CHAPTER

1

Introduction

1.1 HISTORICAL DEVELOPMENT

For centuries, imagination has been the driving force behind creativity. This is true especially for humanoid robots with their origins being traceable back to ancient Greek mythology. The drive to create human-like artificial machines has never ceased during the centuries since then [32]. In modern times, the technological advancements achieved by engineers have empowered them to bring into life the creations of the finest dreamers and science-fiction writers.

The development of humanoid robots was pioneered in Japan with WABOT-1, designed in 1973 by the late professor Ichiro Kato and his students at Waseda university [97]. For years, Japanese engineers remained the sole pursuers of the humanoid dream. Their efforts eventually paid off; the fascinating humanoid platform developed throughout the years by Honda Motor Co. and culminated in the world-renowned ASIMO humanoid [94]. In 1996, the impact of unveiling ASIMO's predecessor P2 to the public was enormous. This eventually led to the accelerating development of humanoid robot technology we are witnessing nowadays. Governments in the developed countries are readily financing robot technology. This will inevitably lead to an ever-accelerating cycle in synchrony with the existing exponential advancements in computing machinery, as revealed by Moore's law.

Humanoid robots are complex machines. It took Honda's engineers a decade to develop a number of prototypes and to arrive at the P2 in 1996 [49,48]. It took another 15 years of development to arrive at the "all-new" ASIMO in 2011 [99]. This robot is considered to be the world's most advanced humanoid robot, capable of running fast, very human-like. The robot can also climb stairs, run backwards, hop on one or two legs continuously, and even walk over uneven terrain. These physical capabilities of the robot have been achieved with perfectionist mechanical design, advanced sensors and actuator technology, and dynamic motion control. Besides improving ASIMO's physical capabilities, Honda's engineers also developed the robot's artificial intelligence abilities such as decision making for motion replanning based on sensor data fusion, natural language, gesture-based communication, and others [118].

Following Honda's pioneering efforts, since the end of the 20th century a number of humanoid robots have been built [33]. Humanoid robots have demonstrated such abilities as driving a lift truck [43] or a backhoe [44], pushing [39], lifting [93,83] or moving by pivoting [137] various heavy objects, opening and closing doors [110], pulling drawers [59], nailing [127], lifting and carrying objects in cooperation with humans [27,16,2], and cooking [34].

Humanoid Robots
https://doi.org/10.1016/B978-0-12-804560-2.00008-0

The robots developed so far, however, are only prototypes. They lack sufficient robustness to function in the real-life environment. The DARPA Robotics Challenge (DRC) competition [100] was conceived to address some aspects of this problem, in particular with regard to an extreme environment such as a disaster zone. Indeed, walking through uneven terrain and rubble and driving a car and getting out of it proved to be too difficult tasks for most of the eighteen biped robots that took part in the competition. Seven of the biped teams used the Atlas robot [95], but only one of them, the runner-up Running Man of team IHMC [96], could complete all of the tasks. With nearly identical hardware (the Atlas robot teams used their own lower-arm/hand designs), the robustness of balance maintenance can be identified as being mainly a control issue. The competition outcome has clearly demonstrated, though, that environment-specific design can also play an important role. The winner and the third-place team (DRC-Hubo of team KAIST [61] and CHIMP of CMU team Tartan Rescue [98]) incorporated design elements that deviated from human-like forms, such as a biped-plus-wheel and caterpillar-based locomotion, respectively.

Biped humanoid robots cannot be expected to be commercialized in the near future. In fact, Honda has announced the retirement of ASIMO [103]. The company is developing a new humanoid robot with a design to solve specific tasks in a disaster-related environment [138]. The company also revealed its plan to apply the know-how, accumulated throughout the years of research, in such areas as physical therapy and self-driving vehicles. Without a doubt, pursuing mankind's dream with continuing research efforts in the field of humanoid robotics will inevitably pay off some day.

1.2 TRENDS IN HUMANOID ROBOT DESIGN

1.2.1 Human Likeness of a Humanoid Robot

The design of a universal humanoid robot capable of performing a variety of tasks within different environments remains an open issue. The common "form follows function" design principle can lead to both advantages and disadvantages in humanoid robot design, as discussed by Stanford university professor Bernard Roth [117]. The external appearance of a humanoid robot, including the way it moves, plays an important role for its acceptance in society, as noted by professor Masahiro Mori of Tokyo Institute of Technology [79]. Attempts of quantifying the human-likeness of a humanoid robot are presented in [104,146].

As an example, consider one of the main functions of a biped robot: walking on a level ground. Walking has been realized with the help of a 3D linear inverted pendulum (LIP) model [62]. This, however, has resulted in "crouched" gaits without straightening the knees as in the typical erect gait of the modern-times human. Besides the external appearance problem of the "crouched" robot gait, there is also a functional problem related to gait efficiency. As noted in a study on the bipedal walking of the early hominid *Australopithecus afarensis* [20], net energy absorption is predicted for the "bent" joints, which would have resulted in increased heat load. Indeed, erect (straight-leg) walking is a characteristic of the most energy-efficient machine gait: that of a powerless biped descending a slope, known as passive dynamic walk (PDW) [74]. The bent-knee gait in powered bipeds has been identified as a problem in [119,92] and tackled later on in [70,80,64,124,63,38,71,41,139]. Improved humanoid designs that can circumvent the problematic gait have been demonstrated with WABIAN-2/LL [91], WABIAN-2R [67], and HRP-4C [65,76] and the robot described in [12]. This has been achieved with mechanisms and control methods for ensuring human-like heel-contact and/or toe-off gait phases. A result reported in [35] shows that a straightened-knee gait can be achieved with the Atlas humanoid robot through appropriate control, without involving any special design.

1.2.2 Trade-Offs in Humanoid Robot Design

A design approach aiming at harmony between form and function might not always be possible. Trade-offs between form and function resulting in "environment-specific" designs seem inevitable at present. Consider again the level-ground mobility function. From the viewpoint of stability and safety, a wheel base is definitely preferable instead of bipedalism. It is also preferable in terms of cost effectiveness. These issues are important when bringing humanoids to markets. Hence, commercialized humanoids such as MHI's Wakamaru [101], Hitachi's EMIEW [55] or Softbank's Pepper [102] are all wheel-based. There is also a considerable number of such humanoids that have been designed as research platforms, e.g. [75,24,58,30,123,85,121]. Some of them have been subsequently redesigned and refurbished with a bipedal lower body for increased mobility, e.g. DLR's Rollin' Justin/TORO [30,25] and NASA's Robonaut [23,23,22].

Robonaut-2 is a special case of a "biped" design that does not conform to the human-like form factor; the robot comprises a nice-looking upper body; its legs, however, have a "creepy" appearance. Nevertheless, the leg design seems to best suit the environment on the International Space Station [22,60]. Another example of biped design that differs from the human-like form is the design with legs without feet, i.e. legs that establish point contacts. Such legs are suitable when negotiating highly irregular terrain [106,143]. Another type of environment-specific design is Honda's new prototype, the E2-DR disaster response robot [138].

The existence of the abovementioned form/function design trade-offs has been identified, in fact, as the main reason for the lack of a commonly acceptable definition of the term "humanoid robot" [4].

1.2.3 Human-Friendly Humanoid Robot Design

A class of humanoid robots have been designed especially to support studies in the field of behavioral science, physical embodiment, and social interaction. Various designs have been made, e.g. with a humanoid upper body on a wheel base such as WENDY [81] and TWENDY-ONE [58] by Waseda University, the ARMAR-family humanoids of Karlsruhe Institute of Technology [24], and DB [66,7] and Robovie [75] of the Advanced Telecommunication Research (ATR) Institute in Japan. Other designs include COG of the Massachusetts Institute of Technology (MIT), comprising a fixed-base humanoid upper body [15], the full-body hydraulically driven CB of Sarcos [7,18], and the iCub robot of the Italian Institute of Technology (IIT) [107]. Being equipped with multiple sensory and motor systems and advanced control algorithms, these robots can mimic human abilities quite well. From the viewpoint of this work, the joint torque sensing and control capability of the latter robots deserve special attention. Torque-based control can ensure compliant behaviors of the robot in response to the external force inputs. Such behaviors are useful in exploring physical human–robot interaction paradigms. Compliant behavior is conceived as a necessary condition for robots to function alongside humans. Robot compliance in response to unexpected physical inputs is needed to guarantee the safety of operations [145,3,37,122]. Generally, force/torque control can handle smooth external forces; when dealing with impacts, however, this type of control may not ensure the necessary time of response due to the inherent bandwidth limitations. This led to the design of the intrinsically compliant biped Lucy, powered by pneumatic muscles [128]. More recently, advanced humanoids have been designed that comprise the so-called series-elastic actuators (SEAs), i.e. actuators with embedded passive mechanical elements (springs/dampers) [129]. Such robots are the lower-body humanoid robot M2V2 [112] and the humanoid robots COMAN [126,144] and WALK-MAN [125] developed at IIT, DLR's TORO [25], NASA's humanoid robot Valkyrie [113,105], and others. Other advanced designs for compliant behaviors are those mimicking the human musculoskeletal system [87,77,57,5].

1.3 CHARACTERISTICS OF HUMANOID ROBOTS

There is no commonly accepted definition of the term humanoid robot, as already noted. Nevertheless, the generic characteristics of a humanoid robot can be derived based on the following assumptions. Humanoid robots are designed:

- to operate autonomously in various environments such as dwelling, office, factory, disaster zones;
- to perform a broad spectrum of physical tasks;
- to communicate with humans;
- to come in physical contact with humans without endangering them;
- to operate tools and manipulate objects designed for humans.

From the design viewpoint, these assumptions imply a human-like physical appearance, i.e. a torso, a head, two legs, and two arms with multifingered hands. Only articulated joints are used. From the control viewpoint, these assumptions imply a hierarchical controller structure and a sensor subsystem that are needed to realize:

- perception and cognition,
- learning,
- task sequence planning,
- locomotion trajectory (gait) planning and generation,
- walking control,
- whole-body manipulation planning with motion/force components,
- end-link motion/force trajectory generation, transformation, and tracking control,
- balance and posture control with optimal force distribution in the presence of external disturbances,
- low-level actuator and joint space control.

The upper-level functions, i.e. perception, cognition, learning, and task sequence and motion planning, are related to the advancements in the field of artificial intelligence; they are beyond the scope of the present work. Readers interested in this field are referred to [17] for a treatment from the viewpoint of neuroscience and to [73] and [42] for issues related to human–humanoid communication using natural speech and gestures, respectively. Task sequence and motion planning are currently under extensive development. Some of the problems are covered in [40].

The main focus in this work is on the derivation of kinematic, kinetostatic, and dynamic models of a humanoid robot and the usage of these models in motion/force trajectory generation and control of humanoid robots.

1.4 AREAS OF RESEARCH RELATED TO HUMANOID ROBOTS

Model-based trajectory generation and control design requires an in-depth understanding of the kinematics, kinetostatics, and dynamics of humanoid robots. The following areas of research are well established in the field of robotics and can serve as a basis.

1.4.1 Kinematic Redundancy, Task Constraints, and Optimal Inverse Kinematics Solutions

A humanoid robot comprises a relatively large number of degrees-of-freedom (DoFs). This is the reason why sometimes humanoid robots are characterized as being kinematically redundant. A kinematically redundant robot is modeled as an *underdetermined* system. Such characterization, however, depends on the number of tasks that the robot is supposed to perform. For example, the desired hand position/orientation of the humanoid robot might be reachable in an infinite number of ways when the motion of the trunk is taken under consideration in addition to that of the arm. The motion of the trunk, however, is preferably used in balance control rather than in a reaching task. This simple example demonstrates the fact that when the robot is required to perform a number of tasks *simultaneously*, the DoFs of the robot may not suffice. In this case, the robot should be modeled as an *overconstrained* system rather than as an underconstrained, i.e. as a kinematically redundant one.

From a review on the whole-body control methods used by the teams participating in the DRC [52], it becomes apparent that at present, inverse kinematics–based motion generation and control is the prevailing technique.

Problems related to kinematic redundancy, singularities, and the optimal inverse kinematics solutions of underconstrained and overconstrained systems are discussed in Chapter 2.

1.4.2 Constrained Multibody Systems and Contact Modeling

A humanoid robot is characterized as a *multibody system*. With the exception of jumping or the flight phase of running, a humanoid robot is always in contact with the environment with one or more of its links, e.g. the feet, the hands, the trunk, or the elbows. Existing contacts can be broken and new contacts established at any time instant. The contacts that are formed depend on the geometry of the contacting bodies. The contacts constrain the motion of the generic (i.e. the unconstrained) kinematic chain of the robot. Since the kinematic chain has a tree–like structure, one or more closed kinematic loops will be inevitably formed via the contacts. Thus, a more precise characterization of a humanoid robot would be as a *structure-varying constrained multibody system* [86].

The modeling of the contacts and the instantaneous motion kinematics of a constrained multibody system with closed loops is discussed in Chapter 2. The flow (or distribution) of forces within the closed loops is explained in Chapter 3.

1.4.3 Multifingered Hands and Dual-Arm Object Manipulation

A multifingered hand itself represents a multibody system. When an object is grasped by a multifingered hand, kinematic closed loops are formed. The theory of constrained multibody systems applies in this case as well. Multifingered hands and dual-arm object manipulation have been studied thoroughly throughout the years. An excellent reference text is [84].

Cooperative object manipulation with a multifingered hand, with the two arms of a humanoid robot, and with multiple humanoid robots is discussed in Chapter 6.

1.4.4 Underactuated Systems on a Floating Base

A humanoid robot is characterized as an *underactuated system* since it comprises more DoFs than the number of its actuators. As already noted, the generic kinematic chain of a humanoid robot is structured as a tree. The *root link* of the robot is free to move in 3D space. Such motion implies six nonactuated DoFs.

The root link is quite often referred to as the *floating base* of the robot. The class of underactuated multibody systems on a floating base includes *flexible-base manipulators*, the so-called *macro-micro manipulators* (i.e. a small manipulator mounted at the tip of a larger one), and *free-floating space robots* [90]. Such systems were studied intensively in the late 1980s and 1990s. The studies have contributed to the in-depth understanding of the roles of inertial coupling, angular momentum, and reactionless manipulation. These problems play an important role in balance control of a humanoid robot as well.

The dynamics of floating-base systems are introduced in Chapter 4. Balance control methods are discussed in detail in Chapter 5.

1.4.5 Other Related Areas of Research

Single-Leg, Multilegged, and Multilimb Robots

The development of robots hopping on a single leg has been pioneered by Marc Raibert at MIT [114]. He also developed running bipeds and quadruped robots. At Boston Dynamics, the company Marc Raibert founded after leaving MIT, he used the technology as a basis to design a number of interesting legged robots, including the two biped humanoids Petman and Atlas [95]. Marc Raibert's robots are capable of running fast, negotiating very rough terrain, robust balance control under strong disturbances, and jumping.

Quite similar to humanoid robots, multilegged robots are modeled as constrained multibody systems with a varying kinematic structure. The modeling and control approaches developed for humanoid robots can be directly applied to multilegged robots, and vice versa

[53,56,120,131]. This is also true in the more general case of bio-inspired multilimb robots that provide new ways of locomotion [31,142].

Physics-Based Animation of Articulated Figures

Physics-based animation of articulated figures is a field closely related to humanoid robotics. There are a number of common problems, the main one being motion generation under space-time constraints [135]. The respective methods make use of optimized inverse kinematics solutions [140,141,10,1]. These methods have also been adopted in the field of humanoid robotics [36,68]. Contact modeling, the computation of reaction forces and force-based motion control, is another area of common interest [11,108,82]. This is also the case for interactive motion generation in response to the external perturbations of the character [136, 72,21]. Methods developed for physics-based character animation are also being adopted for motion generation and control in the field of humanoid robotics and vice versa. The key-framing technique, for example, is used in animation to generate the motion of a character by interpolating key postures over time [10]. This technique is also used in the field of humanoid robotics for motion generation [45,46,13,14,26].

Studies on the Biomechanics of Human Movement

In the fields of biomechanics and motor control of human movement [134], physical therapy, and sport sciences there is a large body of research on the mechanism of human balance [88,89,54,29,47], on the ways how the brain controls the balance when perturbations are applied [116,115,69], on the balance during human walking [133,132,9], on the role of arm movements in balance [78,19], and so on. The research results were accumulated well before the advancement of humanoid robotics. Not surprisingly, the human body models used in the research, such as simple inverted pendulums on foot models, were in fact very similar to those that later appeared in the humanoid robotics field (e.g. the LIP model [62]). Two identical concepts, that of the *extrapolated CoM* [51] and that of the *capture point* [111], were derived independently in the biomechanics and robotics fields. Rapid advancements in humanoid robotics have also contributed to the deeper understanding of the human motion control [66, 6], especially by clarifying the role of the angular momentum in balance control [109,50].

With the development of wearable robotics (exoskeletons), a considerable contribution to the field of physical therapy can be attributed to the research in the humanoid robotics field [8].

1.5 PREREQUISITE AND STRUCTURE

This work introduces advanced methods for modeling, motion generation, and control of humanoid robots. It is assumed that readers have a solid general robotics background. A number of excellent textbooks do exist, such as [84] for example. The textbook [28] on rigid-body dynamics would be very helpful. Also, the understanding of the basic concepts in the humanoid robotics field is highly recommended, as presented in [62]. Such concepts include the Zero-Moment Point (ZMP) [130], the Center of Pressure (CoP), the ground reaction forces and moments, the various LIP models in 2D and 3D, the cart-table model and ZMP-based walking pattern generation with preview control, whole-body motion generation, and methods of simulation.

This text is organized as follows. The kinematics, kinetostatics, and dynamics of humanoid robots are discussed in Chapters 2, 3, and 4, respectively. Balance control plays a major role in humanoid robotics; the details are presented in Chapter 5. Chapter 6 explains cooperative object manipulation and control with multifingered hands, with two arms of a robot, and with multiple robots. The research area of motion generation is quite wide. Selected topics with applications are discussed in Chapter 7. Finally, Chapter 8 highlights the importance of simulators and provides step-by-step instructions for implementing a MATLAB-based simulator.

The authors' contribution is as follows. Atsushi Konno contributed Section 5.4.5, Sections 6.1 through 6.4, Section 7.2, Section 7.3, and Section 7.8. Teppei Tsujita wrote Chapter 8. The rest has been written by Dragomir N. Nenchev (Yoshikazu Kanamiya).

References

[1] Y. Abe, M. Da Silva, J. Popović, Multiobjective control with frictional contacts, in: ACM SIGGRAPH/Eurographics Symposium on Computer Animation, 2007, pp. 249–258.

[2] D.J. Agravante, A. Cherubini, A. Bussy, A. Kheddar, Human-humanoid joint haptic table carrying task with height stabilization using vision, in: IEEE/RSJ International Conference on Intelligent Robots and Systems, Tokyo, Japan, 2013, pp. 4609–4614.

[3] A. Albu-Schaffer, O. Eiberger, M. Grebenstein, S. Haddadin, C. Ott, T. Wimbock, S. Wolf, G. Hirzinger, Soft robotics, IEEE Robotics & Automation Magazine 15 (2008) 20–30.

[4] R. Ambrose, Y. Zheng, B. Wilcox, Assessment of International Research and Development in Robotics, Ch. 4 – Humanoids, Technical report, 2004.

[5] Y. Asano, H. Mizoguchi, T. Kozuki, Y. Motegi, J. Urata, Y. Nakanishi, K. Okada, M. Inaba, Achievement of twist squat by musculoskeletal humanoid with screw-home mechanism, in: IEEE International Conference on Intelligent Robots and Systems, 2013, pp. 4649–4654.

[6] C. Atkeson, J. Hale, F. Pollick, M. Riley, S. Kotosaka, S. Schaul, T. Shibata, G. Tevatia, A. Ude, S. Vijayakumar, E. Kawato, M. Kawato, Using humanoid robots to study human behavior, IEEE Intelligent Systems 15 (2000) 46–56.

[7] C.G. Atkeson, J. Hale, F. Pollick, M. Riley, Using a humanoid robot to explore human behavior and communication, Journal of the Robotics Society of Japan 19 (2001) 584–589.

[8] K. Ayusawa, E. Yoshida, Y. Imamura, T. Tanaka, New evaluation framework for human-assistive devices based on humanoid robotics, Advanced Robotics 30 (2016) 519–534.

[9] C. Azevedo, P. Poignet, B. Espiau, Artificial locomotion control: from human to robots, Robotics and Autonomous Systems 47 (2004) 203–223.

[10] P. Baerlocher, R. Boulic, An inverse kinematics architecture enforcing an arbitrary number of strict priority levels, The Visual Computer 20 (2004) 402–417.

[11] D. Baraff, Fast contact force computation for nonpenetrating rigid bodies, in: 21st Annual Conference on Computer Graphics and Interactive Techniques – SIGGRAPH '94, ACM Press, New York, New York, USA, 1994, pp. 23–34.

[12] S. Behnke, Human-like walking using toes joint and straight stance leg, in: International Symposium on Adaptive Motion in Animals and Machines, 2005, pp. 1–6.

[13] K. Bouyarmane, A. Kheddar, Static multi-contact inverse problem for multiple humanoid robots and manipulated objects, in: IEEE-RAS International Conference on Humanoid Robots, Nashville, TN, USA, 2010, pp. 8–13.

[14] K. Bouyarmane, A. Kheddar, Using a multi-objective controller to synthesize simulated humanoid robot motion with changing contact configurations, in: IEEE/RSJ International Conference on Intelligent Robots and Systems, 2011, pp. 4414–4419.

[15] R.A. Brooks, C. Breazeal, M. Marjanović, B. Scassellati, M.M. Williamson, The Cog project: building a humanoid robot, in: C.L. Nehaniv (Ed.), Computation for Metaphors, Analogy, and Agents, in: Lecture Notes in Computer Science, vol. 1562, Springer, Berlin, Heidelberg, 1999, pp. 52–87.

[16] A. Bussy, P. Gergondet, A. Kheddar, F. Keith, A. Crosnier, Proactive behavior of a humanoid robot in a haptic transportation task with a human partner, in: IEEE International Symposium on Robot and Human Interactive Communication, 2012, pp. 962–967.
[17] G. Cheng (Ed.), Humanoid Robotics and Neuroscience: Science, Engineering and Society, CRC Press Book, 2014.
[18] G. Cheng, S.-H. Hyon, J. Morimoto, A. Ude, J.G. Hale, G. Colvin, W. Scroggin, S.C. Jacobsen, CB: a humanoid research platform for exploring neuroscience, Advanced Robotics 21 (2007) 1097–1114.
[19] P.J. Cordo, L.M. Nashner, Properties of postural adjustments associated with rapid arm movements, Journal of Neurophysiology 47 (1982) 287–302.
[20] R.H. Crompton, L. Yu, W. Weijie, M. Günther, R. Savage, The mechanical effectiveness of erect and "bent-hip, bent-knee" bipedal walking in Australopithecus afarensis, Journal of Human Evolution 35 (1998) 55–74.
[21] M. De Lasa, I. Mordatch, A. Hertzmann, Feature-based locomotion controllers, ACM Transactions on Graphics 29 (2010) 131.
[22] M.A. Diftler, T.D. Ahlstrom, R.O. Ambrose, N.A. Radford, C.A. Joyce, N. De La Pena, A.H. Parsons, A.L. Noblitt, Robonaut 2 — initial activities on-board the ISS, in: 2012 IEEE Aerospace Conference, 2012, pp. 1–12.
[23] M.A. Diftler, R.O. Ambrose, S.M. Goza, K.S. Tyree, E.L. Huber, Robonaut mobile autonomy: initial experiments, in: Proceedings – IEEE International Conference on Robotics and Automation, 2005, pp. 1425–1430.
[24] M. Do, P. Azad, T. Asfour, R. Dillmann, Imitation of human motion on a humanoid robot using non-linear optimization, in: IEEE-RAS International Conference on Humanoid Robots, 2008, pp. 545–552.
[25] J. Englsberger, A. Werner, C. Ott, B. Henze, M.A. Roa, G. Garofalo, R. Burger, A. Beyer, O. Eiberger, K. Schmid, A. Albu-Schaffer, Overview of the torque-controlled humanoid robot TORO, in: IEEE-RAS International Conference on Humanoid Robots, IEEE, Madrid, Spain, 2014, pp. 916–923.
[26] A. Escande, A. Kheddar, S. Miossec, Planning contact points for humanoid robots, Robotics and Autonomous Systems 61 (2013) 428–442.
[27] P. Evrard, E. Gribovskaya, S. Calinon, A. Billard, A. Kheddar, Teaching physical collaborative tasks: object-lifting case study with a humanoid, in: IEEE-RAS International Conference on Humanoid Robots, Paris, France, 2009, pp. 399–404.
[28] R. Featherstone, Rigid Body Dynamics Algorithms, Springer Science+Business Media, LLC, Boston, MA, 2008.
[29] J.S. Frank, M. Earl, Coordination of posture and movement, Physical Therapy 70 (1990) 855–863.
[30] M. Fuchs, C. Borst, P. Giordano, A. Baumann, E. Kraemer, J. Langwald, R. Gruber, N. Seitz, G. Plank, K. Kunze, R. Burger, F. Schmidt, T. Wimboeck, G. Hirzinger, Rollin' Justin – design considerations and realization of a mobile platform for a humanoid upper body, in: IEEE International Conference on Robotics and Automation, IEEE, 2009, pp. 4131–4137.
[31] T. Fukuda, Y. Hasegawa, K. Sekiyama, T. Aoyama, Multi-Locomotion Robotic Systems: New Concepts of Bio-Inspired Robotics, 1st edition, Springer, 2012.
[32] T. Fukuda, R. Michelini, V. Potkonjak, S. Tzafestas, K. Valavanis, M. Vukobratovic, How far away is "artificial man", IEEE Robotics & Automation Magazine 8 (2001) 66–73.
[33] A. Goswami, P. Vadakkepat (Eds.), Humanoid Robotics: A Reference, Springer, Netherlands, Dordrecht, 2018.
[34] F. Gravot, A. Haneda, K. Okada, M. Inaba, Cooking for humanoid robot, a task that needs symbolic and geometric reasonings, in: Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006, pp. 462–467.
[35] R.J. Griffin, G. Wiedebach, S. Bertrand, A. Leonessa, J. Pratt, Straight-leg walking through underconstrained whole-body control, in: IEEE International Conference on Robotics and Automation (ICRA), 2018, pp. 5747–5754.
[36] M. Guihard, P. Gorce, Dynamic control of bipeds using ankle and hip strategies, in: IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, Lausanne, Switzerland, 2002, pp. 2587–2592.
[37] S. Haddadin, A. Albu-Schaffer, G. Hirzinger, Requirements for safe robots: measurements, analysis and new insights, The International Journal of Robotics Research 28 (2009) 1507–1527.
[38] N. Handharu, J. Yoon, G. Kim, Gait pattern generation with knee stretch motion for biped robot using toe and heel joints, in: IEEE-RAS International Conference on Humanoid Robots, Daejeon, Korea, 2008, pp. 265–270.
[39] K. Harada, S. Kajita, H. Saito, F. Kanehiro, H. Hirukawa, Integration of manipulation and locomotion by a humanoid robot, in: M.H. Ang, O. Khatib (Eds.), Experimental Robotics IX, in: Springer Tracts in Advanced Robotics, vol. 21, Springer Berlin Heidelberg, Berlin, Heidelberg, 2006, pp. 187–197.

[40] K. Harada, E. Yoshida, K. Yokoi (Eds.), Motion Planning for Humanoid Robots, Springer London, London, 2010.

[41] Y. Harada, J. Takahashi, D.N. Nenchev, D. Sato, Limit cycle based walk of a powered 7DOF 3D biped with flat feet, in: IEEE/RSJ International Conference on Intelligent Robots and Systems, 2010, pp. 3623–3628.

[42] M. Hasanuzzaman, H. Ueno, User, gesture and robot behaviour adaptation for human–robot interaction, in: R. Zaier (Ed.), The Future of Humanoid Robots – Research and Applications, InTech, 2012, pp. 229–256.

[43] H. Hasunuma, M. Kobayashi, H. Moriyama, T. Itoko, Y. Yanagihara, T. Ueno, K. Ohya, K. Yokoi, A tele-operated humanoid robot drives a lift truck, in: Proceedings 2002 IEEE International Conference on Robotics and Automation, 2002, pp. 2246–2252.

[44] H. Hasunuma, K. Nakashima, M. Kobayashi, F. Mifune, Y. Yanagihara, T. Ueno, K. Ohya, K. Yokoi, A tele-operated humanoid robot drives a backhoe, in: IEEE International Conference on Robotics and Automation, 2003, pp. 2998–3004.

[45] K. Hauser, T. Bretl, J.C. Latombe, Non-gaited humanoid locomotion planning, in: IEEE-RAS International Conference on Humanoid Robots, 2005, pp. 7–12.

[46] K. Hauser, T. Bretl, J.-C. Latombe, K. Harada, B. Wilcox, Motion planning for legged robots on varied terrain, The International Journal of Robotics Research 27 (2008) 1325–1349.

[47] J. He, W. Levine, G. Loeb, Feedback gains for correcting small perturbations to standing posture, IEEE Transactions on Automatic Control 36 (1991) 322–332.

[48] K. Hirai, M. Hirose, Y. Haikawa, T. Takenaka, The development of Honda humanoid robot, in: IEEE Int. Conf. on Robotics and Automation, Leuven, Belgium, 1998, pp. 1321–1326.

[49] M. Hirose, T. Takenaka, H. Gomi, N. Ozawa, Humanoid robot, Journal of the Robotics Society of Japan 15 (1997) 983–985 (in Japanese).

[50] A.L. Hof, The equations of motion for a standing human reveal three mechanisms for balance, Journal of Biomechanics 40 (2007) 451–457.

[51] A.L. Hof, M.G.J. Gazendam, W.E. Sinke, The condition for dynamic stability, Journal of Biomechanics 38 (2005) 1–8.

[52] E.M. Hoffman, Simulation and Control of Humanoid Robots for Disaster Scenarios, Ph.D. thesis, Genoa University and Italian Institute of Technology, 2016.

[53] P. Holmes, R.J. Full, D. Koditschek, J. Guckenheimer, The dynamics of legged locomotion: models, analyses, and challenges, SIAM Review 48 (2006) 207–304.

[54] F.B. Horak, L.M. Nashner, Central programming of postural movements: adaptation to altered support-surface configurations, Journal of Neurophysiology 55 (1986) 1369–1381.

[55] Y. Hosoda, S. Egawa, J. Tamamoto, K. Yamamoto, Development of human-symbiotic robot "EMIEW" – Design concept and system construction –, Journal of Robotics and Mechatronics 18 (2006) 195–202.

[56] M. Hutter, H. Sommer, C. Gehring, M. Hoepflinger, M. Bloesch, R. Siegwart, Quadrupedal locomotion using hierarchical operational space control, The International Journal of Robotics Research 33 (2014) 1047–1062.

[57] S. Ikemoto, Y. Nishigori, K. Hosoda, Advantages of flexible musculoskeletal robot structure in sensory acquisition, Artificial Life and Robotics 17 (2012) 63–69.

[58] H. Iwata, S. Sugano, Design of human symbiotic robot TWENDY-ONE, in: IEEE International Conference on Robotics and Automation, 2009, pp. 580–586.

[59] A. Jain, C.C. Kemp, Pulling open novel doors and drawers with equilibrium point control, in: IEEE-RAS International Conference on Humanoid Robots, Paris, France, 2009, pp. 498–505.

[60] C. Joyce, J. Badger, M. Diftler, E. Potter, L. Pike, Robonaut 2 – building a robot on the international space station, 2014.

[61] T. Jung, J. Lim, H. Bae, K.K. Lee, H.M. Joe, J.H. Oh, Development of the Humanoid Disaster Response Platform DRC-HUBO+, IEEE Transactions on Robotics 34 (2018) 1–17.

[62] S. Kajita, H. Hirukawa, K. Harada, K. Yokoi, Introduction to Humanoid Robotics, Springer Verlag, Berlin, Heidelberg, 2014.

[63] K. Kameta, A. Sekiguchi, Y. Tsumaki, Y. Kanamiya, Walking control around singularity using a spherical inverted pendulum with an underfloor pivot, in: IEEE-RAS International Conference on Humanoid Robots, 2007, pp. 210–215.

[64] K. Kameta, A. Sekiguchi, Y. Tsumaki, D. Nenchev, Walking control using the SC approach for humanoid robot, in: IEEE-RAS International Conference on Humanoid Robots, 2005, pp. 289–294.

[65] K. Kaneko, F. Kanehiro, M. Morisawa, K. Miura, S. Nakaoka, S. Kajita, Cybernetic human HRP-4C, in: IEEE-RAS International Conference on Humanoid Robots, Paris, France, 2009, pp. 7–14.
[66] S. Kotosaka, Synchronized robot drumming with neural oscillators, in: International Symposium on Adaptive Motion of Animals and Machines, 2000.
[67] P. Kryczka, K. Hashimoto, H. Kondo, A. Omer, H.-o. Lim, A. Takanishi, Stretched knee walking with novel inverse kinematics for humanoid robots, in: IEEE International Conference on Intelligent Robots and Systems, 2011, pp. 3221–3226.
[68] S. Kudoh, T. Komura, K. Ikeuchi, Stepping motion for a human-like character to maintain balance against large perturbations, in: IEEE International Conference on Robotics and Automation, 2006, pp. 2661–2666.
[69] A.D. Kuo, F.E. Zajac, Human standing posture multi-joint movement strategies based on biomechanical constraints, Progress in Brain Research 97 (1993) 349–358.
[70] R. Kurazume, S. Tanaka, M. Yamashita, T. Hasegawa, K. Yoneda, Straight legged walking of a biped robot, in: IEEE/RSJ International Conference on Intelligent Robots and Systems, 2005, pp. 337–343.
[71] Z. Li, N.G. Tsagarikis, D.G. Caldwell, B. Vanderborght, Trajectory generation of straightened knee walking for humanoid robot iCub, in: IEEE International Conference on Control, Automation, Robotics and Vision, 2010, pp. 2355–2360.
[72] A. Macchietto, V. Zordan, C.R. Shelton, Momentum control for balance, ACM Transactions on Graphics 28 (2009) 80.
[73] Y. Matsusaka, Speech communication with humanoids: how people react and how we can build the system, in: R. Zaier (Ed.), The Future of Humanoid Robots – Research and Applications, InTech, 2012, pp. 165–188.
[74] T. McGeer, Passive walking with knees, in: IEEE International Conference on Robotics and Automation, 1990.
[75] N. Mitsunaga, T. Miyashita, H. Ishiguro, K. Kogure, N. Hagita, Robovie-IV: a communication robot interacting with people daily in an office, in: IEEE International Conference on Intelligent Robots and Systems, 2006, pp. 5066–5072.
[76] K. Miura, M. Morisawa, F. Kanehiro, S. Kajita, K. Kaneko, K. Yokoi, Human-like walking with toe supporting for humanoids, in: IEEE/RSJ International Conference on Intelligent Robots and Systems, San Francisco, CA, USA, 2011, pp. 4428–4435.
[77] I. Mizuuchi, M. Kawamura, T. Asaoka, S. Kumakura, Design and development of a musculoskeletal humanoid, in: IEEE-RAS International Conference on Humanoid Robots, Osaka, Japan, 2012, pp. 811–816.
[78] P. Morasso, Spatial control of arm movements, Experimental Brain Research 42 (1981) 223–227.
[79] M. Mori, The uncanny valley, IEEE Robotics & Automation Magazine 19 (2012) 98–100.
[80] M. Morisawa, S. Kajita, K. Kaneko, K. Harada, F. Kanehiro, K. Fujiwara, H. Hirukawa, Pattern generation of biped walking constrained on parametric surface, in: IEEE International Conference on Robotics and Automation, 2005, pp. 2405–2410.
[81] T. Morita, H. Iwata, S. Sugano, Development of human symbiotic robot: WENDY, in: 1999 IEEE International Conference on Robotics and Automation, vol. 4, 1999, pp. 83–88.
[82] U. Muico, Y. Lee, J. Popović, Z. Popović, Contact-aware nonlinear control of dynamic characters, ACM Transactions on Graphics 28 (2009) 81.
[83] M. Murooka, S. Noda, S. Nozawa, Y. Kakiuchi, K. Okada, M. Inaba, Manipulation strategy decision and execution based on strategy proving operation for carrying large and heavy objects, in: International Conference on Robotics and Automation, 2014, pp. 3425–3432.
[84] R.M. Murray, Z. Li, S.S. Sastry, A Mathematical Introduction to Robotic Manipulation, CRC Press, 1994.
[85] K. Nagasaka, Y. Kawanami, S. Shimizu, T. Kito, T. Tsuboi, A. Miyamoto, T. Fukushima, H. Shimomura, Whole-body cooperative force control for a two-armed and two-wheeled mobile robot using generalized inverse dynamics and idealized joint units, in: IEEE International Conference on Robotics and Automation, Anchorage, AK, USA, 2010, pp. 3377–3383.
[86] Y. Nakamura, K. Yamane, Dynamics computation of structure-varying kinematic chains and its application to human figures, IEEE Transactions on Robotics and Automation 16 (2000) 124–134.
[87] Y. Nakanishi, T. Izawa, M. Osada, N. Ito, S. Ohta, J. Urata, M. Inaba, Development of musculoskeletal humanoid Kenzoh with mechanical compliance changeable tendons by nonlinear spring unit, in: IEEE International Conference on Robotics and Biomimetics, 2011, pp. 2384–2389.
[88] L.M. Nashner, Brain adapting reflexes controlling the human posture, Experimental Brain Research 72 (1976) 59–72.

[89] L.M. Nashner, G. McCollum, The organization of human postural movements: a formal basis and experimental synthesis, Behavioral and Brain Sciences 8 (1985) 135–150.
[90] D.N. Nenchev, Reaction null-space of a multibody system with applications in robotics, Mechanical Sciences 4 (2013) 97–112.
[91] Y. Ogura, T. Kataoka, H. Aikawa, K. Shimomura, H.-o. Lim, A. Takanishi, Evaluation of various walking patterns of biped humanoid robot, in: IEEE International Conference on Robotics and Automation, 2005, pp. 603–608.
[92] Y. Ogura, H.-o. Lim, A. Takanishi, Stretch walking pattern generation for a biped humanoid robot, in: IEEE/RSJ International Conference on Intelligent Robots and Systems, 2003, pp. 352–357.
[93] Y. Ohmura, Y. Kuniyoshi, Humanoid robot which can lift a 30kg box by whole body contact and tactile feedback, in: IEEE/RSJ International Conference on Intelligent Robots and Systems, IEEE, San Diego, CA, USA, 2007, pp. 1136–1141.
[94] ASIMO by Honda: the world's most advanced humanoid robot, http://asimo.honda.com [online].
[95] Boston dynamics: dedicated to the science and art of how things move, https://www.bostondynamics.com/atlas [online].
[96] DARPA robotics challenge — IHMC robotics lab, http://robots.ihmc.us/drc [online].
[97] Development of Waseda robot, http://www.humanoid.waseda.ac.jp/booklet/katobook.html [online].
[98] DRC Tartan rescue team, https://www.nrec.ri.cmu.edu/solutions/defense/other-projects/tartan-rescue-team.html [online].
[99] Honda worldwide, Honda unveils all-new ASIMO with significant advancements, http://hondanews.com/releases/honda-unveils-all-new-asimo-with-significant-advancements/videos/all-new-asimo, November 8, 2011 [online].
[100] The DARPA robotics challenge, http://archive.darpa.mil/roboticschallenge [online].
[101] Wakamaru, Mitsubishi Heavy Industries, Ltd., https://en.wikipedia.org/wiki/Wakamaru [online].
[102] Who is Pepper, https://www.softbankrobotics.com/emea/en/robots/pepper [online].
[103] Honda's Asimo robot bows out but finds new life – Nikkei Asian Review, https://asia.nikkei.com/Business/Companies/Honda-s-Asimo-robot-bows-out-but-finds-new-life [online].
[104] E. Oztop, T. Chaminade, D. Franklin, Human-humanoid interaction: is a humanoid robot perceived as a human?, in: IEEE/RAS International Conference on Humanoid Robots, 2004, pp. 830–841.
[105] N. Paine, J.S. Mehling, J. Holley, N.A. Radford, G. Johnson, C.-L. Fok, L. Sentis, Actuator control for the NASA-JSC Valkyrie humanoid robot: a decoupled dynamics approach for torque control of series elastic robots, Journal of Field Robotics 32 (2015) 378–396.
[106] H.-W. Park, A. Ramezani, J. Grizzle, A finite-state machine for accommodating unexpected large ground-height variations in bipedal robot walking, IEEE Transactions on Robotics 29 (2013) 331–345.
[107] A. Parmiggiani, M. Maggiali, L. Natale, F. Nori, A. Schmitz, N.G. Tsagarakis, J.S. Victor, F. Becchi, G. Sandini, G. Metta, The design of the iCub humanoid robot, International Journal of Humanoid Robotics 09 (2012) 1250027.
[108] N. Pollard, P. Reitsma, Animation of humanlike characters: dynamic motion filtering with a physically plausible contact model, in: Yale Workshop on Adaptive and Learning Systems, 2001.
[109] M. Popovic, A. Hofmann, H. Herr, Angular momentum regulation during human walking: biomechanics and control, in: IEEE International Conference on Robotics and Automation, 2004, pp. 2405–2411.
[110] M. Prats, S. Wieland, T. Asfour, A. del Pobil, R. Dillmann, Compliant interaction in household environments by the Armar-III humanoid robot, in: IEEE-RAS International Conference on Humanoid Robots, 2008, pp. 475–480.
[111] J. Pratt, J. Carff, S. Drakunov, A. Goswami, Capture point: a step toward humanoid push recovery, in: IEEE-RAS International Conference on Humanoid Robots, Genoa, Italy, 2006, pp. 200–207.
[112] J. Pratt, B. Krupp, Design of a bipedal walking robot, in: G.R. Gerhart, D.W. Gage, C.M. Shoemaker (Eds.), Proceedings of SPIE – The International Society for Optical Engineering, 2008.
[113] N.A. Radford, P. Strawser, K. Hambuchen, J.S. Mehling, W.K. Verdeyen, A.S. Donnan, J. Holley, J. Sanchez, V. Nguyen, L. Bridgwater, R. Berka, R. Ambrose, M. Myles Markee, N.J. Fraser-Chanpong, C. McQuin, J.D. Yamokoski, S. Hart, R. Guo, A. Parsons, B. Wightman, P. Dinh, B. Ames, C. Blakely, C. Edmondson, B. Sommers, R. Rea, C. Tobler, H. Bibby, B. Howard, L. Niu, A. Lee, M. Conover, L. Truong, R. Reed, D. Chesney, R. Platt, G. Johnson, C.-L. Fok, N. Paine, L. Sentis, E. Cousineau, R. Sinnet, J. Lack, M. Powell, B. Morris, A. Ames, J. Akinyode, Valkyrie: NASA's first bipedal humanoid robot, Journal of Field Robotics 32 (2015) 397–419.
[114] M.H. Raibert, Legged Robots that Balance, MIT Press, 1986.

[115] C.F. Ramos, L.W. Stark, Postural maintenance during fast forward bending: a model simulation experiment determines the "reduced trajectory", Experimental Brain Research 82 (1990) 651–657.
[116] C.F. Ramos, L.W. Stark, Postural maintenance during movement: simulations of a two joint model, Biological Cybernetics 63 (1990) 363–375.
[117] B. Roth, How can robots look like human beings, in: IEEE International Conference on Robotics and Automation, IEEE, 1995, p. 1.
[118] Y. Sakagami, R. Watanabe, C. Aoyama, S. Matsunaga, N. Higaki, K. Fujimura, The intelligent ASIMO: system overview and integration, in: IEEE/RSJ International Conference on Intelligent Robots and System, 2002, pp. 2478–2483.
[119] A. Sekiguchi, Y. Atobe, K. Kameta, D. Nenchev, Y. Tsumaki, On motion generation for humanoid robot by the SC approach, in: Annual Conference of the Robotics Society of Japan, 2003, 2A27 (in Japanese).
[120] C. Semini, V. Barasuol, T. Boaventura, M. Frigerio, M. Focchi, D.G. Caldwell, J. Buchli, Towards versatile legged robots through active impedance control, The International Journal of Robotics Research 34 (2015) 1003–1020.
[121] L. Sentis, J. Petersen, R. Philippsen, Experiments with balancing on irregular terrains using the Dreamer mobile humanoid robot, in: Robotic Science and Systems, Sydney, 2012, pp. 1–8.
[122] D. Shin, I. Sardellitti, Y.L. Park, O. Khatib, M. Cutkosky, Design and control of a bio-inspired human-friendly robot, The International Journal of Robotics Research 29 (2009) 571–584.
[123] M. Stilman, J. Wang, K. Teeyapan, R. Marceau, Optimized control strategies for wheeled humanoids and mobile manipulators, in: IEEE-RAS International Conference on Humanoid Robots, IEEE, Paris, France, 2009, pp. 568–573.
[124] K. Takahashi, M. Noda, D. Nenchev, Y. Tsumaki, A. Sekiguchi, Static walk of a humanoid robot based the singularity-consistent method, in: IEEE/RSJ International Conference on Intelligent Robots and Systems, 2006, pp. 5484–5489.
[125] N.G. Tsagarakis, D.G. Caldwell, F. Negrello, W. Choi, L. Baccelliere, V.G. Loc, J. Noorden, L. Muratore, A. Margan, A. Cardellino, L. Natale, E. Mingo Hoffman, H. Dallali, N. Kashiri, J. Malzahn, J. Lee, P. Kryczka, D. Kanoulas, M. Garabini, M. Catalano, M. Ferrati, V. Varricchio, L. Pallottino, C. Pavan, A. Bicchi, A. Settimi, A. Rocchi, A. Ajoudani, WALK-MAN: a high-performance humanoid platform for realistic environments, Journal of Field Robotics 34 (2017) 1225–1259.
[126] N.G. Tsagarakis, S. Morfey, G. Medrano Cerda, Z. Li, D.G. Caldwell, COMpliant huMANoid COMAN: optimal joint stiffness tuning for modal frequency control, in: IEEE International Conference on Robotics and Automation, 2013, pp. 673–678.
[127] T. Tsujita, A. Konno, S. Komizunai, Y. Nomura, T. Owa, T. Myojin, Y. Ayaz, M. Uchiyama, Humanoid robot motion generation for nailing task, in: IEEE/ASME International Conference on Advanced Intelligent Mechatronics, 2008, pp. 1024–1029.
[128] B. Vanderborght, Dynamic Stabilisation of the Biped Lucy Powered by Actuators with Controllable Stiffness, Springer, 2010.
[129] B. Vanderborght, A. Albu-Schaeffer, A. Bicchi, E. Burdet, D.G. Caldwell, R. Carloni, M. Catalano, O. Eiberger, W. Friedl, G. Ganesh, M. Garabini, M. Grebenstein, G. Grioli, S. Haddadin, H. Hoppner, A. Jafari, M. Laffranchi, D. Lefeber, F. Petit, S. Stramigioli, N. Tsagarakis, M. Van Damme, R. Van Ham, L.C. Visser, S. Wolf, Variable impedance actuators: a review, Robotics and Autonomous Systems 61 (2013) 1601–1614.
[130] M. Vukobratovic, B. Borovac, Zero-moment point — thirty five years of its life, International Journal of Humanoid Robotics 01 (2004) 157–173.
[131] P.M. Wensing, L.R. Palmer, D.E. Orin, Efficient recursive dynamics algorithms for operational-space control with application to legged locomotion, Autonomous Robots 38 (2015) 363–381.
[132] D. Winter, Human balance and posture control during standing and walking, Gait & Posture 3 (1995) 193–214.
[133] D.A. Winter, Foot trajectory in human gait: a precise and multifactorial motor control task, Physical Therapy 72 (1992) 45–53, discussion 54–56.
[134] D.A. Winter, Biomechanics and Motor Control of Human Movement, Wiley, 2009.
[135] A. Witkin, M. Kass, Spacetime constraints, Computer Graphics 22 (1988) 159–168.
[136] K. Yin, D. Pai, M.V.D. Panne, Data-driven interactive balancing behaviors, in: Pacific Graphics, 2005, pp. 1–9.
[137] E. Yoshida, M. Poirier, J.-P. Laumond, O. Kanoun, F. Lamiraux, R. Alami, K. Yokoi, Pivoting based manipulation by a humanoid robot, Autonomous Robots 28 (2009) 77–88.
[138] T. Yoshiike, M. Kuroda, R. Ujino, H. Kaneko, H. Higuchi, S. Iwasaki, Y. Kanemoto, M. Asatani, T. Koshiishi, Development of experimental legged robot for inspection and disaster response in plants, in: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2017, pp. 4869–4876.

[139] Y. You, S. Xin, C. Zhou, N. Tsagarakis, Straight leg walking strategy for torque-controlled humanoid robots, in: IEEE International Conference on Robotics and Biomimetics (ROBIO), 2016, pp. 2014–2019.
[140] J. Zhao, N.I. Badler, Real-Time Inverse Kinematics with Joint Limits and Spatial Constraints, Technical Report MS-CIS-89-09, University of Pennsylvania, 1989.
[141] J. Zhao, N.I. Badler, Inverse kinematics positioning using nonlinear programming for highly articulated figures, ACM Transactions on Graphics 13 (1994) 313–336.
[142] Y. Zhao, A Planning and Control Framework for Humanoid Systems: Robust, Optimal, and Real-Time Performance, Ph.D. thesis, The University of Texas at Austin, 2016.
[143] Y. Zhao, B.R. Fernandez, L. Sentis, Robust optimal planning and control of non-periodic bipedal locomotion with a centroidal momentum model, The International Journal of Robotics Research 36 (2017) 1211–1243.
[144] C. Zhou, Z. Li, X. Wang, N. Tsagarakis, D. Caldwell, Stabilization of bipedal walking based on compliance control, Autonomous Robots 40 (2016) 1041–1057.
[145] M. Zinn, O. Khatib, B. Roth, J. Salisbury, Playing it safe, IEEE Robotics & Automation Magazine 11 (2004) 12–21.
[146] J. von Zitzewitz, P.M. Boesch, P. Wolf, R. Riener, Quantifying the human likeness of a humanoid robot, International Journal of Social Robotics 5 (2013) 263–276.