

# ECCE1: the first of a series of anthropomorphic musculoskeletal upper torsos

Hugo Gravato Marques, Michael Jäntsch, Steffen Wittmeier, Owen Holland, Cristiano Alessandro, Alan Diamond, Max Lungarella and Rob Knight

**Abstract**—The human body was not designed by engineers and the way in which it is built poses enormous control problems. Its complexity challenges the ability of classical control theory to explain human movement as well as the development of human motor skills. It is our working hypothesis that the engineering paradigm for building robots places severe limitations on the kinds of interactions such robots can engage in, on the knowledge they can acquire of their environment, and therefore on the nature of their cognitive engagement with the environment. This paper describes the design of an anthropomorphic humanoid upper torso, ECCE1, built in the context of the ECCEROBOT project. The goal of the project is to use this platform to test hypotheses about human motion as well as to compare its performance with that of humans, whether at the mechanical, behavioural or cognitive level.

## I. INTRODUCTION

Standard humanoid robots mimic the human form, but the mechanisms used in such robots are very different from those in humans [1]. Typically these robots are designed according to the same engineering techniques that are used in industrial robots, as is shown by the characteristics of their bodies: they are heavy and stiff, and use precise and powerful motors to control joints with easily identifiable axes of rotation. This contrasts heavily with the human body, which is relatively light and compliant, and has a noisy and redundant actuation system controlling some complex joints (e.g. the shoulder).

One important constraint that separates the human body from that of an industrial robot is the environment that each has to cope with. Whereas the environment of the industrial robot can be tailored to facilitate its interactions and achieve its mission, the human body has to cope with an extremely dynamic environment which is often hostile, partially unknown and unpredictable [2].

It is not only to interact with human environments that a robots body has to conform to certain principles; it is also to interact with humans themselves. The stiff actuation principle

This work was supported in part by the European Commission FP7 Cognitive Systems and Robotics project ECCEROBOT, contract no. 231864.

H. G. Marques, C. Alessandro and M. Lungarella are with the Institut für Informatik, University of Zürich, Switzerland hgmarques@ifi.uzh.ch, alessandro@ifi.uzh.ch, lungarella@ifi.uzh.ch

M. Jäntsch, S. Wittmeier are with the Institut für Informatik VI Technische Universität München, Germany michael.jaentsch@in.tum.de, wittmeis@in.tum.de

R. Knight is with the RobotStudio company, France rob.knight@therobotstudio.com

O. Holland and A. Diamond is with the University of Sussex, UK o.e.holland@sussex.ac.uk, a.diamond@sussex.ac.uk

of most humanoids poses a major threat to humans due to the large amounts of inertia produced. Although advances in robot control have shown that it is possible to build safer robots using standard actuation methods with computationally controlled compliance, this has the weakness that it is not intrinsic to the robots body.

Probably the best known conventional humanoid robot is Honda's ASIMO [3]. Although the engineering behind ASIMO is of the highest quality, when looking at ASIMO interacting with its environment it is clear that the movement patterns are often quite different from those of humans. For example, when the robot walks, its torso is kept straight and stiff, unlike the human torso which flexes and swings like a pendulum to facilitate bipedal locomotion in an upright posture. If pushed while walking, ASIMO compensates with stiffly controlled precise movements, quite different in character from the largely passive compensatory flexing of a human or animal.

Our working hypothesis is that the engineering paradigm for building robots places severe limitations on the kinds of interactions such robots can engage in, on the knowledge they can acquire of their environment, and therefore on the nature of their cognitive engagement with the environment. The reasoning behind the complex platform described here is that an anthropomorphic (truly human-like) robot body will facilitate human-like environmental interactions, and will also require the use of control systems similar to those used by the brain, which in turn will mediate the knowledge acquired from the environment, and hence the forms of the cognitive engagement with the environment.

This paper describes ECCE1 (see Fig. 1), the first anthropomorphic robot chassis produced in the context of the ECCEROBOT project. The first section introduces the motivations of the project. The second section identifies a set of four design principles present in the human body that are usually not considered in the design of classical humanoids. The third section offers a short description of three robots which are built according to (at least some) of these principles. The fourth section briefly describes ECCEOS, the physics-based simulator being built for the project. Finally, the last section identifies the improvements that will be made in future iterations of the robot prototype.

## II. MOTIVATION

ECCEROBOT (Embodied Cognition in a Compliantly Engineered Robot) is a three-year project funded by the 7th Framework Programme of the EU that aims to build



Fig. 1: ECCE1 – the first prototype of the ECCEROBOT series of anthropomorphic robots.

and control an anthropomorphic robot, and to investigate the extent to which it displays human-like cognitive features. Instead of just possessing a human-like external shell, the body of an anthropomorphic robot is closely modeled on the inner structures and mechanisms of the human body – bones, joints, muscles, and tendons – and thus has the potential for human-like action and interaction in the world.

The main goals of the project are the following:

- to design and build an anthropomorphic torso mounted on a powered mobile platform;
- to develop methods of characterising such robots in terms of the information flows emerging from their human-like intrinsic dynamics and sensory-motor coupling;
- to investigate ways of controlling the robot during movement, interaction, and mobile manipulation, and to combine successful control strategies in a single architecture deploying them appropriately according to circumstances and tasks;
- to exploit the anthropomorphic nature of the robot in order to achieve some human-like cognitive characteristics through sensory-motor control; and
- to evaluate the functional and cognitive abilities of the robot, both absolutely and in comparison with a state of the art conventional robot.

### III. ANTHROPOMIMETIC DESIGN PRINCIPLES

The major role of the ECCEROBOT platform is to enable the study and testing of hypotheses about human functionalities at the mechanical, behavioural and cognitive level. This distinguishes the ECCEROBOT project from almost all other research projects on humanoid robots, and motivates the requirement for a humanoid robot that mimics as closely as possible the mechanical structures of the human body. There are obvious difficulties in achieving this requirement, especially since much current technology cannot yet perform at the level of its biological counterparts. For example, the power to weight ratio of current actuators is still far below that of human muscle.

Even though we face obvious technological challenges, we believe that we have developed a first robot prototype which displays a complexity comparable to that of the human body. In [1], Owen Holland and Rob Knight outlined what they referred to as the anthropomorphic principle, calling for a robot which imitates not just the human form, but also the biological structures and functions that enable and constrain perception and action. In the following subsections we put forward four mechanical design principles of the human musculoskeletal system which are followed in our robot, and which we think are essential if one wants to explore hypotheses about human motion generation: tendon-driven redundant actuation, multiple joint actuators, compliance and complex joints.

#### A. Tendon-Driven Redundant Actuation

In today's humanoid robots the actuators are usually positioned at the joints to control particular axes of rotation, with each axis of rotation being controlled by one motor. This principle can be seen in well-known robots such as ASIMO [3]. The human body, on the other hand, exploits tendon-based techniques to move its limbs. Instead of placing the actuators directly on a joint's axis of rotation, it uses contractile muscles attached to bones via elastic tendons. During muscle contraction a force is exerted on the anchor points of the muscle which, if sufficiently high, causes a movement of the relevant limb-parts. Muscles are asymmetric, in that they can only pull, not push. Typically this entails having a redundantly actuated body, i.e. a body in which there are more actuators than there are degrees of freedom (DoF).

#### B. Multi-articular Joint Actuators

In addition to muscles providing straightforward actuation at a single joint, the human body has muscles which pass across two or more joints, and can therefore move the relevant limb-parts at more than one joint [4]. For example, the biceps is attached to the scapula and to the radius, forming a parallel muscle. Although its primary role is the supination and flexion of the forearm, it also has an effect on the shoulder, and so an anthropomorphic robot should include this structure in order to capture fully the character of the possible movements.

#### C. Compliance

In order to enable precise control, humanoid robotic actuators are typically stiff. The muscles and tendons in the human body, on the other hand, are elastic, providing two practical advantages: the compliant structure and actuation shields the mechanisms from imposed shock loads, and the compliance and low mass allow safe interaction with the environment such as grasping a fragile object (cf. [5]). The elastic nature of muscle systems is typically represented (for example, in the popular Hill muscle model) as an arrangement of lightly damped springs.

#### D. Complex joints

The joints of humanoid robots usually have clearly identifiable axes of rotation. From the classical control point of view this allows their motion to be dealt with in a tractable mathematical framework. However, the human body has joints which do not match this description. For example, the shoulder is an extremely complex structure which includes the clavicle, the scapula, and the humerus. Although it is connected to the sternum via the clavicle, the scapula does not have clearly defined axes of rotation as it is held in place mainly by ligaments and muscles. This arrangement produces a wide range of motions (rotations and translations) that are not easy to classify. The spine is another complex structure central to our embodiment which also poses enormous challenges from the perspectives of both the design and the control.

#### IV. STATE OF THE ART

There are a small number of humanoid platforms which comply with at least some of the anthropomorphic design principles identified, and it will be useful to discuss three examples: the iCub, Kojiro and the ZAR5. The iCub platform is designed to represent a 3 year old child. The robot is about 1m height, weighs about 22Kg, and has 53 DoF [6]. It is driven both by conventionally actuated joints, and by tendon-driven muscles (in the hands, shoulders, waist and ankles) each consisting of a brushless motor in series with a cable. The types of joints actuated via the tendons are classically engineered 1 DoF, 2 DoF and 3 DoF joints; for example, both the shoulder and the spine have been simplified into 3DoF joints [7]. The cables used are inelastic, but the tendon-driven structure gives the robot some incidental compliance. Finally, although the robot uses tendons, it is not redundantly actuated.

In its structure, the Kojiro robot, as well as its predecessor, Kotaro, is close to the system that is the target of the ECCEROBOT project. However, the aim of the Kojiro project is quite different, as it is directed towards identifying and investigating the benefits of this technology for practical robotic applications rather than serving as a tool to investigate humanoid motor and cognitive development [8]. Kojiro is redundantly actuated by analogues of human muscles; a brushless motor is placed in series with a cable and an elastic component which gives the system intrinsic compliance.

The robot includes some complex joints. The spine consists of rigid disks stacked on top of each other with spherical joints in between. The shoulder blade is also a complex structure inspired by the human body, and includes a spherical thorax, a scapula and a clavicle [9]. However, there is no mention of multi-articular actuation in any of the publications we have studied.

Like the two other robots, ZAR5 (Zwei-Armiger Roboter) is also designed according to biological principles: not only its shape, proportions, and radii of action, but also its joints and musculo-tendon-skeletal structure were inspired by its anthropological counterparts [10]. The actuation scheme uses pneumatic contractile elements (or fluidic muscles), which

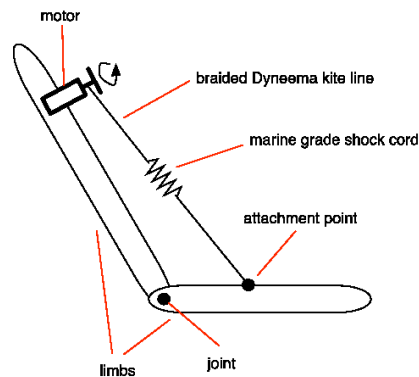


Fig. 2: The actuation principle of the ECCE1 (see details in the text).

have a high power-to-weight ratio and display no stick-slip behavior. Although the Dyneema tendons are inelastic, the use of air-driven actuation technology gives intrinsic compliance to the robot. Muscle pairs arranged in antagonistic configurations drive all the joints apart from the fingers. Unlike Kojiro, this robot does not have complex joints.

#### V. ECCE1 – AN ANTHROPOMIMETIC ROBOT

ECCE1, the first platform developed within the ECCEROBOT project, aims to capture the dynamics, the geometry, and the degrees of freedom of the human upper body. It is a reworked version of CRONOS, the final prototype from the CRONOS project [1],[2] during which the anthropomorphic principle was first articulated. The most outstanding feature of the design is the way in which the active and passive compliance and the many degrees of freedom combine to produce a robot in which every movement, whether active or passive, is a whole body movement, and one with a recognisably human character.

##### A. Musculoskeletal Structure

The skeleton of ECCE1 consists of a set of rigid limb structures modeled on the corresponding human bones, which are connected by the appropriate joints, or simplifications of them [1]. It consists of an upper torso built on top of a spine-like structure. For both historical and functional reasons, the two shoulders of the robot are structurally different. The left shoulder has an anatomically correct joint structure with a scapula carrying a ball-and-socket joint for the humerus, and a clavicle jointed to the sternum; the right shoulder is a classically engineered joint of three orthogonal 1 DoF joints fixed to the trunk. This arrangement allows the comparison of the anthropomorphic shoulder with the rationalised version. On top of the torso sits a rather elongated articulated neck (similar in structure to the spine) which supports the head.

The material used for most of the skeleton is an engineering grade thermoplastic, a caprolactone which can be easily hand moulded into the desired shape when heated to around 60C. (We have not yet observed any softening of this material



Fig. 3: The flexible spine.

as a result of motor heating when the robot is actuated, but it is a possible hazard.) Each limb provides points for attaching the actuators (or muscles), which consist of high-torque DC motors in series with one or more strands of marine grade shock cord (sleeved natural rubber). The motors, which are controlled by the electronic control units described in (H), pull on the shock cord via Dyneema kite line wound round the gearbox output shaft; the other end of the shock cord is attached to the actuated limb structure as shown in Fig. 2. Motor position is derived from potentiometers mounted on the output shaft.

The muscle locations and attachment points are designed to match those of human muscles, and so many of the arrangements are antagonistic. However, the elasticity of shock cord is linear, except at the extremes, and so the joint compliance under co-contraction is fixed rather than variable. The functional consequences of this limitation are unknown, and will be established by experiment.

### B. Flexible Spine and Neck

The torso is held vertically by means of a chain of four vertebrae-like elements separated by compliant disks; this allows the robot to bend both in the sagittal and in the coronal planes (see Fig. 3). Movements are produced by two agonist-antagonist groups of muscles placed on all four sides of the spinal structure. An additional actuator is mounted in the front (at the abdominal level) to assist in handling the heavy static load. Other non-actuated passive elastic components are used to stabilize the entire torso.

The neck is similar to the spine, with three rather elongated vertebral elements allowing bending in the sagittal and coronal planes. An additional 2 DoF joint is used to rotate the head around its longitudinal and lateral axes. The neck-head kinematic chain is held together by several longitudinally arranged shock cord segments, and the whole complex is moved by four elastically coupled actuators.

### C. Head and Eye

Unlike most human beings, ECCE1 is a cyclops – it has only one eye – but future examples will be binocular. ECCE1 is currently equipped with a single camera with a  $90^\circ$  field of view mounted in an eyeball-like structure (see Fig. 4). Like the human eye, the eyeball of ECCE1 can pan, tilt and rotate around the axis perpendicular to the image plane.

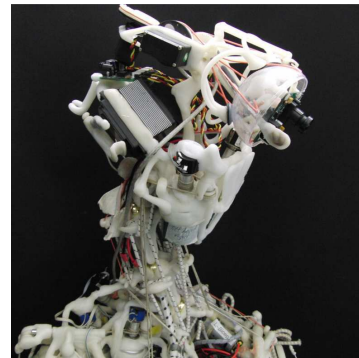


Fig. 4: The single eye.

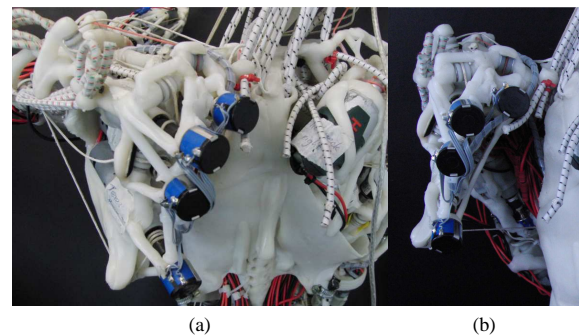


Fig. 5: Detail of the scapula of ECCE1. As can be seen in b), at the back the scapula can be slightly detached from the torso.

The camera is actuated by three orthogonally arranged servos each of which controls the desired angle of orientation in the relevant dimension.

### D. Shoulder Joint

The right shoulder conforms to a classical structure consisting of three orthogonal hinge joints, and is actuated by five artificial muscles, one of which, the biceps, is a bi-articular muscle which also flexes the lower arm about the elbow. The left shoulder replicates the structure of the human shoulder (see Fig. 5). A ball-and-socket joint between the humerus and the scapula allows the rotation of the humerus about three orthogonal axes. The scapula is connected to the clavicle using ligaments; the clavicle, in turn, is connected to the torso at the sternum by means of a non-actuated ball joint. The scapula is held in place by muscles, and by elastic and inelastic ligaments. Five actuators are used to move the scapula, and the ball-and-socket joint it carries is actuated by four artificial muscles including the biceps, which is a bi-articular muscle as in the right arm.

### E. Elbow Joint and Rotators

The elbows consist of 1 DoF hinge joints allowing for the flexion and extension of the lower arm. They are actuated by three artificial muscles (including the biceps mentioned in the previous section). A stiffly actuated conventional



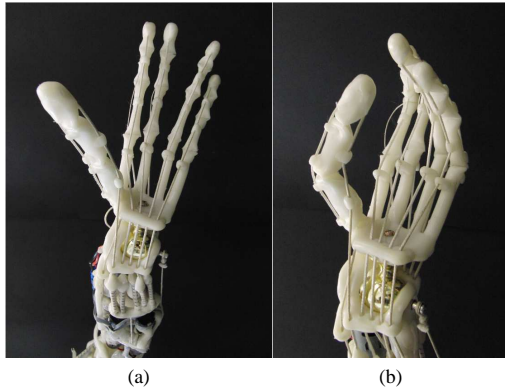


Fig. 6: Detail of the hand: a) hand opened, b) hand half-closed.

arrangement controls the rotation of the forearms around their longitudinal axes.

#### F. Wrist

Each wrist comprises a 2 DoF joint actuated by two agonist-antagonist pairs of actuators. This mechanism is able to produce radial and ulnar deviation (movements towards the thumb and the little finger) as well as flexion and extension (tilting towards the palm and the back of the hand). The flexor muscle also controls the closing motion of the hand.

#### G. Hand and Fingers

At present only one artificial muscle is used to actuate each hand, with all the fingers being connected to the muscle so that as the muscle contracts, the grip closes (see Fig. 6). The opening of the grip is achieved by a passive elastic structure.

#### H. ECUs – Electronic Control Units

Typically, robot control is done using a centralized control scheme where all the sensor values are fetched by a central controller and new actuation values are calculated. This is possible when the number of DoFs are limited. As ECCE1 has 43 actuators, each with several sensors, such an approach is infeasible due to the complexity of the wiring and the computational timing, and a distributed approach is necessary. We have therefore developed electronic control units (ECUs) for sensor-actuator control. Each of these ECUs has enough processing power to handle two actuators and their associated sensors, and can run dedicated control algorithms (e.g. force, position and impedance control) as well as preprocessing of sensor data. The control programs running on each of the distributed control units are controlled from a central controller by sending asynchronous commands via a CANbus system.

To reduce cabling and avoid running vulnerable analog sensor signals along the robot's limbs, the ECUs are designed to be placed in strategic locations around the robot torso, and so size and weight were critical design factors.

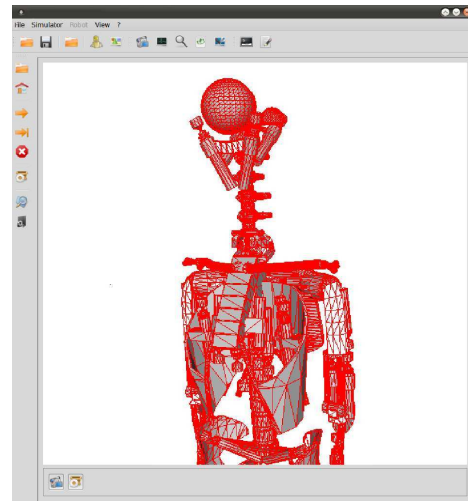


Fig. 7: ECCEOS.

The ECUs have a powerful STMicroelectronics STM32F microcontroller, incorporating a 72 MHz ARM Cortex-M3 processor, several Analog-to-Digital converters and an integrated CAN interface, as well as power electronics for two motors. The motors are controlled by PWM, using two full H-bridges, with current feedback being given by an integrated Hall-effect unit in the motor loop. The PWB measures 6 cm by 7.8 cm.

To be able to handle the complexity of a distributed system with 43 nodes, each node can be parameterized dynamically at run-time, while the firmware image is the same for all nodes. Parameters that can be changed dynamically include the control parameters of the different control loops as well as general control parameters. Only a unique identifier and bootloader need to be stored in flash, and the software image can be changed easily via the CANbus at system startup.

### VI. ECCEOS – A GENERAL TENDON DRIVEN PHYSICS-BASED SIMULATOR

In the ECCEROBOT project we are also developing a generic, highly customizable, physics-based simulator, ECCEOS, capable of utilizing CAD robot models (see Fig.7). The simulator framework uses a CORBA-based platform which is highly modular and has a programming-language-independent communication protocol for easy interfacing with existing software components. The design is generic, and so is applicable to a wide range of other robotic systems in addition to the ECCE series.

ECCEOS makes use of (1) a physics engine for computing the dynamics of the simulated bodies, performing collision detection and solving constraint equations, (2) a graphics engine for rendering the simulated scene and (3) a user interface enabling flexible user interaction with the simulation. The physics engine is the Bullet Physics Library<sup>2</sup>, an open-source rigid- and soft-body simulator.

The graphics engine is Coin3D, an OpenGL-based clone of the SGI Open Inventor 3D graphics API (also open-



Fig. 8: ECCEROBOT Design Study (EDS).

source). It is cross-platform compatible (using Qt) and provides a variety of pre-defined viewers for basic user interaction with the simulated scene. The graphical user interface, which we use to visualize and to interact with the physical model, is Qtapplication. Integration is easy since Coin3D already includes a Qt render widget.

Physics based simulation models are often hard-coded in some high-level programming language using the application programming interface (API) of the physics engine. Our approach in the ECCEOS, however, is more flexible, in that ECCEOS will allow CAD models to be loaded into the simulator at runtime, the only requirement being that the entire simulation model (the graphical as well as the physical data) must be stored in a file according to the Collaborative Design Activity (COLLADA) specifications.

COLLADA [11] is already supported by most CAD tools available, and so a physical and a graphical model of the robot can be obtained directly from CAD data. Since ECCE1 was hand-moulded, no CAD data are available from the production process, but ongoing work involves obtaining a CAD model from the 3D laser scanning of individual skeleton components. Muscle related parameters such as spring and damping constants, as well as the anchor points themselves, will need to be added manually to the CAD-derived COLLADA file. Until then, a hand-coded Blender model can be used.

## VII. FUTURE WORK

In this paper we have identified four principles for designing a robot which closely mimics the mechanics of the human body. We have described ECCE1, the first upper-torso prototype of the ECCEROBOT series, which includes all these principles in its design. Although ECCE1 lacks force

sensors and joint positional sensors, which are essential for controlling dynamic behaviours, we have already learned a great deal about the intrinsic characteristics of the structure and its constituent mechanisms. The major problem with ECCE1 is friction, both at the joints, and in places where tendons make contact with parts of the body. A test rig revealed that the use of Teflon on all joint and rubbing surfaces, combined with higher quality and more powerful motors, produced acceptably smooth movements even when under load; a complete full-scale structural prototype, the ECCEROBOT Design Study (EDS), has confirmed that these techniques will deliver the same benefits on a functional robot (see Fig. 8).

The next robot in the series, ECCE2, is scheduled for completion by the end of 2010. It is designed to include the tension and position sensing necessary for controlling dynamic movements, and will be the first robot in the series to provide experimental performance data. Theoretical work within the project [12] has indicated that the stable positional control of compliant antagonistic actuators of the type used here may be possible, and it will be important to assess any practical limitations. ECCE2 will also include a binocular vision system and a more capable hand.

## REFERENCES

- [1] O. Holland and R. Knight, The anthropomorphic principle, in Proceedings of the AISB06 Symposium on Biologically Inspired Robotics edited by J. Burn and M. Wilson, 2006.
- [2] O. Holland, R. Knight, and R. Newcombe, A robot-based approach to machine consciousness, in Artificial Consciousness, edited by A. Chella, Imprint Academic, 2007.
- [3] Honda Motor Co. ASIMO year 2000 model, available at <http://world.honda.com/ASIMO/technology/spec.html>, 2000.
- [4] B. Prilutsky, Coordination of two-and one-joint muscles: Functional consequences and implications for motor control, *Motor Control*, 4:144, 2000.
- [5] G. A. Pratt, M. M. Williamson, P. Dillworth, J. Pratt, K. Ull, and A. Wright, Stiffness isn't everything, in Proceedings of ISER, pp. 253262, 1995.
- [6] G. Metta, G. Sandini, D. Vernon, L. Natale, and F. Nori. The iCub humanoid robot: an open platform for research in embodied cognition, in PerMIS: Performance Metrics for Intelligent Systems Workshop, Washington DC, USA, 2008.
- [7] W. M. Hinojosa, N. G. Tsagarakis, G. Metta, F. Becchi, G. Sandini, and D. Caldwell, Performance assessment of a 3 d.o.f. differential based waist joint for the iCub baby humanoid robot, in RO-MAN 06: The 15th IEEE International Symposium on Robot and Human Interactive Communication, pp. 195201, Hatfield, United Kingdom, 2006.
- [8] I. Mizuuchi, Y. Nakanishi, Y. Sodeyama, Y. Namiki, T. Nishino, N. Muramatsu, J. Urata, K. Hongo, T. Yoshikai, and M. Inaba An advanced musculoskeletal humanoid Kojiro, in Proceedings of International Conference on Humanoid Robots (Humanoids07), 2007.
- [9] Y. Sodeyama, T. Nishino, Y. Namiki, Y. Nakanishi, I. Mizuuchi, and M. Inaba, The designs and motions of a shoulder structure with a spherical thorax, scapulas and collarbones for humanoid Kojiro, In 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems, Nice, France, 2008.
- [10] I. Boblan, R. Bannasch, A. Schulz, and H. Schwenk, A human-like robot torso ZAR5 with fluidic muscles: Toward a common platform for embodied AI, in 50 Years of Artificial Intelligence, edited by M. Lungarella, F. Iida, J. Bongard, and R. Pfeifer, Springer-Verlag, 2007.
- [11] COLLADA digital asset schema release 1.5.0, available at [www.khronos.org/collada/](http://www.khronos.org/collada/)
- [12] V. Potkonjak, B. Svetozarevic, K. Jovanovic, O. Holland, Control of compliant anthropomorphic robot joint, ICNAAM 2010 - 8th International Conference of Numerical Analysis and Applied Mathematics, Rhodes, Greece, 2010