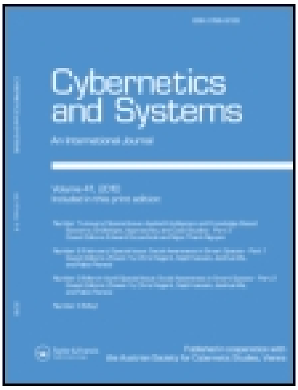

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TEO: Full-Size Humanoid Robot Design Powered by a Fuel Cell System

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This article deals with the design of the full-size humanoid robot TEO, an improved version of its predecessor Rh-1. The whole platform is conceived under the premise of high efficiency in terms of energy consumption and optimization. We will focus mainly on the electromechanical structure of the lower part of the prototype, which is the main component demanding energy during motion. The dimensions and weight of the robotic platform, together with its link configuration and rigidity, will be optimized. Experimental results are presented to show the validity of the design.

KEYWORDS *energy consumption, humanoid robot design, lower body improvement*

INTRODUCTION

The humanoid robotics group RoboticsLab, at the University Carlos III of Madrid, has been working for many years on the Rh project, a robust and open humanoid platform for research on biped walking, balancing control, sensor fusion, human–robot interaction (HRI) for collaborative task, and other related issues.

Rh-1 is an anthropomorphic robot with 21 degrees of freedom (DOF), a height of 1.5 m, and a weight of about 50 kg. The main research objectives of this platform have been the stability of the robot (Kaynov et al. 2009) and gait generation (Pardos and Balaguer 2005; Arbulú and Balaguer 2007), though

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other research activities have focused on human–robot interaction (Staroverov, Marcos, et al. 2007; Staroverov, Martinez, et al. 2007) and collaboration (Pierro et al. 2008). In fact, these two first versions aim at studying stable walking and do not consider upper part movements related to physical collaboration.

Though stable walking has been achieved in this platform, several aspects have to be improved. As a main problem, the mechanical structure of this prototype is not very robust and presents limitations such as the high flexibility of the whole body and joint looseness, which not only complicates the stability control but also limits the range of applications to be performed with the robots, not to mention the increase in energy consumption.

However, the most relevant humanoid platforms occurred as a step-by-step improvement of different versions, such as Asimo (Sakagami et al. 2002), HRP-3 (Kaneko et al. 2008), Hubo (Park et al. 2005), and Wabian-2 (Ogura et al. 2006). Other relevant platforms were specifically designed for peculiar applications: Jonnie (Pfeiffer et al. 2002) was initially designed for fast-walking, and i-Cub (Metta et al. 2008) for research on embodied cognition. In this line, the new prototype TEO appears as an improved version of its predecessor Rh-1.

TEO (Martinez et al. 2009; Pabon et al. 2009) addresses challenges in the fields of motion, safety, energy efficiency, and power autonomy performance. The mechatronics of this platform is inspired by human natural and adaptive locomotion, and its design is oriented to achieve human physical capacities and performances.

An important issue is that the whole platform is conceived under the premise of high efficiency in terms of energy consumption and optimization. In general terms, the existing prototypes of humanoid robots are heavy to carry and have limited energy capacity. A Honda humanoid robot can walk for only 30 min with a battery pack it carries on the back. Energy is one of the most important challenge for mobile robots in general. For instance, Rybski et al. (2000) showed that power consumption is one of the major issues in their robot design.

There are several components in a humanoid robot that demand energy consumption, such as motors, sensors, microcontrollers, and embedded computers. However, one of the most relevant terms in the whole energy balance is motion power. DC motors transform direct current into mechanical energy to drive the robots. The electromechanical structure is therefore the main component demanding energy. The dimensions and weight of the robotic platform, together with its link configuration and rigidity, will affect the final energy consumption. We will focus mainly on these electromechanical aspects when designing the new prototype TEO, more specifically its lower part, as will be detailed in this article. In addition, other aspects, such as motion planning, will be considered to reduce motion power.

The rest of the article is organized as follows. The following section shows some previous experiences with Rh-1, stating the improvements required for TEO design. In the next section a methodology is established in order to perform the new design steps successfully. Then we present three case studies focusing on each of the main components of the lower part of the robot: the ankle, the tibia–thigh set, and the hip. Simulation and experimental results of these designs are given. Finally, some conclusions and future works are presented.

PREVIOUS EXPERIENCES WITH Rh-1

As stated before, the Rh-1 version of the robot was realized from scratch, and even if it has been possible to perform different walking and stability strategies, it presented several limitations.

However, the platform had its strengths in the following points:

- Structural analysis: In order to perform an accurate analysis, support of external forces, links geometries, and material properties were considered, including reaction forces and material stresses.
- Design of the mechanical part: the mechanical design used the human structure as a reference.
- Inverse dynamics analysis: this tool has been reused for future calculations in TEO.
- Behavior of the structure during the movements: once the platform was designed, it was successfully tested under stress conditions due to continuous walking movements.

Nevertheless, the Rh-1 robot presented great limitations that did not allow correct motion performance in terms of mechanical robustness (high joint looseness), stability, and energy consumption (necessary to be connected to the electrical net becaus thee battery could not supply the required energy for very long), not to mention the realization of high-level tasks such as manipulation, complex gait generation, or complex human–robot interaction.

One of the main problems with the design was that the structure was oversized, which implies overweight of the prototype. This led not only to mechanical looseness of the body but also to devoting more control efforts to guarantee the stability of the system, computationally and mechanically speaking.

In the analysis of the mechanical structure, only the strength analysis was considered. A precise study of displacement methods—which make use of the components stiffness relations for computing forces in the structure—was omitted. The design constraint was only a large factor of safety. As a result, the mechanical structure caused wide backlashes in positioning, which were undesirable for the high precision required.

In addition, the upper part of the robot presented several limitations. In fact, the workspace for both legs and arms needed to be extended. In

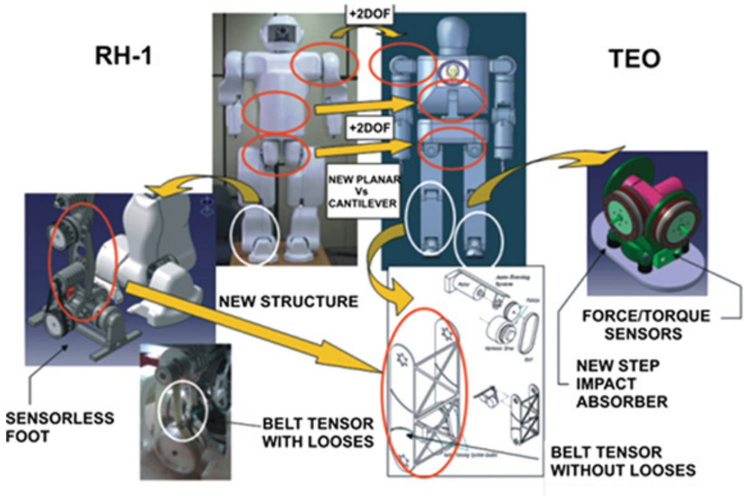

FIGURE 1 Improvements in the electromechanical structure (color figure available online).

particular, it was concluded that 2 DOF had to be added to each arm and two more to the waist of the robot, resulting in a wider workspace and higher manipulability in the different configurations. This new configuration has been set in the new TEO, with a total of 26 DOF.

Finally, it is important to stress the difference between the structure of these previous prototypes and the new one. Rh-1 presented a structure based on the human one: the robot had a real skeleton to which all of the electronic components were attached. This caused several problems when new electronic components needed to be added, due to the lack of space.

The new structure of TEO is based on a box concept: the robot structure itself is a container in which all of the electronic components are inserted. More details will be given in the following sections of the article. A scheme summarizing the improvements proposed of the electromechanical structure is presented in Figure 1.

DESIGN PROPOSALS FOR THE LOWER BODY IMPROVEMENT

Once the main limitations of the prototype were studied, a design methodology was needed to carry out the improvements successfully, focusing on the lower part of the robot (though the same flow was applied to the upper part). We followed the scheme shown in Figure 2.

As can be seen in this figure, the process was divided into three stages:

1. Design stage. The concept for the lower part was stablished and a first mechanical structure was proposed and modeled. The main result of this

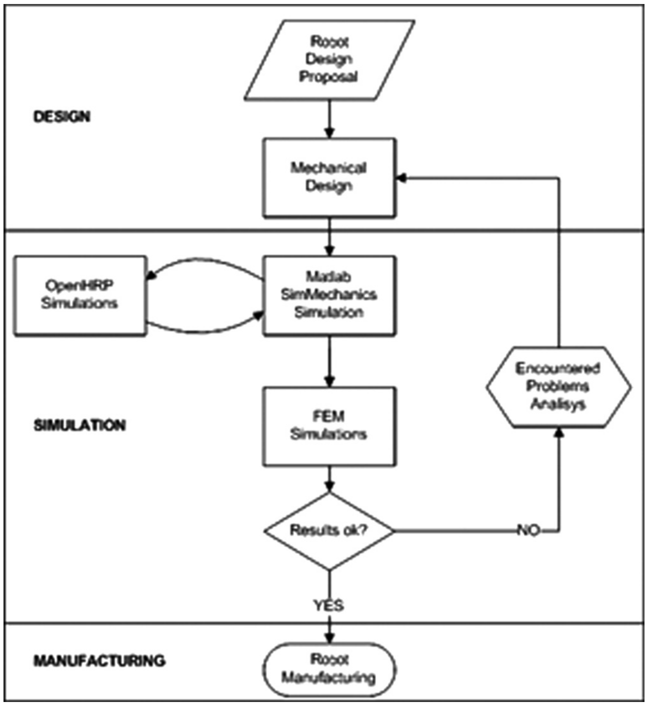

FIGURE 2 Development process flow.

process was the 3D computer-aided design (CAD) model of the robot parts and assemblies.

2. Simulation stage. The aim of this stage was to obtain numerical data that allow the optimization of the structural parts of the robot, selection of the appropriate movement chain (motor + reduction), and estimation of the energy consumption. This process was divided into two parts: (a) a task simulation step, in which torques, work angles, and other performance parameters were calculated, and (b) a finite element (FEM) study of each structural component. There was feedback between both simulations steps in order to optimize the parts and systems through several iterations.
3. Manufacturing stage. Once design, simulation, and optimization processes were finished, manufacturing of the structural parts and their assembly was the final step.

Taking into account a more realistic evolution of the efforts that the lower part of the robot suffers during the walking of TEO, a dynamic simulation of the multibody model of the robot had to be performed in order to obtain the real forces and loads applied to each piece. In this way, these pieces could be redesigned so that they could support those efforts with the minimum weight.

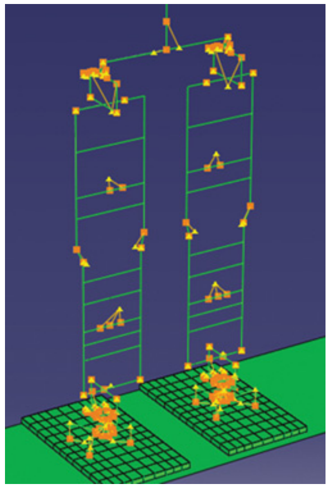

FIGURE 3 Multibody model of the lower part of the humanoid robot TEO (color figure available online).

Therefore, the first step was to obtain a multibody model of the lower part that allows the study of the dynamics of the pieces, taking into account the interaction between them and the reaction forces. Figure 3 presents the resulting model, showing the situation of the different centers of masses and the corresponding links between elements. All of the calculations were made using Abaqus/Standard (Dassault Systemes™, France), a commercial software specially devoted to the advanced calculus of static and dynamic efforts over elements.

The floor was characterized as a horizontal infinitely rigid surface and the contact between this surface and the inferior surface of the foot was defined. All pieces were made of aluminum, and the sole of the foot was made of a generic type of polymer. To model the behavior of both the aluminum and the polymer, the characteristics shown in Table 1 were considered.

It is necessary to clarify that a null density was given to the elements of the robot, because the masses were considered as concentrated in the centers of gravity of each element.

Under these conditions, a nominal trajectory was simulated (see Figure 4), leading to the necessary conclusions for the redesign of the lower part according to the forces and moments obtained for each element and their directions.

TABLE 1 Characteristics of Aluminum and Polymer

	Young's modulus	Poisson's ratio	Density (kg/m^3)
Aluminum	$E = 70$ GPa	$\nu = 0.4$	2,810
Polymer	$E = 250$ GPa	$\nu = 0.05$	1,800

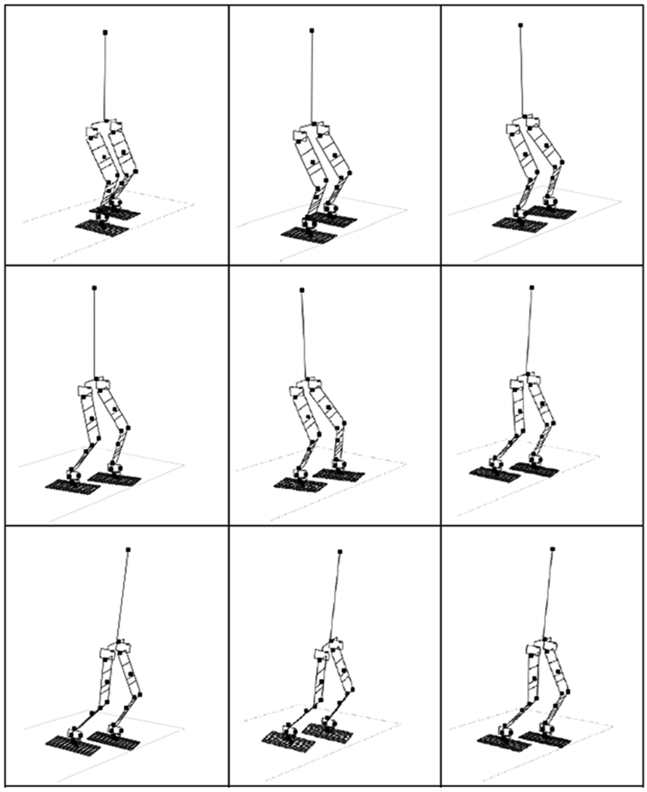

FIGURE 4 Global model walking.

CASE STUDIES

This section addresses the design of the three main components of the lower part of the humanoid robot TEO. The improvements of the ankle, the tibia–thigh set, and the hip are presented and discussed as three different case studies, including simulation and experimental results regarding their specific and more restrictive requirements of design.

Case Study 1: The Ankle

During the walking motion, the ankle is the most critical joint due to the forces and torques it has to bear. On the one hand, this joint must support the weight of the robot during the single support phase in a locomotion task, in which only one foot has contact with the ground. On the other hand, the ankle is the nearest joint of the robot kinematic chain to the ground. When the flying foot lands, the force of the impact is transmitted firstly to this joint. These two effects have to be taken into account in the design of the ankle.

Because its structure must have a compact size, very little backslash in this joint causes balance loss or increases instability. The mechanical design of this joint should avoid this problem, assuring stability while the robot is walking. In addition, avoiding backslash helps control system to perform precise walking movements.

In a first stage of design, the 3D CAD model of the ankle parts and assemblies was obtained, as shown in Figure 5.

Then the simulation stage was addressed, as explained in the previous section. The humanoid robot is a dynamical system and the loads on its parts vary depending on the task executed. The robot walking task was selected for this simulation stage, because it is one of the most demanding. The walking task was simulated using MATLAB SimMechanics (Maxon Motor™, Sachseln, Switzerland) and data regarding joints torques, angular velocities, and accelerations were obtained. Figure 6 shows the results of the right ankle during the two phases that one foot goes through in a walking period: on the ground (supporting phase) and flying.

As can be observed in Figure 6, the torque depends on the supporting phase during the walking task. The moments in which the torques are higher correspond to the end of each support phase. Analysis of the torques is useful in selection of the transmission chain and motors of the joints. The root mean square (RMS) value determines the nominal torque that the motor must support during a walking period. In addition, the peak torque determines the minimun stall torque that the motor must supply in order to start the movement. A summary of the walking simulation results is shown in Table 2.

Other simulation tools were used to test other features during the walking action. For example, one important aspect of the task performance is the stability. Using OpenHRP (University of Tokyo; see Figure 7), a simulation software for humanoid platforms, this feature was tested and gaits were

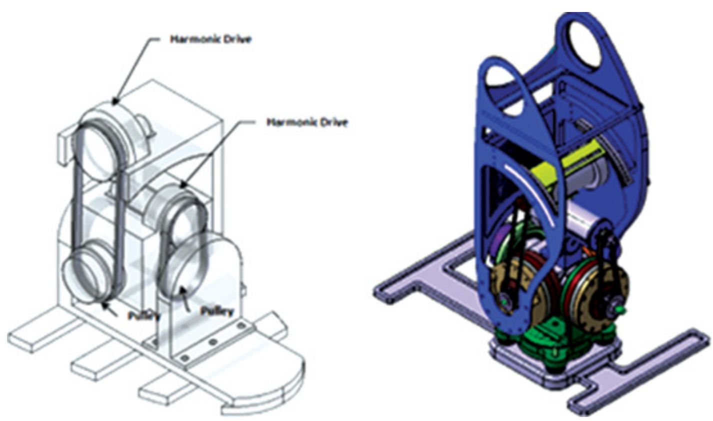

FIGURE 5 Previous design of robot ankles (color figure available online).

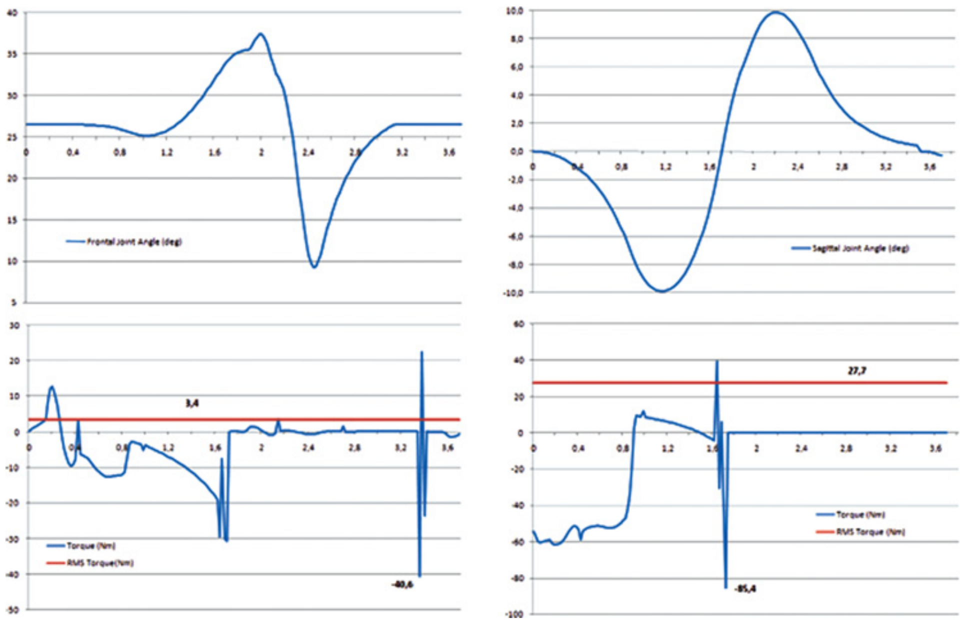

FIGURE 6 Frontal and sagittal angles and torques of the right ankle (color figure available online).

modified and improved in order to guarantee the stability of the structure during the walking action.

After OpenHRP simulations, using Abaqus/Standard numeric simulation software, the main parts of the ankle that were analyzed and optimized are the fork and the so-called cross. These parts allow the ankle to turn in the frontal and sagittal planes and support the whole weight of the robot during the single support phase. These parts are joined to the leg by means of the transmission pack, a mechanical structure that contains the harmonic drive components, assembled with steel screws. The main goal of this optimization loop was the reduction of weight without losing strength features.

Figures 8 and 9 show the results of the FEM simulation of the ankle. The fork and cross were made of aluminum 7075 alloy. For the study, the elastic limit ($R_{P0.2} = 110$ Mpa) was considered instead of the fracture limit ($R_m = 160$ MPa), because permanent deformations of the parts are not

TABLE 2 Summary of Results from MATLAB SimMechanics Simulations

	Joint torque	Reduction	Motor torque	Selected motor
Sagittal joint	RMS = 3.4 Nm Max = 40.6 Nm	235.2	RMS = 14.4 mNm Max = 173 mNm	Maxon Brushless EC45 Flat 251601
Frontal joint	RMS = 27.7 Nm Max = 85 Nm	320	RMS = 86.6 mNm Max = 265 mNm	Maxon Brushless EC45 Flat 339287

Note: Maxon Brushless, Maxon Motor™, Sachseln, Switzerland.

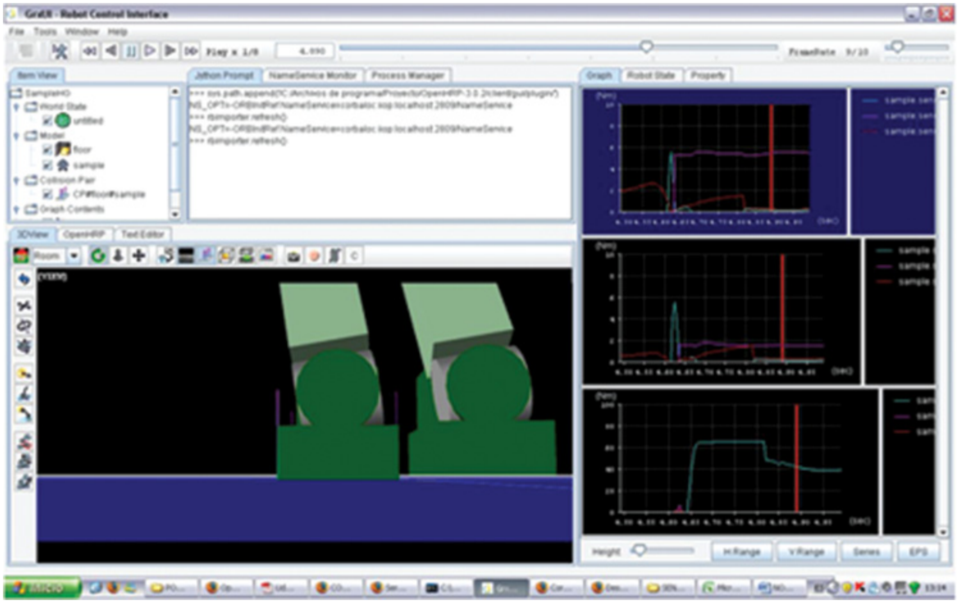
FIGURE 7 OpenHRP simulations (color figure available online).

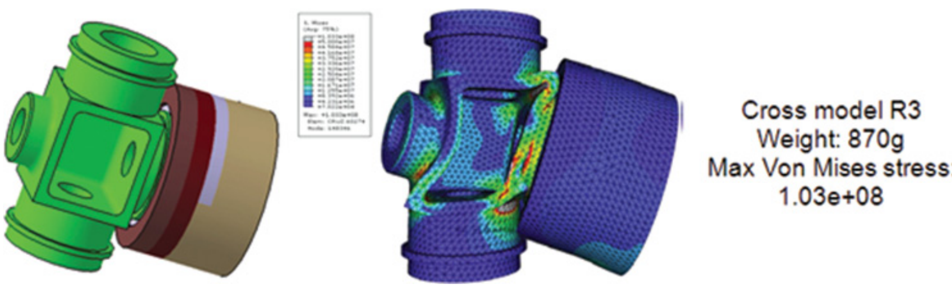

FIGURE 8 FEM study of the cross part (color figure available online).

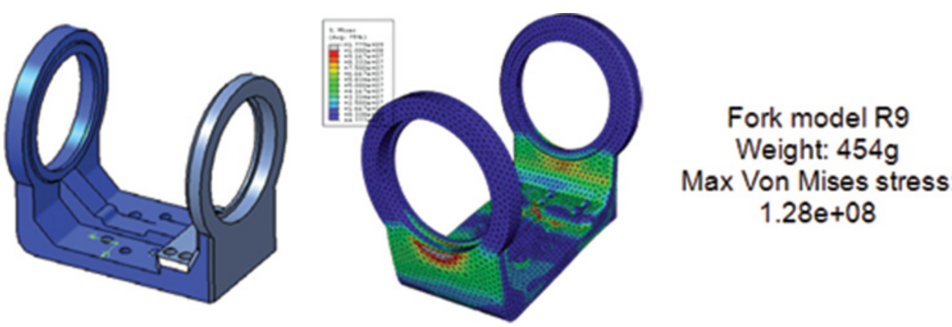

FIGURE 9 FEM study of the fork part (color figure available online).

allowed and R_P is more restrictive. The resulting physical features of the model were fed back to the Matlab SimMechanic model to perform a new iteration of simulations.

Once the design, simulation, and optimization processes were finished, manufacturing of the structural parts and their assembly was carried out, as shown in Figure 10.

Case Study 2: The Tibia–Thigh Set

Under the premise that the new prototype must fulfill strict requirements of weight, a redesign of the tibia–thigh set was also carried out. The initial design was very conservative when considering security criteria and forces applied over this set during the walking action in different conditions.

In this respect, it is important to remark that Rh-1 presented a structure based on the human form: the robot had a real skeleton to which all of the electronic components were attached. This caused several problems when new electronic components needed to be added, due to the lack of space.

The new structure of TEO is based on a box concept: the robot structure itself is a container in which all of the electronic components are inserted. This kind of structure involves all electronic and mechanical subsystems, protecting them, and provides more stiffness and robustness in general, especially in case of a fall.

Taking this into account, a procedure similar to the one explained in the previous case study was followed. Based on the results of this process, redesign of the different pieces was performed taking as input conditions (forces, moments) those given by the simulations. After 12 iterations, the final model

FIGURE 10 Assembled ankle: cross and fork manufactured parts (color figure available online).

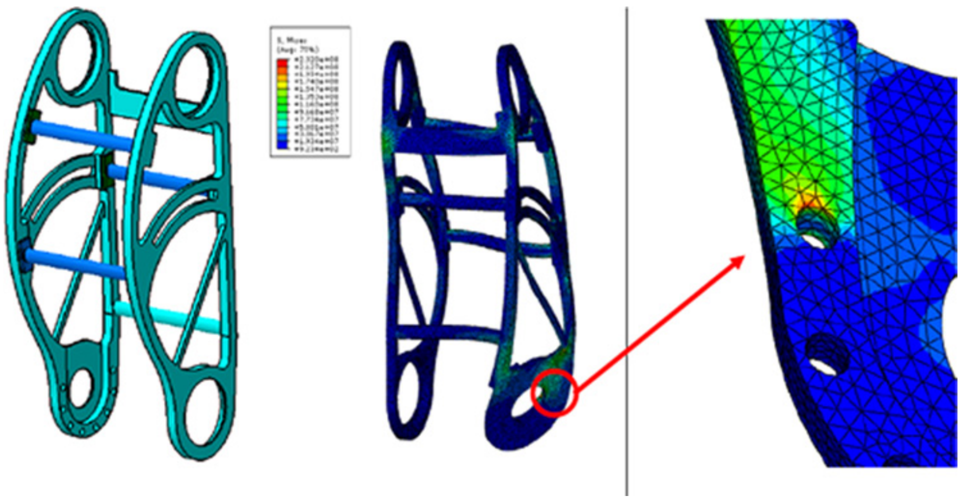

FIGURE 11 Tibia model R24. Weight: 917 g; maximum Von Mises tension: 2.32 $e^8 N/m^2$ (color figure available online).

for the tibia was the one shown in Figure 11, with the maximum possible reduction in weight.

The final manufactured tibia and thigh are presented in Figure 12.

Case Study 3: The Hip

The last significant improvement regarding the mechanical design of the lower part was replacement of the cantilever supporting structure of Rh-1 by a planar design in TEO. Though it implies more design efforts, the robot stiffness was considerably improved, avoiding the flexural problems that were not solved in Rh-1.

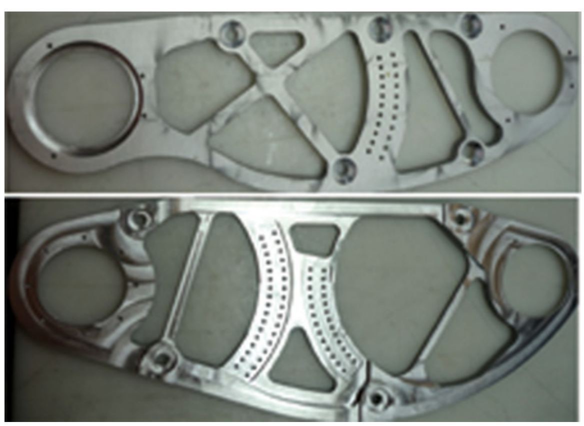

FIGURE 12 Manufactured tibia (top) and thigh (bottom) (color figure available online).

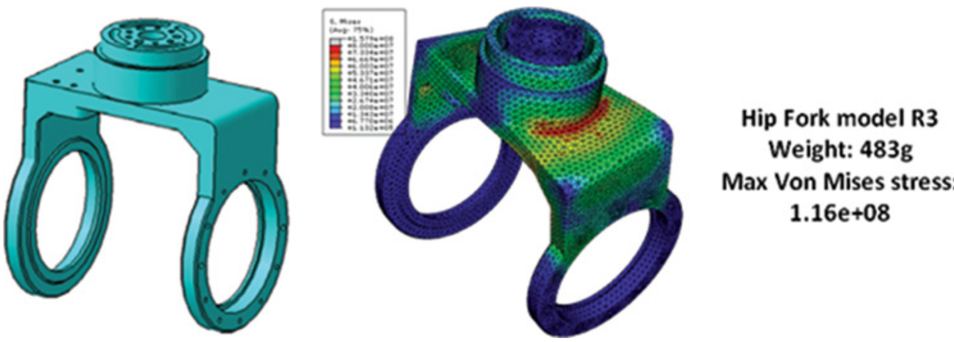

FIGURE 13 Hip cross part model of the humanoid robot TEO (color figure available online).

Based on required trajectories, dynamic simulations were performed in order to optimally define the geometrical shape of the hip and its thickness (both fork and cross parts, as in the ankle) and to avoid internal tension concentration points. Figure 13 shows the FEM analysis performed to the fork part of the hip. The FEM study presented for the cross part of the ankle validates the fork part of the hip, because in this case the hip mechanical efforts are lower than the ankle ones. Special consideration of required speed and torque of the additional motors was taken in account in order to keep the power requirements lower enough.

A picture of the manufactured parts of the hip is shown in Figure 14.

Performing a similar FEM study with the rest of elements of the legs, the final result is a weight reduction of 356 g per leg, which implies a global weight reduction of 712 g in the lower body of the humanoid robot. This reduction is still conservative and a high design security coefficient for structural integrity is guaranteed to ensure the correct performance of the structure in the worst walking conditions.

FIGURE 14 Manufactured hip cross part (left) and hip fork part (right) (color figure available online).

CONSIDERATIONS ON THE ENERGY SYSTEM DESIGN

After analyzing TEO's power requirements, the average continuous power required due to the electronic onboard system is about 150 W; that is, when there is no movement at any extremity but all of the drives are enable and holding the robot position. The power requirements are shown in Table 3 for typical walking speeds. This global consumption must be taken into account when considering the type of energy source to be used in our platform.

As a first approach, we considered a fuel cell (Hoogers 2003) as the energy source for our TEO platform, in order to avoid the energy problems previously experienced with Rh-1. The key feature of small fuel cells to be used as battery replacements is the running time without recharging. Obviously, by definition, the size and weight are also important. Power units with either significantly higher power densities or larger energy storage capacities than other existing batteries may find applications in portable computers, communication, and transmission devices.

The fuel cell electric generator system proposed for TEO is composed of five elements: hydrogen storage system, fuel cell system, balance of plant (BoP), control system, and power conditioning system. A scheme of the whole system is presented in Figure 15. The energy source of the fuel cell (hydrogen) will be stored in the fuel storage system, which will consist of several high-pressure hydrogen tanks that will be installed in the waist of the robot. The fuel cell system is based on proton exchange membrane fuel cell (PEM). This fuel cell takes advantage of the energy content in hydrogen to generate electrical power. The BoP refers to supporting and/or auxiliary components (regulators and valves) that help the hydrogen reach the fuel cell in appropriate conditions.

TABLE 3 Summary of Typical Power Requirements of the Lower Train

	Load per joint (Nm)	Power (W)
Ankle sagittal joints (×2)	18.7 RMS	56.6
	40.6 Max	123.8
Ankle frontal joints (×2)	27.7 RMS	30.6
	85.0 Max	94.3
Knee joints (×2)	25.4 RMS	31.3
	72.0 Max	90
Hip frontal joints (×2)	10.2 RMS	18
	26.0 Max	46.8
Hip sagittal joints (×2)	19.1 RMS	36
	84.0 Max	158.4
Hip axial joints (×2)	3.2 RMS	7.2
	7.3 Max	18
	Total P_{RMS} (W)	360
	Total P_{max} (W)	1,062

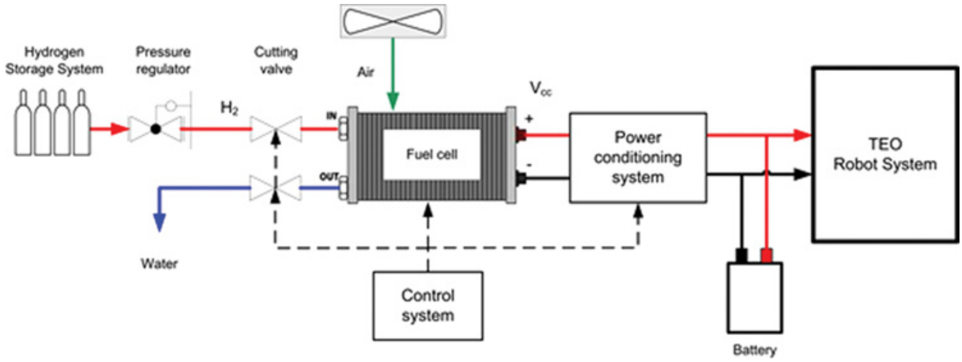

FIGURE 15 Hybrid fuel cell simplified scheme (color figure available online).

The ideal power requirement for the hydrogen cell is a continuous current discharge. Obviously, the robot actuators require nonhomogeneous performance curves, which means that the peak and continuous (RMS) power requirements must be addressed. Therefore, a converter is necessary to smooth the power demand at the cell side and is responsible for the power conditioning system. The role of this system is crucial to optimize energy transfer during task cycles. In this sense, the auxiliary rechargeable battery must both add peak power capabilities and store energy when the generated power is higher than the total consumption. Finally, the control system manages the operation of the fuel cell engine, collects operational data, and controls the possible alarms.

Taking into account the configuration and properties of the whole fuel cell generator, the space requirements for the installation of this system must be evaluated. Figure 16 shows the allocation of the elements of the power system, to be placed at the back of the robot (left), and the adaptation of the real fuel cell to the robot (right). Other additional volumes along the

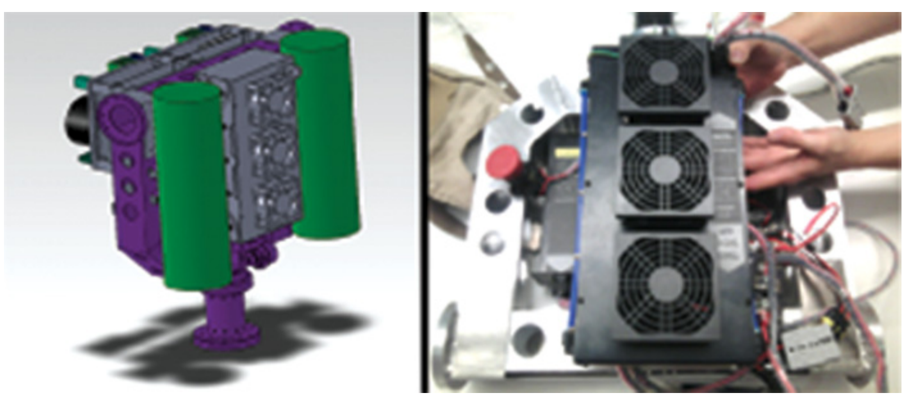

FIGURE 16 Volume and allocation of the power system (color figure available online).

robot structure can be used in case of necessity. The challenge here is to adjust the power capability of the whole hybrid system optimizing at the same time: volume, weight, power transferences from/to the energy system, and its allocation inside the robot body.

We are currently working on the specific requirements regarding the whole fuel system installation and studying the dynamic model of the cell in order to control its working point according to the power demand from the different taks being performed.

CONCLUSIONS AND FUTURE WORKS

The humanoid robot TEO is the successful result of several years of research by the humanoid robotics group RoboticsLab at University Carlos III of Madrid. The design of this full-size humanoid robotic platform was presented in this article. The methodology in the electromechanical design of a robotic platform is one of the critical points in this work. In fact, the new version has been adapted to the planned constraints related to the tasks to be realized.

The previous version (Rh-1) presented strong limitations with regard to energy efficiency. The proposed methodology focuses on reduction of energy consumption. It has been shown how it is possible to increase the energy efficiency through an optimal mechanical design of the structure and a correct choice of the electrical components.

The Rh-1 robot presented several additional weak points. The first critical point was the high flexibility of the structure, which complicated the control and the stabilization of the robot. The new design has been oriented to overcome such drawback.

In particular, the article focuses on the design of the lower part of the robot, which is the most critical from the energy point of view and also from the control point of view. Attention has been paid to the design of the ankle joint. The improvements with respect to the Rh-1 robot ankle are related to the increment of the joint motion range and its payload. Thus, the axis joint has a wide section and is made in one piece. Moreover, this axis permanently aligns the three pieces of the harmonic drive with three bearings, ensuring load transmission along the mechanical chain. In addition, range of motion is increased in the sagittal plane. This improvement allows longer steps and the center of gravity is lower compared to the Rh-1 humanoid robot. With all of these advantages, faster and more stable motion will be obtained.

Another great limitation of the previous version was the reduced workspace of the upper part, which is now the main point of study of the research group. In particular, the aim is to provide the upper part with wider workspace and greater manipulability.

Optimization of the fuel cell is also a current research activity of the humanoid robotics group RoboticsLab.

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REFERENCES

Arbulú, M. and Balaguer, C. "Real-Time Gait Planning for Rh-1 Humanoid Robot, Using Local Axis Gait Algorithm." In *7th IEEE-RAS International Conference on Humanoid Robots*, Vol. 6, 563–68. Pittsburgh, PA: IEEE, 2007. Available at: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4813927 (accessed 10 February 2011).

Hoogers, G. *Handbook of Fuel Cell Technology*. New York: CRC Press, 2003. Available at: http://www.loc.gov/catdir/toc/fy035/2002067086.html (accessed 10 February 2011).

Kaneko, K., Harada, K., Kanehiro, F., Miyamori, G., and Akachi, K. "Humanoid Robot HRP-3." In *2008 IROS 2008 IEEE-RSJ International Conference on Intelligent Robots and Systems*, 2471–78. Nice, France: IEEE, 2008.

Kaynov, D., Souères, P., Pierro, P., and Balaguer, C. "A Practical Decoupled Stabilizer for Joint-Position Controlled Humanoid Robots." In *IEEE-RSJ International Conference on Intelligent Robots and Systems*, 3392–97. IEEE, 2009. Available at: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5354431 (accessed 15 February 2011).

Martinez, C., Pierro, P., Martinez, S., Pabon, L., Arbulú, M., and Balaguer, C. "RH-2 an Upgraded Full-Size Humanoid Platform." In *Proceedings of the Twelfth International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines*, edited by O. Tosun, H. L. Akin, M. O. Tokhi, and G. S. Virk, 471–78. Istanbul, Turkey: World Scientific, 2009.

Metta, G., Sandini, G., Vernon, D., Natale, L., and Nori, F. "The iCub Humanoid Robot: An Open Platform for Research in Embodied Cognition." *Electronics* 1 (2008): 50–56. Available at: http://portal.acm.org/citation.cfm?id=17746831 (accessed 15 February 2011).

Ogura, Y., Aikawa, H., Shimomura, K., Kondo, H., Morishima, A., Lim, H.-O., and Takanishi, A. "Development of a New Humanoid Robot WABIAN-2." In *Proceedings of the IEEE International Conference on Robotics and Automation*, 76–81. Orlando, FL: IEEE, 2006. Available at: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1641164 (accessed 17 March 2011).

Pabon, L., Martinez, C., Villagra, J., and Balaguer, C. "Mechatronic Design and Control of a Critical Biped Robot Joint." In *2009 IEEE International Conference on Mechatronics*, 1–6. Malaga: IEEE, 2009. Available at: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4957206 (accessed 21 March 2011).

Pardos, J. M. and Balaguer, C. "Humanoid Robot Kinematics Modeling Using Lie Groups." In *Climbing and Walking Robots*, 569–75. New York: Springer,

2005. Available at: http://roboticslab.uc3m.es/publications/ICRA05_a773_v1.pdf.

Park, I.-W., Kim, J.-Y., Lee, J., and Oh, J.-H. "Mechanical Design of Humanoid Robot Platform KHR-3 (KAIST Humanoid Robot-3: HUBO)." In *Proceedings of 2005 5th IEEE-RAS International Conference on Humanoid Robots*, 321–26. Tsukuba, Japan: IEEE, 2005.

Pfeiffer, F., Loffler, K., and Gienger, M. "The Concept of Jogging JOHNNIE." In *Proceedings of the IEEE International Conference on Robotics and Automation*, Vol. 3, 3129–35. Washington, DC: IEEE, 2002. Available at: http://www.csa.com/partners/viewrecord.php?requester=gs&collection=TRD&recid=627511CI (17 February 2011).

Pierro, P., Monje, C., and Balaguer, C. "Modelling and Control of the Humanoid Robot RH-1 for Collaborative Tasks." In *International Conference on Humanoid Robots*, 125–31. Daejon, Korea: IEEE, 2008.

Rybski, P. E., Papanikolopoulos, N. P., Stoeter, S. A., Krantz, D. G., Yesin, K. B., Gini, M., Voyles, R., Hougen, D. F., Nelson, B., and Erickson, M. D. "Enlisting Rangers and Scouts for Reconnaissance and Surveillance." *IEEE Robotics & Automation Magazine* 7, no. 4 (2000): 14–24.

Sakagami, Y., Watanabe, R., Aoyama, C., Matsunaga, S., Higaki, N., and Fujimura, K. "The Intelligent ASIMO: System Overview and Integration." In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Vol. 3, 2478–83. Lausanne, Switzerland: IEEE, 2002. Available at: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1041641.

Staroverov, P., Marcos, S., Kaynov, D., Arbulú, M., Cabas, L., and Balaguer, C. "Creating a Gesture Recognition System Based on Shirt Shapes." In *Advances in Climbing and Walking Robots Proceedings of 10th International Conference CLAWAR 2007*, edited by M. Xie, S. Dubowsky, J.-G. Fontaine, M. Osman Tokhi, and G. S. Virk, 591–98. Singapore: World Scientific, 2007.

Staroverov, P., Martinez, R., Kaynov, D., Arbulú, M., Cabas, L., and Balaguer, C. "Detecting Sound Sources with the Humanoid Robot Rh-1." In *Advances in Climbing and Walking Robots Proceedings of 10th International Conference CLAWAR 2007*, edited by M. Xie, S. Dubowsky, J.-G. Fontaine, M. Osman Tokhi, and G. S. Virk, 615–22. Singapore: World Scientific, 2007.