JOURNAL OF AUTOMATIC CONTROL, UNIVERSITY OF BELGRADE; VOL. 12:4-8, 2002 ©

The Man-Machine Analogy in Robotics and Neurophysiology

Arthur Prochazka

Abstract — **Since the time of Descartes the machine-like control of movement in animals and the animal-like control of movement in automata has fascinated and inspired scientists, engineers and philosophers alike. In 1966, Drs. Rajko Tomović and Robert McGhee proposed the concept of a "cybernetic actuator," a new type of control system which "possesses the property of producing continuous controlled motion from an input which may assume only four distinct states" [1]. The specific application at the time was an artificial limb prosthesis. Signals from sensors monitoring joint angle and ground contact were to be continuously compared to a set of threshold values corresponding to specific moments in the step cycle. The binary signals (above or below threshold) were listed in a look-up chart which associated sensory combinations with actuator states. It was proposed that this system would provide all of the known state transitions required of an above-knee prosthesis. In this and later papers Tomović was careful to point out the differences between such "artificial reflex control" systems and neural control systems in animals [2]. Nonetheless in the last few years it has become commonplace to see the control of locomotion and other rhythmical behaviors described in terms of "sensory rules," that is in terms of finite state systems. With the advent of neural nets and fuzzy logic control, robotic devices are taking on more and more of the features of biological control systems. In turn, neurophysiologists borrow more and more from the concepts and mechanisms of modern control theory. The influence of Tomovic's simple but powerful idea continues to spread.**

Index Terms — **cybernetic actuator, finite state control, fuzzy logic.**

I. INTRODUCTION

THE aim of this chapter is to place Rajko Tomović's notion of the "cybernetic actuator" in the context of bioengineering and neurophysiology, past and present.

Since the earliest discussions of animal movement it has always been acknowledged that sensory input is important for coordinated control, but the neural mechanisms involved are complex and therefore remain the subject of study and debate. From the first description of sensory input being reflected into motor action [3], one can trace a line of theories, the central idea of which was that movements, no matter how complex, can be broken down into elemental sensorimotor reactions or reflexes. Thus Herbert Spencer [4] referred to reflexes as "atoms of the psyche" and proposed that "instincts" (inherited behaviors) were assemblies of reflexes consolidated by repetition. Sechenov suggested that all movements, including those considered "voluntary," were simply chains of reflexes and this was echoed a century later by B.F. Skinner, who suggested that any given behavior was simply a combination of conditioned (learnt) reflexes [5]. These views do of course beg the question, what is voluntary and what is reflex? This question has implications that extend far beyond neurophysiology, into the philosophical and legal domains of free will and personal accountability [6].

The neural mechanisms controlling locomotion were among the first neural systems to be analyzed in detail [7, 8, 9, 10, and 11]. Several interesting and puzzling results emerged quite early in the piece. For example, studies were performed on spinally-transected dogs to explore the capabilities of the spinal cord deprived of descending input. It was found that a locomotor rhythm could be set in train in the pendent limbs by suddenly dropping one limb from a flexed position [7]. Sherrington found that the locomotor rhythm could be abolished by stopping the movement of a limb in mid-cycle [10, 11]. These results suggested that the proprioceptive input signaling extreme extension or extension triggered the limb into the next half-cycle. On the other hand Sherrington's student Graham Brown found that locomotor-like rhythms could persist after abolishing sensory input with extensive surgical transection of sensory roots entering the spinal cord [12]. Brown concluded that an "intrinsic factor" in the spinal cord produced the rhythm autonomously and that the role of sensory input was to regulate this centrally generated activity to cope with irregularities and variations in the external environment.

Another troubling paradox was that whereas stretch reflexes clearly provided continuous proportional feedback control of muscle activation, the transitions from flexion to extension at the end of each half-cycle were discontinuous switch-like events. Stretch reflex control apparently terminated abruptly in one set of muscles and started just as abruptly in their antagonists. How were these various

The original manuscript received on the March 25 2002. The manuscript accepted in the final form on the April 7 2002.

This work was supported in part by Canadian Institutes of Health Research and Alberta Heritage Foundation for Medical Research, Canada.

Arthur Prochazka is with the Centre for Neuroscience, University of Alberta, Edmonton, Edmonton, Alberta, T6G 2S2 Canada. E-mail: arthur.prochazka @ualberta.ca

mechanisms of rhythm generation and load compensation to be reconciled into a single smoothly operating control system?

From the late 1920s neurophysiologists turned their attention inward to the cellular details of neuronal circuitry. Simple neural loops such as the stretch reflex became the focus of study because they were accessible examples of neural circuitry that could be analyzed in a reductionist manner. Most experiments were done under static conditions in reduced preparations, in the absence of voluntary movement. However in the 1960s and 1970s there was a resurgence of interest in the control of complex movement. Graham Brown's intrinsic factor concept was revived, given a new name (central pattern generator, "CPG"), and applied to different systems and species [13, 14, 15, and 16]. The activity patterns of sensory afferents were recorded during normal limb movements, and found to be rather different than in the anesthetized or decerebrate state [17, 18, 19, 20, and 21]. Muscle spindles emerged as displacement and velocity transducers whose gain and offset were modulated according to task and context by fusimotor outflow from the central nervous system (CNS). Another important development was the realization that activity-dependent muscle stiffness was a crucial element of load compensation [22]. It was realized that the length-dependence of muscle force in effect represented displacement feedback [23]. Locomotor reflexes were shown to be modulated or even to reverse in sign depending on the phase of the step cycle [24, 25, and 26]. And finally, in relation to the topic of this chapter, Freusberg and Sherrington's classical experiments showing that sensory input could trigger or block the switch from one phase of locomotion to the next were confirmed and extended [27, 28, and 29].

II. Technological Developments

The term "finite state system" evolved from Alan Turing's concept proposed in 1936 of a machine that could perform logical operations analogous to the transitions between 'states of mind' of a human being performing a mental process. The "Turing machine" soon became known as the "computer." The word "cybernetics" was coined by Norbert Wiener in 1948 from the Greek kubernetes: "the art of steering." Like many before him, Wiener had been struck by the similarity between control systems in animals and machines [3, 30, and 31]. The Roman poet Ovid used the word "reflex" in the sense of "turn back, bring back." Substitute "feed" for "bring" and we have Wiener's neologism "feedback" which replaces *reflex* in control systems theory.

In the biomedical engineering domain, the 1960s saw the birth of functional electrical stimulation for the restoration of movement in partially paralysed people [32, 33]. This created a need for a better understanding of the control of human limb movement in particular. The development of actuator-driven prostheses provided another important impetus. Tomović and McGhee were among the first to bring these various concepts together.

III. Reconciling CPGs, Proportional Feedback and Finite-State Control

As mentioned above, prior to the advent of modern control theory and hybrid control systems in robotics it was hard for neurophysiologists to reconcile continuous proportional control with discontinuous phase-switching. Moreover, it continues to be a challenge to determine the relative importance of the centrally-determined components of muscle activation as opposed to proportional and finite-state feedback control [34, 35]. Tomović and his colleagues sidestepped this issue to some extent by acknowledging that continuous feedback occurred in the biological system, but they did not go on to speculate how it might interact with finite state mechanisms of control [36, 37].

Recently, this issue has been tackled head on from a number of different directions. For example, Cruse and his colleagues have studied stick insect locomotion from the viewpoint of robotic applications. To quote from their recent paper: *"The locomotor system of slowly walking insects is well suited for coping with highly irregular terrain and therefore might represent a paragon for an artificial six-legged walking machine. Our investigations of the stick insect Carausius morosus indicate that these animals gain their adaptivity and flexibility mainly from the extremely decentralized organization of the control system that generates the leg movements. Neither the movement of a single leg nor the coordination of all six legs (i.e., the gait) appears to be centrally pre-programmed. Thus, instead of using a single, central controller with global knowledge, each leg appears to possess its own controller with only procedural knowledge for the generation of the leg's movement. This is possible because exploiting the physical properties avoids the need for complete information on the geometry of the system that would be a prerequisite for explicitly solving the problems. Hence, production of the gait is an emergent property of the whole system, in which each of the six single-leg controllers obeys a few simple and local rules in processing state-dependent information about its neighbors [38].*

Several robotics laboratories have found that hybrid control which combines finite-state rules with proportional control is a good way to ensure stability in walking robots [39, 40]. Presently the most advanced walking robot, the Honda Asimo humanoid robot, has three levels of control: 1) local proportional-integral-differential (PID) control about individual joints, 2) finite-state phase switching and hazard rules and 3) a global command comprising a moving target of ground reaction force against which the actual ground reaction vector is compared. Along similar lines, hybrid systems combining PID, finite-state and global state control have been utilized successfully in the biomechanical modeling of human locomotion [41, 42, 43, 44, 45, and 46].

IV. CONTROL SYSTEMS DEVELOPMENTS: FUZZIFYING THE STATES

As Tomović and his colleagues were at pains to point out, the rigorous definition of a finite state system differs from sensorimotor control in animals in some clear and obvious ways [1, 2]. One of these is that "real dynamical systems are not capable of discontinuous changes of state." Another is that whether one considers stereotypical movements in a robot, a biomimetic model, or an animal, nearly always there is a clearly defined sequence of states, i.e. a given state is usually preceded by another particular state and not by some random state.

In the original definition, states in a finite state system were "ignorant of each other" and of past history. In other words, any state could be "fired" from any other state provided only that the sensory conditions were met. Finally, in finite-state control, sensory thresholds, actuator states and state-transition rules were rigidly defined. There was no provision for the input and output states to be described in vague linguistic terms or for sensory inputs to be weighted such that the sums of *weighted* inputs fired state transitions as opposed to *every* sensory input having to exceed its specified threshold. Over the years, finite-state systems have either been "softened" to incorporate such probabilistic features, or they have been replaced by systems such as fuzzy controllers [47], Kalman filters and Hidden Markov models that can cope with uncertain sensory inputs and uncertain motor outputs in a probabilistic manner.

V. RECENT NEUROPHYSIOLOGICAL DEVELOPMENTS

In neurophysiology, recent developments have included:

1. The discovery of positive force feedback during locomotion. When gait starts, the force-sensing receptors, the tendon organs, switch from reflexly inhibiting to reflexly exciting the motoneurons of their muscles of origin [48, 49]. Unlike a linear PID system, positive force feedback of muscles remains stable because when muscles shorten they produce less force for a given change in input, which automatically limits loop gain [50].

2. Input from muscle receptors causes the abrupt phase-switching between stance and swing in the step cycle [48]. Finite-state rules have been proposed, that describe these phase transitions in a variety of animal species [Prochazka, 34, 51]. Fuzzy logic, which uses combinations of weighted sensory inputs rather than sets of fixed thresholds, may provide a more realistic analogy [51, 52].
3. The components of muscle activation in the step cycle attributable to spinal reflexes mediated by muscle receptors are modest and delayed [35, 53, 54, and 55]. These reflex components are only really crucial if the CPG activation profiles are weak, otherwise it seems that they may play a rather minor role such as regulating speed and overall limb-segment postures [35].

4. In the presence of vision, locomotor movements are adjusted to terrain two or three steps in advance [56, 57, 58, and 59]. Firing of motor cortical neurons is correlated with these predictive changes [60, 61, and 62]. Interestingly, "one-step-ahead control" was independently suggested as a strategy for an FES application [63].

5. The notion of an "internal model" whereby multimodal sensory input is processed to produce muscle commands based on internal predictions of the biomechanical consequence of these commands [64]. This idea is in fact the "Smith predictor" in a new guise [65, 66].

6. As a preface to the concluding comments below, we should also mention the idea of the cerebellum as a state analyzer, performing probabilistic operations on sensory information analogous to Bayesian statistics or Kalman filtering [67, 68,69, and 70].

VI. CONCLUDING REMARKS

In a recent review of the control of locomotion we recently drew the following general conclusions [35]:

1. The intrinsic stiffness of limb muscles, when activated with optimized cyclical patterns can generate stable locomotion in the face of small variations in speed and terrain. Stretch reflexes contribute to load compensation within a given phase of the step cycle, and provide a limited means of changing gait speed and posture.

2. Larger adjustments in speed and terrains require higher-level control strategies such as finite-state logic.

3. Global rules that use multisensory input are required for movement selection, predictions about upcoming movements and overall balance.

In the spirit of Rajko Tomović's "cybernetic actuator" I would like to conclude this chapter with some further speculations. From what we have seen above, the man-machine analogy has clearly cross-fertilized ideas in the fields of robotics and neurophysiology. Hybrid control is now an indispensable feature of complex robot design and neurophysiological theory. In light of this, can we identify properties that are common to many sensorimotor control systems, whether artificial or biological? These should not be restricted to systems controlling simple motor acts such as locomotion; recognition of visual images, the phonemes of speech and the printed word are also sensorimotor tasks done by machines as well as by animals. Taking all such processes into account, I would propose the following general statements:

1. Sensory input is generally multivariate, complex and "noisy."
2. Motor actuators are nonlinear and often somewhat unpredictable.
3. Nonlinear properties of actuators may allow control strategies that would be inappropriate or unstable in a linear system, e.g. positive feedback.
4. There may be numerous ways of performing a sensorimotor task successfully.
5. Combinations of control strategies (PID, finite state, fuzzy logic, global targets) are more likely to control complex systems successfully than single strategies.

REFERENCES

[1] R. Tomović and R. McGhee, "A finite state approach to the synthesis of control systems," *IEEE Transactions on Human Factors Electronics*, vol. 7, pp. 122-128, 1966.
[2] D. Popović, R. Tomović, D. Tepavac and L. Schwirtlich, "Control aspects of active above-knee prosthesis," *International Journal of Man-Machine Studies*, vol. 35, pp. 751-767, 1991.
[3] R. Descartes, *Trait" de l'homme* (*Treatise of man*). French text with English translation and commentary. Cambridge, Massachusetts: Harvard University Press 1972 (originally by Le Gras, Paris), 1664.
[4] H. Spencer, *Principles of Psychology* (2nd Edition published in 1873), vol. 2, 2nd ed. New York: Appleton, 1855.
[5] B. F. Skinner, "Cognitive science and behaviorism," *British Journal of Psychology*, vol. 76, pp. 291-301, 1985.
[6] A. Prochazka, F. Clarac, G. E. Loeb, J. C. Rothwell, and J. R. Wolpaw, "What do reflex and voluntary mean: Modern views on an ancient debate," *Experimental Brain Research*, vol. 130, pp. 417-32, 2000.
[7] A. Freusberg, "Reflexbewegungen beim Hunde," *Pflügers Archiv für die gesamte Physiologie*, vol. 9, pp. 358-391, 1874.
[8] R. Magnus, "Zur Regelung der Bewegungen durch das Zentralnervensystem. Mitteilung I," *Pflügers Archiv für die gesamte Physiologie des Menschen und der Tiere*, vol. 130, pp. 219-252, 1909.
[9] R. Magnus, "Zur Regelung der Bewegungen durch das Zentralnervensystem. Mitteilung II," *Pflügers Archiv für die gesamte Physiologie des Menschen und der Tiere*, vol. 130, pp. 253-269, 1909.
[10] C. S. Sherrington, "Flexion-reflex of the limb, crossed extension-reflex, and reflex stepping and standing," *Journal of Physiology* (London), vol. 40, pp. 28-121, 1910.
[11] C. S. Sherrington, "Further observations on the production of reflex stepping by combination of reflex excitation with reflex inhibition", *Journal of Physiology*, vol. 47, pp. 196-214, 1914.
[12] T. G. Brown, "The intrinsic factors in the act of progression in the mammal," *Proceedins of the Royal Society London Serial B*, vol. 84, pp. 308-319, 1911.
[13] S. Grillner and P. Zangger, "How detailed is the central pattern generation for locomotion," *Brain Research*, vol. 88, pp. 367-71, 1975.
[14] A. I. Selverston, D. F. Russell, and J. P. Miller, "The stomatogastric nervous system: structure and function of a small neural network," *Progress in Neurobiology*, vol. 7, pp. 215-90, 1976.
[15] J. M. Ramirez, S. W. Schwarzacher, O. Pierrefiche, B. M. Olivera, and D. W. Richter, "Selective lesioning of the cat pre-Botzinger complex in vivo eliminates breathing but not gasping," *Journal of Physiology*, vol. 507, pp. 895-907, 1998.
[16] D. R. McCrimmon, J. M. Ramirez, S. Alford, and E. J. Zuperku, "Unraveling the mechanism for respiratory rhythm generation," *Bioessays*, vol. 22, pp. 6-9, 2000.
[17] K. E. Hagbarth and A. B. Vallbo, "Discharge characteristics of human muscle afferents during muscle stretch and contraction," *Experimental Neurology*, vol. 22, pp. 674-94, 1968.
[18] A. Taylor and F. W. Cody, "Jaw muscle spindle activity in the cat during normal movements of eating and drinking," *Brain Research*, vol. 71, pp. 523-30, 1974.
[19] G. M. Goodwin and E. S. Luschei, "Discharge of spindle afferents from jaw-closing muscles during chewing in alert monkeys," *Journal of Neurophysiology*, vol. 38, pp. 560-71, 1975.
[20] A. Prochazka, R. A. Westerman, and S. P. Ziccone, "Discharges of single hindlimb afferents in the freely moving cat," *Journal of Neurophysiology*, vol. 39, pp. 1090-1104, 1976.
[21] G. E. Loeb, M. J. Bak, and J. Duysens, "Long-term unit recording from somatosensory neurons in the spinal ganglia of the freely walking cat," *Science*, vol. 197, pp. 1192-4, 1977.
[22] A. G. Feldman, "[On the functional tuning of the nervous system in movement control or preservation of stationary pose. II. Adjustable parameters in muscles]," *Biofizika*, vol. 11, pp. 498-508, 1966.
[23] L. D. Partridge, "Signal-handling characteristics of load-moving skeletal muscle," *American Journal of Physiology*, vol. 210, pp. 1178-1191, 1966.
[24] H. Forssberg, S. Grillner, and S. Rossignol, "Phase dependent reflex reversal during walking in chronic spinal cats," *Brain Research*, vol. 85, pp. 103-7, 1975.
[25] H. Forssberg, S. Grillner, and S. Rossignol, "Phasic gain control of reflexes from the dorsum of the paw during spinal locomotion," *Brain Research*, vol. 132, pp. 121-39, 1977.
[26] P. Wand, A. Prochazka, and K. H. Sontag, "Neuromuscular responses to gait perturbations in freely moving cats," *Experimental Brain Research*, vol. 38, pp. 109-14, 1980.
[27] O. Andersson and S. Grillner, "Peripheral control of the cat's step cycle. II. Entrainment of the central pattern generators for locomotion by sinusoidal hip movements during "fictive locomotion"," *Acta Physiologica Scandinavica*, vol. 118, pp. 229-39, 1983.
[28] S. Rossignol, "Neural control of stereotypic limb movements," In: *Handbook of Physiology. Section 12. Exercise: Regulation and Integration of Multiple Systems*, L. Rowell and J. T. Sheperd, Eds. New York: American Physiological Society, 1996, pp. 173-216.
[29] K. G. Pearson, "Proprioceptive regulation of locomotion," *Current Opinion in Neurobiology*, vol. 5, pp. 786-91, 1995.
[30] d. L. Mettrie, J.O., *L'Homme-Machine*. English translation: *Man a machine*; and *Man a plant* (1994). Indianapolis: Maya Hackett, 1745.
[31] M. Jeannerod, *The brain machine. The development of neurophysiological thought*. (English translation *of Le Cerveau-Machine: Physiologie de la Volonte*, Librairie Artheme Fayard, Paris, 1983).: Harvard University Press, Cambridge Massachusetts, 1985.
[32] L. Vodovnik, C. d. Long, J. B. Reswick, A. Lippay, and D. Starbuck, "Myo-electric control of paralyzed muscles," *IEEE Transactions on Biomedical Engineering*, vol. 12, pp. 169-72, 1965.
[33] L. Vodovnik, W. J. Crochetiere, and J. B. Reswick, "Control of a skeletal joint by electrical stimulation of antagonists," *Medical & Biological Engineering*, vol. 5, pp. 97-109, 1967.
[34] A. Prochazka and S. Yakovenko, "Locomotor control: from spring-like reactions of muscles to neural prediction," in *The Somatosensory System: Deciphering The Brain's Own Body Image*, R. Nelson, Ed. Boca Raton: CRC Press, 2001, pp. 141-181.
[35] A. Prochazka, V. Gritsenko, and S. Yakovenko, "Sensory control of locomotion: reflexes versus higher-level control," in *Sensori-Motor Control*, S. G. Gandevia, Proske, U. & Stuart, D.G., Ed. London, New York: Kluwer Academic/Plenum Publishers, 2002, (in press)
[36] D. Popović, R. Tomović, and L. Schwirtlich, "Hybrid assistive system- the motor neuroprosthesis," *IEEE Transactions on Biomedical Engineering*, vol. 36, pp. 729-37, 1989.
[37] D. Popović, M. N. Oguztoreli, and R. B. Stein, "Optimal control for the active above-knee prosthesis," *Ann Biomed Eng*, vol. 19, pp. 131-50, 1991.
[38] J. Schmitz, J. Dean, T. Kindermann, M. Schumm, and H. Cruse, "A biologically inspired controller for hexapod walking: simple solutions by exploiting physical properties," *Biological Bulletin*, vol. 200, pp. 195-200, 2001.

[39] K. S. Espenschied, R. D. Quinn, R. D. Beer, and H. J. Chiel, "Biologically based distributed control and lcal reflexes improve rough terrain locomotion in a hexapod robot," *Robotics and Autonomous Systems*, vol. 18, pp. 59-64, 1996.
[40] R. D. Quinn and R. E. Ritzmann, "Biologically based distributed control and local reflexes improve rough terrain locomotion in a hexapod robot.," *Connection Science*, vol. 10, pp. 239-254, 1998.
[41] G. Taga, Y. Yamaguchi, and H. Shimizu, "Self-organized control of bipedal locomotion by neural oscillators in unpredictable environment," *Biological Cybernetics*, vol. 65, pp. 147-59, 1991.
[42] G. Taga, "A model of the neuro-musculo-skeletal system for human locomotion. II Real-time adaptability under various constraints," *Biological Cybernetics*, vol. 73, pp. 113-21, 1995.
[43] G. Taga, "A model of the neuro-musculo-skeletal system for human locomotion. I. Emergence of basic gait," *Biological Cybernetics*, vol. 73, pp. 97-111, 1995.
[44] G. Taga, "A model of the neuro-musculo-skeletal system for anticipatory adjustment of human locomotion during obstacle avoidance," *Biological Cybernetics*, vol. 78, pp. 9-17, 1998.
[45] N. Yamazaki, K. Hase, N. Ogihara, and N. Hayamizu, "Biomechanical analysis of the development of human bipedal walking by a neuro-musculo-skeletal model," *Folia Primatologica*, vol. 66, pp. 253-271, 1996.
[46] N. Ogihara and N. Yamazaki, "Generation of human bipedal locomotion by a bio-mimetic neuro-musculo-skeletal model," *Biological Cybernetics*, vol. 84, pp. 1-11, 2001.
[47] A. Prochazka, "The fuzzy logic of visuomotor control," *Can J Physiol Pharmacol*, vol. 74, pp. 456-62, 1996.
[48] B. A. Conway, H. Hultborn, and O. Kiehn, "Proprioceptive input resets central locomotor rhythm in the spinal cat," *Experimental Brain Research*, vol. 68, pp. 643-56, 1987.
[49] K. G. Pearson and D. F. Collins, "Reversal of the influence of group Ib afferents from plantaris on activity in medial gastrocnemius muscle during locomotor activity," *Journal of Neurophysiology*, vol. 70, pp. 1009-17, 1993.
[50] A. Prochazka, D. Gillard, and D. J. Bennett, "Implications of positive feedback in the control of movement," *J Neurophysiol*, vol. 77, pp. 3237-51, 1997.
[51] A. Prochazka, "Proprioceptive feedback and movement regulation," In: *Handbook of Physiology. Section 12. Exercise: Regulation and Integration of Multiple Systems*. edited by:, L. Rowell and J. T. Sheperd, Eds. New York: American Physiological Society, 1996, pp. 89-127.
[52] M. Y. Pang and J. F. Yang, "Interlimb co-ordination in human infant stepping," M. A. Gorassini, A. Prochazka, G. W. Hiebert, and M. J. Gauthier, "Corrective responses to loss of ground support during walking. I. Intact cats," *J Neurophysiol*, vol. 71, pp. 603-10, 1994.
[53] R. B. Stein, J. E. Misiaszek, and K. G. Pearson, "Functional role of muscle reflexes for force generation in the decerebrate walking cat," *Journal of Physiology*, vol. 525, pp. 781-91, 2000.
[54] V. Gritsenko, V. K. Mushahwar, and A. Prochazka, "Locomotor stretch reflexes increase after partial denervation of cat triceps surae muscles," *Journal of Physiology*, vol. 533, pp. 299-311, 2001.
[55] A. E. Patla, A. Adkin, and T. Ballard, "Online steering: coordination and control of body center of mass, head and body reorientation," *Experimental Brain Research*, vol. 129, pp. 629-34, 1999.
[56] A. E. Patla and J. N. Vickers, "Where and when do we look as we approach and step over an obstacle in the travel path", *Neuroreport*, vol. 8, pp. 3661-5, 1997.
[57] A. E. Patla, A. Adkin, C. Martin, R. Holden, and S. Prentice, "Characteristics of voluntary visual sampling of the environment for safe locomotion over different terrains," *Experimental Brain Research*, vol. 112, pp. 513-22, 1996.
[58] A. E. Patla, S. D. Prentice, S. Rietdyk, F. Allard, and C. Martin, "What guides the selection of alternate foot placement during locomotion in humans," *Experimental Brain Research*, vol. 128, pp. 441-50, 1999.
[59] T. Drew, W. Jiang, B. Kably, and S. Lavoie, "Role of the motor cortex in the control of visually triggered gait modifications," *Canadian Journal of Physiology & Pharmacology*, vol. 74, pp. 426-42, 1996.
[60] T. Drew, "Motor cortical activity during voluntary gait modifications in the cat. I. Cells related to the forelimbs," *Journal of Neurophysiology*, vol. 70, pp. 179-99, 1993.
[61] T. Drew, "The role of the motor cortex in the control of gait modification in the cat," in *Neurobiological basis of human locomotion*, vol. 74, M. Shimamura, S. Grillner, and V. R. Edgerton, Eds. Tokyo: Japan Scientific Societies Press, 1991, pp. 201-212.
[62] M. H. Granat, B. W. Heller, D. J. Nicol, R. H. Baxendale, and B. J. Andrews, "Improving limb flexion in FES gait using the flexion withdrawal response for the spinal cord injured person," *Journal of Biomedical Engineering*, vol. 15, pp. 51-6, 1993.
[63] R. Shadmehr and F. A. Mussa-Ivaldi, "Adaptive representation of dynamics during learning of a motor task," *Journal of Neuroscience*, vol. 14, pp. 3208-24, 1994.
[64] O. J. M. Smith, "A controller to overcome dead time," *Instrumentation Society of Americas Journal*, vol. 6, pp. 28-33, 1959.
[65] R. C. Miall, "The cerebellum, predictive control and motor coordination," *Novartis Foundation Symposium*, vol. 218, pp. 272-84; discussion 284-90, 1998.
[66] M. G. Paulin, "The role of the cerebellum in motor control and perception," *Brain, Behavior & Evolution*, vol. 41, pp. 39-50, 1993.
[67] J. H. Gao, L. M. Parsons, J. M. Bower, J. Xiong, J. Li, and P. T. Fox, "Cerebellum implicated in sensory acquisition and discrimination rather than motor control," *Science*, vol. 272, pp. 545-7, 1996.
[68] M. G. Paulin, "Neural representations of moving systems," *International Review of Neurobiology*, vol. 41, pp. 515-33, 1997.
[69] J. M. Bower, "Control of sensory data acquisition," *International Review of Neurobiology*, vol. 41, pp. 489-513, 1997.