2014 IEEE International Conference on Robotics & Automation (ICRA)
Hong Kong Convention and Exhibition Center
May 31 - June 7, 2014. Hong Kong, China

Pneumatic Big-hand Gripper with Slip-in Tip Aimed for the Transfer Support of the Human Body

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***Abstract*—This paper proposes a pneumatic gripper that allows gripping of the human body aimed for the transfer support, whether the body is lying down or leaning against the back support on the chair. To grip the body safely and comfortably under any conditions, two functions are newly introduced. One of them is "shape adaptive joints" which enable every gripping force to be equally distributed at each contact point regardless of body shape. The other is "slip in tip" which helps to reduce both the risk of injury and the uncomfortable friction between the body and the gripper, realized by a new pneumatic actuator to draw out the inner chambers without rubbing against the contact surface. It allows to bend following to the body shape and can also retract the chamber to release the patient safely. The validity of these functions are verified by a developed prototype called "Big-hand", and its effectiveness for the transfer support is experimentally confirmed by lifting a mannequin and a human being.**

I. Introduction

The number of people over the age of 60 is increasing all around the world. This phenomenon is even dire when it comes to Japan. The increasing number of old people leads to increase in demand of caregiver. Among the entire task carried out by caregiver, human body lifting task is the most physically challenged. This task can be transferring a person from a place to the next one which can take place either in bed room, living room, bathroom or toilet. Due to the physical requirement of the task itself, caregivers are prone to inflict injury onto themselves as human being tends to exert more force when they are dealing with delicate objects. Therefore, a human body lifting system is needed in this situation to reduce the burden of caregiver. Current research on human body lifting system can be separated into two major groups which are power suit and stand-alone human transfer unit device. The power suit type normally could be used by caregiver or the old people and their purpose is to boost the user strength. One of good examples for this kind of system is HAL which was developed by Tsukuba University[1]. The problem with this kind of system is the need for wearing and taking off takes time and the system might obstruct some of the daily activity movement while it is being worn. For better freedom in doing daily simple task, the later system is much preferred choice as the system will not get in the way of users.

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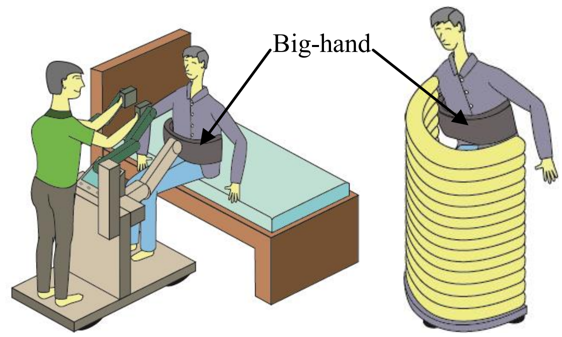

Figure 1. Big-hand concept application

There are several different types of standalone human transfer system devices being developed up to now. RIBA is one of the human lifting robots that has been developed to help caregiver transferring patient [2,3,4]. The problem with this robot is that it needs to be operated by a third person and the old people hardly can operate the robot themselves. Besides, this robot system can only carry a human being in a certain posture where the both legs of the human are lifted off ground. This would be bad for old people as it eliminate the chance for them to exercise and strengthen their muscle. Toyota has also come up with a patient transferring system called Toyota Care Assist Robot[5]. This robot is a wheel chair type and it can lift a patient from bed directly and being push to the desired destination. The problem with this device is that the patient must be pushed by caregiver and it could not lift the patient when it is lying against something on their back. There are also some other human lifting apparatus where some are operated fully mechanical and some with simple electrical motor control[6~9]. These apparatus are designed specifically for big facilities like hospital. As this apparatus may help in reducing the required number of people when a patient is being transfer, the time taken to prepare a patient for transferring is longer than manual transfer due to the need of a special strap and jacket to be worn on the patient first. Some nurses or caregiver would opt not to use this device and prefer to transfer patient manually due to the time consuming procedure. Among all the apparatus and devices, the main issue is still the connection between the human being and the apparatus. A quick connection system would be highly desirable and it would promote the use of supporting device in caregiver industry. In this paper, a human body gripper that allows quick connection between the apparatus and human body is being proposed.

The gripper for this quick connection between the human body and transferring device is called Big-hand. This Big-hand gripper has two main components. First component is

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the shape adaptive joint which it allows the gripper to conform to the shape of the human body when gripping occurs. To allow gripping under any condition, the second slip-in tip comes into play as it enables the gripper to slip its tip in between the human body and the surface the body is lying against. The detail of this gripper design will be discussed in this paper. This proposed gripper will be used in a human body supporting system where it has three different operating modes. The system can be operated by a care giver onsite or the old person can operate the system on their own as shown in Figure 1. The system can be made into remote control where the caregiver controls the supporting system through telecommunication networking.

The contents that will be discussed in this paper are separated into four major sections. First of all, the concept of Big-hand will be discussed. Then it will follow by the Big-hand shape adaptive joint. Slip-in tip operating principle will be discussed in the following section and finally the fabrication and experiment of the Big-hand will be discussed in the final section.

II. BIG-HAND GRIPPER

Big-hand gripper is designed to grip onto human body allowing transfer apparatus or supporting system to manipulate the human body. There are a few number of gripper out there but most of the grippers are gripping object having all the force concentrated on two points. Soft robot gripper developed by Harvard University[10] is able to handle delicate objects without deforming it but the gripper is not able to grip and lift up an actual human. Besides, the gripper is lifting its object using mainly frictional force between the gripper and the object it is manipulating. In terms of even force distribution, the gripper developed by Hirose Laboratory from Tokyo Institute of Technology is able to do so[11]. The gripper is form from multiple linkages and gripping action is done with curling action. If the human is leaning towards something at their back, the gripper could not grip the object in that situation. Besides, the relative torque between the joints in the gripper is fixed and could not be change as all of the joints are connected with the same wire. The proposed Big-hand gripper is able to grip a human body under any situation regardless of the spacing behind the back of the body.

The design for Big-hand is shown in Figure 2. In this Big-hand design, all actuator are powered using pneumatic pressure with aluminum frame for structural support. The whole gripper has 4 different groups of and they are gripping joint chamber, release chamber, slip-in tip and tip retraction chamber embedded within the slip-in tip. First of all, the aluminum frame and hinges provide structural support to the whole system. Each and every four chamber in Big-hand drives different action. Gripping joint chamber provides gripping force action. Using pneumatic as a power source, it allows a switching of torque control to allow grasping feature switch from shape adaptive gripping and slip in push. The slip-in chamber drives the slip-in motion of the tip and the retraction chamber drives the retraction action of the tip. Lastly, the release chamber will force the gripper to open when the chamber is being pressurized.

For the grasping sequence, initially the slip-in tip is hidden within the in Figure 3(i). While the tip stays within the gripper, the gripper enters a body trailing mode where the tip of the gripper trail against the body from the side to the back as shown in Figure 3(ii). Having the slip-in tip kept within the gripper, the gripper grips a human body without the tip extending out as shown in Figure 3(iii). This kind of gripping does not require slip in as it does not extend to the back of the human body. The

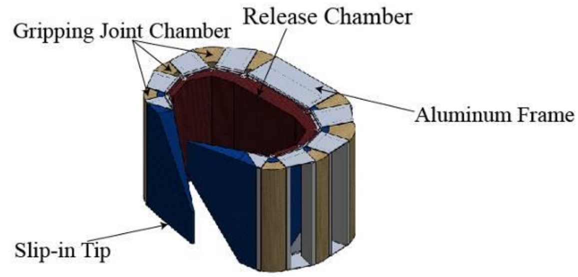


Figure 2. Big-hand gripper design

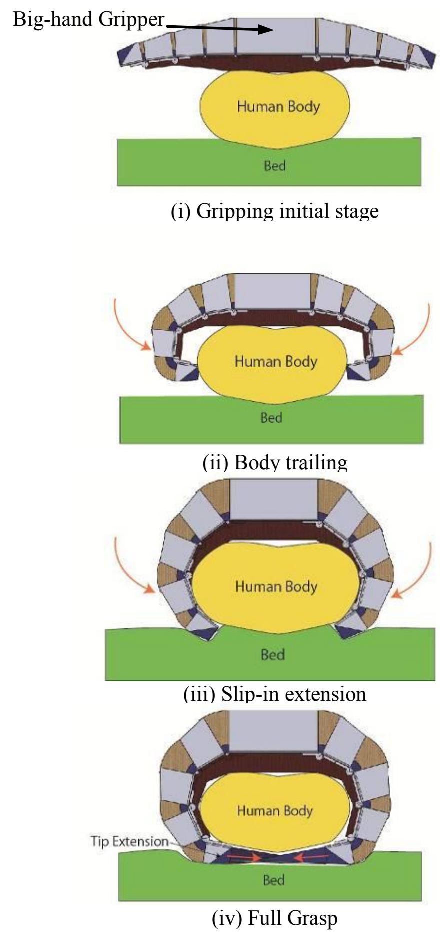


Figure 3. Big-hand gripping sequence

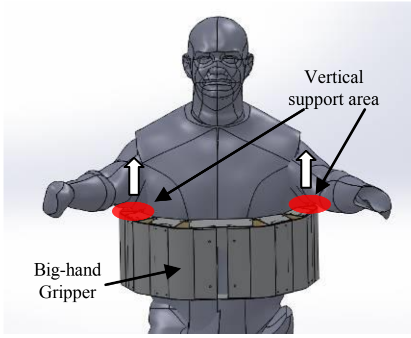


Figure 4. Vertical gripping support

required torque to complete this gripping action is also low and can be done using very low pressure. The human body still could not be lifted at this point as there is no support at the back of the body. The gripper will then extend its tip to provide its support to the back of the human body as shown in Figure 3(iv). Once the gripper tip is fully extended, lifting of the human body can be done without causing much problem as the main upward force is transferred through the tip of the gripper.

When grasping the patient while they are lying down, the lifting action is mainly comes from the tip of the gripper. As the patient body is oriented vertically, the main support does not come from the grasping force. Instead, main support comes from the aluminum structure of the gripper. The gripper is grasping the patient chest where there are organs under it and applying too much force would be not desirable. As shown in Figure 4, the aluminum structure of the gripper will support the patient armpit in the vertical orientation. Gripping force is used for ensuring the patient does not detach off the gripper where it will be very small.

III. Shape Adaptive Joint

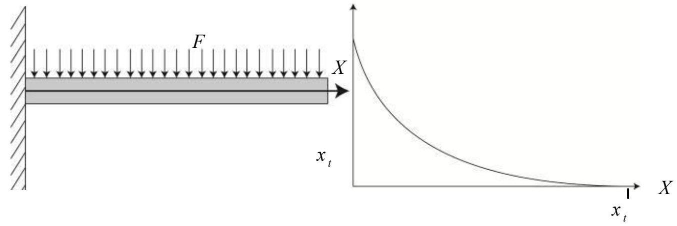
Normal gripper will grip onto an object with all the force focusing on two points. If this were to happen onto human, the person being gripped by the gripper will experience a great deal of discomfort. Even force distribution must be achieved to provide higher level of comfort when gripping.

From Figure 5(a), if a cantilever beam sustaining an evenly distributed force throughout the beam, the internal moment will follow a parabolic curve. This parabolic reduction is found from double integration of a constant force. Therefore, the torque generated in the gripper joint must follow the torque profile shown in Figure 5(b). To find the thickness for each of the joint in Big-hand, the equation for the thickness calculation starts from equation (1) below.

$$\frac{d^2\tau(x)}{dx^2} = F(x) \tag{1}$$

With the condition of differentiation of torque and torque at the tip of the gripper equals to zero, the derived equation for torque is shown in equation (2). As the gripping force is the same, $F(x)$ for every location within x is equals to f and L is the

τ



(a) Cantilever even force model (b) Required torque profile

Figure 5. Even force distribution torque requirement

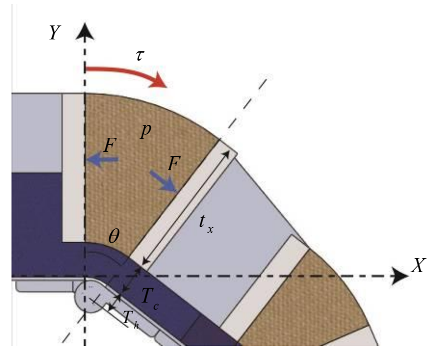


Figure 6. Joint torque model

total length of the gripper measuring from the base which is defined by the designer.

$$\tau(x) = \frac{fL^2}{2}\left(\frac{x}{L}-1\right)^2 \tag{2}$$

Equation (2) only allows the calculation of the torque at each joint provided the desired output force, f, and also the length of the gripper, L, is known in first place. Joint torque for Big-hand is generated using air-bladder fixed in onto the joint as shown in Figure 6. When the bladder is being pressurized, expansion of the air bladder will create a pushing force towards the plate on the adjacent linkages which will then turn into torque. As shown in equation (3), the output force from the air bladder normal to the linkage plate is equals to pressure times the area.

$$F = pA \tag{3}$$

Assuming that the force output on the plate is uniform, the total output force can be replaced with a single point force situated at the middle of the plate. Using this point force, the output torque equation for this joint is shown in equation (4).

$$\tau = p\big(t(x)w\big)\left(\frac{t(x)}{2}+T_c+T_h\right) \tag{4}$$

The T_c in equation (4) is the clearance thickness for the slip-in tip chamber and the T_h is the distance between the hinge rotation axis and the linkage base. Both of this parameter is fixed by the designer. The w in equation (4) is the width of the gripper. Combining equation (2) and equation (4) the relationship between the required torque and the joint thickness and be formed. Supplied pressure, p, force output from gripper, f, and the width of the gripper, w, is eliminated and the equation to calculate the joint thickness is shown in equation (5). From the equation, the designer need to decide on the length of the gripper and also the first joint thickness, t_0, in the first place. The rest of the joint thickness can be found using equation (5) using numerical calculation.

$$t(x)\left(\frac{t(x)}{2}+T_c+T_h\right)=2\frac{t_0}{L^2}\left(\frac{t_0}{2}+T_c+T_h\right)\left(\frac{x^2}{2}-Lx+\frac{L^2}{2}\right) \quad (5)$$

IV. SLIP-IN TIP

Having a gripper tip to slip under a person body is very crucial to provide a full enclosure gripping. Without the tip of the gripper slipped under the body, the gripper can only lift a person only relying of the gripping friction when that person is lying horizontally. If the tip of the gripper is being forced under the patient, the force that is required is very large as it needs to overcome the friction between the gripper tip with the bed, $F_n\mu_n$, and patient body, $F_b\sin\Theta + F_b\cos\Theta\mu_b$. Figure 7 shows the model of the tip slipping under a human body.

$$F_h = F_b \sin\theta + F_b \cos\theta\mu_b + F_n\mu_n + Ma \quad (6)$$

Deriving from Figure 7 model, the horizontal force required to push in the gripper tip can be shown in equation (6) with Ma as the final gripper tip movement. The force from the body and also the bed is increasing as the gripper is being pushed in due to the displacement caused by the gripper tip thickness.

To reduce this slip in resistance, a roll in method is preferred. The main characteristic of roll in method is that the contact surface of the gripper tip is always in static condition with relative to the surface of the human body and bed. When the point position on the tip surface is not moving with relative to the contact surface, the friction force is at minimal. C-Pam bed to bed transfer system[12] and Panasonic Power Motion Assist[13] is using this concept to reduce the slip in friction. These two design are using electrical motor to power the motor that drives the belt when slip in is being done. If this method is being used at the tip of the gripper slip-in motion, the size of the tip will become very large due to the need to accommodate gears and motor and also weight is also an issue. Moreover, the system require precise rolling rate so that it does not create any unnecessary friction onto the person body.

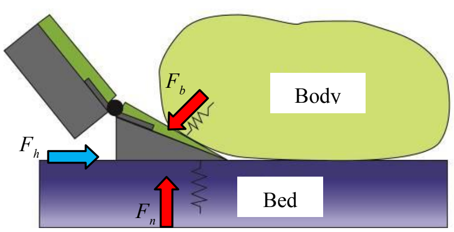
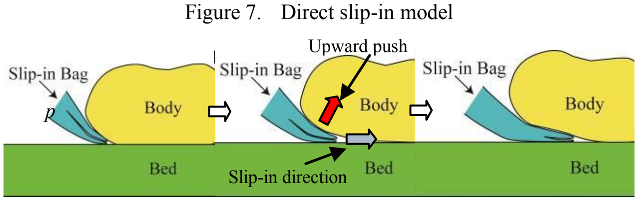


Figure 7. Direct slip-in model



(a) Initial state (b) Slip-in in process (c) Final state

Figure 8. Air bag slip-in process

A. Inverse pneumatic air bag slip-in tip

Roll in method using electrical motor is impossible without sacrificing the design size and weight. Using pneumatic method, the weight and size problem can be solved easily. As shown in Figure 8(a), having a sealed bag with one side of it being inversely inserted back into the bag, the initial size of the bag will be half of its original length. When air pressure being supplied into the air bag, the air inside the air-bag will try to create as much space as possible thus forcing the inversely inserted side of the bag to expand out. In Figure 8, as the inversed side is slipped under the human body, the only place it could expand is under the human body. Once all the empty space is being occupied by the bag, the pressure in the bag will slowly increases and will then push the human body upward which then create more space for the bag to expand in front. Figure 8(b) illustrate on the direction of expansion and also the pushing force of the air bag. This sequence will keep on repeat itself until all the inverse portion is fully drawn out which is shown in Figure 8(c) below.

This airbag slip in principle is proposed to be used on the tip of Big-hand gripper. The arrangement of the bag is shown in Figure 9. Before gripping is carried out, gripper tip air bag is slip into the gripper. When pressure supplied to the slip-in tip chamber, the tip will extend itself out under the human body. The work done by this slip-in tip can be calculated using equation (7). Work of a pneumatic air-bag can be represented by pressure, p, times the change of volume, ΔV. There is a string connecting to the tip of the gripper used for retraction purpose and it will cause some frictional force when slip in occurs. This frictional force is represented with $T_r\Delta d_t$ in the equation. Lastly, the work for lifting the human body is represented with $F_b\Delta d_b$.

$$p\Delta V = T_r\Delta d_t + F_b\Delta d_b \quad (7)$$

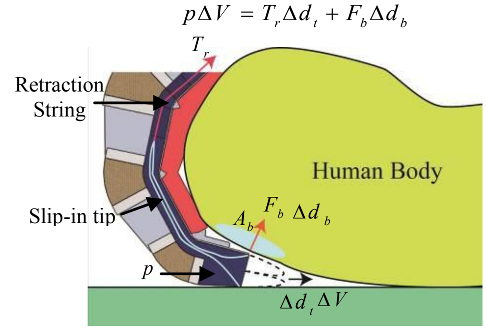


Figure 9. Slip-in tip model

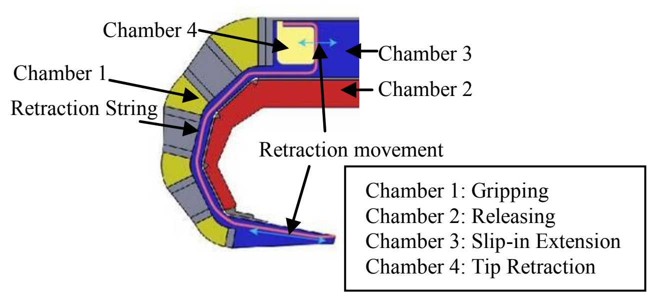


Figure 10. Tip retracting mechanism

The output force of that lift up the patient body, F_b, shown in equation (8) is related to the area of the gripper tip, A_b, shown in Figure 9. This area is increasing as the gripper tip expands. Therefore as the gripper tip expands, the lifting force is increasing as well if the supplied pressure remains constant.

$$F_b = pA_b \tag{8}$$

B. Tip retracting mechanism

Expanding the gripper tip under a human body is an easy job by just pressurizing the air gripper tip air bag. Without a retracting mechanism, the gripper could not retract its tip. Retracting mechanism allows the gripper tip to be extracted out from the gap under the patient body smoothly and allowing the gripper to release the patient.

To make this retracting mechanism, a string is attached to the tip within the airbag and the string is being pulled up to the base of Big-hand. At the base, another air-bag within this extending tip air bag is being attached as shown in Figure 10. By expanding this retraction air-bag, it will create pulling force along the string which will then pull back the tip of the gripper.

The required retraction length for the tip is double the length of the gripper base. Due to this problem the retraction string is loop around the retracretractionon air bag which produces twice the pulling length with the same expansion distance.

V. FABRICATION AND TEST

A. High pressure duty air bag

All the actuators in Big-hand are pneumatic actuated and the components used are not conventional cylinder or pneumatic actuators. The actuators used in Big-hand require specific shape which allows it to behave accordingly. For custom shapes, a custom made bag is required. Polyurethane can be made into desired shape easily using heat. The strength of polyurethane material by itself is not strong enough to withstand high pressure. An air bag made from 0.5mm thick polyurethane is only able to withstand 0.1MPa pressure. The failure of the bag starts from plastic elongation and will lead to rupture in the end. To strengthen the air bag, polyurethane is reinforced with nylon fiber as nylon fiber has high tensile strength.

Nylon fabric can merge with polyurethane sheet under high pressure and heat. Pressing polyurethane sheet against nylon fabric at 200°C for 4 minutes to 5 minutes will have the sheet melted and sip into nylon fabric cavity. Polyurethane coated nylon fabric is then cut and merged into the desired shape. Merging of the edge of the shape is also done at 200°C for 4 minutes to 5 minutes at high pressure. The result from this fabrication method is a high pressure duty air bag. Test has been done on the fabricated bag and it shows that it could sustain up to 0.55MPa without showing any sign of failure. As the application for this design does not require pressure higher than 0.2MPa, the limit of the air bag is not tested.

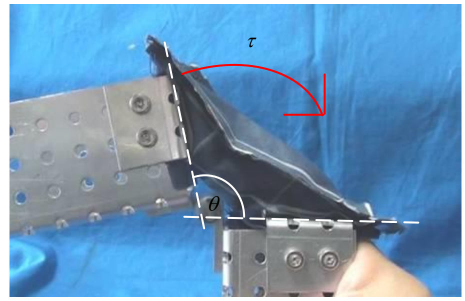


Figure 11. Air bag joint

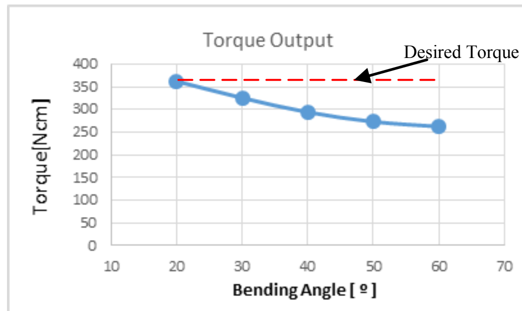


Figure 12. Air bag joint torque output

B. Air bag joint

Air bag for the joint is fabricated using nylon reinforced polyurethane method. For this fabrication, the shape of the air bag must be done at a bending angle larger than the desired bending angle. This is to ensure that the bending torque does not suffer from sudden drop. The fabricated joint is shown in Figure 11. For torque test, the fabricated joint has a plate area of 2250mm^2 and a gap of 25mm from the hinge joint.

Torque of the air bag joint is measured using 0.05MPa pressure and the result is shown in Figure 12. From the graph, it shows that the joint torque drops a little as the bending angle increases. The generated torque is very satisfying and is enough to be implemented in this Big-hand design. But still a constant torque output is still desirable for simple control.

C. Big-hand gripper

A human size Big-hand prototype gripper is being built. The gripper linkage length ratio is following the actual size. A test has been done using the gripper to grip a human body. The test result shows that the gripper can grip the human body following its shape. The result shows that the gripper is able to grip following the shape of the human body which can be seen in Figure 13.

D. Slip-in tip

A slip in tip has been fabricated using the same nylon reinforced polyurethane method. The fabricated slip-in tip is shown in Figure 14. The tip of the bag is slowly reducing in width until it is 5cm at the tip. This is to allow overlapping of both sides gripper at the back of the human body. The slip in tip has two metal plate slip where one is placed on top and another one is at the bottom of the bag. These plates are to ensure that the tip is easily slipped under a human body at initial condition so that body lifting can be carried out to create space for the tip extension.

Using the fabricated tip, test is being done by having this slip-in tip slip under a heavy object weighing 10kg. Pressure less than 0.05MPa is being used in this experiment. The entire slip in process is being captured and shown in Figure 15. From the process it is seen that the tip is able to expand smoothly under the heavy object.

Using the same slip-in gripper tip, test has been done on actual human with various weights from 65kg to 85kg. The test is done with the subject lying against soft bed and hard

Figure 13. Big-hand gripper

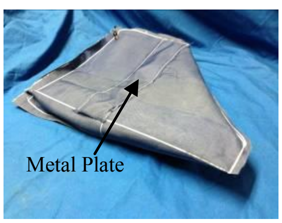


Figure 14. Slip-in gripper tip

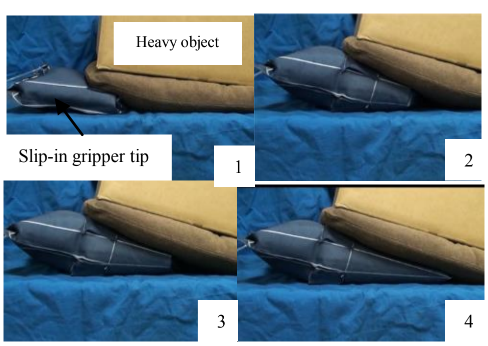


Figure 15. Slip-in sequence

Figure 16. Actual human test

flooring as shown in Figure 16. Various slip-in angles of the gripper tip are also tested. It is found out that regardless of the flooring, slip-in angle and also the weight of the subject, the slip-in action can be carried out with 0.1MPa pressure. A horizontal supporting force is required to prevent the gripper tip from rebound back out and the required force does not exceed 40N at any time of the slip in action. When the gripper tip is fully inflated at 0.1MPa, the stiffness is very high is hardly deformed when external force is being applied to it.

The retracting mechanism air bag within the slip-in gripper tip is being build and is shown in Figure 17. The mechanism consists of an air bag mounted on a rail to ensure expansion is running along a specific direction. String attached to the tip of the gripper is passed through the air bag. This railed air bag is then attached within the gripper tip air bag as shown in Figure 18(a). Pressure supply of the retracting air bag is being done by connecting the tube through tightly sealed tube connector to the outside of the bag as shown in Figure 18(b). The bag is then sealed up to form the gripper tip air bag.

The fabricated slip-in tip with embedded retracting mechanism is being tested and test result is being shown in Figure 19. The figure shows that retracting mechanism is able to pull back the gripper tip without the need of any external force.

D. Gripper Combination with Carrier

A prototype of carrier using the Big-hand is being built. In this carrier, it is able to provide upward push support for

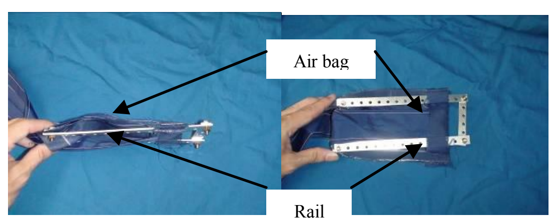
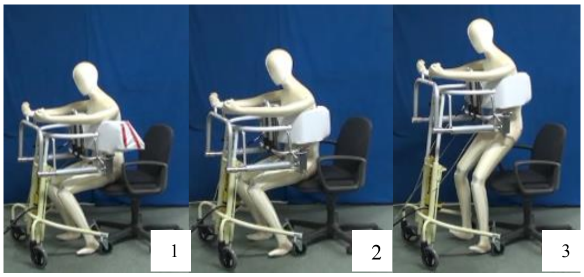


Figure 17. Retracting air bag

(a) Retracting air bag mounting (b) tube connection

Figure 18. Retracting air bag mounting and tubing

Figure 19. Gripper tip retraction test



(a) Mannequin test

(b) Human test

Figure 20. Big-hand with carrier test

standup motion. At the same time, the carrier is able to provide some body posture adjustment. Test has been done on a mannequin showing in Figure 20(a) and actual human test is shown in Figure 20(b).

VI. Discussion and Conclusion

An actual human size gripper without slip-in tip has been fabricated and tested on a mannequin and human being. The test shows that it can grab onto the mannequin perfectly. The proposed slip-in tip in this paper shows that roll in action can be done with a lighter and smaller design using pneumatic power. The concept of the slip in gripper tip with retracting mechanism in it has been tested and it shows that the tip can be carried out perfectly without the need of precise control. This slip in concept can be alter and implemented as a stretcher for slip in sheet under patient or casualties. This stretcher can also be used to extract casualty in rubble under a small gap during search and rescue operation. In the future, an actual adult size Big-hand gripper with the slip-in tip will be fabricated and the torque control system will be focused as well. Balancing of the lifting up motion will be looked into as well in the future.

References

[1] H. Satoh, T. Kawabata, Y. Sankai, "Bathing Care Assistance with Robot Suit HAL" *Proc. 2009 IEEE International Conference on Robotics and Biomimetics*, Guilin, China, pp. 498-503, 2009

[2] T. Mukai, S. Hirano, H. Nakashima, Y. Sakaida, "Realization of Patient-Transfer Tasks Using Nursing-Care Assistant Robot RIBA and Its Safety Measures" *Proc. 2010 JSME Conference on Robotics and Mechatronics*, Asahikawa, Japan, 2010.

[3] T. Mukai, S. Hirano, H. Nakashima, Y. Kato, Y. Sakaida, S. Guo, S. Hosoe, "Development of a Nursing-care Assistant Robot RIBA That Can Lift a Human in Its Arm" *International Conference on Intelligent Robot and Systems*, Taipei, pp. 5996-6001, 2010

[4] T. Mukai, S. Hirano, M. Yoshida, H. Nakashima, S. Guo, Y. Hayakawa, "Tactile-Based Motion Adjustment for the Nursing-Care Assistant Robot RIBA" *IEEE International Conference on Robotics and Automation*, Shanghai, pp. 5435-5441, 2011

[5] Toyota Care Assist Robot, http://www.toyota-global.com/innovation/partner_robot/family_2.html, June 2012

[6] C.L. Wilson "Lifting and Walking Jacket" U.S. Patent 3252704, May 24, 1966.

[7] J.P. Bakker "Patient Lifting Apparatus" U.S. Patent 3694829, Oct 3, 1972.

[8] J.B. Murray "Patient Lifting Device" U.S. Patent 4202063, May 13, 1980

[9] T.J. Lucas "Patient Lifting Apparatus" International Patent WO 2011/151639, Dec 8, 2011.

[10] F. Ilievski, A.D. Mazzeo, R. F. Shepherd, X. Chen, G.M. Whitesides, "Soft Robotics for Chemists" *Angew. Chem. Int. Ed.* Vol. 50, pp. 1890-1895, 2011.

[11] S. Hirose, Y. Umetani, "The Development of Soft Gripper for the Versatile Robot Hand" *Mechanism and Machine Theory Journal*, Vol 13, pp. 351-359, 1978

[12] H. Wang, F. Kasagami, "A Patient Transfer Apparatus between Bed and Stretcher" *IEEE Trans. Systems, Man, and Cybernetic-Part B: Cybernetics*, Vol. 38, pp.60-67, February 2008.