificial muscles connected to one hydraulic actuating module, and totally nine muscles are used. These muscles were responsible for exerting reaction force against human motion thereby providing kinesthetic feeling. The developed glove equipped artificial muscles only for extensors because most applications involve expressing the shape of a virtual object in the hand. However, the glove could be modified to reflect bidirectional force if an antagonistic flexor is attached to the inside of the fingers.

The hydraulic modules and pressure sensors were attached to the forearm to actuate the muscles. The flex of each finger was measured as one DOF simplified motion by a flex sensor, and adduction and abduction were ignored. The resistance of the flex sensor changes from 10k Ohm to 40k Ohm when it bent. After filtering the measured signal, the noise level was enough to detect the just noticeable difference (JND) of the finger joint [14]. A wearable controller was designed for the developed haptic glove and attached to the waist of the user, and the controller communicated with the simulation PC for virtual environment via a wireless LAN. Since the battery for the controller and the micro hydraulic actuation system is also attached on the waist, all the wires for connecting to external equipment (i.e. power lines and communication cables) were removed. As a result, the developed glove operated completely independently and the user could move freely while wearing it. The specification of the integrated system was shown in Table I and II.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SPECIFICATION OF HYDRAULIC ACTUATING MODULE</th>
</tr>
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<tbody>
<tr>
<td>Weight</td>
<td>120 g (61.5 g) a</td>
</tr>
<tr>
<td>Volume</td>
<td>$16\phi \times 170 \text{ mm}^3$ (16\phi \times 50.9 \text{ mm}^3 ) b</td>
</tr>
<tr>
<td>Power of installed motor</td>
<td>2.7 watt</td>
</tr>
<tr>
<td>Max. continuous torque of installed motor</td>
<td>41.46 Nmm</td>
</tr>
<tr>
<td>Max. pressure</td>
<td>0.597 Mpa</td>
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<table>
<thead>
<tr>
<th>TABLE II</th>
<th>SPECIFICATION OF WEARABLE HAPTIC GLOVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>2.62 kg (1.6 kg) a</td>
</tr>
<tr>
<td>Resolution of finger angle</td>
<td>0.12 degree</td>
</tr>
<tr>
<td>Max. force at each finger</td>
<td>12N</td>
</tr>
<tr>
<td>Control sample time</td>
<td>1 msec</td>
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* weight of controller and battery
B. Application to virtual environments

To evaluate wearability and prove the glove’s effectiveness, a virtual environment for edutainment was constructed as one application of the wearable haptic glove, as shown in Fig. 10.

![Wearable Haptic Glove Integrated with a Virtual Environment](image)

The virtual environment included a table on which dominoes were placed. The user could pick up the domino tiles and make rows for domino toppling. An electromagnetic 6DOF Polhemous position tracker was used to measure the motion of hand. Finger angles were captured by the flex sensors on the glove, and the angles were sent to the simulation PC for the virtual environment. When the finger of the user touched the table or the domino tile, the contact force was calculated and sent to the controller for the haptic glove. The artificial muscles exerted forces on the fingers not to penetrate into the virtual objects. The user could move around the immersive virtual environment and feel tactile forces on virtual objects while wearing the haptic glove.

VI. CONCLUSION

In this research, a micro hydraulic actuating system was developed for integration into a wearable haptic glove. It was composed of an artificial muscle, a compact hydraulic module, and a micro pressure sensor. Since the artificial muscle was specifically designed to be thin and flexible, it could be attached along the body contour. A compact hydraulic module was developed to actuate the muscle using a motor-driven piston and cylinder. The module achieved a small enough size to attach to the forearm and even provided sufficient force to hold the finger. The micro pressure sensor enabled the system to regulate pressure without loss of flux. The characteristics of the muscle were examined for control, and the performance of the micro hydraulic system was evaluated for step and sinusoidal inputs.

A lightweight and compact actuation system was obtained which could provide enough force to enable tactile feeling on the finger. The measured mechanical bandwidth of the developed prototype was not sufficient for precision haptic applications, but capable of applying to haptic applications for education or entertainment. The performance could be easily improved by changing the motor in the actuating module or the working fluid, and the integrated haptic glove shown that concept of the developed micro hydraulic system was useful for a wearable system. By virtue of the micro hydraulic actuation system, the wearable haptic glove was operated completely independently without external equipment. With wearing the wearable haptic glove, the user could move freely without any restriction from electric wires or hydraulic tubes connected external equipments. The wearable haptic glove was actually applied in a virtual environment where its practicality and usefulness were successfully tested.

REFERENCES