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Development of a pneumatically-driven Growing Sling to assist patient transfer

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Abstract— **In this study, a new type of sling for assisting bedridden patients is developed using a pneumatic growing mechanism. Growing Sling focuses on minimizing the labor input of the caregivers by automating the sling insertion and retraction process while maintaining safety and comfort. Improvements over the typical growing mechanism were made by reinforcing the sling with shafts and filament tape for restricting the height of the sling to ensure its design purpose. Analysis of forces exerted on the structure was made to interpret the driving power of the automated insertion process and to ensure the structural integrity of components. Experiments on materials and prototype devices were conducted to determine the quantitative load that the sling needs to endure and what type of material is suitable for fabrication. Further, we propose a fabrication process for the Growing Sling, including its dimensions, and validate the performance of the fabricated prototype.**

I. Introduction

Patient transfer is a necessary procedure for providing basic care to bedridden patients and the elderly. The process consists of lifting patients who are lying down on a bed and transferring them to required places, such as another bed, a chair, or a wheelchair. In Korea, many caregivers currently perform the patient transfer manually, both at healthcare facilities and in homes, by pulling the patient against friction or by lifting them. It can take up to four caregivers at a time, depending on the body condition of the patient, and can take a substantial amount of labor intensity [1]. However, as the aging population increases in many societies, the demand for caregiving increases, while the workforce for caregiving industry is insufficient. In addition, the procedure of patient transfer can cause musculoskeletal injury to caretaking personnel if performed incorrectly. In these situations, the automation of patient transfer has been researched [2] to reduce the workload and injury of caregivers.

Existing transfer devices can be categorized into two types according to their use of slings. A sling is a fabric sheet that can enclose the patient's body to support weight and is attached to devices by fastening them to device supports or cables [3].

One category of the transfer assist device, without a sling, is the bed type transfer assist device. They are based on the idea of utilizing or transforming the area where the patient is lying down. Examples of bed type transfer assist devices include a commercial product, such as the AgileLife Transfer & Mobility System (TMS, Next Health, CT, USA) [3], and some research devices, such as The Reconfigurable Holonomic Omnidirectional Mobile Bed with Unified Seating (RHOMBUS, d'Arbeloff Laboratory for Information Systems and Technology, MA, USA) [4]. This type of device can stably transfer the patient. However, the bed type transfer assist device is mechanically complex and economically disadvantageous. These devices can only be used for one bedridden patient per device and are not able to provide bed-to-bed transfer.

Another sling-less transfer assist device type includes robots that have arms and hold up patients. Robot for Interactive Body Assistance (RIKEN-TRI Collaboration Center for Human-Interactive Robot Research, Japan) is a care assistant robot that can transfer a patient from one bed to another bed, or a wheelchair, by holding the patient with two robotic arms that each has seven degrees-of-freedom [5]. These types of devices directly transfer the patient; thus, there is no sling inserted under the patient. However, the serial link mechanism of the arm requires high torque capacity, and the high degree of freedom of the robot arms increase the cost of the device. Moreover, the stability of the patient is limited compared to devices using a sling because the patient is supported only by limited supporting points. Thus, use for the elderly or immobile patients is limited for these types of devices.

Sling-type transfer assist devices lift the body of the patient and support them using a sling. Manual patient lifts, such as BestLift® PL182 (Bestcare, GA, USA), are the most common examples of sling-type devices. To use these devices, the sling needs to be placed underneath the patient's body by manual operations done by caregiver. This includes lifting the patient, spreading the sling under the patient's body, and connecting the sling to the transfer assist device. The transfer assist robot SASUKE (MUSCLE Corporation, Japan) is a more advanced form of sling-type device developed to give an extra degree of freedom in the patient's posture. It can rotate its two arms to change the posture of the patient from the laying down position to sitting position to handle patient

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transfer between a bed and wheelchair. However, the shortcoming of SASUKE's sling remains the same. The complicated sling insertion process increases the time and labor required for operation, which limits the usability of the device. Therefore, in related studies, the labor-saving effect of hoist devices using a sling is low, and caretaking personnel does not often utilize such devices [7].

In this study, we propose a Growing Sling to increase the usability of the transfer assist device while maintaining the safety and comfort of the patient. The new sling design can be automatically and smoothly inserted underneath a patient by adopting the growing mechanism [8]. In Section II, the concept of a Growing Sling is introduced in detail. Design parameters related to the applied pressure are studied in section III. Material selection based on the derived design parameters and fabrication are explained in Sections IV and V. The developed Growing Sling is experimentally evaluated in Section VI.

II. Concept of the Growing Sling

A. Design Requirements

The primary requirement for the proposed Growing Sling is the ability to be automatically inserted and removed under the patient lying on a bed and a wheelchair as shown in Figure 1. To satisfy this with minimal effort of the caregiver, the patient or objects under the patient, such as clothes, bed sheets should not be moved during sling insertion and removal. This can be satisfied by allowing insertion and removal of the sling without relative movement between the surface of the sling and the environment such as patient, bedsheets. In general, the relative movement induces friction force which moves the environmental objects.

Another requirement of the sling is that the sling must ensure the safety and the comfort to the patient. To meet this requirement, the length and width of the sling should fully cover the patient's body. The height of the sling must be as low as possible to prevent the patient from falling from the sling. The surface of the sling should be flat to prevent the application of unnecessary force on the patient. Lastly, to apply the sling to a wide range of the population, it should at least be applicable for patients weighing up to 75 kg.

B. Basic concept: Growing Mechanism

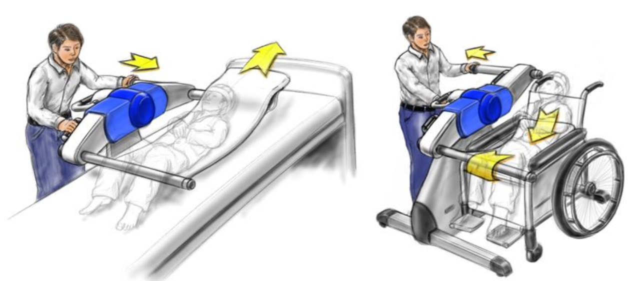

Figure 1. Schematic illustrating the concept of the Growing Sling patient transfer assist device. The Growing Sling is inserted under the patient (left), and the sling is removed after the patient is transferred to a wheelchair (right).

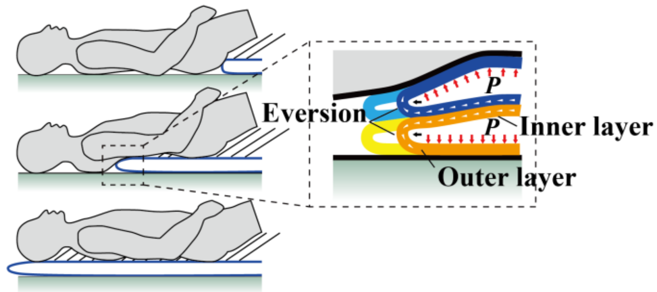

Figure 2. Schematic illustrating the growing mechanism concept of the pneumatically driven Growing Sling.

The growing mechanism is adapted to the Growing Sling to achieve the requirements mentioned above. The previously studied growing mechanism dealt with the ability of the device to lengthen, navigate a restricted environment, and control its direction [9]. Research has shown that a specially designed growing mechanism allows the insertion or removal of the structure in small gaps without relative motion against contact surfaces.

The concept of a Growing Sling using a growing mechanism is illustrated in Figure 2. The growing mechanism consists of a thin film layer that was originally part of a tube with one end sealed consisting of the outer layer of the tube. By inverting the layer at the tip into the inside of the tube, the layer is divided into outer and inner layers, as shown in the enlarged view of Figure 2. The mechanism utilizes air pressure as the driving force. By applying air pressure, the growing mechanism initiates. The inner layer spreads out from the tip of the structure to form a new outer layer. The film segment that everted from the tip and formed the body remains stationary, so no sliding friction is produced with contact surfaces.

However, this mechanism has limitations when it comes to our requirements. Since the thin film material used in the mechanism can only withstand tension and is not able to endure a bending moment, the cross-section of the mechanism forms a circle. This is because only tension is applied to the wall in the axis-symmetric structure. Therefore, the height of the mechanism will be the same as its diameter. The device contains non-flat surface, which makes it physically unstable for lifting a patient. The ideal geometric design of the growing mechanism as a sling is one with enough width to cover the human body and, at the same time, have a low height to provide comfort and safety for the patient.

A special design is adopted to realize low height Glowing sling. Generally, to form a low height profile, an air-inflated mattress is designed as connecting the upper side and the lower side together. However, in order to use the growing mechanism, the inner space of the tube should be left empty. The method proposed in this paper is to form flat surfaces on the top and bottom sides of the sling. This turns the cross-sectional shape from a circle to a horizontally long rectangle. A patient using the sling can lie down on a flat surface, which is far more stable and safer. The flat surface will be under the evenly distributed vertical force due to pressure inside of the sling. The tension of the sidewalls of the cross-section exert force at the side edge of the flat surface and balance the force by pressure as shown in Figure 4. The forces exerted by the pressure inside the sling will produce a bending moment across the flat surfaces of the sling. Therefore, rigid structural elements are applied to withstand the bending moment as shown as the shafts in Fig. 2.

C. Growing mechanism with shaft-reinforced structure

The material used for making flat surfaces at the top and bottom sides of the sling should meet the following two conditions. First, the material must withstand the bending moment that makes a cross-section to create a circle, as discussed in the previous section. In addition, the material should freely be rolled and unrolled, which means that bending in a longitudinal direction should be achieved easily. To achieve these characteristics, we propose applying multiple shafts placed in a parallel manner. By adhering shafts to the film layer, the shafts bear all the bending moment for maintaining a rectangular cross-section as shown in Figure 4. Also, because the shafts are connected by a soft film material, they can be rolled and perform as a Growing mechanism based on the eversion of the inner layer.

III. Force Analysis

All the force that drives the sling originates from applied internal pressure. Higher pressure generates more force to operate the sling insertion. The insertion lifts the patient by supporting their body weight and lengthening the sling under the patient by pushing the inner layer out at the tip. However, the higher pressure increases the specification of the sling structure to maintain the shape of the sling. Therefore, it is important to choose the appropriate value of internal pressure.

A. Pressure requirement

Figure 3 shows how Growing Sling meets the patient's body and then lifts the patient's body vertically. The Growing Sling penetrates under the patient's body while simultaneously deforming itself (the sling). If the width w of Growing Sling is constant, a relationship between the internal pressure P and the changed height y of the Growing Sling is given by $PA = P(y - y_{\min})w = Const$, according to reference [9]. $y_{\min}$ is the minimum height of the Growing Sling without the internal pressure. As a result, the changed height y of Growing Sling is derived as:

$$y = \frac{Const}{Pw} + y_{min}. \tag{1}$$

To simplify the calculation, we assumed the contacted body of the patient to be an inclined slope, as shown in Figure 3. We obtained the horizontal contact distance x_{dist} between the Growing Sling and the patient's body by using the height and angle of the slope. The equation is given by

$$x_{dist} = \frac{(y^* - y)}{\tan\theta} \tag{2}$$

where, y^* is the unchanged height of the Growing Sling, and θ is the angle of the body slope which depends on patient's body shape and stiffness.

The lifting force F_{lift} is obtained by the internal pressure and the contacted area and derived to be:

$$F_{lift} = Pwx_{dist} = Pw\left(\frac{y^* - \left(\frac{Const}{pw} + y_{min}\right)}{\tan\theta}\right)$$
$$= P\frac{w(y^* - y_{min})}{\tan\theta} - \frac{Const}{\tan\theta}. \tag{3}$$

From (3), we determined that the force F_{lift} and the internal pressure P are proportional.

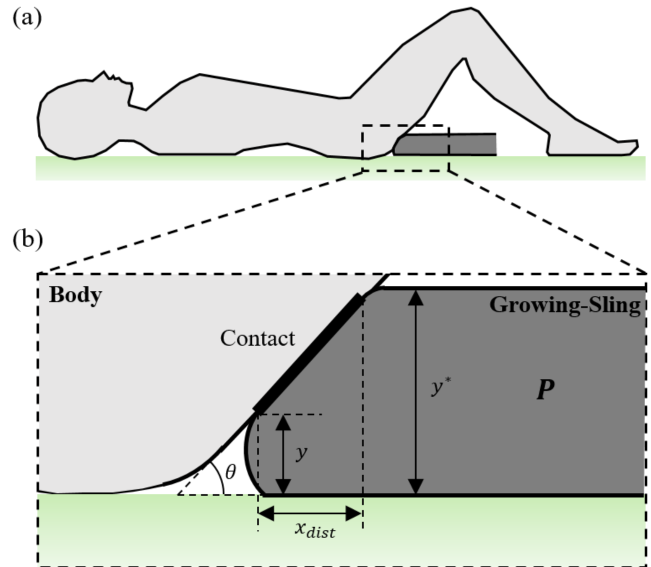

Figure 3. Schematic of the Growing Sling insertion process. (a) Sling insertion from the lower body of a bedridden patient. (b) The geometric variables of the sling tip during contact with the patient.

The pressure generates force to lift the body weight at the contact surface between the sling and the body. The patient's body is lifted by the lifting force between the bed and the empty space underneath the patient's body. Through these spaces, the sling can lengthen until it reaches the patient's body and creates an additional contact surface. The force for lengthening is generated by the inner pressure. By repeating this process, the sling can progress forward while lifting the patient's body that was lying down on the bed. To understand this process and the behavior of the sling under a certain load, future analysis of each force element will be conducted in further detail. Elementwise force and stress analysis were done to give robustness and structural integrity to the sling. Furthermore, this analysis also helped to optimize the material and the design of the Growing Sling elements.

B. Bending moment exerted to shaft

The bending stiffness about the longitudinal axis of the sling is ensured by the shafts attached to the surface layer of the sling. These shafts undergo pure bending. The air pressure applied to the flat surface can be considered as a uniformly distributed load while its reaction force comes from the tensile force at the sidewall element, as illustrated in Figure 4. This approximation assumes that the pressure-induced force applied to the area between each shaft is completely transferred to the shaft. The distributed pressure force is indicated by multiplication of distance between each shaft i

and the internal pressure P. The maximum bending moment exerted to a single shaft, M_{max} is proportional to the distributed pressure force and to the square of the shaft length w. The relationship between bending moment and pressure force is indicated by:

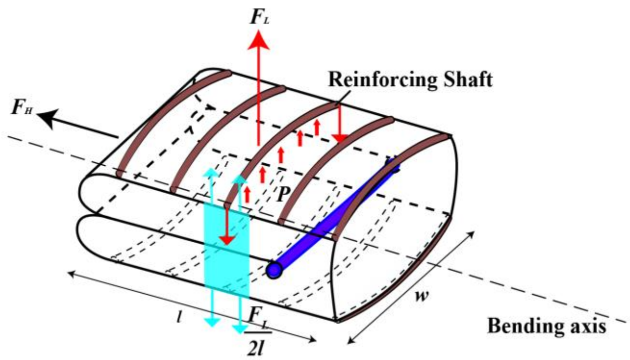

Figure 4. Schematic of the bending moment and tensile load exerted on the shaft and sidewall, respectively. The force derived from internal air pressure is in equilibrium with tension from both sidewalls.

$$M_{max} = \frac{Piw^2}{8}. \quad (4)$$

Also, the maximum deflection of the shaft, δ_{max} by the pressure force is expressed using the Young's modulus of material E and the second moment of area I and is indicated by:

$$\delta_{max} = \frac{5Piw^4}{384EI}. \quad (5)$$

C. Sidewall tension

The sidewall of the sling connects the top and bottom layers. Since the top and bottom surfaces are under vertical forces, which have the same magnitude and opposite direction, the sidewall is under tension and is responsible for the force equilibrium of both surfaces. The magnitude of the tensile force is determined by both the vertical lifting force and the pressure-induced force acting on the sidewall area itself. The area of the top and bottom surfaces is much greater compared to the sidewall area, thus making the portion of the vertical lifting force dominant. Therefore, the magnitude of tensile force is expressed as half of the vertical lifting force, and the tensile force per unit length exerted to the sidewall film element is expressed as

$$\frac{F_L}{2\ell} = \frac{Pw}{2}, \quad (6)$$

which is tensile force divided by film width. As shown in Equation (6), the tensile strength of the sidewall element determines the maximum pressure threshold that the sling can endure. This determines the maximum vertical lifting force and horizontal lengthening force of the sling. Thus, the high tensile strength of the sidewall element is required to maximize the performance of the sling. At the same time, the film material's ability to fold, roll, and squeeze through the constraint environment is critical to performance. The selection of the appropriate film material with suitable properties will be discussed in the following section.

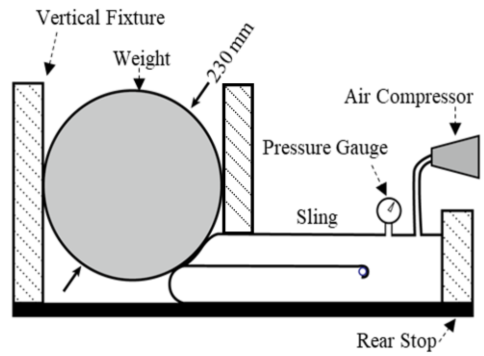

Figure 5. Schematic of the preliminary experiment.

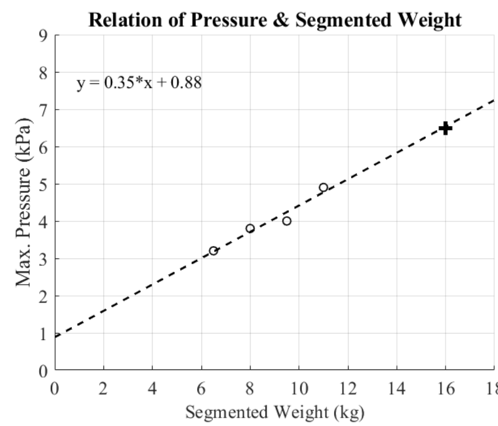

Figure 6. Graph indicating the linear regression relation of maximum internal pressure of the sling and the segmented weight that the sling is lifting. Circles indicates measured values of maximum pressure and dotted line indicates linear regression relation of measured values. Cross indicates data point of linear regression relation of measured values.

IV. PRELIMINARY EXPERIMENT

A preliminary experiment was conducted to determine the appropriate design dimensions and material of the sling to meet the required specifications. The segmented weight of the patient's body is the key factor determining the operation of the sling. Also, the internal pressure of the sling, expressed as P, is the main factor deciding design requirements and dimensions. Therefore, the preliminary experiment is about understanding the relationship between the segmented weight and sling inner pressure. The objective of the experiment is to predict the internal pressure required when lifting 75 kg patient.

The experimental setup is illustrated in Figure 5. The sling is fixed at a rear stop and inflated by pressurized air supplied by an air compressor through connected tubing. When the sling is obstructed by the weight during the lengthening process, it exerts a force to lift the cylindrical weight. The diameter of the weight was determined by considering the shape of the human hip, where the maximum pressure is required to insert the sling. Also, the experiment is designed to vary the weight. Since the sling exerts both horizontal and vertical forces to the weight, the weight will be displaced without horizontal fixing equipment during the lifting process. Therefore, two vertical fixtures are used to constrain the horizontal movement of the weight against the horizontal force so that only vertical force displace the weight. A digital pressure sensor connected to the sling measured the maximum inner pressure of the sling during the experiment. 6.5 kg, 8 kg, 9.5 kg, 11 kg of weights were used for each pressure measurement.

The results are presented in Figure 6. As expected, there is a linear relationship between the internal pressure and load. The maximum segmented weight of a 75 kg human is assumed as 15.9 kg by assuming that the weight of the lower trunk concentrates on the hips [11]. Therefore, the expected internal pressure of the sling when lifting 75-kg human subject is 6.48 kPa. The design requirements can be derived by the required internal pressure. The width of the sling and the length of the reinforcing shafts are 450 mm. By substituting the target pressure of 6.48 kPa into (6), a tensile load per unit length of 1.46 kN/m is obtained. In the same way, according to (5), the reinforcing shaft should support 164 N/m per unit length.

V. FABRICATION

In this section, the selection process for determining suitable materials based on force analysis and the preliminary experiment will be presented. Additionally, the fabrication process for a functioning Growing Sling prototype with the selected materials will be described.

A. *Material Selection*

1) *Film layers*

Since the film material should have the property to form an enclosed space and endure a tensile load, considerations of heat-sealing properties, tensile strength, and maximum elongation have been made to candidate materials. Five materials, Polyethylene (PE), Polyethylene Terephthalate (PET), Polyvinyl Chloride (PVC), soft PVC (sPVC) and Polyurethane (PU), were considered as candidates based on their availability. All specimens underwent heat-sealing testing with the same continuous band sealer (CS-1500, South Korea) that can control the temperature and sealing speed.

Material	Thickness(mm)	Temp. range(℃)	Compatibility
PE	0.10	150-250	No
PET	0.10	150-250	No
PVC	0.15	150-200	Yes
sPVC	0.18	150-200	Yes
PU	0.25	150-170	Yes

Table 1. Set of polymer film materials used in a heat-sealing test and their results. The thickness of each material, the temperature range tested, and their compatibility to be heat-sealed are listed.

The experiment conditions are listed in Table 1. Sealing speed was fixed to the slowest (about 160 mm/s), and only the temperature was adjusted to control the amount of heat flux to the specimens. The temperature at the fusion plane can be controlled by the heat flux given to the specimens [10]. For each specimen, the initial trial was done with the lowest settable temperature (150 °C) of the sealer and turned up 10 °C at a time when the heat flux was not sufficient to fuse two layers. PE and PET could not easily be sealed using the continuous band sealer and behaved similarly. In the lower temperature region (150-200 °C), these specimens did not show any deformation or melting. However, when the temperature reached a certain point over 200 °C, the specimen melted completely and deformed, failing to make a seal. In case of PE and PET, precise temperature control is necessary to ensure proper sealing. Contrarily, PVC, sPVC, and PU formed a completely bonded seal within wider the temperature range. Temperature higher than the presented range resulted in melting for all specimens.

A tensile strength experiment was conducted for materials that were able to heat-seal, namely, PVC, sPVC, and PU. To determine the effect of sealing temperature on the maximum tensile strength for each material, specimens sealed at temperatures of 150 °C, 160 °C, and 170 °C were used. Tensile strength tests were done by a Universal Testing Machine (QMESYS QUATRO 100).

The maximum load that each specimen could endure was tested. As indicated in Figure 7, the tensile load per unit length was highest in PU (2.5 kN/m) and the lowest in sPVC (1.5 kN/m). The strength of the material was also shown to increase as the sealing temperature was increased, indicating that sealing at higher temperatures was advantageous in terms of strength to the extent that the material did not melt. In addition, as indicated in Figure 8, the maximum elongation of specimens was different for each material. Specimens with a total length of 60 mm, 10 mm of which were heat-sealed region, were used, and the PU sealing remains bonded until the elongation exceeded 500% from the original length. When the elongation was greater than 500%, the seal began to tear, but the load applied continued to increase, reaching the maximum value just before the failure. PVC and sPVC seals began to tear right after the tensile force was applied to the specimen, and, similarly, the load was at a maximum just before the failure. PVC increased by only 10-mm in length, equal to the length of the sealing itself. sPVC showed about 100% elongation until it failed.

The PU sample showed the highest tensile load per unit length and elongation rate to meet the design criteria of 1.46 kN/m. Unlike other materials, heat-sealed PU did not tear under a tensile load lower than the threshold, making it durable for repeated loads. Additionally, PU is elastic enough to be rolled into a small radius of curvature and has relatively stable heat-sealing characteristics. These characteristics are advantageous for building the Growing Sling; thus, PU was selected as the film material.

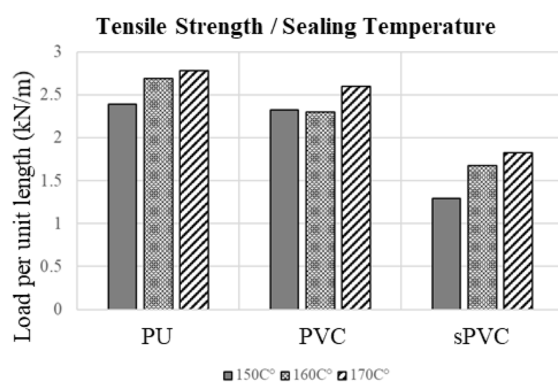

Figure 7. Graph indicating the maximum load per unit length for film materials sealed in different temperature conditions.

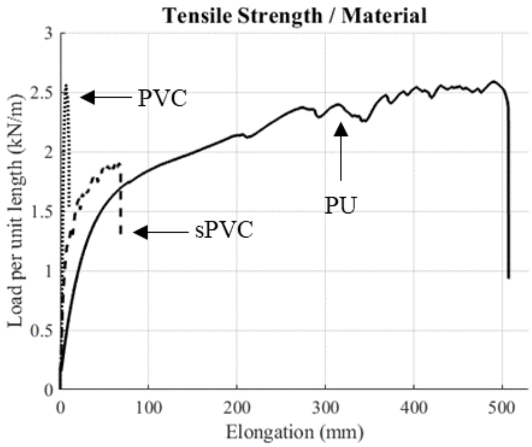

Figure 8. Graph indicating tensile load per unit length of different materials when elongated.

However, due to the high elongation rate of PU under a tensile load, the height of the sling made of PU will increase when internal pressure is applied. It will deteriorate the sling's design objectives, the safety, and comfort of the bedridden patient, by not restricting the height. To overcome this weakness, a composite material of PU and filament tape, with a relatively large Young's modulus, as reinforcement was used as the sidewall material. The filament reinforcement tape (3M 8915) has 6.3 kN/m of tensile load per unit length and 3% of an elongation of break, which indicates this material has a high Young's modulus. By adding the reinforcement tape to the sidewall and connecting the upper and lower reinforcement shaft with the tape, it is possible to reduce the tensional load that is applied to the reinforce shaft on each interval while PU film endure the load between each shafts.

2) Reinforcing shafts

The material of the reinforcing shaft is selected in order to endure target internal pressure while minimizing weight. Carbon fiber reinforced composite is selected as the shaft material because of its high Young's modulus and strength compared to its weight. The material has Young's modulus E of 140 GPa, and maximum compression strength of 1.6 GPa. Minimizing shaft diameter is desirable to reduce the weight and volume of Growing Sling, but it results in narrower shaft intervals. Thus, selecting moderate shaft diameter is required. When the carbon fiber composite shaft of 5 mm in diameter is applied, a single shaft can endure 19.65 Nm without plastic deformation. With these shafts, the interval between the shafts can be 120 mm. However, to minimize the deflection of the shaft and by considering the secure safety factor, the interval was determined to 60 mm.

B. Structure of Growing Sling and fabrication process

The Growing Sling was fabricated by adhering edges of two film layers to form a tube. As shown in Figure 9, the top and bottom layers have the same structure, which consists of three sublayers and shafts. Sublayer 1 is a polyurethane film that forms the tube structure and has a total length of 1200 mm. Sublayer 1 of the top and bottom layers are joined together to seal the air pressure and form the tube. Sublayer 2 is also polyurethane. The shafts are fixed to the structure, in between sublayers 1 and 2, by adhering the layers by applying heat with a heat gun. The shafts were placed at 60 mm intervals. Additionally, since polyurethane films have a high coefficient of friction when rubbed against each other, friction between the upper and lower layer can hinder the performance of the sling. Therefore, sublayer 3 was made with polypropylene, which has a low coefficient of friction and was attached to sublayer 2 using double-sided tape. The layers are tapered to ease the sling operation process and create an 800-mm width at the starting side and a 450-mm width at the ending side, where the retraction belts are located. Therefore, the length of the shafts also varies to keep the sling at a constant height of 80 mm.

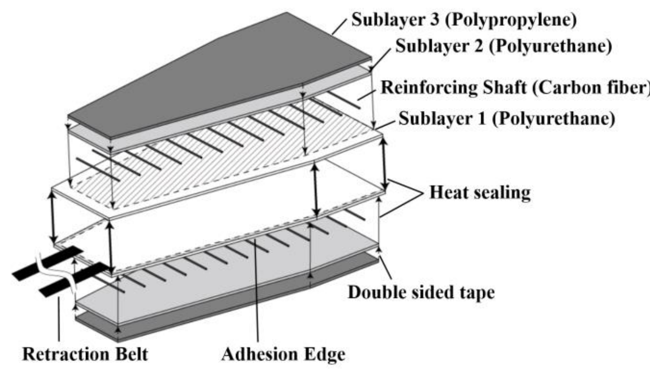

Figure 9. Schematic of components and the fabrication process of the Growing Sling. Lined arrows indicate assembly of the parts and dashed arrows designate components.

The upper and lower side assemblies overlapped each other such that sublayer 3 of the bottom layer faced downward, and the sublayer 3 of the top layer faced upward. The three edges of the layers, indicated as an adhesion edge in Figure 9, were sealed using a continuous band sealer. Two retraction belts were placed between the upper and lower sublayer 1 and heat-sealed at the same time. These belts pull the tip side of the sling when the sling is retracted and rolled back into a scroll. The last edge at the opposite side of the retraction belt was left unsealed to invert the inside and outside of the upper and lower layers and sealed afterward. This inversion process is needed to place sealing joints inside of the sling, preventing them from interrupting sling operation. The last edge was also heat-sealed using a continuous heat sealer.

Finally, reinforcement of the sling was made by filament tape (3M 8915). The tape encircled the entire cross-section, connecting the upper l and lower layer reinforcement shafts.

VI. Performance Evaluation

In order to validate the workability of the pneumatically driven Growing Sling, the performance of the sling was measured through a series of experiments. First, the overall shape of the sling and structural elements of the sling is properly maintained with respect to the internal pressure during the injection of the compressed air were investigated. Next, the lengthening capability with respect to the internal pressure under a human was studied in order to simulate real-life use.

A. Features of the Growing Sling with respect to the internal pressure

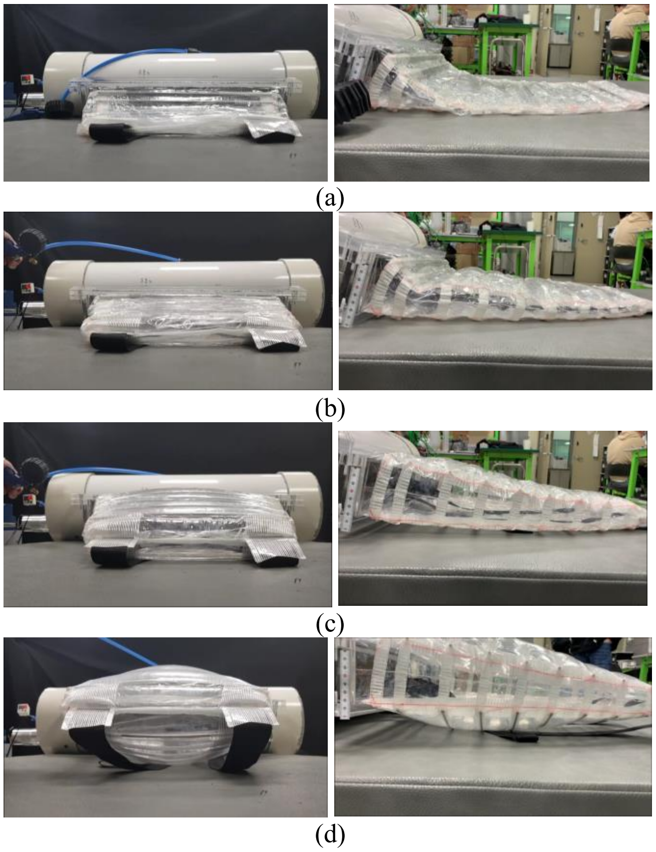

Figure 10. Pictures of the Growing Sling from the side and front when initial pressure varies from 0 kPa to 12 kPa; (a) Initial state, 0 kPa; (b) Lengthening state, 0.1 kPa; (c) Final state, 2.5 kPa (d) When deformation occurred, 12 kPa.

To investigate the features of the sling with respect to internal pressure, the prototype, which does not have a taper feature 450-mm wide and 400-mm long, was integrated into a test chamber made out of PVC pipe (diameter of 24 mm and width of 700 mm) to collect the internal pressure while injecting compressed air. Pressure in the chamber was recorded with a pressure sensor (PSAN-01CV, Autonics, South Korea) and Compact DAQ (National Instrument, USA). The extension of the sling was captured by a camera to detect the transformation of the feature.

The sling prototype was prepared as an unfolded state as shown in Figure 10 (a), and compressed air was injected through a tube attached to the test chamber. The feature of the prototype in Figure 10 (b) indicates that it starts to swell at 0.1 kPa, along with injecting compressed air. Required pressure for the prototype to fully expand, as shown in Figure 10 (c), is 2.5 kPa. Until the pressure reaches 12 kPa, the height keeps increased as the reinforcing shafts bend.

The deformation of the reinforcing shafts is measured under different internal pressure up to 5 kPa. Internal pressure of 2 kPa, 2.5 kPa, 3 kPa and 5 kPa was applied to the Growing Sling and bending of the shaft was measured by measuring the difference of the height of the Growing Sling with respect to the following pressure. Also, calculated values for each pressure values are derived from equation (5) and compared with measured values.

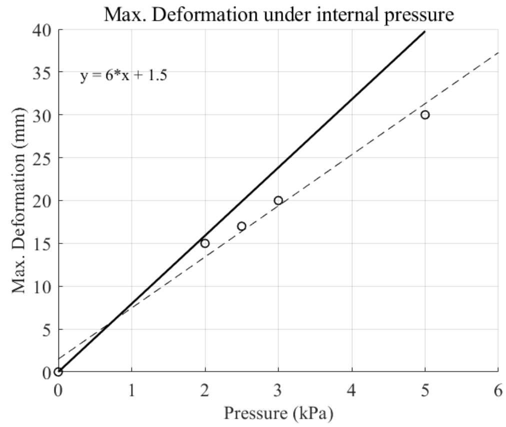

Figure 11. Graph indicating measured values and calculated values of the deformation of the shaft of length 450mm with respect to the internal pressure applied. Solid line indicates calculated value of shaft deformation and dotted line indicates linear regression relation of measured values.

As indicated in Figure 11, the measured values of the deformation of the shafts had linear relation like the calculated values, supporting the validity of the force analysis. In addition, it is confirmed that the usage of the Growing Sling under target pressure of 6.48 kPa does not result in plastic deformation of the reinforcing shafts.

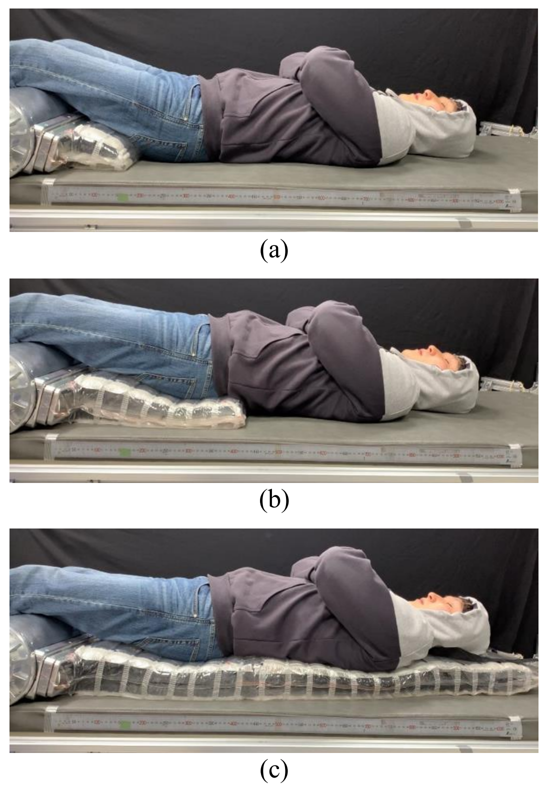

Figure 12. Images of the Growing Sling under a 75-kg human subject at the (a) initial state, (b) lengthening state, and (c) final state.

B. Demonstration of Growing Sling insertion capabilities

Figure 12 (a) displays the experimental set up of the lengthening test. A 75-kg adult male lay down on a 700-mm wide and 1800-mm long medical bed. The Growing Sling was folded like a roll in the sealed aluminum chamber, which was driven by a BLDC motor (PG43-BL42100, motorbank, South Korea).

The compressed air was injected through the tube connected to the sealed aluminum chamber while actuating the BLDC motor to release Growing Sling. Figure 12 indicates the process of lengthening Growing Sling, and Figure 13 shows the inserted length of the sling with respect to the internal pressure. More pressure was required when the sling passed the hip, back, and head regions of the test subject. The hip section especially appeared to be the most resistive region, requiring the highest pressure while the lengthening process was around 4.5 kPa. The back and head regions required around 3.3 kPa and 2.8 kPa, respectively, in order to extend the Growing Sling. The lengthening rate tended to slow down when confronting each body part. When the Growing Sling passed through the resisting region, there was an immediate release of the sling, the inserting speed jumped up, and the pressure dropped down.

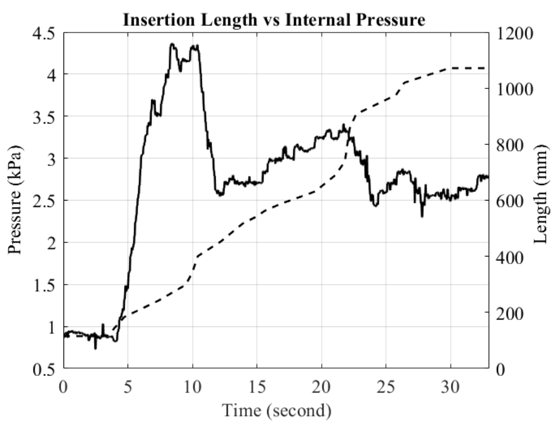

Figure 13. The internal pressure of the Growing Sling with respect to the inserting length. Solid line indicates internal pressure in kPa and dotted line indicates insertion length of the Growing sling.

VII. Conclusion

We have developed a new type of sling that can replace existing slings used to assist an inpatient transfer. To ensure the safety and comfort of the bedridden patient during the transfer process, a growing mechanism capable of restricting height by using a film material and shaft was designed. The sling was tested on a 75-kg subject and the insertion performance was verified. Moreover, from the opinion of the subject, the sling was comfortable when inserted under the subject.

Several issues can be improved to advance Growing Sling. The payload of Growing Sling, which is 75 kg currently, needs to be increased to be applicable to more patients with heavier weight. Also, more detailed modeling of Growing Sling including the force in elongation direction of the Growing Sling will be further studied in the future. The force elongating Growing Sling is related to the shape and stiffness of the body part located above the sling. The height of Growing Sling, which is currently restricted around 80 mm, needs to be decreased to enhance the comfort and safety of patients. Growing Sling can be improved by changing the shape of its cross-section. With a concaved cross-section, the falling of the patient can be prevented. Finally, control options such as growth orientation control for the non-flat surface like insertion under the patient on a wheelchair can be added for more utility.

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