An Active Compliant Impact Protection System for Humanoids: Application to WALK-MAN Hands

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Abstract—This paper reports on the development of a new pneumatically actuated impact protection system which can be applied to protect humanoid robots during high impact physical interactions. The proposed device is based on a soft inflating vessel which is integrated and validated on the hands of a humanoid robot WALK-MAN. The system incorporates an active pressure control unit with on-off solenoid valves that permit the regulation of the air pressure of the protection chamber. The impact protection system is smaller and lighter than a rubber-based passive protection previously mounted on the hands, while it offers better impact reduction performance via fast and accurate pressure control. The effectiveness of the system is verified by actual physical interaction experiments with WALK-MAN while the robot is falling against an inclined surface, making contact with its hands to support its body and prevent falling and damage.

I. INTRODUCTION

Recent advances in robotics, including whole-body control, motion planning, and perception have enabled humanoids robots to operate outdoors and perform relatively complex tasks. Nevertheless, the 2015 DARPA Robotics Challenge (DRC) demonstrated that legged robots may inevitably fall over in an unstructured environment, as seen in Fig. 1; either when they walk on a flat or rough terrain, or even when they are at stance performing a manipulation task. In most of the falling incidents serious damages can be caused to the robot hardware due to high impact forces. Hence, not only preventing the falling, but also reacting and surviving after a fall becomes an important requirement.

After the pioneered works from Fujiwara [1] and Kajita [2], researches on the humanoid falling have been actively investigated in the areas of fall detection [3], [4], prevention [4], [5], motion planning and reaction [6], [7]. Along with the controlled falling strategies the impact protection design for humanoids has been first studied for locomotion, e.g. the feet design in [8], [9] or the use of hip and back protectors in HRP2 [2]. There are also developments on the actuator principles such as the introduction of series elastic and variable stiffness actuators [10]–[14], torque limiter [15], or tendon mechanisms [16]. The incorporation of soft skin has been also considered in a few 'soft' humanoid robots offering enhanced human-robot interaction skills [17]-[19]. However, the aforementioned protection mechanical designs are in their majority passive systems and specifically customized for a certain robot.



Fig. 1. The humanoid WALK-MAN fell down to the ground while walking through a door during the DRC Finals.

This work introduces an adaptable impact protection solution for humanoids robot which has the following characteristics:

- intrinsically compliant,
- fully sensorized with actively controlled compliance,
- modular, customizable, and light weight
- low complexity and cost.

Striving to satisfy the above features, we developed a new pneumatically-controlled impact protection system which consists of two modular units: i) a soft inflating vessel and ii) a pneumatic controller. The whole system was designed to be easily mounted on the body of the humanoid at the location of interest. The inflating vessel was mounted on the hands of the humanoid robot WALK-MAN [20], [21] and its effectiveness was experimentally validated throughout physical interaction test scenarios where the robot was pushed to fall forward against an inclined surface.

The rest of the paper is organized as follows: the overview of the developed system is presented in Section II. Sections III and IV introduce the design details of the soft inflating vessel and the active pneumatic control unit. Sections V and VI discuss the experimental validation of the system. Finally, conclusions and future works are drawn in Section VII.

II. OVERVIEW OF THE IMPACT PROTECTION SYSTEM

Figure 2 illustrates an overview of the developed active soft impact protection system. The system consists of two units: a soft inflating vessel and a pneumatic control unit. The soft inflating vessel unit is devised to physically reduce the force peak at the first impact moment through the regulation

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Fig. 2. The overall diagram of the developed impact protection system.



Fig. 3. The soft inflating vessel unit mounted on WALK-MAN hand.

of air pressure by the pneumatic control unit. The targeted functionality of the developed system is as follows: 1) the soft vessel is able to inflate and remain in a stable inflation mode when this action is requested; 2) the actual impact instance can be automatically detected; and 3) once the impact is detected, the vessel is able to deflate to dissipate the impact energy. To achieve this functionality a low-level pneumatic valve control is locally implemented on a micro-controller, Fig. 2, running at 1kHz update rate. A pressure sensor provides not only the feedback signal for the controller, but also the impact force detection. This is straightforward since the applied force can be easily calculated from the measured relative pressure and the area of the vessel, if the soft inflating vessel is pressurized. The following sections present the details of the design and implementation of the two modular units, the soft inflating vessel and the pneumatic valve controller.

III. DESIGN OF THE SOFT INFLATING VESSEL UNIT

This section provides the design procedure of a soft inflating vessel unit. While the soft inflating vessel may be designed in any forms for any points of interest on humanoids, for a more comprehensive and detailed example, it is introduced to be mounted on the hand of humanoid robots; in particular we consider WALK-MAN SoftHands [20], [22]. Note that, in the existing design of the hands, a rubber pad is attached at the palm, to endure unexpected impact forces during various manipulation tasks. This pad is 100×100 mm big, 18mm thick, and weighs 196g.

The aim of the new design is to develop such a soft inflating vessel that can alter the existing protection in terms of the size, yet provide not only an improved protection from high impacts such as falling, but also lightness in weight. The design of this vessel is shown in Fig. 3, while

TABLE I MECHANICAL SPECIFICATION OF SOFT INFLATING VESSEL UNIT

	width \times length	$100 \times 100 \text{ mm}$
frame	thickness	13.5 mm
design	hole radius at a clamper (R)	39 mm
	weight	86.6g
	thickness (t_0)	1 mm
selected	hardness (S)	Shore A50
silicon	ultimate strength (σ_u)	870 psi
rubber	yield strength (σ_y)	350-800 psi
	Poisson ratio (ν)	0.49



Fig. 4. A simplified diagram of the soft inflating vessel: the silicon rubber is inflated from the dotted line to the solid one, when the vessel is pressurized.

its mechanical specifications are given in Table I. In the following subsections, the detailed design method and the actual fabrication process are introduced.

A. Design Method

The soft inflating vessel is considered to be a hemisphere when it is pressurized as illustrated in Fig. 4. The soft silicon rubber is placed on a solid base frame that has a pipe hole to allow an air/gas filling source connectivity; R represents the hemisphere radius of the silicone rubber and P denotes the pressure inside the vessel, while t_0 denotes the silicone rubber thickness at an initial flatten condition and t_1 its thickness after an h size of deformation.

The pressure inside the soft inflating vessel is $P = F_a/A$, where $A = \pi R^2$ denotes a section vessel area before the inflation, and F_a denotes the force acting on the soft inflatable vessel, uniformly distributed onto the area. When the vessel is pressurized and inflated under pressure P, it changes from the flat shape to almost a hemisphere, while t_0 becomes smaller due to the deformation that is described as $t_1 = t_0(\pi/2)^{-\nu}$, where ν denotes the Poisson ratio which is assumed to be 0.49 for the silicone rubber.

As the silicone rubber is clamped in such a way to form a circular shape, as shown in Fig. 3, the required pressure to inflate the vessel up to a certain deformation (i.e., height) at the center of the circle is given as follows [23]:

$$P_r = 64f_R h/AR^4,\tag{1}$$

where f_R denotes a flexural rigidity obtained by

$$f_R = Et^3/12(1-\nu^2), \tag{2}$$

where E denotes Young's modulus and t denotes an average value of thickness with t_0 and t_1 . The hardness of the silicon rubber is often defined as a Shore durometer, S;



Fig. 5. (a) Dynamic simulation of the humanoid WALK-MAN falling on the ground, and (b) resultant impact forces measured in XYZ-axes.

and the scale of the silicon rubber selected in this paper is the Shore A50 with ASTM D2240 standard, i.e., S = 50, provided by the manufacturer. Its Young's modulus can then be obtained as E = 340.0 (psi) by the lookup table shown in [24]. The calculated pressure P_r can be a guideline to select the valve such that the maximum operating pressure is sufficiently larger than this value. Note that, in this paper, we assume that the maximum inflation of the soft vessel is limited to a hemisphere shape, that is, $h_{max} = R - t_1$. The stress appeared at the maximum inflation is then obtained as follows:

$$\sigma_{i,max} = 3PAh_{max}^2/4t_1^2. \tag{3}$$

The yield strength of the silicon rubber σ_y needs to be greater than this stress, i.e., $\sigma_y > \sigma_{i,max}$. The pressure when the maximum force is externally applied to the vessel needs to also be considered, since the valve should resist against this external pressure. Similar to (1), it can be calculated as

$$P_{f,max} = 64h_{max}f_R/AR^4 + P_{ext},\tag{4}$$

where $P_{ext} = F_{ext}/A$, where F_{ext} is the external force applied to the system such as interaction and impact forces. In this paper, F_{ext} was taken from simulation as a rough estimate¹, in such a case that the WALK-MAN robot is free-falling on the ground, as shown in Fig. 5. The Gazebo simulator along with a physics engine ODE and a full dynamic model of WALK-MAN was used for the implementation. One can then determine the required proof pressure of the valve.

Finally, to determine the thickness of the silicon rubber, the maximum stress from the aforementioned external force is investigated and it can be obtained by the following:

$$\sigma_{f,max} = 3P_{f,max}AR^2/4t_1^2. \tag{5}$$

The thickness can be selected for the soft silicon rubber to resist against the possible external forces, i.e., its ultimate strength σ_u with a certain thickness can afford $\sigma_{f,max}$.



Fig. 6. The detailed structure design of the soft inflating vessel unit including: (a) an exploded view, and (b) a section view.

The above parameters are mainly required for selections of the silicon rubber, its thickness, and the pneumatic valve, which are calculated and listed in Table II.

TABLE II PARAMETERS REQUIRED FOR THE DESIGN

Parameters	Values	Description
P_r	6.03 psi	required pressure to maximum inflation
$P_{f,max}$	91.95 psi	required pressure to endure impact
$\sigma_{i,max}$	51.13 psi	stress at the maximum inflation
$\sigma_{f,max}$	780.27 psi	maximum stress to endure impact

B. Design Details and Fabrication

In this section the design of the inflating vessel unit is described in details, using the methodology described in Section III-A. Moreover, the fabrication technique to reduce air leakage from the inflatable vessel is analyzed. Figure 6 presents the detailed soft inflating vessel design placed on WALK-MAN robot's palms. Its main parts include a base structure, a clamper, a spacer, and a silicone rubber plate. In particular, the base structure (in magenta color) contains an air tube holding fixture, while the clamper part (in light blue color) have a set of screw holes at its peripheral edge to be attached to the base structure and the silicone rubber (in yellow color). The spacer (in black color) is placed between the base structure and the clamper to allow compression of the silicon rubber prevent air leakage. The rigid part is fabricated using rapid prototyping with STRATASYS Dimension Elite. The design result is summarized in Table I. Compared to the rubber-based passive protection, the developed soft-inflating vessel is 4.5mm thinner (depth reduction of 25%) and 109.4g lighter (weight reduction of 54%), yet has the same height and width $(100 \times 100 \text{ mm})$. This implies that the developed design does not impair the manipulation capabilities of the hand when it is in the deflated state.

IV. DESIGN OF THE PNEUMATIC CONTROL UNIT

A. Electrical Components

The purpose of the pneumatic control unit (PCU) is to regulate the air pressure inside the vessel. We developed

¹Since the free falling of the real 130Kg WALK-MAN robot is highly risky, the reliability of the simulation will be verified by real experiments with dummies which is an authors' ongoing work.



Fig. 7. (a) Schematic diagram and (b) hardware implementation of the pneumatic control unit.

a compact and modular PCU which mainly consists of three components: two valves for air supply and exhaust, a pressure sensor, and a micro controller, as illustrated in Fig. 7.

1) Valves: To achieve fast pressure control performance as well as a light weight and miniature size implementation, a set of pneumatic 3-port solenoid valves, S070 by SMC, were used. A single valve is $21 \times 11 \times 7$ mm big and weighs only 5g, while ensuring that the response time is less than 3ms under a maximum operating pressure of 101.5 psi. (Its proof pressure is 145 psi.)

2) *Pressure Sensor:* The pressure in the soft inflating vessel is measured by an absolute piezo-resistive silicon pressure sensor SSC-150PA by Honeywell. It's pressure range is from 0 to 150 psi, while the reported response time is 1ms.

3) Micro Controller: The low-level valve control is implemented on an ARM Cortex-M4F micro controller TM4C123AH6PM, by Texas Instrument, with a separate EtherCAT communication controller. The control signal is a pulse width modulation (PWM) waveform the duty cycle of which is programmed to perform on-off control of the valves via commands triggered from a high level controller, as shown in Table III. The signal from the pressure sensor is obtained by a 16-bit analog-to-digital converter (ADC) in the range between 0 and 150 psi.

The command of the valves is transmitted through an EtherCAT communication channel at 1 kHz rate. The pressure feedback control implemented on the high-level con-

TABLE III CONTROL COMMANDS OF THE LOW-LEVEL VALVE CONTROLLER

command (V_c)	supply valve	exhaust valve	vessel status
0	off	off	no flow
1	on*	off	flow-in (inflating)
-1	off	on*	flow-out (deflating)

* The PWM duty cycle is set to 100% for 'on' state of the valve.

troller is described in the following subsection. Figure 7(b) presents the hardware implementation. The PCU only weighs 120 g in total and has a compact size of $150 \times 80 \times 30$ mm.

B. Active Pressure Control

1) Pressure Feedback Control Algorithm: The control objective is to regulate the pressure inside the soft vessel to track the reference pressure value, P_{ref} . The valve command V_c is generated by a pressure controller which uses the pressure sensor feedback P, and it is finally sent to the low-level valve controller which drives the two valves as aforementioned in Table III. A bang-bang control algorithm with a dead zone is applied as follows:

$$V_c = \begin{cases} 1, & \text{if } P_e > \delta, \\ -1, & \text{if } P_e < -\delta, \\ 0, & \text{if } -\delta \le P_e \le \delta, \end{cases}$$
(6)

where $P_e \triangleq (P - P_{ref})$ denotes the pressure error and $\delta > 0$ is a positive constant value for a dead zone threshold. The use of such an on-off pneumatic valve system makes this type of algorithm simple, yet it has been reported to be superior to a standard proportional PWM control [25]. The dead zone is introduced due to a practical need to attenuate a noise effect of the pressure sensor, mainly originated from the AD conversion process. While a narrow dead zone threshold can achieve better accuracy, it may cause a severe control chattering due to the noise, and vice versa. Hence, the threshold was empirically selected with an investigation of the peak noise level, which was five times of the resolution, i.e., $\delta = 0.012$ psi.

2) Operation of Impact Protection: As stated in Section II, the aimed behaviour of the developed impact protection system is to inflate the soft vessel in such a way to reduce the maximum impact forces, as well as to deflate it to attenuate oscillations after the impact. To have this functionality on the top of the low-level valve and pressure feedback control, an intuitive operation logic is developed for the high-level controller as shown in Fig. 8.

Once an action trigger is activated, the feedback controller regulates the pressure in the soft-inflating vessel unit, by inflating until $P = P_{ref}$. Note that the action trigger can be a manual command from a pilot interface of the humanoid robot, or an automatic command incorporating a high-level motion planner of the robot, such as a falling detection algorithm. We only use the manual action trigger in this work, since exploring the automatic one is out of its scope.

If a certain impact force is applied to the soft inflating vessel, it can be simply detected by monitoring the pressure



Fig. 8. The operation flow chart of the impact protection system.



Fig. 9. The soft inflating vessel is pressurized until the height attained is equal to its radius, R = 39mm.

such that $P > P_{max}$, where P_{max} denotes the set value of the impact threshold at the point of interest. It is worthwhile to notice that this value can be more intuitively set from the force value as $P_{max} = (F_{max}/A)$, where A is the effective area defined by the soft vessel design. Once the impact is detected, the soft inflating vessel vents out the air. This endows a physical damping behaviour which dissipates the high impact energy, whereas the system may also act as a pure spring system without the ventilation.

V. EXPERIMENTAL VALIDATION

This section introduces the experimental evaluation of the developed impact protection system. For the experiments, high level pressure controller is implemented in Simulink Real-TimeTM, running a 1 ms real-time control loop, with EtherCAT communication.

A. Performance Tests

1) Pressure with a Maximum Inflation: To prove that the effectiveness of the vessel design introduced in Section III we monitor the resulting pressure inside the vessel. In the design stage, the level of the maximum inflation is predetermined as the height not exceeding its radius of the hole at the topside clamper, R = 39 mm; and the expected pressure is 6.03 psi as presented in Table II. Through ten experiments as described in Fig. 9, the average value of the measured pressures with the maximum inflation is obtained as 5.94 psi, i.e., the error with the expected theoretical pressure (6.03) is therefore 1.49 %. This close matching on the pressure level verifies the correct design, modelling and behaviour of the soft-inflating vessel.

2) Force Sensing: One interesting feature of the developed system is the capability to indirectly measure the contact forces through the pressure sensor, when the soft



Fig. 10. Plot of the measured pressure sequentially adding three different weights after an initial pressure regulation at 3 psi.

TABLE IV Result of Force Sensing Test

weights	calcula	error	
weights	by digital scale	by pressure sensor	- 61101
1	20.26 N (2065g)	19.08 N	5.8 %
2	9.39 N (957g)	9.55 N	1.7 %
3	5.88 N (599g)	6.18 N	5.2 %

TABLE V Result of Inflation Speed Test

supply pressure (psi)	10	20	40	60	80	100
settling time (s)	2.08	1.37	1.09	0.88	0.74	0.62

inflating vessel is pressurized with a P_0 value. The contact force F_c is then given by

$$F_c = (P - P_0)A,\tag{7}$$

where P is the value of the pressure sensor and A denotes the effective section area; $A = \pi R^2 = 0.0048m^2$ in the developed system. This force sensing functionality is evaluated by an experiment of adding three weights, whose values are measured by an accurate digital scale with an 1g resolution. The responses during the experiment are presented in Fig. 10. One can notice from Table IV that in the proposed system, the contact force can be properly measured within a level of 5.8% error. (In the following Section VI, the force sensing is used to obtain the estimated impact forces generated during humanoid falling experiments.)

3) Inflation Speed: Once the developed impact protection system is triggered, the soft vessel should be immediately inflated to confront expected impacts. The inflation speed of the soft vessel is thus important. This response relies not only on the performance of the active pressure controller, but also on the level of supply pressure. To evaluate the inflation speed under the variations of the supply pressure, the air pump with a pressure-adjustable regulator is used; and for a fair comparison, the reference pressure is set to $P_{ref} = 3$ psi, while the supplied pressure is gradually increased up to 100 psi, which is the maximum operating pressure of valves used. The result of the experiments are summarized in Table V. One can observe that the maximum inflating speed of 0.62 seconds can be achieved in the developed system. (Also, see the submitted video.)



Fig. 11. The impact test bench with a force-torque sensor and a weight on a linear slide guide.

TABLE VI Result of Comparative Impact Experiments

weight	height	maximum	impact reduction	
		rubber (A)	proposed (B)	(A-B)/A
1 kg	100 mm	241.0 N	166.12 N	31.12 %
1 kg	150 mm	303.4 N	210.50 N	30.62 %
2 kg	50 mm	355.6 N	217.11 N	38.84 %
2 kg	100mm	501.6 N	241.83 N	31.85 %

B. Comparative Impact Tests

To verify the impact protection performance of the system, a test bench was used as shown in Fig. 11, where a linear slide guide provides a consistent impact condition with various weights and heights. Given that the soft-inflating vessel is designed considering the WALK-MAN robot hands, the proposed system is experimentally compared to the existing rubber-made protection pad of the hands, shown in Fig. 11. In particular, both protectors are placed on a force-torque sensor to directly measure the impact forces transmitted throughout the protector and the sensed data is sent to the high-level PC with a 1kHz update rate. The results of the impact test are summarized in Table VI. As the 1 and 2 kg weights are free-falling from different heights, the proposed system shows 30-38% superior performance regarding the first maximum impact reduction when compared to that of the rubber protection pad. However, as shown in Fig. 12, more oscillation is introduced after the second peak force even if it vents the air to damp it out.

C. Discussion on the oscillating response

As it can be seen from the impact tests, while the developed impact protection system can effectively reduce the maximum peak force from the impact, it introduces more oscillation and this re-bouncing behaviour is undesirable in most cases. The limited damping performance of the system is mainly correlated with the capacity of the exhaust valve as air ventilation can generate damping action connected to the effective spring behaviour of the soft system. In the development stage of the PCU, the size and weight of the valves are limited for the sake of the miniaturization, and a single valve is used to respectively supply and vent out air. For this reason, the damping capability is limited in the



Fig. 12. The result of the impact test with 2kg weight freely dropped from 100mm height, compared between the rubber protection pad (upper) and the proposed impact protection system (lower).

current prototype. In an active pressure control, it has been suggested that a flow rate of the exhaust valve is at least 1.4 times larger than that of the supply valve; and it is also wellknown that multiple parallel valves can promote charging and discharging responses faster. Therefore, a possible improvement is possible in a future development, considering the trade-offs between the size and damping capability.

VI. HUMANOID FALLING EXPERIMENTS

This section presents the impact reduction performance of the proposed active soft impact protector system installed on the humanoid WALK-MAN, as the robot starts falling against an inclined surface and interacts with the hands to prevent the falling.

The WALK-MAN humanoid approximates the dimensions of an adult human, whose height is 1.87m and the weight is 130 kg. It has two anthropomorphic hands called, WALK-MAN SoftHands. As shown in Fig. 13, the proposed soft inflating vessel unit was installed on the hands with a slider adapter and the PCU on its backpack, where the high-level PC is mounted. The robot is also equipped with a CMU Multisense-SL visual sensor. The experimental scenario in this paper is as follows: the robot falls onto an inclined desk surface, which has been set in three different inclination angles of 10, 30, and 50 deg. Human subjects randomly push the robot from its backside as shown in Fig. 14 (for the details, refer to the submitted video).

Particularly, as an intuitive falling reaction, two hands are automatically adjusted to be landed on the desk surface at the palm side equipped with the soft inflating vessel; the desk surface is visually detected to automatically plan the motions according to the inclination angles of the surface. 3D perception is used to acquire the point cloud data of the environment, where the RANdom SAmple Consensus (RANSAC) algorithm has been used to extract all the planar point clusters in the environment in the close proximity of the robot. The largest planar surface is selected, expressed as a frame with the y-axis collinear to the plane's normal, positioned at the closest perpendicular to the surface point, as shown in Fig. 14.



Fig. 13. The humanoid WALK-MAN is equipped with the developed active soft impact protection system.

 TABLE VII

 MAXIMUM IMPACT FORCES SHOWN IN FIG. 15

	impact 1	impact 2	impact 3	impact 4
50 deg	78.87 N	79.79 N	92.05 N	-
30 deg	108.09 N	105.26 N	115.64 N	-
10 deg	84.51 N	99.60 N	185.39 N	101.47 N

Note that to focus on the performance verification of the protection system itself, the following assumption hold in this experiment: 1) the robot falling has been already happened and detected, so that the protection system is being triggered to activate the soft inflating vessel; and 2) the robot reacts aligning both hands to face the desk surface, similar to what humans do. The falling experiments were performed three or four times for each inclination angle in a continuous manner.

The plots in Fig. 15 show the controlled pressure responses of the proposed impact protection system as well as the generated control action. Throughout all the experiments, the reference pressure of the active controller is set to P_{ref} =3.5 psi, which is intended to give the inflation height as an approximately 60 % level of the maximum height; and the impact is detected with $P_{max}=5$ psi, that is, the impact threshold of $(P_{max} - P_{ref})A = 50N$. From the pressure responses, shown in Fig. 15, one can observe that the pressure in the soft vessel is rapidly and accurately controlled to be regulated at 3.5 psi before and even after the fall. Moreover, the operation algorithm of the impact protection system works properly despite several falls. Since the WALK-MAN has been differently pushed by untrained subjects and fallen with respective velocities, the amount of impact forces randomly differs from each trials and it is not proportional to the inclination angles. Nevertheless, the maximum impact forces are observed to be less than 200 N throughout the experiments as indicated in Table VII. The weakest part in the WALK-MAN upper body is the forcetorque sensor at the wrist which can endure the torque of 75Nm which means an approximate level of the force to be 500N at the palm. The robot thus has not been damaged during all the experiments.



Fig. 14. The snapshots of WALK-MAN robot being fallen on the desk with 10deg inclination pushed by a human subject.



Fig. 15. The pressure response and valve commands of the developed impact protection system placed at the right hand (Those of the left hand are omitted due to the limited space.)

VII. CONCLUSION AND FUTURE WORKS

This paper presents an actively controlled impact protection system, designed to prevent damages of humanoid robots from impacts in cases of falling. Physical impact reduction is achieved using both a soft inflating mechanism and a rapid and accurate pressure regulation. As an application study, the system was mounted to protect the hands of the WALK-MAN robot. The device is 56 % lighter and 25 % thinner than a rubber-based passive protection previously mounted on the hands, yet offers higher impact reduction. While the robot hand is considered as an application example for the protection system, the proposed device concept can be also mounted in other parts of the body and its shape can be customized. Future work will focus on the application of the system on other parts of the humanoid robot body such as the knee, the elbow, or the hip, which can be subject of high impact forces when the robot falls. We also plan to integrate a high-level visual perception module for reactive and compliant motion planning [26], [27], for the falling protection.

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