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HUMANOID ROBOT LEG DESIGN

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Abstract. *In this paper we show the design and manufacture of a new leg for a humanoid robot developed by the ITAndroids group, because the current leg presents manufacturing imperfections, which affect the robot kinematic chain. First, we conducted an investigation to understand why such problems occur. Then, in order to design a new leg mechanism, a full simulation of the robot was used to obtain the forces acting on the leg during walking. Thus, a new geometry is proposed and analyzed by the finite element method (FEM). After this, the first prototype of the new leg was manufactured and assembled in the robot, thus providing a more precise kinematic chain.*

Keywords: *Humanoid robots, Manufacturing, Legged locomotion, Structural Analysis.*

1. INTRODUCTION

Throughout these past years, legged robotics has gained focus from both academic and media communities. One can cite the works from Boston Dynamics, such as the robots Atlas (Kuindersma *et al.*, 2016) and Spot. In this context, many robotics competitions were established in order to encourage the development in this area. One of them is RoboCup, more specifically the Humanoid KidSize League, in which two teams composed of four humanoid robots play soccer against each other (Comitee, 2018).

The Chape Robot is a small robot platform (53 cm of height) which was developed for both research and competitions. It was fully designed in the Autonomous Computational Systems Lab (LAB-SCA) at Aeronautics Institute of Technology (ITA). The robot's original design was based on the open source project Robotis OP2 robot (Ha *et al.*, 2013), whose parts are mostly manufactured using bent aluminum sheets.

For a company, such as the manufacturer Robotis, perfectly bending metal sheets in right angles may be straightforward, however a typical robotics laboratory usually does not possess neither machinery nor expertise to execute this manufacturing process with the required precision. This may lead to misalignment in the robot kinematic chain that can cause difficulties in the walking control algorithm and also in performing other tasks, such as standing up. Due to imprecise folds, the mechanical structure of Chape presents errors in alignment that may be observed by the naked eye.

This problem was mitigated by software, by manually setting new zero positions for the servos, but not without some degradation of the robot performance. Observing other teams, we noticed this is a recurring problem within the RoboCup community. An option is to avoid bent sheet parts in the the leg structure, and to use a design assembled with a docking system that do not require these folds (Nitin *et al.*, 2018; Stephanie *et al.*, 2018; ArRazi *et al.*, 2018; Teimouri *et al.*, 2018). Therefore, we decided to redesign the leg of the robot to avoid sheet bending, while also respecting other manufacturing constraints imposed by the machinery at our disposal. Another important feature of the new design is to provide easier access to nuts and bolts, which often get loose during robot operation and require frequent maintenance.

In the Literature, there are papers that evidence the research in robot leg development, Wu *et al.* (2016) presents a new humanoid with legs that combines aesthetics and design theory with the aim of creating movements that most closely resembles the human's movements. In Schwartz *et al.* (2014) the design of the thumb, the flexible leg and the improved hip structure are used in a teen size humanoid robot, required in HuroCup 2015, another robotics competition, in order to ensure the strength of each mechanism and the deformation in a safe range. In both works the stress analysis is adopted.

In this paper, we present a novel leg design along with the analyses used to verify its proper operation. We believe other humanoid robotics researchers may benefit from the proposed leg design as much as from the design process described here. The remaining of this paper is organized as follows. Section 2 shows the load cases that the robot is subject to. Section 3 describes the proposed design and the finite element method (FEM) simulation considering the most relevant load scenario. Section 4 explains the optimization process to reduce the mass of the pieces. Section 5 presents the final piece. Finally, Section 6 concludes and shares our ideas for future work.

2. LOAD SCENARIOS

In order to ensure that the robot is able to perform its usual tasks, one needs to calculate the loads endured by each body part. The torque on each joint may be obtained through the manipulator equation, as seen in Eq. 1 (Craig, 2005):

$$\mathbf{T} = \mathbf{M}\ddot{\boldsymbol{\theta}} + \mathbf{C}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) + \mathbf{G}(\boldsymbol{\theta}), \tag{1}$$

where $\mathbf{T}$ is the torque vector, $\mathbf{M}$ is the mass matrix, $\boldsymbol{\theta}$ is the joint angle vector. $\mathbf{C}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})$ is the velocity dependent terms (Coriolis forces), and $\mathbf{G}(\boldsymbol{\theta})$ is the gravity vector.

To calculate the loads endured by the legs, a simulation in the robotics simulator Gazebo was performed. The simulation consists of a virtual model of the robot, with the same walking control algorithm as the real one. Figure 1 presents the virtual model of the robot. Figure 2 shows measured forces on left tibia and left thigh during walking, the results were filtered through a moving average filter to avoid peaks caused by numerical imprecision in simulation. It is also important to highlight that this simulation software considers a fully rigid robot body, which may lead to higher propagated forces through the structure, since the impact forces are not being dumped along the structure, leading to a conservative approach of loads calculation. Table 1 shows the load scenarios considered most relevant to the leg design.

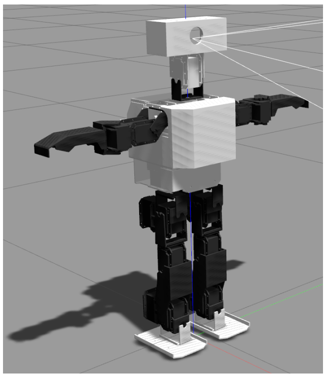

Figure 1. Model used for the Gazebo simulation.

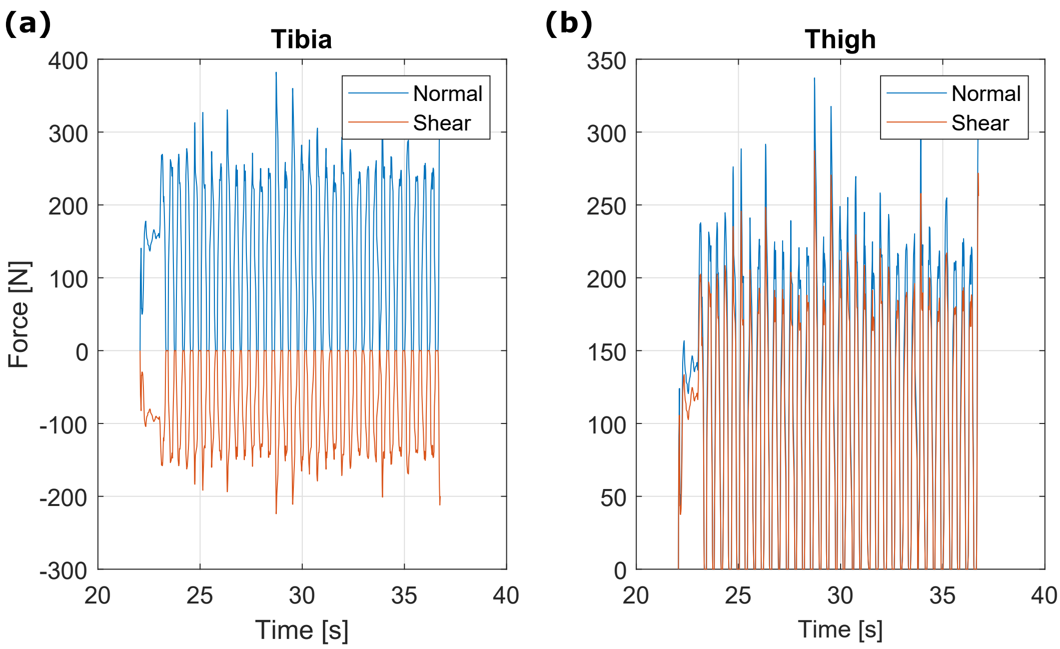

Figure 2. Forces on each leg part during walking: (a) tibia, (b) thigh

Table 1. Load scenarios

Body part	Vertical force [N]	Horizontal force [N]
Tibia	250	-150
Thigh	225	225

Vertical: (+) compression; horizontal: (+) forwards.

3. RESULTS

3.1 Leg Design

Respecting all constraints, a prototype was defined for the new leg of Chape. The 5052 H34 aluminum alloy was chosen mainly because it is already being used in other robot parts due to its excellent foldability, and it also presents good corrosion resistance, which is desirable since the robot is constantly being manipulated by the laboratory members.

To ensure that the new legs would be able to perform the same movements of the previous one, initially an outer geometry was designed and tested. The goal of this preliminary design was to analyze if the new geometry could present mechanical interference that could lead to motion restrictions, and also to test the easiness of assembling and cable routing. Figure 3(a) shows the leg preliminary design.

In Fig. 3(b), the new tibia is represented, where the part A5 acts as a connector of the two parts A7. Notice that based on the Chape's load test, we estimated that at least 2 of these parts are required. The main function of these parts is to increase the rigidity and to avoid that the assembly undergoes torsion. In Fig. 3(c), the thigh is shown where the part A6 acts as a spacer so that parts A8 can connect to the servomotor A4.

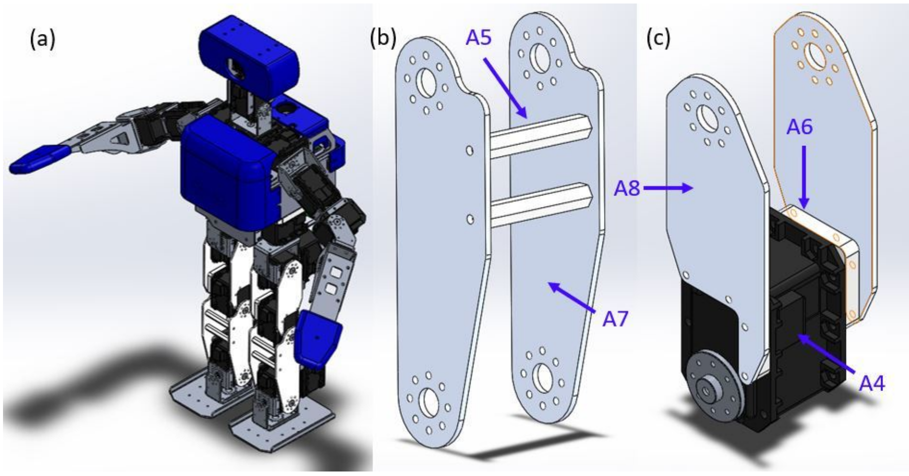

Figure 3. (a) Chape with the new leg; (b) The new tibia; and (c) The new thigh.

3.2 Structural Analysis

In this section, a FEM static analysis is performed using Ansys Workbench platform. The load case was presented in Section 2.

Figure 4(a) shows the simulation results for the tibia. For the boundary conditions, the six smaller lower holes were fixed support, i.e. without translation and rotation. The components x and y of the maximum load at this moment are -150N and -250N, respectively, being applied to the inner face of the largest upper hole in this geometry.

Its mesh contains 7745 nodes, as well as 1248 three-dimensional elements of type SOLID 186 and 18 flat elements of type SURF154.

Since the alloy is a ductile material, the von Mises criterion was used to evaluate the simulation, which in this case shows a maximum tension of 100.4 MPa, which is lower than the rupture strength. Therefore the part is fit to be fabricated.

Figure 4(b) shows the simulation results for the thigh. As boundary conditions, the four lower holes were considered fixed support. The loads were applied on the upper larger hole, with x and y components of 225N and -225N, respectively. Its mesh contains 2559 nodes, as well as 1167 three-dimensional elements of type SOLID 187 and 10 flat elements of type SURF154.

The material is the same as the thigh, once more the von Mises criterion was used. Now the simulation has a maximum value of 53.4 MPa, it is still within the flow limit of the material. Again, the part is ready to be manufactured.

After the positive simulation results, the preliminary leg was manufactured in order to test the assembly, the kinematic

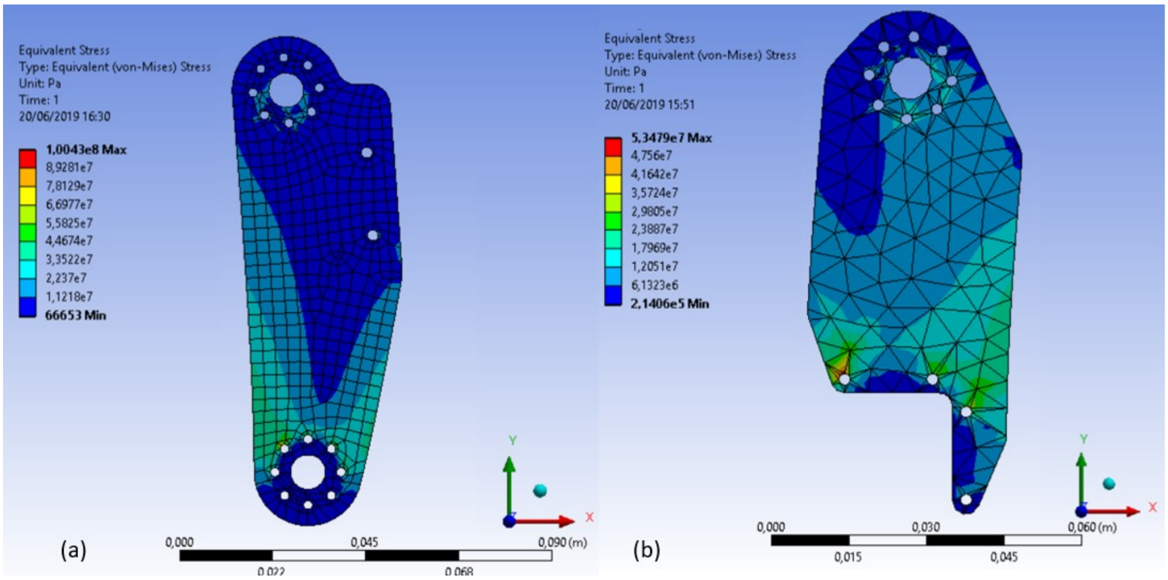

Figure 4. (a) von Mises equivalent stress for tibia; (b) von Mises equivalent stress for thigh.

restrictions of the new leg and cable routing. Figure 5 shows the manufactured preliminary leg design being tested.

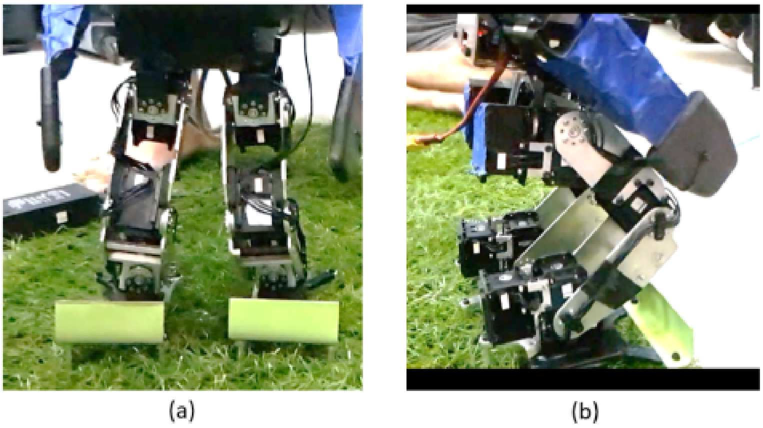

Figure 5. Manufactured preliminary leg design: (a) front view, (b) side view.

4. OPTIMIZATION

After the positive results shown in Section 3.2 the parts were submitted to a topological optimization for project improvement.

The parameter chosen for the optimization was mass minimization. The simulations were performed for both the tibia and thigh, using the percentage of mass remaining in both pieces as a criterion, as shown in Fig. 6.

Figure 6(a) shows the results of the topological optimization of the thigh, their respective percentages of remaining mass are shown on the right-hand side of each figure. Figure 6(b) shows the results of the topological optimization of the tibia, also with their respective percentages of remaining mass shown on the right-hand side of each figure.

Based on the topological results, new designs were proposed for both the thigh and the tibia. The criteria for the new geometries were: manufacturing feasibility, results of the topological optimization and design requirements by the ITAndroids team.

Then, to evaluate the structural integrity of the new geometries, the FEM analysis was redone using the same loading scenarios and boundary conditions of the section 3.2. Now, for the thigh, its mesh contains 2134 nodes, as well as 264 three-dimensional elements of type SOLID 186 and 5 flat elements of type SURF154. And for the tibia, its mesh contains 7739 nodes, as well as 264 three-dimensional elements of type SOLID 1188 and 18 flat elements of type SURF154

The results are shown in Fig. 7, again the von Mises criterion was used for this analysis, as seen in Fig. 7. Despite the increased stress on both parts, the tensions are still lower than the yield strength of this material. On the thigh, von Mises shows a maximum value of $63.4\ MPa$, there was an increase of 18.60% of stress and reduction of 0.10% of the mass. On the tibia, the von Mises criterion shows a maximum value of $102.4\ MPa$, there was an increase of 15.94% of stress

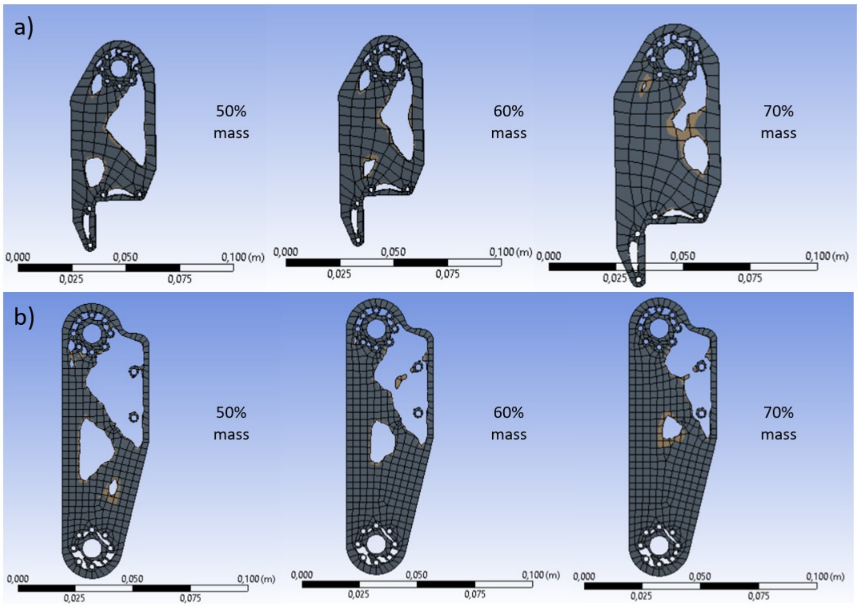

Figure 6. (a) Topological optimizations of the thigh; (b) Topological optimizations of the tibia.

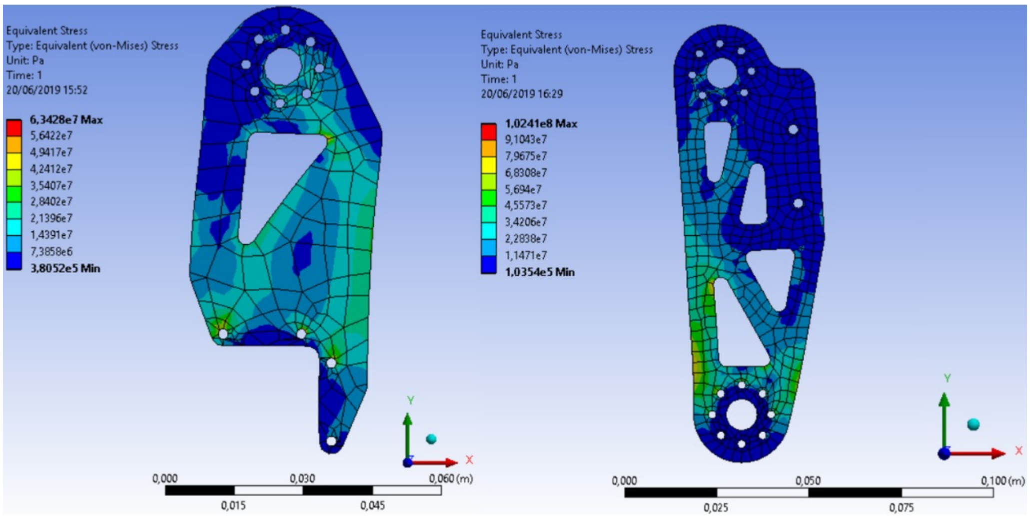

Figure 7. FEM for thigh and tibia, respectively.

and reduction of 3.59% of the mass.

5. FINAL RESULTS

Figure 8 shows the final CAD assembly of the Chape robot with the new leg design. Fig. 8(a) illustrates the assembly of the entire Chape. Fig. 8(b) illustrates the assembly of the Chape's leg.

The pieces were made with 5052-H34 aluminum, 2 mm plates. Figure 9 shows the final assembly of Chape with its new legs, it is important to emphasize that the holes made in the optimization are used as passage for the cables, helping with the maintenance of the robot. We may add that the robot with the new legs indeed required a lot less software calibration for keeping the robot upright, which indicates that we have fewer misalignments in the robot's kinematic chain. Finally, the optimized version of the leg was tested in some robots during the international robotics competition RoboCup 2019, where team ITAndroids placed within top 8.

6. CONCLUSIONS AND FUTURE WORK

This paper presented a new leg design for a humanoid robot. The previous leg designed required precise metal sheet folds at right angles, which are hard to execute using machinery commonly available at research laboratories. Therefore, the new leg was designed to avoid metal sheet folds. Furthermore, the leg design was submitted to topological optimization

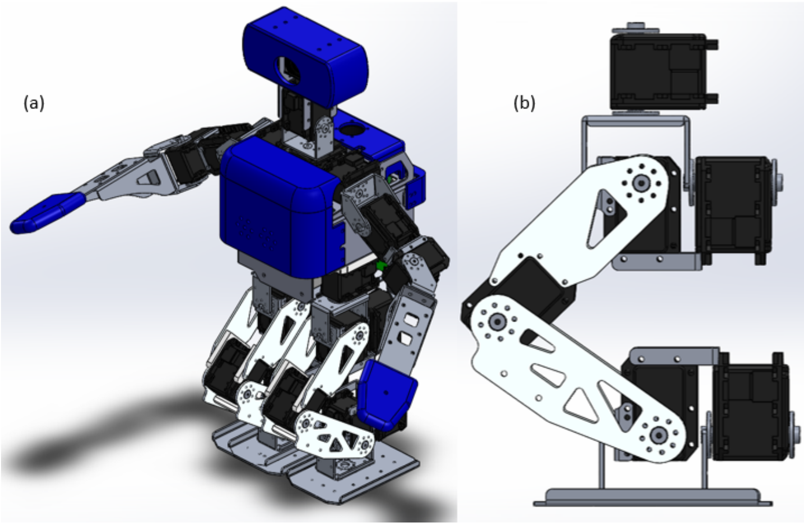

Figure 8. a) Chape assembly. b) Chape's leg assembly.

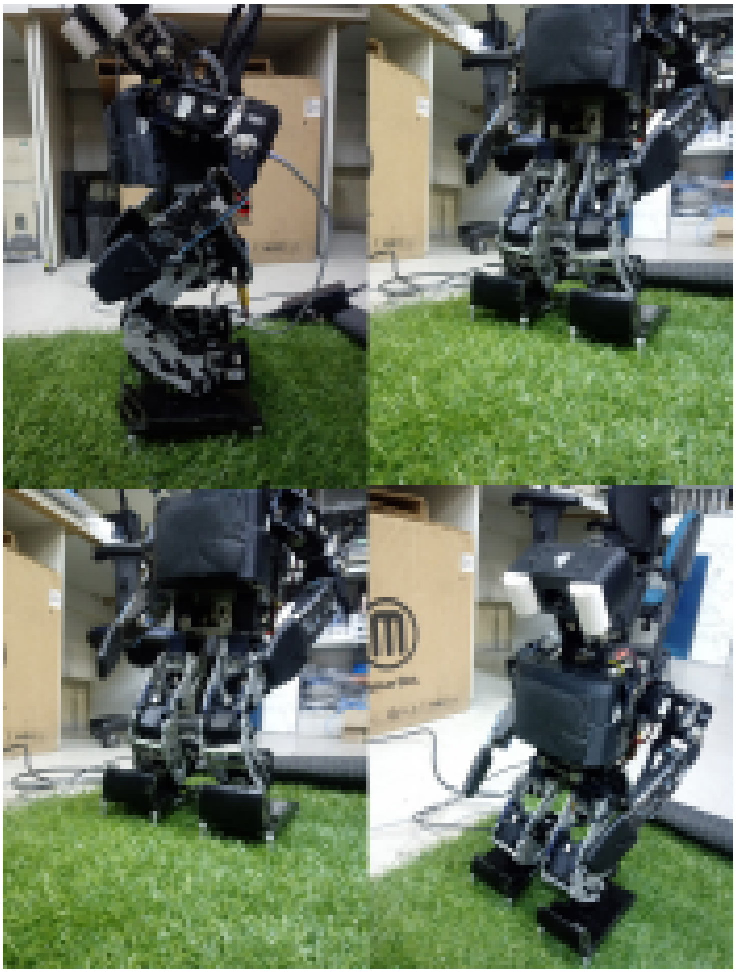
Figure 9. Chape with new legs.

in order to reduce the piece mass.

For future work, we intend to expand the design principles used here for designing other parts of the robot. Moreover, we are designing a new generation of the Chape robot with 65 cm of height, which will benefit from the design principles presented here.

7. ACKNOWLEDGEMENTS

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