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REVIEW ARTICLE

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LARM PKM solutions for torso design in humanoid robots

Abstract Human-like torso features are essential in humanoid robots. In this paper problems for design and operation of solutions for a robotic torso are discussed by referring to experiences and designs that have been developed at Laboratory of Robotics and Mechatronics (LARM) in Cassino, Italy. A new solution is presented with conceptual views as waist-trunk structure that makes a proper partition of the performance for walking and arm operations as sustained by a torso.

Keywords humanoid robots, torso design, parallel manipulators (PKM), conceptual design

1 Introduction

Human torso plays an important role in human body both in capability and performance during actions. Its anatomy is quite complex as composed of several systems whose integration ensures a very efficient functioning. Understanding of the anatomy of human torso is very helpful for achieving successful humanoid designs not only to replicate human anatomy but even for better functioning of human-like operations.

Humanoid robots have been designed and built in the last decades as much as the technology has permitted complex integration of multi-body systems with suitable capabilities in actuators, sensors, control equipment, artificial intelligence and interfaces [1,2]. They have been used within lab environments, but even in some implemented applications, with the main purposes of exploring design solutions and performance capabilities in mimicking humans and their actions. Recently, solutions have reached market availability with user-oriented performance, like Nao [3] and Pino [4], although they still require high expertise for a proper operation and use.

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Humanoid robots have been studied and developed by many research groups. Japanese have been leaders in this research field since the beginning of modern developments of humanoid robots. A first prototype named WABOT-1 started walking since 1972 [5]. This and many other prototypes have been developed at Waseda University, Tokyo [6]. In Japan, prototypes such as BLR-G2 have been also built at Gifu University [7], and ASIMO by Honda Motor Corporation [8]. In Japan many other research groups are still working in this field. In fact, the National Institute of Advanced Industrial Science and Technology in Tokyo (AIST) is sponsoring a humanoid project, which has begun in 1998, by supporting 15 research institutes throughout Japan [9], with last HRP-2P solutions.

Also in USA and Europe there are many researchers working on humanoid robots. Some interesting prototypes of humanoid robot are:

1) JOHNNIE and ERMES at the University of Munich (Germany) [10,11];

2) ARMAR at University of Karlsruhe (Germany) [12];

3) ELVIS at Chalmers University in Goteburg (Sweden) [13];

4) ROBONAUT, DART and EVA by NASA (USA) [14];

5) COCO, COG and KISMET at MIT (USA) [15];

6) The hydraulic and pneumatic humanoid robots for entertainment by SARCOS (USA) [16];

7) Humanoid robot CENTAUR at KIST (South Korea) [17];

8) The human robot at KAIST (South Korea) [18];

9) JOHNNY WALKER at the University of Western Australia (Australia) [19].

The increasing activity of the research groups working on humanoid robots is also shown in a very high number of papers published in many international conferences such as, IFToMM congress, ICRA, RoManSy and other international conferences. There is also an IEEE-RAS international conference only on humanoid robots. A specific journal is focused on humanoid robots as well.

In general, a special attention on torso structures in humanoid robots can be understood as focused along two main directions, namely, design developments of sophisticated solutions towards fully android behaviors and design arrangements of limited-skill solutions towards low-cost easy-operation systems. Most interesting advances are worked out in project developments for sophisticated solutions, for example the above mentioned Honda Asimo, Wabian and HRP. But those advances are also used in the second category of approaches where challenges are attached to achieve torso designs and operations with less complicated solutions for a more user-friendly operation and practical implementation.

This paper refers to an activity at LARM in Cassino that aims to develop a torso solution for humanoid robots with a design that is based on parallel manipulator kinematic architectures (PKM). In the paper, problems and requirements are discussed by referring to main aspects that can motivate and justify a new Laboratory of Robotics and Mechatronics (LARM) solution that is proposed herein from a conceptual viewpoint with a kinematic design as a result of previous experiences and designs.

2 Torso features in humanoid robots

In general, humanoid robots are developed to fully mimic the structure and operation capabilities of human beings within research and development projects both with application purposes and study aims.

Human torso is a central platform of human body to which limbs are attached and within which most of the organs are located. Its anatomy is very compact and complex, mainly consisting of a skeleton system and muscle assembly as concerning with biomechanical functions shown in Fig. 1 [20].

(a) (b)

Fig. 1 Anatomy of human torso. (a) Skeleton structure; (b) muscle system

Main requirements and design structures of torso for a humanoid robot can be summarized as shown in Fig. 2, in which a segmentation of the system emphasizes primary functions of the subsystems as specifically focused on mechanical properties related to trunk and waist. A numerical estimation of the merits of motion performances of human torso is summarized in Table 1 as related to degree of freedom (d.o.f.) identification for operation capability in main tasks.

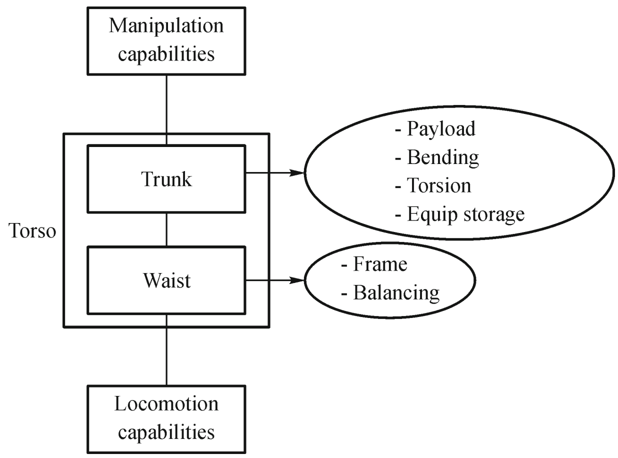
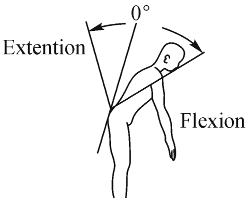
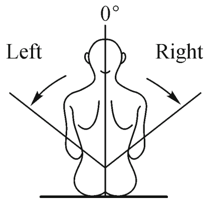
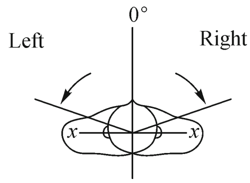


Fig. 2 A scheme for torso main features towards robot design

It is remarkable that although the gross motion of the torso can be described with 3 d.o.f.s as in Table 1, the human torso is a multi-d.o.f. system whose d.o.f. identification can be related to the gross d.o.f.s and local d.o.f.s by looking at the skeleton structure and muscle assembly both independently and dependently to each other. There are hundred pairs of muscles and ligaments, complex blood and nervous systems with different functions to make a human torso an important part of the human body with high performance capabilities.

The main mechanical operation capability of human torso can be summarized in the relatively small ranges of gross motions as reported in Table 1 and in the high payload capacity with adaptable stiffness. These characteristics in general are the main design goals in designing such a torso platform in humanoid robots. This aspect is stressed in the scheme of Fig. 2 where additionally the torso is partitioned in trunk and waist to which different main functions are demanded as recognized in motion capability and organ/equipment storage for the trunk, and frame structure and balancing motion for the waist. This permits to design humanoid torso structures with independent designs and operations of trunk and waist with the aim to simplify the control and action of such a torso platform also in terms of manipulation capability with arms that attached to the trunk and locomotion performance with legs that are attached to the waist.

Table 1 Motion ranges of human torso in three body planes

Sagittal plane		Coronal plane		Transverse plane	
Flexion extension		Lateral bending		Transverse rotation	
					
Front	Back	Left	Right	Left	Right
45°	30°	40°	40°	50°	50°

By considering gross motions and main features of human torso it is also possible to model the torso system with three main body segments as reference platforms likewise it is proposed in Fig. 3 [21], according to the idea of segmentation of parts in a robotic humanoid structure.

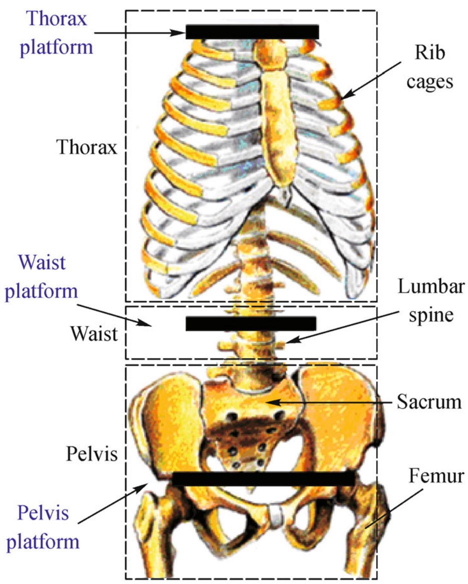


Fig. 3 A scheme for platform identification in human torso

Figure 3 shows a scheme of the skeleton of human torso versus a design model for humanoid robots. It consists of three parts: pelvis, waist and thorax. The rib cages and spine column of the upper part contribute to thorax which contains important human organs like heart, lung, liver and stomach.

The lumbar spine, which is the waist segment, is the most important and largest part of human spine. The spine articulates with the pelvis by sacrum; the pelvis articulates with two femurs in the lower part. The three body platforms are identified as the thorax platform, the waist platform and the pelvis platform. The trunk segmentation can be considered as referring to the thorax platform connected to the waist platform whereas the waist segment can be considered as related to the waist platform and pelvis platform.

Alternatively, as indeed it is in general a used solution in current humanoid robots, the torso structure is designed with a serial chain structure with well identified actuators for the corresponding gross motions, like in the case in Fig. 4 [22], where the platform body of the torso is reduced just to the connection link.

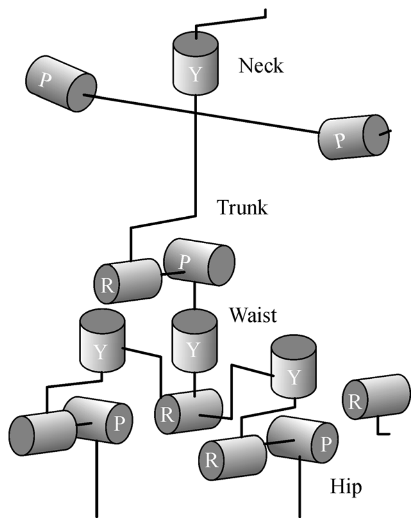


Fig. 4 A design scheme for humanoid torso in Wabian 2 in 2005 [22]

The advantages of such a design can be considered mainly in a fairly simple mechanical design and direct operation control of those gross motions, whereas main drawbacks can be recognized in a limited payload capability with poor stiffness.

Thus, following the conceptual idea in Fig. 2 a torso for humanoid robots can be designed according to the scheme in Fig. 3 to obtain a structure with the three body platforms connected by suitable mechanisms as shown in Fig. 5.

The thorax platform is the frame for arms and neck with

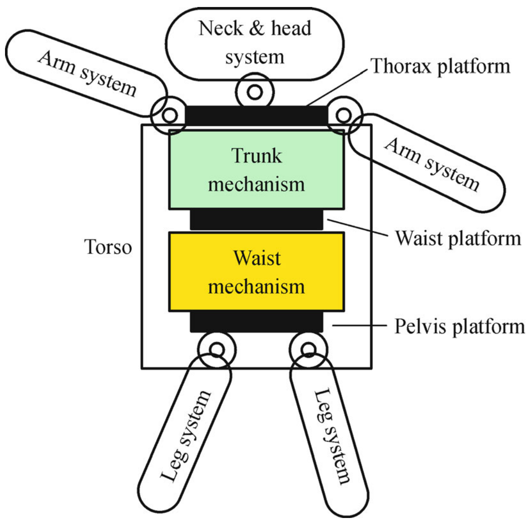


Fig. 5 A conceptual design for a torso humanoid design with waist and trunk mechanisms

a suitable motion coordination through the mechanism that connects it to the waist platform. The pelvis platform is the frame for the legs with a suitable motion coordination through the mechanism that connects it to the waist platform. The waist platform can be considered the reference frame platform for the torso body and is the central body for the mechanisms connecting with the other platforms so that it can be conceived as the prescribed/required functions both in terms of motion performance and load capability.

Thus, the core of the torso design will be in the mechanism design. Because of the above mentioned main torso characteristics, those mechanisms can be thought to be preferable with a parallel manipulator architecture in order to achieve successfully a compact design with suitable high motion performance and stiff high payload capacity.

3 LARM PKM solutions

Design solutions for torso structure have been attempted and elaborated at LARM in Cassino, Italy since 2001. A discussion of these attempts is useful to outline problems and features of PKM-based design for humanoid torso designs.

A summary of LARM designs and corresponding experiences is reported in Table 2 as an overview of the evolution of the attempted designs with the variety of experienced solutions. The PKM-based solutions were conceived and inspired by referring to CaPaMan (Cassino parallel manipulator) [23] and its other designs [24].

In particular, the proposed humanoid robot in Fig. 6 [25], was designed in 2001 with the main goals of a mechanism-based design by using prototypes of robotic systems that were developed at LARM originally for other purposes. In addition, main features were thought for a fairly simple operation with a reduced number of actuated d.o.f.s for a humanoid whose size could be of a weight of 500 N, 160 cm tall and 60 cm large. The modules of previously developed LARM designs with prototypes built at LARM are:

1) A parallel-serial manipulator, named as CaHyMan (Cassino hybrid manipulator), that has been adjusted to be trunk and neck by using CaPaMan design as it is;

2) A modular two-finger gripping mechanism with force controlled operation;

3) A biped walking machine, named as EP-WAR (electropneumatic walking robot), to be adjusted for the payload and operation of the humanoid.

Unfortunately, there were no possibilities to go further in the design and study of this conceptual design and no prototype assembly was attempted since the single parts in the existing prototypes were not conveniently sized and indeed not arranged for a humanoid assembly. Nevertheless, the idea of such a humanoid robot with a reduced number of actuated d.o.f.s, mechanism-based design and assembly of LARM prototypes received attention and

Table 2 Chronicle of LARM PKM solutions for humanoid torso

Year	Short description	Reference	Figure
2001	First conceptual design with LARM prototypes	[25]	6
2003	CALUMA design	[26–28]	7
2008	LARM waist-trunk system	[21,29]	3, 8
2010	trunk design with two CaPaMan structures	[30]	9
2013	CaPaMan 2 with simplified waist	[31]	10

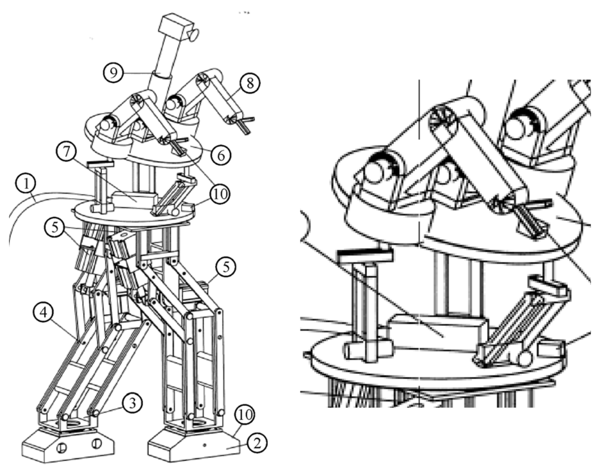


Fig. 6 A scheme of humanoid robot with CaPaMan-based trunk design and other LARM structures as conceived in 2001 [25]

credit for possible developments in a low-cost user-oriented humanoid solution, even if with limited performance capabilities that were investigated with preliminary conceptual simulations.

The idea was reconsidered some years later since 2003, after improvements in those other part prototypes and mainly as a consequence of the successful design of LARM hand and experiences of collaboration at Waseda University in Tokyo with Wabot humanoid robot, as the one reported in Ref. [22].

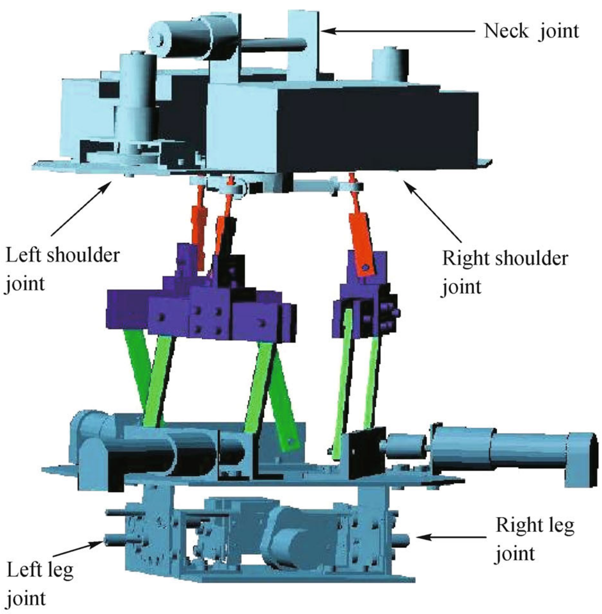
Figure 7 shows a first design architecture for CALUMA (Cassino low-cost humanoid robot) [26]. In particular, Fig. 7(a) shows the trunk design with the design of CaPaMan 2bis; Figure 7(b) shows a 3D-CAD model that has been used for several dynamic simulations and design optimizations [27,28]. CALUMA is again composed by prototypes that have been designed and built at LARM in Cassino whose maximum dimensions are 962 mm height, 839 mm width and 413 mm depth. The CALUMA design is still based on mechanism designs even with linkage solutions for a simplified robust manufacturing of main parts, with developments up to 2009. Figure 7(b) shows a 3D-CAD model of CaPaMan 2bis as adjusted as humanoid trunk [27]. It is composed of a movable plate as thorax plate that is connected to a fixed plate as pelvis plate by means of three leg mechanisms. Each leg mechanism is composed of an articulated parallelogram whose coupler carries a rotational joint, a connecting bar which transmits the motion and a spherical joint. The leg module is a biped prototype that requires only one actuator for the two legs. This design uses a Chebychev-pantograph mechanism in order to transmit the movement to the feet.

The solution in Fig. 8 was developed since 2008 after a reconsideration of the CALUMA design. The humanoid robot design is centered on the trunk design with two PKM structures [21,29], that work separately but in combination, as inspired by human torso in the model of Fig. 3.

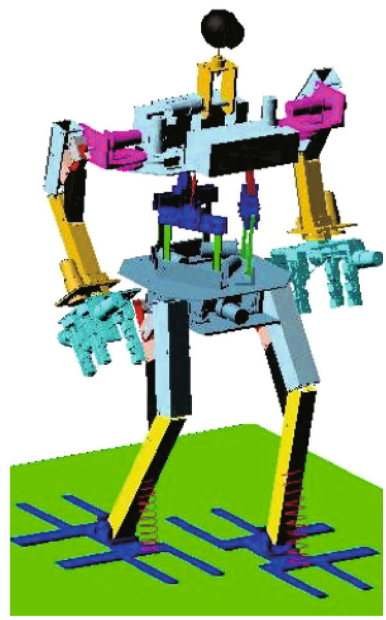
The proposed waist-trunk system is illustrated by a kinematic scheme with design parameters in Fig. 8(a) and a 3D model within a humanoid design in Fig. 8(b). The proposed waist-trunk system consists of two classical parallel architectures which are connected together in a serial chain architecture. In addition, the combination of the two systems is a novel design as a complex system with easy operation performance because of their well understood behavior of each single.

The upper part of waist-trunk system is the trunk module which consists of a thorax platform, a waist platform and six identical leg mechanisms to obtain a 6 d.o.f.s parallel manipulator structure with the aim to imitate the movements of human lumbar spine and thorax. Each leg mechanism is composed of a universal joint, a spherical joint and an actuated prismatic translation joint.

The lower part of waist-trunk system is the waist module which consists of a pelvis platform, a waist platform and three identical leg mechanisms to obtain a 3 d.o.f.s parallel manipulator structure. The waist module shares waist platform with the trunk module but the leg mechanisms are installed on the counter side in a downward architecture. The pelvis platform is connected to the waist platform with three leg mechanisms and a passive spherical joint. There are six bars connected with the passive spherical joint with the waist platform and pelvis platform. The waist module is an orientation platform and has three rotation d.o.f.s around the yaw, pitch and roll axes, respectively. The waist module is aimed to imitate the function of human pelvis



(a)



(b)

Fig. 7 CALUMA design developed since 2003 [26]. (a) Torso design as CaPaMan 2bis structure; (b) the whole humanoid robot

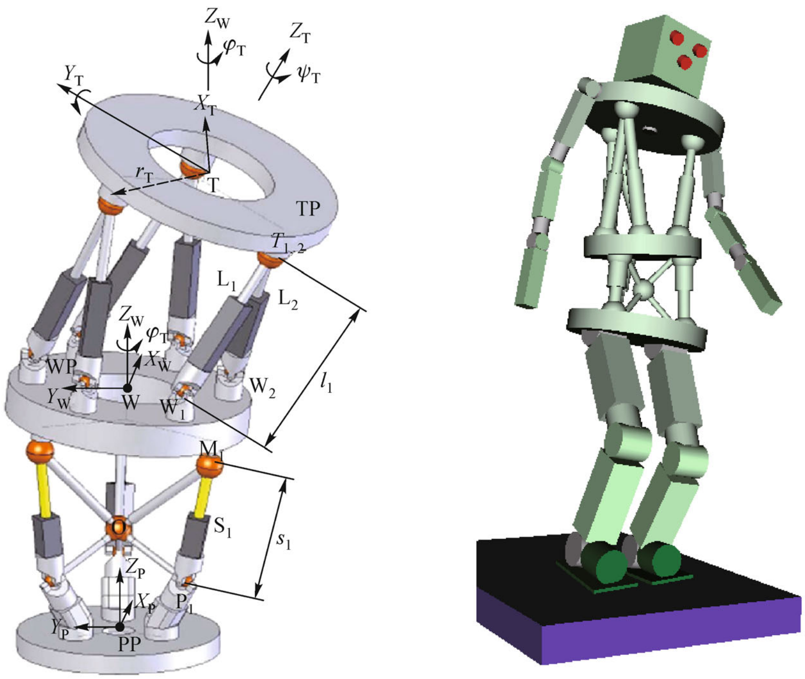


Fig. 8 A LARM waist-trunk system with parallel manipulator architectures as developed for humanoid robot since 2008 [21]. (a) The PKM design; (b) the whole humanoid robot

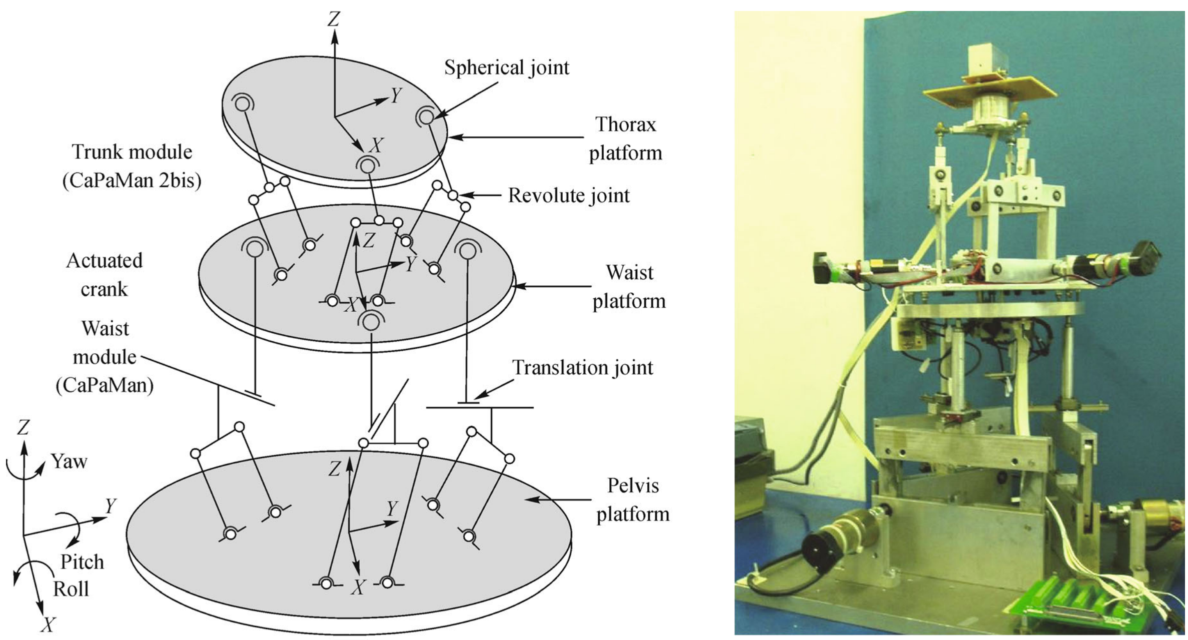
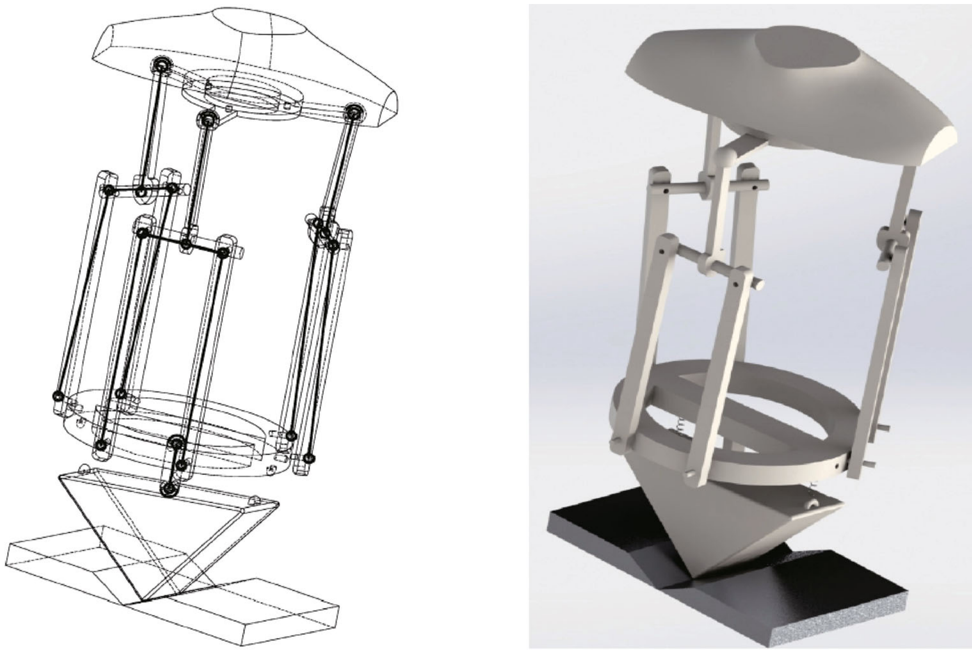


Fig. 9 A waist-trunk system by using two CaPaMan manipulators as experienced in 2010 [30]. (a) A kinematic scheme; (b) the experimental set up

during walking, running and other locomotion movements.

In Fig. 9(a) specific structure for a torso design with LARM PKM prototypes is shown as arranged in 2010 to perform lab experiences for experimental characterization of motion and actuation characterization [31]. The experiments were carried out successfully with the simultaneous motions of the 6 d.o.f.s coming from the used CaPaMan 2bis prototype as trunk module and



(a) (b)

Fig. 10 A simplified waist-trunk design by using CaPaMan 2bis structure and reduced waist body as conceived in 2013 [31]. (a) A CAD scheme; (b) a rapid prototyping design

CaPaMan as waist module. The experienced motion was aimed to mimic human bending and torsion by looking at the motion of the thorax platform as the mobile plate of the CaPaMan 2bis module and the waist platform as the mobile plate of CaPaMan. Interesting was to check that the moving parts of the two PKM modules did not interfere with the possible workspace of a humanoid torso structure by even leaving room inside available for other equipment. The used sensors registered smooth feasible accelerations during the motion and the actuator toques remained within proper ranges that will permit even further motion planning.

In Fig. 10, a scheme and a rapid prototyping design are reported for a simplified solution that is under development with the idea to limit the moving parts and actuated d.o.f.s in a very compact solution. The core of the torso mobility is still demanded to the PKM solution of CaPaMan 2bis [31].

4 A new design and its challenges

The LARM designs and experiences can be summarized together with the conceptual structure in Fig. 3 by outlining comments for new designs according to the schemes of Figs. 5 and 11. In particular, Fig. 11 is aimed to stress that a minimum of 5 rotation motions for a humanoid torso (3 for the trunk and 2 for the waist) can be obtained by the suitable platforms of PKMs by using proper mechanisms in the PKM structures. This is to indicate PKMs with few d.o.f.s are good candidates for the different peculiarities of trunk and waist functionalities. Challenges are typical of PKM design, such as avoidance of singularities in the operation workspace, suitable workspace volume both in position and orientation capabilities, torque power for suitable small actuators and so on, but they should also be adjusted and optimized to the peculiarities of humanoid torso design.

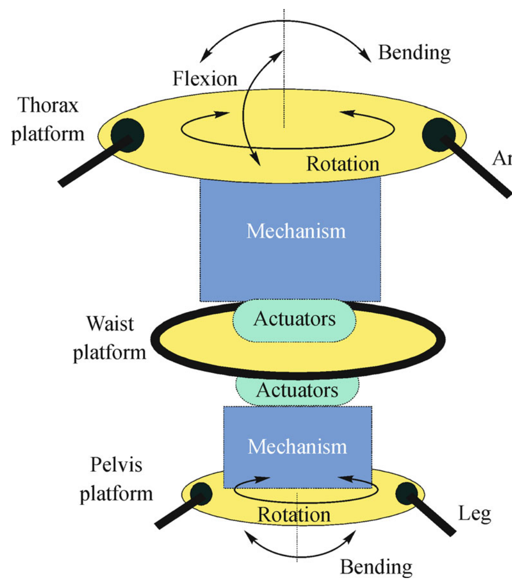


Fig. 11 The new conceptual trunk-waist design under development at LARM with two PKM modules

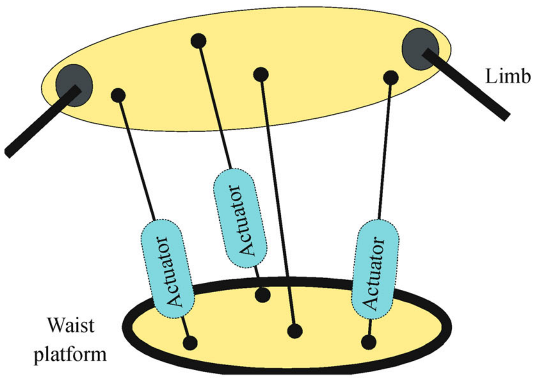


Fig. 12 A design of PKM module of humanoid torso under development at LARM in Fig. 11. (a) A kinematic scheme for 3 d.o.f.s solution; (b) a CAD design for rapid prototyping of a 2 d.o.f.s solution

The above considerations are under development at LARM for a new design with modular structures as the one indicated in Fig. 11 by looking at fairly simple PKMs. In Fig. 12 a conceptual design is outlined in which a central rod is thought to function as the bone spine with spherical joints on both platforms so that it will act as a passive limb with function of load capacity. Three actuated limbs will give the necessary d.o.f.s whereas the actuators of the actuating power source will be located on the central waist platform. As it can be noted from Fig. 12(b) details of mechanical design will be constrained in achieving compact solutions with proper functionalities.

5 Conclusions

Torso design plays an important role in human-like operation of humanoid robots. The characteristics of human torso can be partitioned into waist and trunk as structures that perform mainly supporting actions for leg walking and arm manipulations, respectively. LARM solutions are presented as based on PKM architectures to discuss problems and experiences indicating challenging and promising results in successful designs for high performance humanoid robots. A new conceptual design is presented with a modular design for mechanism-based solution with compact structure with few actuated d.o.f.s.

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