International Journal of Control, Automation and Systems 15(1) (2017) 36-44
http://dx.doi.org/10.1007/s12555-016-0477-9
ISSN:1598-6446 eISSN:2005-4092
http://www.springer.com/12555

Development of a Transformable Wheel Actuated by Soft Pneumatic Actuators

Sung-Sik Yun, Jun-Young Lee, Gwang-Pil Jung, and Kyu-Jin Cho*

Abstract: Small mobile robots with transformable wheels have recently emerged thanks to their increased mobility and maneuverability. When a high payload is applied to these robots, however, wheel transformation becomes difficult because they must directly overcome the payload's weight. In this paper, we propose a wheel that can be transformed from its starting circular shape (radius, 56 mm) to a wheel with three legs (radius, 99 mm) under a high payload with low operating force. The key design principle of this wheel is to kinematically decoupled legs and passive locking. Its legs are kinematically decoupled but operated by a single air pump using a pneumatic channel connected to soft pneumatic actuators installed at each leg. Application of pressure causes the legs to behave like a coupled system through the pneumatic channel. With pressurization, the two legs that are not in contact with the ground easily emerge from body, and the leg in contact with the ground emerges once the wheel rotates. Once emerged, each leg is supported by a rigid pawl instead of by the soft pneumatic actuators. This setup enables the legs to be transformed independently with low air pressure, even under high payloads. It reduces system weight and the energy required to maintain the transformed shape. This legged wheel can overcome obstacles up to 2.9 times the radius of the wheel in its circular form, and wheel transformation can be accomplished with 85 kPa air pressure for payloads up to 1115 g.

Keywords: Soft actuators, soft pneumatic actuators, transformable wheel.

1. INTRODUCTION

Small mobile robots have been widely used to reach places that are difficult for humans to access, such as dangerous, narrow, or hidden areas. Their small size, however, limits their mobility and maneuverability in rough terrain. To solve this issue, several researchers have proposed small mobile robots with legged wheels that help them to overcome obstacles.

Whegs [1] and Mini-Whegs [2] have three biologically inspired wheel spokes that allow them to climb a rectangular obstacle 1.5 times larger than the wheel's radius. RHex also has a biologically inspired semicircular leg [3]. By simply rotating six legs with open-loop control, RHex can easily maneuver rough terrain, but its wheels are not as efficient as circular wheels when moving on flat surfaces. The Epi.q-1 wheel has three legs, each of which have a small wheel at their end, and the leg lengths change according to terrain, which may improve efficiency [4].

Mobile robots with legged wheels overcome obstacles much better than normal round wheels. They are, though, inefficient on flat ground since their center of mass oscillates vertically. To resolve this problem, the concept of transformable wheels has emerged. AZIMUT has legs that can work like those of a caterpillar, and it can use a leg as a circular wheel by controlling its angle, allowing the robot to overcome obstacles by using various types of locomotion [5]. IMPASS has a wheel with three legs whose length can be controlled to suit the terrain [6]. Some robots have a wheel at the end of multi joint legs and can move by rolling their wheels or by walking their legs, a form of locomotion termed roller-walking [7–9]. One class of wheeled robots can transform its wheel to a shape that allows the robot to overcome obstacles. The rolling disk biped (RDB) robot rolls as a cylinder on flat surfaces and changes to a long snake-like shape to overcome obstacles [10]. The Retractable Wheel-Leg Module is also cylindrical on flat surfaces but can be unfolded to have multi-joint legs [11] that permit it to overcome obstacles. The Wheel Transformer has three coupled legs on its wheel [12, 13]. When the triggering leg is operated by friction between the leg and a wall, the other two legs open

Manuscript received August 1, 2016; revised October 28, 2016; accepted October 29, 2016. Recommended by Guest Editor Sungwan Kim. This work was supported by the Technology Innovation Program (10051287, Development of fundamental technology of soft robotics for advanced soft gripper) funded by the Ministry of Trade, Industry & Energy (MOTIE, Korea). This work was supported by the National Research Foundation of Korea(NRF) Grant funded by the Korean Government(MSIP)(No.NRF-2016R1A5A1938472).

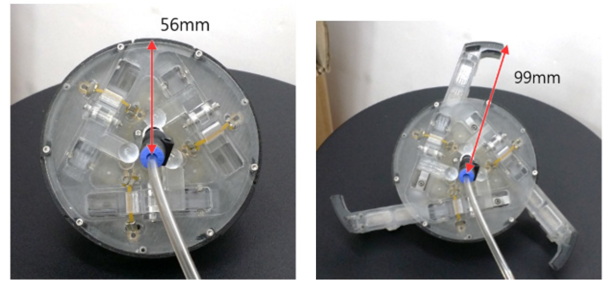
Sung-Sik Yun, Jun-Young Lee, Gwang-Pil Jung, and Kyu-Jin Cho are with the Department of Mechanical and Aerospace Engineering/SNU-IAMD, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 151-742, Korea (e-mails: {yss1215, ljy.onefineday, ceaser97, kj cho}@snu.ac.kr).
* Corresponding author.

and the whole system assumes a legged-wheel shape. After the robot passes the obstacle, the legs close automatically, and the whole system returns to a round shape. Finally, certain transformable robots have origami-based wheels [14, 15]. These wheels are made of soft materials (e.g., film and fabric) that have been patterned to allow them to fold into a variety of shapes. Wheel size is increased or decreased by applying force to the wheel in one direction or the other.

These wheeled robots have shown great performance on both flat ground and rough terrain, but their performance declines when a large payload is applied, making transformation difficult. Several studies have been performed to solve this payload issue. She et al. proposed a transformable wheel that has four active legs and one passive leg [16], all of them coupled. If the passive leg is in contact with the ground when transformation begins, the active legs open and rotate the wheel, without lifting the body, until the passive leg can be opened. One advantage of this robot is that it can transform its wheel with a small amount of force, even if a payload is applied. The Quattroped robot has a donut-shaped wheel that can be transformed to a wheel-leg by being folded [17, 18]. Following transformation, the wheel-leg is locked into place with a small DC motor, and thereafter no additional energy is needed to maintain the leg mode. PEOPLER-II has four wheels on which additional legs are installed [19]. To minimize total energy loss, the robot is controlled such that the payload is distributed.

In this paper, we suggest a transformable wheel that can be easily transformed under a high payload condition and even while the robot is moving. Its key design principles are kinematically decoupled legs and a passive locking mechanism. Most existing transformable wheels use kinematically coupled mechanisms to reduce both the number of degrees of freedom and the number of actuators required, enabling simple and energy-efficient structures. When a high payload is applied to such wheels, however, much torque is required to transform the wheel since the payload weight must be directly overcome. To solve this issue, the legs of proposed wheel are kinematically decoupled but operated by a single air pump using a pneumatic channel. The pneumatic channel has three soft pneumatic actuators installed at each of three legs. When pressure is applied, these legs are "half" coupled through the pneumatic channel, enabling them to transform independently with low air pressure, even under high payload. Once extended, each leg is supported by a rigid pawl instead of by the soft pneumatic actuators. This locking mechanism maintains the transformed shape without assistance from the air pump, which minimizes energy consumption.

In its initial state the wheel is circular and has a radius of 56 mm. Following transformation to the legged shape, its radius is 99 mm (Fig. 1). The wheel can climb an obstacle up to 163 mm high, which is 2.9 times the radius



(a) (b)

Fig. 1. The two modes of the transformable wheel. (a) Circular mode. (b) Legged mode.

of the wheel in its circular mode. The wheel can be transformed with equal air pressure of 85 kPa for payloads up to 1115 g.

In the following sections, The design and behavior of this transformable wheel and its soft pneumatic actuators will be introduced. Then we will model and analyze the wheel in its legged mode and the soft pneumatic actuators. Finally, we will experimentally evaluate wheel performance and conclude with a discussion of the findings and future design changes.

2. DESIGN

2.1. Design of transformable wheel

The wheel has three straight legs, each of which can freely move through a linear guide of 65 mm length. The tip of each leg is bent to allow it to hang onto obstacles. The three legs are positioned on the wheel body to form an equilateral triangle, to maximize radius change of wheel when it is transformed from the circular to the legged mode. Each leg is connected to the body of the wheel by a rubber band. When the leg is emerged from body, the rubber band pulls the leg toward the center of the wheel. The initial length of the rubber bands was carefully designed to ensure suitable compressive force when the wheel is fully transformed to legged mode. The rubber bands are installed with pulleys to ensure a suitable initial length and compact use of space in the wheel (Fig. 2[a, b]). At the distal end of each leg, a soft pneumatic actuator pushes the leg to transform the wheel from circular mode to legged mode (Fig. 2[c]). When the leg retracts into the body of the wheel, the wheel returns to a perfectly round shape and behaves like a normal round wheel. The outer edge of the wheel is covered with rubber to increase grip force.

2.2. Design of soft pneumatic actuator

The soft pneumatic actuator is made with a cylindrical latex balloon. Both ends of the balloon are sealed with plastic plugs, one of which connects to an air hose via a hole. The balloon is wrapped in a cylinder of fabric that

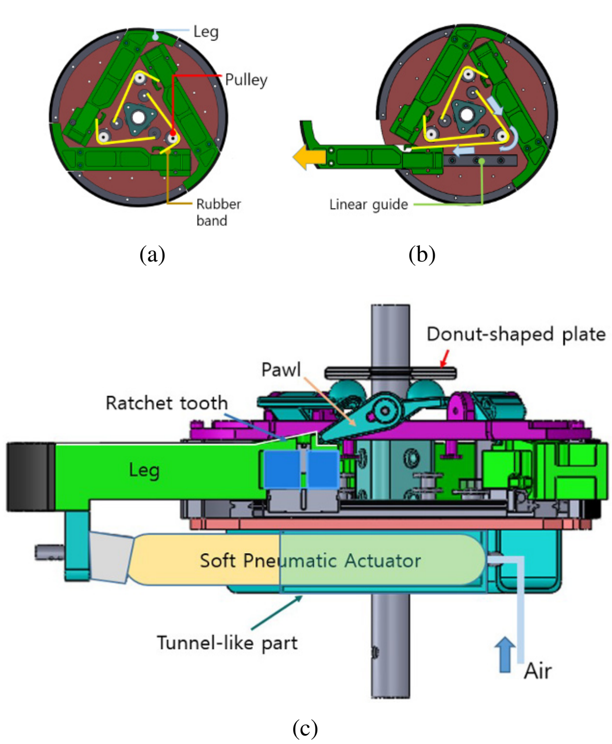


Fig. 2. Cross-sectional diagram and components of the transformable wheel. (a) Path of the rubber band in the circular mode. (b) Path of the rubber band in the legged mode. (c) Overall placement of components.

is more than twice the length of the balloon (Fig. 3). This fabric serves two purposes: (1) it limits expansion of the balloon to prevent it from exploding when inflated to high pressure, and (2) it allows the balloon to function as a linear actuator because it only allows longitudinal expansion. When air pressure is applied to the balloon, the soft actuator elongates and applies force to the one end of the leg, causing the wheel to transform to legged mode. To prevent buckling of the pneumatic actuator during elongation, one end of the actuator is covered with a three-dimensionally (3D) printed tunnel-like part. This soft actuator can stretch more than twice its initial length. It shortens itself via elastic force originating from its material properties. Therefore, the wheel does not need additional components to be transformed from legged mode to circular mode.

2.3. Design of the locking and releasing mechanism

Fig. 2(c) shows the ratchet tooth at one end of the leg. The ratchet tooth on the leg is held by the pawl, which is held in place by an elastic band attached to it (Fig. 4[c]). This mechanism ensures that the legs are automatically locked when the wheel is transformed to legged mode. To transform the wheel from legged mode to circular mode, the locked pawls must be released as the leg rotates. To accomplish this with a single actuator, a donut-shaped plate attached to the wheel's axis sequentially releases the pawls (Fig. 5). The following section explains how this mechanism works.

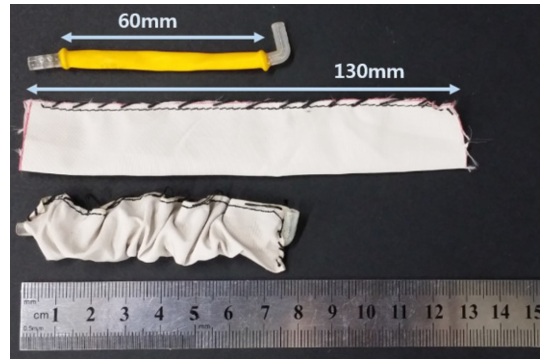


Fig. 3. Soft pneumatic actuator. From top to bottom: Cylindrical balloon sealed with plugs, expansion-limiting fabric, and assembled soft pneumatic actuator.

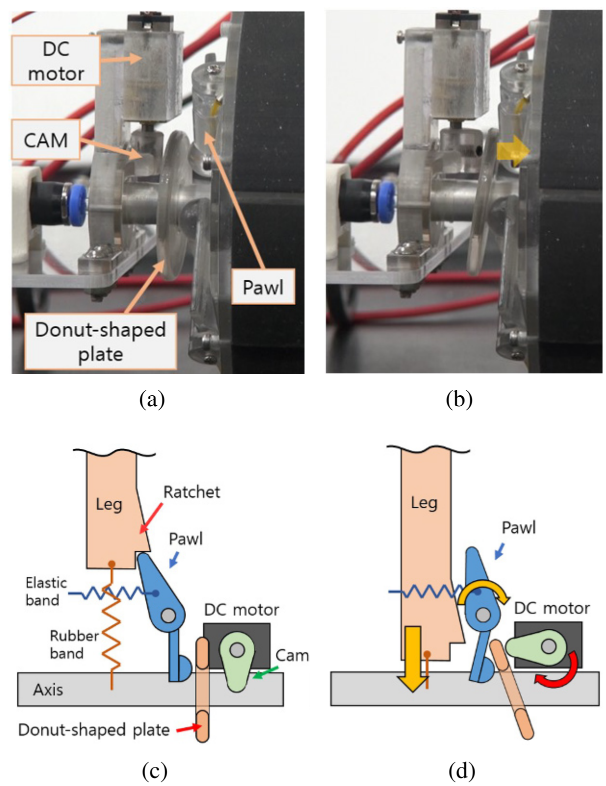


Fig. 4. The leg-releasing mechanism. (a) The cam is at 0°. (b) The cam moves to 90° to release and return the legs. (c) Schematic diagram of the releasing mechanism when the wheel is in the legged mode. (d) Schematic diagram of the releasing mechanism when the wheel transforms to the circular mode.

Releasing the leg in contact with the ground requires a

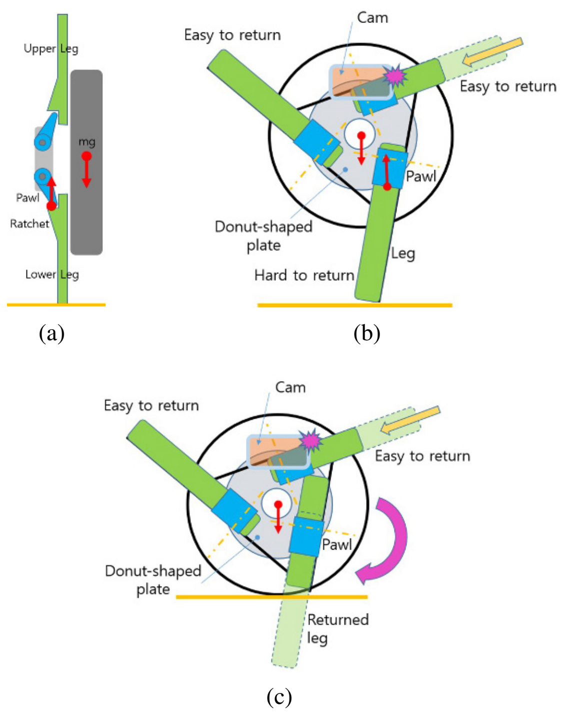


Fig. 5. Releasing process of the wheel. (a) The whole weight of the robot has been transferred to the ratchet tooth and pawl of the lower leg. (b) The cam pushes the donut-shaped plate to release the pawl. (c) The legs are sequentially returned, and the wheel is transformed from legged mode to circular mode while the wheel is rotating.

large amount of force, because a normal force increases surface friction between the pawl and the ratchet. Therefore, releasing all three pawls simultaneously would require a large amount of force. This issue is avoided by sequentially releasing the pawls with a tiny DC motor.

2.4. How the wheel transforms

Air pressure applied to the three soft pneumatic actuators causes the legs to emerge from the wheel, but not simultaneously. Initially, with the wheel standing on its edge, only the two legs that are pointed away from the ground emerge and lock into place. The leg that is in contact with the ground cannot emerge because it is bearing the weight of the wheel and so requires more air pressure than the other two legs to emerge. However, as the wheel rotates, the third leg is moved away from contact with the ground, at which point it emerges and locks into place.

In the releasing mechanism, the small DC motor rotates the cam from 0° to 90°. The rotating angle of the cam is structurally limited. To move the legs into the body, the cam rotates to push on the donut-shaped releasing plate, as shown in Fig. 4(a) and (b). As the wheel rotates, the tilted donut-shaped plate sequentially pushes the base of each pawl, releasing the pawl from the ratchet (Fig. 4[c] and [d]). When this happens, the leg that was formerly locked in the emerged position returns into the body by the elastic force of the rubber band attached to the leg. The entire transformation process is depicted in Fig. 6.

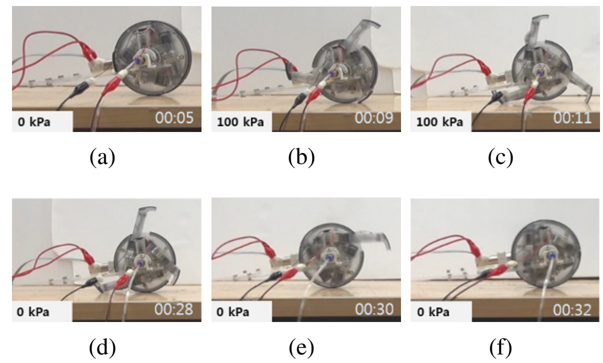


Fig. 6. Locking and releasing processes. (a) Circular mode. (b) Applying air pressure to the soft pneumatic actuators. (c) Transformation to legged mode: The legs have emerged from the body and locked. (d) Rotation of the cam in the releasing mechanism to 90°. (e) Wheel rotation while the cam is at 90°. (f) Transformation of the wheel to circular mode.

3. WHEEL GEOMETRY ANALYSIS

3.1. Maximum accessible height and hook angle

The hooked shape of the legs is designed to allow the wheel to climb large obstacles. To do this, the wheel's leg must hook the upper side of the obstacle. To maximize the height of the obstacle that the wheel can overcome, the wheel's geometry, including the angle of the leg, needs to be analyzed. Fig. 7 shows the geometry of the transformed wheel at any angle θ. The radius of the wheel body, R, is 56 mm, and the length of the emerged leg, L, is 50 mm, which is determined by the size of the linear guide. The timing of the point when the wheel's upper leg first touches the obstacle may be analyzed as follows:

$$W_1 = R\cos\alpha + L\cos\theta = R\cos(30^\circ + \theta) + L\cos\theta, \quad (1)$$

$$W_2 = R\sin\beta - L\sin\gamma = R\sin\theta + L\sin(\theta - 30^\circ), \quad (2)$$

where W_1 is the projected length of the upper leg in the x axis, W_2 is the projected length of the lower leg in the x axis, $\alpha = 30^\circ + \theta$, $\beta = \theta$, and $\gamma = \theta - 30^\circ$.

The upper leg cannot reach the top of the obstacle if W_2 is larger than W_1 or if the wheel body is protruded more than the upper leg in the x axis. In other words, the upper leg can reach the top of the obstacle when W_1 is larger than both W_2 and R (Fig. 8). To analyze this condition,

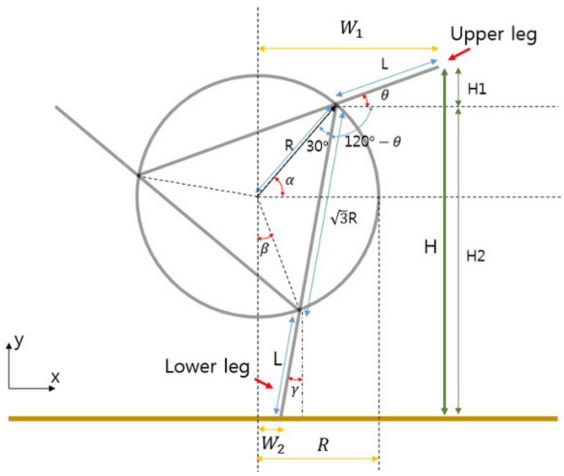
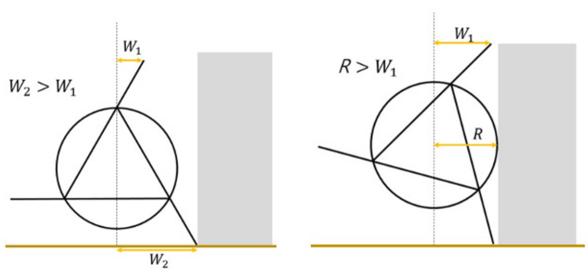


Fig. 7. Geometric diagram of the legged mode.



(a) (b)

Fig. 8. Examples of hooking failure. (a) W_2 is larger than W_1. (b) R is larger than W_1.

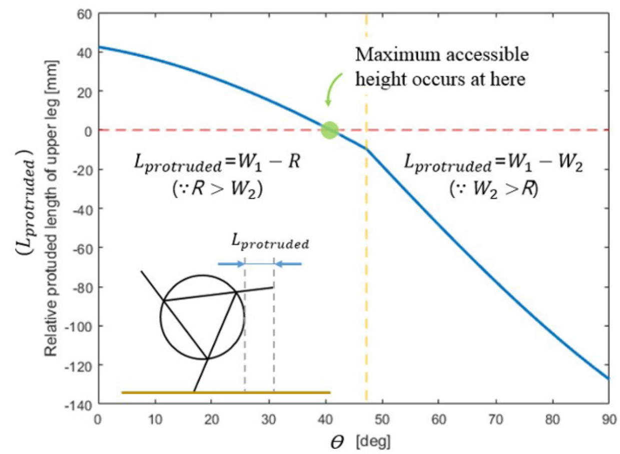


Fig. 9. Relative length of the protruded upper leg in the x axis in relation to the lower leg and the wheel body according to θ. When W_2 is larger than R, the relative protruded length is $(W_1 - W_2)$. Otherwise, the length is $(W_1 - R)$.

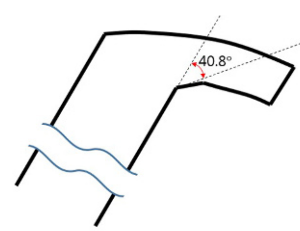


Fig. 10. The hook of the leg and the corresponding hook angle.

the relation between the relative protruded length and the tilted angle of the upper leg, θ, is calculated in Fig. 9. This value is positive when θ is $0^\circ \sim 40.8^\circ$ and becomes 0 at 40.8°.

The maximum accessible height for the wheel is given by calculating the height of the upper leg tip when θ is 40.8°. H_1, H_2, and total height, H, of the wheel at any angle is obtained as follows:

$$H_1 = L\sin\theta, \tag{3}$$

$$H_2 = (L+\sqrt{3}R)\sin(120^\circ - \theta), \tag{4}$$

$$H = (L+\sqrt{3}R)\sin(120^\circ - \theta) + L\sin\theta. \tag{5}$$

According to the result, the maximum accessible height is 177.1 mm when θ is 40.8°. To climb an obstacle when θ is 40.8°, the angle between the leg and its hook must be larger than 40.8° to prevent slippage (Fig. 10).

4. SOFT PNEUMATIC ACTUAOR ANALYSIS

4.1. Minimum required pressure of the soft pneumatic actuator

Legs of the transformable wheel is controlled by soft pneumatic actuator. Therefore, information about operating pressure is necessary. Since the legs are on-off controlled, pressure does not have to be larger than minimal required pressure to completely emerge the leg. We conducted theoretical analysis to find out minimal required air pressure value.

The relationship between the actuating force and inner pressure of the pneumatic actuator is represented as follows:

$$F = PA, \tag{6}$$

where F is force, A is cross-section area, and P is pressure.

Force F is determined by mechanical condition of leg and elastic force of extended rubber band. We pulled its leg with experiment equipment connected with load cell (333FB Cell, Ktoyo Co., Ltd., Korea) until it is completely locked not using air, and measured required force during this whole process. Maximum measured force during this measurement was 2.85 N. It means that the minimal required force (F_{required}) of soft pneumatic actuator is 2.85 N to completely transform wheel to legged mode. Minimal required air pressure (P_{required}) is calculated as follows:

$$P_{\text{required}} = \frac{F_{\text{required}}}{A} = \frac{2.85}{A} \tag{7}$$

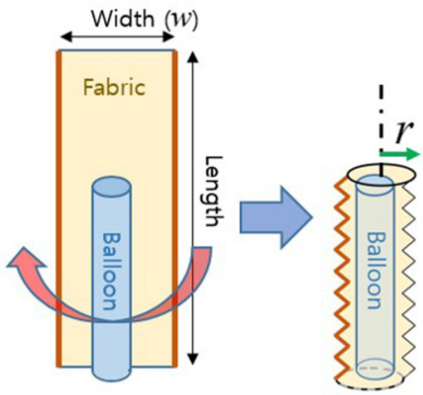


Fig. 11. Geometries of fabric cylinder of soft pneumatic actuator.

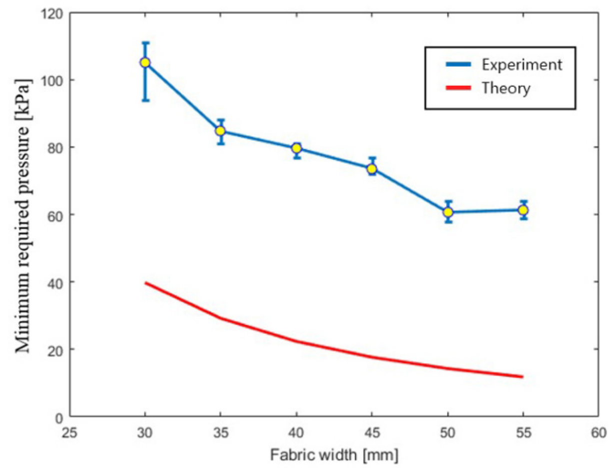


Fig. 12. Comparison of minimum required pressure between theoretical analysis and experiment.

where the units of P_{required} and A are Pa and N, respectively.

Since making fabric cylinder with certain cross-section area is complicate, width of flat fabric (w) is used as a standard (Fig. 11). Required pressure can be expressed as width of fabric as follows:

$$w = 2\pi r, \quad A = r^2\pi,$$

$$\therefore \; A = \frac{w^2}{4\pi}, \tag{8}$$

$$P_{\text{required}} = \frac{2.85}{A} = 4\pi\frac{2.85}{w^2} \approx \frac{35.8}{w^2}, \tag{9}$$

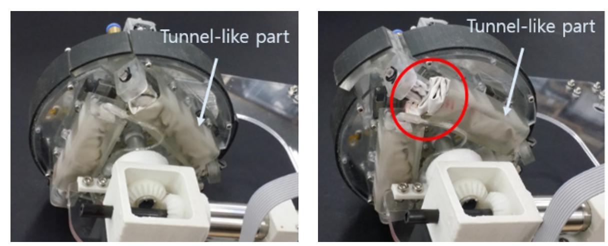
where r is radius of circular fabric cylinder (Fig. 11). Unit of both r and w is m.

However, this result may be discordant with real result because effect of buckling is not considered at this analysis. To compare theoretical analysis and real result, we built soft pneumatic actuators with fabric cylinders of varying widths and measured the minimum pressure required to push the leg out of the body far enough to be locked by the ratchet. This experiment was repeated three times for each soft pneumatic actuator.

The results of theoretical analysis and experiment are compared in Fig. 12. Overall, shape of two plots are similar, but in experiment result, average 55 kPa higher pressure is required compared with theoretical analysis. According to the both results, using a wider fabric cylinder has an advantage than narrow ones, because a wider cylinder requires less air pressure to generate sufficient force for wheel transformation. It helps reduce the size and weight of the air pump and thus of the entire robot. It also contributes to make untethered mobile robot.

4.2. Optimum fabric cylinder width

However, we noticed that if the fabric cylinder exceeds a certain diameter, it folds into thick wrinkles within the tunnel-like part, which interrupts the leg returning process (Fig. 13[b]). The design limitations of the tunnel-like part mean that this problem cannot be avoided, so we optimized the fabric cylinder design through another experimentation. We drew various version of legs to outer direction, which are connected with different width of soft pneumatic actuators, and then observed leg returning performances. This experiment conducted 10 times for each soft pneumatic actuator. Number of returning failure for each actuator is written in Table 1.



(a) (b)

Fig. 13. Returned leg shape at different soft pneumatic actuator. (a) Completely returned with fabric of width 45 mm. (b) Incompletely returned with fabric of width 55 mm because of wrinkle.

As a result, 45 mm is the optimal width for a fabric cylinder that will not interrupt leg release (Fig. 13[a]) (45 mm fabric sometimes slightly interrupts leg retraction, but it is solved by rotating the wheel). In the next section we describe experiments performed with wheeled mobile robots that contained soft pneumatic actuators built with fabric cylinders whose width and length are 45 mm and 130 mm respectively.

5. EXPERIMENTS

To evaluate performance of the wheel, we built a robot with a transformable wheel at the front and a 335-mm-

Table 1. Experimental results of leg returning.

Fabric width [mm]	30	35	40	45	50	55
Number of failure	0/10	0/10	0/10	1/10	6/10	9/10

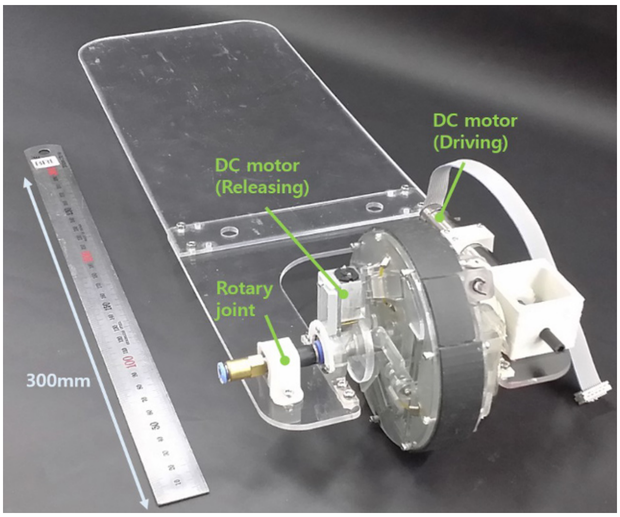


Fig. 14. Mobile robot using the transformable wheel.

long tail to support climbing (Fig. 14). This tail can be replaced by a rear transformable wheel. The wheel was driven by a DC motor (Maxon motor AG), and the releasing mechanism was actuated by a tiny DC motor (Pololu Corp.).

5.1. Minimum transforming pressure

We performed two experiments to determine the minimum pressure needed to transform the wheel under two different conditions: 1) transforming the wheel by applying air pressure to the soft pneumatic actuators while driving the motor that rotates the wheel and 2) transforming the wheel solely by applying air pressure to the soft pneumatic actuators. During the tests, we applied various loads to the axis of the wheel by placing weights into baskets fixed on its axis (Fig. 15). Fig. 16 shows the test results. We found no relationship between payload and the minimum transforming pressure when the wheel was transformed while rotating. In this situation, the wheel was transformed to legged mode at 85 kPa of air pressure, regardless of the payload, up to a maximum load. The maximum payload that we were able to test was 1,115 g because of limitations in the wheel's driving motor power and durability of gearbox. When the wheel was transformed by pressurizing the legs without rotation, the minimum transforming pressure increased as the payload increased, reaching 330 kPa at a payload of 815 g. The soft pneumatic actuator punctured at an air pressure of about 330 kPa.

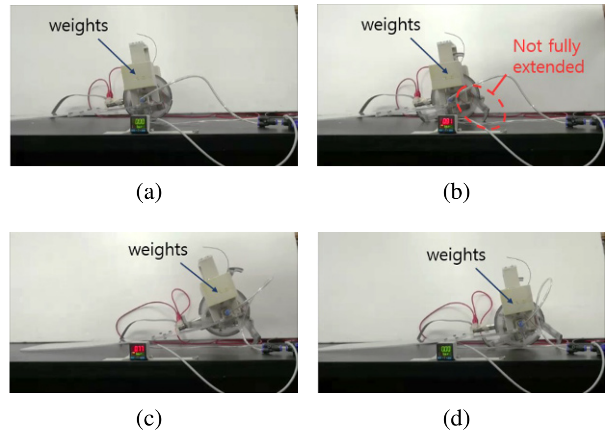


Fig. 15. Transformation of the wheel by air pressure and the driving motor under payloads. (a) Circular mode before transformation. (b) Emergence of the upper two legs with pressurization. (c) Wheel rotation with the driving motor. (d) Complete transformation of the wheel to legged mode.

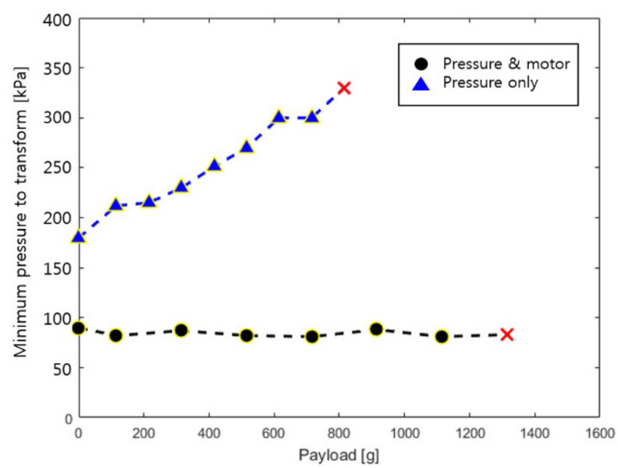


Fig. 16. The minimum transforming pressure according to payload.

5.2. Overcoming obstacles

To evaluate how well the wheel overcomes obstacles, we tested its performance at climbing tetragonal obstacles that were 50 mm, 106.5 mm, and 163 mm high, or 0.89, 1.9, and 2.9 times the wheel radius, respectively (Fig. 17). In circular mode, the wheel could not overcome even the 50-mm obstacle, but when transformed, it overcame the 163-mm-high obstacle.

6. CONCLUSIONS

In this study, we developed a wheel that can be transformed from a circular to a legged conformation under heavy payload by soft pneumatic actuators. The wheel

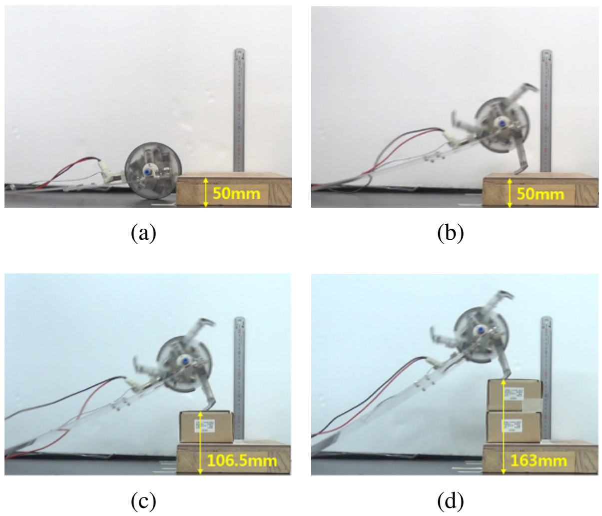


Fig. 17. Experimental results of overcoming obstacles. (a) The circular wheel mode cannot overcome a 50 mm obstacle. (b) The legged wheel mode can climb and overcome the 50 mm obstacle. (c) The wheel overcomes 106.5 mm obstacle with legged mode. (d) The wheel overcomes 163 mm obstacle with legged mode.

can change its shape from a circle with a radius of 56 mm to a legged wheel with a radius of 99 mm. The three legs of the wheel are kinematically decoupled but operated by a single air pump through pneumatic channels. Because the legs can transform independently, the wheel can be transformed under a payload of up to 1115 g with only 85 kPa of air pressure. Once a leg emerges from the body, it is locked in place and supported by a ratchet mechanism, therefore no additional energy is needed to maintain the transformed shape. The legs return to their initial state one by one via the leg-releasing mechanism. In legged mode, the robot can climb an obstacle up to 163 mm tall, representing 2.9 times the radius of the circular wheel.

Since the legs are protruded from the wheel, large impact is exerted to the end of the leg when the leg contacts the ground. According to the video analysis, we observed that rotation speed of the end of the wheel decreases to almost zero at the moment of impact, which means the wheel recovers its speed from zero periodically to keep moving. Also, effect of impulse hardly changes the allowable payload of the robot because the allowable payload is mainly dependent on the maximum torque of the DC motor.

However, high payload has potential to cause the large impact force and high collision speed, which may result in damage to the wheel structure, the robot body and the transmission. Therefore, to bear higher payload than used in this paper, shock prevention would be important to protect robot from breakdown. In this case, damping materials can be used to lengthen the contact time and lower the peak force of the impact.

Certain performance issues remain to be addressed. We could not predict effect of buckling in performance of soft pneumatic actuator because of nonlinearity and unpredictable degree of fabric wrinkles. As a future work, analytical model of soft pneumatic actuator which considers buckling will be investigated. The prototype robot used in our experiments have only one transformable wheel at its front, so it cannot change its direction. In the future, we will design and build a two- or four-wheeled mobile robot. In addition, we will work to lighten the robot, currently made heavy by its linear guide, and improve the deformation ratio of the wheel, currently being limited by the length of the linear guide and the wheel diameter. We will also embed the soft pneumatic actuator into the frame of the wheel to improve the robot's durability. Finally, we plan to build a locking and releasing system that uses only air so that wheel transformation can be controlled by air pressure alone, which will allow us to minimize the system.

REFERENCES

[1] R. D. Quinn, J. T. Offi, D. A. Kingsley, and R. E. Ritzmann, "Improved mobility through abstracted biological principles," *Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 2652-2657, 2002.

[2] J. M. Morrey, B. Lambrecht, A. D. Horchler, R. E. Ritzmann, and R. D. Quinn, "Highly mobile and robust small quadruped robots," *Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2003)*, pp. 82-87 , 2003.

[3] U. Saranli, M. Buehler, and D. E. Koditschek, "Rhex: A simple and highly mobile hexapod robot," *The International Journal of Robotics Research*, vol. 20, pp. 616-631, 2001.

[4] G. Quaglia, D. Maffiodo, W. Franco, S. Appendino, and R. Oderio, "The Epi. q-1 hybrid mobile robot," *The International Journal of Robotics Research*, 2009.

[5] F. Michaud, D. Letourneau, M. Arsenault, Y. Bergeron, R. Cadrin, F. Gagnon, *et al.*, "Multi-modal locomotion robotic platform using leg-track-wheel articulations," *Autonomous Robots*, vol. 18, pp. 137-156, 2005. [click]

[6] J. B. Jeans and D. Hong, "IMPASS: Intelligent mobility platform with active spoke system," *Proc. of IEEE International Conference on Robotics and Automation ICRA'09*, pp. 1605-1606, 2009.

[7] S. Hirose, "Variable constraint mechanism and its application for design of mobile robots," *The International Journal of Robotics Research*, vol. 19, pp. 1126-1138, 2000. [click]

[8] G. Endo and S. Hirose, "Study on roller-walker-energy efficiency of roller-walk," *Proc. of IEEE International Conference on Robotics and Automation (ICRA)*, pp. 5050-5055, 2011.

[9] J. A. Smith, I. Sharf, and M. Trentini, "PAW: a Hybrid Wheeled-leg Robot," *Proc. of ICRA*, pp. 4043-4048, 2006. [click]

[10] C. C. Phipps, B. E. Shores, and M. A. Minor, "Design and quasi-static locomotion analysis of the rolling disk biped hybrid robot," *IEEE Transactions on Robotics*, vol. 24, pp. 1302-1314, 2008.

[11] K. Tadakuma, R. Tadakuma, A. Maruyama, E. Rohmer, K. Nagatani, K. Yoshida, et al., "Mechanical design of the wheel-leg hybrid mobile robot to realize a large wheel diameter," *Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 3358-3365, 2010.

[12] Y.-S. Kim, G.-P. Jung, H. Kim, K.-J. Cho, and C.-N. Chu, "Wheel transformer: A miniaturized terrain adaptive robot with passively transformed wheels," *Proc. of IEEE International Conference on Robotics and Automation (ICRA)*, pp. 5625-5630, 2013.

[13] Y.-S. Kim, G.-P. Jung, H. Kim, K.-J. Cho, and C.-N. Chu, "Wheel Transformer: A Wheel-Leg Hybrid Robot With Passive Transformable Wheels," *IEEE Transactions on Robotics*, vol. 30, pp. 1487-1498, 2014.

[14] D.-Y. Lee, G.-P. Jung, M.-K. Sin, S.-H. Ahn, and K.-J. Cho, "Deformable wheel robot based on origami structure," *Proc. of IEEE International Conference on Robotics and Automation (ICRA)*, pp. 5612-5617, 2013.

[15] D.-Y. Lee, J.-S. Kim, S.-R. Kim, J.-S. Koh, and K.-J. Cho, "The deformable wheel robot using magic-ball origami structure," *ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pp. V06BT07A040-V06BT07A040, 2013.

[16] Y. She, C. J. Hurd, and H.-J. Su, "A transformable wheel robot with a passive leg," *Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 4165-4170, 2015.

[17] S.-C. Chen, K.-J. Huang, W.-H. Chen, S.-Y. Shen, C.-H. Li, and P.-C. Lin, "Quattroped: a leg-wheel transformable robot," *IEEE/ASME Transactions on Mechatronics*, vol. 19, pp. 730-742, 2014.

[18] S.-C. Chen, K. J. Huang, C.-H. Li, and P.-C. Lin, "Trajectory planning for stair climbing in the leg-wheel hybrid mobile robot quattroped," *Proc. of IEEE International Conference on Robotics and Automation (ICRA)*, pp. 1229-1234, 2011.

[19] T. Okada, W. T. Botelho, and T. Shimizu, "Motion analysis with experimental verification of the hybrid robot PEOPLER-II for reversible switch between walk and roll on demand," *The International Journal of Robotics Research*, vol. 29, no. 9, pp. 1199-1221, 2009. [click]

Sung-Sik Yun received his B.S. degree in mechanical engineering from Seoul National University, Seoul, Korea, in 2016. His current research interests include the design and fabrication of soft robotics and rehabilitation and assistive robotics.

Jun-Young Lee received his B.S. degree in mechanical engineering from Yonsei University, Seoul, Korea, in 2012. His research interests include soft robotics, mechanical designs, and biomimetics.

Gwang-Pil Jung received his B.S. degree in mechanical engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 2010 and a Ph.D. degree from Seoul National University in 2016. His current research interests include the design and fabrication of biologically inspired soft robots and novel mechanisms using smart materials, structures, and actuators.

Kyu-Jin Cho received his B.S. and M.S. degrees from Seoul National University, Seoul, Korea, in 1998 and 2000, respectively, and a Ph.D. degree in mechanical engineering from the Massachusetts Institute of Technology in 2007. He was a Postdoctoral Fellow with the Harvard Microrobotics Laboratory until 2008. At present he is an Associate Professor of mechanical and aerospace engineering and the Director of the BioRobotics Laboratory at Seoul National University. His research interests include biologically inspired robotics, soft robotics, soft wearable devices, novel mechanisms using smart structures, and rehabilitation and assistive robotics. He has received the 2014 IEEE RAS Early Academic Career Award, the 2014 ASME Compliant Mechanism Award, the 2013 IROS Best Video Award, and the 2013 KSPE Paik Am Award.