Sensory Systems in the Control of Movement

Arthur Prochazka[1] and Peter Ellaway[*2]

▶ ABSTRACT

Animal movement is immensely varied, from the simplest reflexive responses to the most complex, dexterous voluntary tasks. Here, we focus on the control of movement in mammals, including humans. First, the sensory inputs most closely implicated in controlling movement are reviewed, with a focus on somatosensory receptors. The response properties of the large muscle receptors are examined in detail. The role of sensory input in the control of movement is then discussed, with an emphasis on the control of locomotion. The interaction between central pattern generators and sensory input, in particular in relation to stretch reflexes, timing, and pattern forming neuronal networks is examined. It is proposed that neural signals related to bodily velocity form the basic descending command that controls locomotion through specific and well-characterized relationships between muscle activation, step cycle phase durations, and biomechanical outcomes. Sensory input is crucial in modulating both the timing and pattern forming parts of this mechanism. © 2012 American Physiological Society. *Compr Physiol* 2:2615-2627, 2012.

Introduction

"A mother while nursing her infant was seized with a paralysis, attended by the loss of sensibility on one side of her body. The surprising, and, indeed, alarming circumstance here was, that she could hold her child to her bosom with the arm which possessed muscular power, but only as long as she looked at the infant. If surrounding objects withdrew her attention from the state of her arm, the flexor muscles gradually relaxed and the child was in danger of falling."

Charles Bell wrote this compelling description in 1834 (13). The motor consequences of sensory loss have since been studied in many animals: insects, crustaceans, amphibia, reptiles, birds, fish, and mammals, including humans (reviews in references 58, 135). In nearly all cases, though strong voluntary muscle contractions were still possible, purposive movements were uncoordinated, inaccurate, and unstable, especially when visual guidance was absent. Bell attributed the problem to a loss of what he called *muscular sense*. This term was later replaced by *kinesthesia*, the conscious perception of movement (12). Sensations from muscle, tendon, skin, and joints were all assumed to contribute to kinesthesia. Sherrington coined the term *proprioception* to describe the sensing of bodily movement by "*interoreceptors*" in muscles, joints, and the vestibular apparatus (156). Bell and Sherrington both assumed that input from muscle proprioceptors mediated subconscious sensorimotor responses and kinesthesia. In 1992, Richard Burgess summarized much of the above in the title of a Society for Neuroscience symposium: "You can only control what you sense." This simple statement could well serve as an underlying principle of sensorimotor control.

Sensory input from a variety of sources is involved in the control of movement. The receptors include muscle spindles (90), Golgi tendon organs (144), joint receptors (95), skin receptors (196), visual and vestibular receptors (5, 38, 123, 166), and receptors that influence circulatory and respiratory adjustments during exercise (101). In this article, we will first review the properties of the sensory receptors that are the most closely involved in the sensory control of movement. We will then consider how sensory input from these receptors interacts with neural networks in the central nervous system (CNS) to generate purposeful movement.

The human upper extremity contains about 4000 muscle spindles, 2500 Golgi tendon organs, and a few hundred joint receptors (11, 91, 182). The human hand alone has around 17,000 myelinated cutaneous afferents (96).

Muscle Spindles

More effort has gone into understanding the structure, functioning, and reflex action of muscle spindles than of all the other mammalian mechanoreceptors combined. Group Ia afferents of muscle spindles are the largest axons in the mammalian nervous system and they have strong reflex actions on α-motoneurons, so it was long assumed that they played an important role in movement control.

Depending on its size, a mammalian muscle may contain up to 500 muscle spindles located amongst the force-producing "extrafusal" muscle fibers (91, 135). Generally, muscles involved in accurate postural or dexterous control have the largest number of muscle spindles. A typical spindle has a primary and a secondary sensory ending (1^0 and 2^0),

*Correspondence to p.ellaway@imperial.ac.uk

[1]Centre for Neuroscience, University of Alberta, Edmonton, Alberta, Canada

[2]Division of Experimental Medicine, Imperial College London, London, United Kingdom

innervated respectively by group Ia and II axons. The spindle is innervated by several γ-motoneurons that activate specialized "intrafusal" muscle fibers whose only role is to control the stretch sensitivity and background firing rates of the spindle sensory afferents. Intrafusal fibers may also receive branches of α-motoneurons, so-called β-innervation (51). γd action increases 1^0 afferent stretch sensitivity (gain) up to 5-fold, except when muscle displacements are very small, and adds a small amount of background firing (bias). γs action adds a large bias to 1^0 and 2^0 afferent firing and attenuates 1^0 gain by up to 50%. An interactive animation of these effects is available online (102).

There is still some disagreement on the way the CNS uses γ-motoneurons to control the sensitivity of muscle spindles during voluntary movement. Five hypotheses have been proposed:

1. *The follow-up servo.* It was posited that γ-motoneurons indirectly *initiated* movement by activating intrafusal muscle fibers, which activated spindle afferents, which in turn reflexively activated α-motoneurons (113). This theory was discarded for lack of evidence that spindle afferents started firing before α-motoneurons in voluntarily initiated movements.

2. *α-γ coactivation.* Here it was proposed that γ-motoneurons were coactivated with α-motoneurons, keeping the noncontractile sensory region in the middle of the spindle taut during muscle shortening (110). In this view, spindle afferent firing should remain fairly constant unless unexpected length changes occur. Data emerged showing that spindle firing rates actually fluctuated significantly during movements (62, 172). Nonetheless much evidence, notably from human microneurography, suggests that at least some portion of γ-activation is indeed linked to α-activation (7, 26, 98, 117).

3. *Tonic and phasic γ-activation.* The third hypothesis, or *group* of hypotheses, originated in studies of decerebrate or spinal locomotion. It was posited that γd- and γs-motoneurons have distinct firing patterns and muscle distributions (27, 130), one type having deeply modulated firing rates during locomotion and the other type firing more tonically. The deeply modulated patterns were initially equated with α-γ-coactivation (131), but in the more recent studies α- and γ-motoneurons showed significant differences. Recordings from ankle extensor γ-motor axons in the decerebrate locomotor cat (118) suggested that the firing rates of γd-motoneurons were deeply modulated compared to those of γs-motoneurons. Other evidence indicated that ankle extensor γs-axons increased their firing during muscle shortening while γd-axons fell silent but then abruptly resumed firing at the transition from muscle shortening to lengthening, a pattern that would sensitize the 1^0 endings to the onset of muscle stretch during the swing phase of the step cycle (174) (Fig. 1). It was sug-

gested that the firing patterns of 2^0 endings were "temporal templates of the expected movements."

4. *Fusimotor set.* Spindle afferent firing recorded in normally active monkeys and cats was usually better correlated with muscle length changes than with muscle activity, which argued against α-γ-coactivation being the dominant influence. The firing patterns of spindle afferents recorded during locomotion were consistent with fairly steady levels of γs drive, similar to that in Figure 1A. In situations involving novelty, anxiety, or difficulty, spindle 1^0 endings had large, length-related modulations of firing rate, suggesting increased γd action (140). This gave rise to the notion of behaviorally related "fusimotor set." In line with this, Loeb and co-workers suggested that fusimotor set optimizes spindle sensitivity according to anticipated variations in kinematics (105). Recordings from human spindle afferents have generally favored α-γ-coactivation (7, 188), but evidence supporting fusimotor set in humans has also been adduced (87, 147, 148).

5. *Forward sensory models.* Edin and colleagues recently recorded spindle afferent firing during finger and wrist movements in humans performing keyboard tasks. The firing not only reflected muscle length changes and contraction, but also appeared to predict future intended movements (40). It was proposed that fusimotor drive reflected internal predictive models (41, 191), an idea similar to that of the "temporal template of intended movement" (173). Finally, two other groups using human microneurography came to the conclusion that the direction of tuning of individual spindle afferents was mainly related to the length changes of the parent muscle, more consistent with the data from behaving cats and monkeys (36, 97).

Toward an understanding of the role of muscle spindles

From the above, it is evident that theories of the role of muscle spindles range widely, from variable-gain feedback to feed-forward prediction. The complexities of spindle structure and fusimotor control probably allow for overlapping modes of control, depending on motor task. We will now briefly consider some of the factors that have contributed to the uncertainty. The decerebrate locomotor recordings were done under conditions of physical restraint and partial denervation. It is debatable whether γ-motoneurons fire normally in a decerebrate animal with open surgical wounds and body weight support. Human microneurography has not been able to resolve the action potentials of the small diameter axons of γ-motoneurons or the spectrum of Gp II axons innervating 2^0 endings of muscle spindles. The range and velocities of movement have generally been restricted so as to avoid dislodging the tips of microelectrodes resting in peripheral nerves. Most of these data therefore represent a subset of slow movements performed under constrained conditions. The chronic
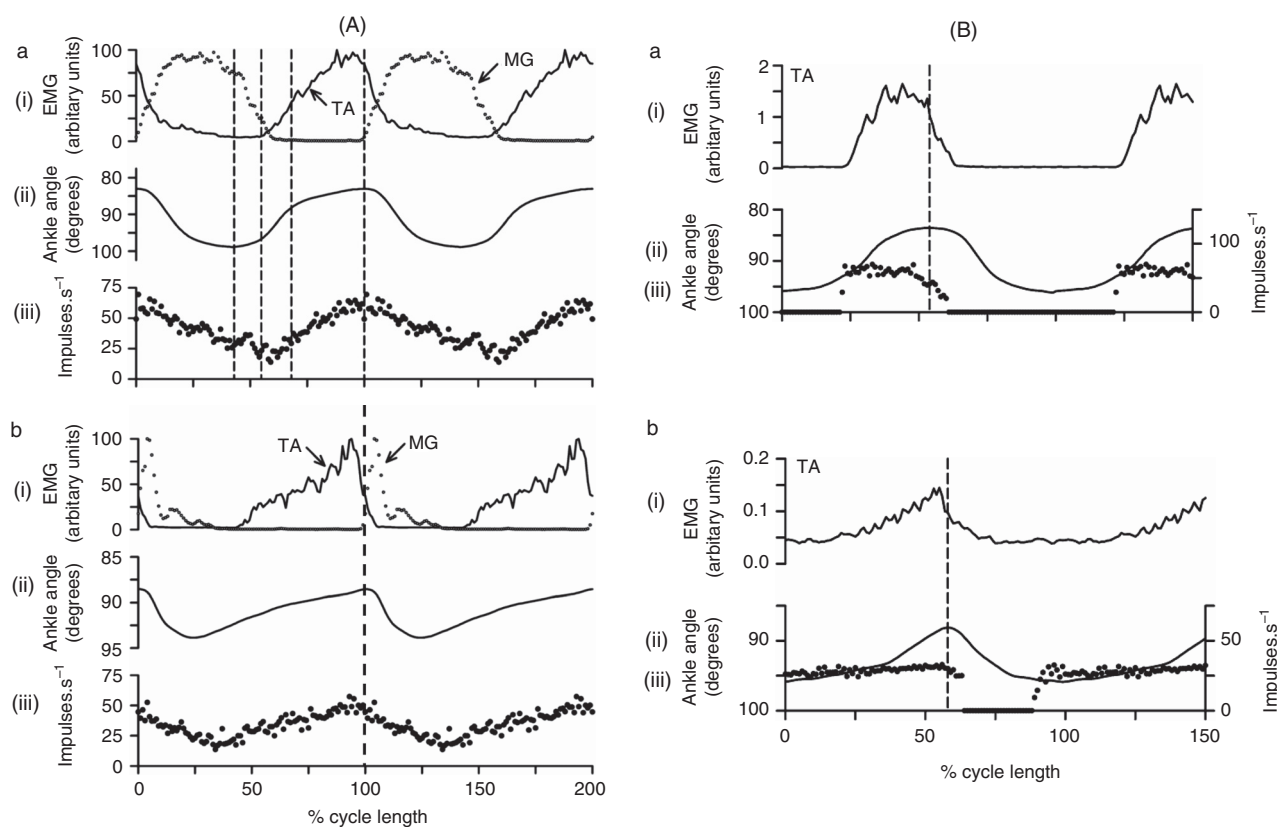
Figure 1 Ensemble cycle averages of the firing of γs and γd motoneurons (A and B), recorded in the common peroneal nerve innervating the ankle flexor tibialis anterior (TA) during spontaneous locomotion in the high decerebrate cat. (A) Three simultaneously recorded γs motoneurons in two cats (panels a and b), in each case an average of 20 step cycles aligned to TA length minima (thick vertical dashed line) and normalized in time. (i) TA electromyogram (EMG: continuous line), medial gastrocnemius (MG) EMG (dotted line), (ii) ankle angle corresponding to TA shortening upward, and (iii) mean firing rate of the γs motoneurons. Mean cycle times in (a) 640 ms and in (b) 800 ms. The three thin vertical dashed lines in A(a) indicate the three phases of TA muscle shortening. B(a) discharge of a γd motoneuron, average of 9 step cycles aligned to TA length minima in each cycle and normalized in time, mean cycle duration 740 ms, B(b) similar data from a γd motoneuron in another cat, average of 12 step cycles with mean duration 735 ms. Note the sudden onset of γd firing at the onset of TA shortening, and the cessation of firing shortly after the start of lengthening. Adapted, with permission, from Figures 3 and 7 in Taylor et al. (174).

recordings in intact monkeys and cats involved a large range of movement types, amplitudes and velocities, but the problem here was the relatively small database. Until recently, recordings were made with single or small numbers of implanted microelectrodes that only remained viable for a few days, so the yield per animal was low. Therefore, the ensemble afferent firing data shown in Figure 2 should be considered preliminary. More recently, microelectrode arrays implanted in dorsal root ganglion have enabled recording from up to 20 afferents simultaneously in freely moving cats, about half being muscle afferents (184, 185). The focus of this work was to develop sensory implants to control neuroprostheses, but the technique could also be used to settle some of the above controversies.

Differences between humans and experimental animals?

Firing rates of muscle spindle afferents recorded in behaving cats and monkeys are typically four to five times higher than

those in humans (3, 4, 35, 139). There is no a priori reason to expect a fundamental species difference, as the morphology and fusimotor innervation are similar and isolated human spindles stretched at comparable velocities have similar firing properties to those in cats (99, 120, 132). It is possible that the discrepancy is due to the large differences in muscle velocities in the human and animal experiments (136). Alternatively, perhaps fusimotor control in the more "voluntary" upper extremity muscles, which have been the focus of the human studies, differs from that in the jaw muscles of the monkey and the hind limb muscles of cats.

Tendon compliance: Do tendons change length significantly during active movements?

In recent human studies using ultrasonography, it was concluded that in imposed ankle movements in the absence of muscle activity, triceps surae tendons took up over 50% of the length change measured from muscle origin to insertion (79, 82). It follows that in active movements with varying forces,
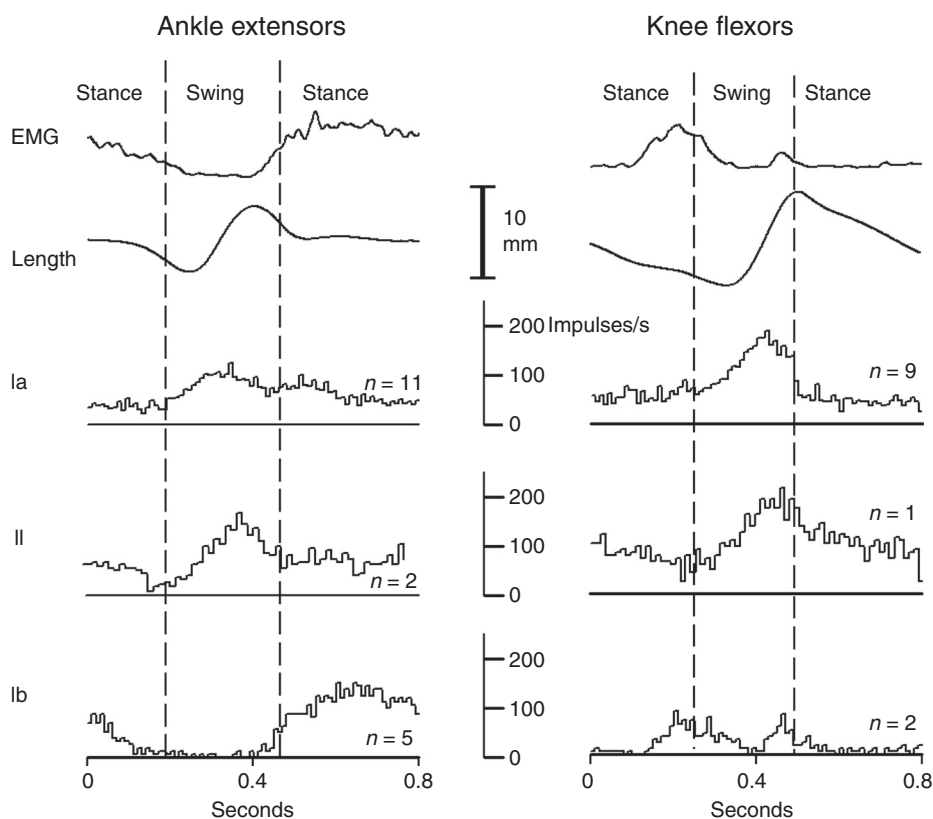
Figure 2 Ensemble averages of firing rates of group Ia, II, and Ib afferents in ankle extensors (left) and knee flexors (right), recorded during overground locomotion in normal cats. Traces from top to bottom: electromyogram (EMG) and length of receptor-bearing muscles (lengthening upwards), firing rates of group Ia, II, and Ib afferents. The number of afferents contributing to each average is shown on the right of each firing rate plot. Step cycles were aligned to peaks in either the ankle extensor (triceps surae) or knee flexor (posterior biceps) length signals. The length signals were also used to estimate stance-swing and swing-stance transitions in the step cycle (vertical dashed lines). Note the high mean firing rates of Ia and II afferents, indicating high levels of γs drive and the increase in the ankle extensor Ia firing rate prior to the onset of lengthening at the stance to swing transition, compatible with increased γs drive. Derived, with permission, from Figure 6 (139).

muscle fibers and their associated spindles would "see" length changes quite different from those of the whole muscle (70, 84). Unfortunately, it also follows that if tendons were really so compliant, it would be impossible to walk or run, because the forces involved would stretch the tendons by several muscle lengths. A basic assumption in this and other ultrasonography studies (57, 108, 109) may well be flawed: muscle fibers pull not only on the tendinous fibrils upon which they insert but also on surrounding muscle fibers, the tendinous aponeurosis and indeed the whole distal tendon (145). Earlier experiments had shown that spindles see origin-to-insertion length changes, with little distortion during muscle contractions (6, 49). In the Herbert (2002) study, one subject's tendon was surgically exposed. Virtually no stretch was seen in the distal tendon. The authors concluded that the stretching derived from the ultrasound method must have occurred in tendon within the muscle belly. But intramuscular tendinous fascicles are bound to surrounding muscle fibers, so they cannot be viewed as free tendon. It is important to settle this issue, not only to provide a clear basis for biomechani-

cal and control systems models (146), but also to help deduce fusimotor action from spindle firing, muscle force, and muscle length (106).

Golgi Tendon Organs

The sensory endings of the large diameter Ib afferents that innervate Golgi tendon organs are entwined amongst the tendinous fibrils of between 10 and 20 motor units (94, 143). Ib afferents respond to force actively generated by the motor units engaging their endings (8, 66, 88, 168). When the firing of several tendon organs is summed, the net firing rate is closely related to whole-muscle force (138). Unlike spindles, tendon organs do not have a mechanism to modulate their sensitivity. Recently it has been suggested that Ib afferents also contribute to the sensing of position and velocity: in a study of human grasp (39) spindle 1^0 and 2^0 afferent firing rates were well correlated with joint velocity but not with position. The decoding of velocity was improved on including the discharge of Golgi tendon organs, as previously predicted

for "ensemble coding" of mixed afferent populations (18). The fact that ensembles of Golgi tendon organ afferents signal muscle force through the whole physiological range from zero to maximal active contraction contradicted the idea that they were "overload protectors," for example, responsible for the clasp-knife reflex. Though this theory had effectively been discarded two decades ago (31, 32), the overload protection theory still lingers on in some present-day medical and physiological texts.

Receptors in Joints, Ligaments, and Skin

Joint receptors were initially assumed to mediate position sense over the full range of motion (23), but two research groups reported that most joint receptors were unresponsive in the mid-range (25, 177). Subsequent work indicated that at least some joint receptors do signal over the full range of motion (29, 53, 54, 61, 107, 195), though some of these may have been muscle spindles or tendon organs in nearby muscles (30, 67, 112). Loading of the joint capsule may be necessary to sensitize joint receptors enough to confer mid-range responsiveness on them (71). Most joint afferents have group II conduction velocities (25) and their reflex connections with α-motoneurons are polysynaptic and relatively weak (95). They may have a special role in inhibiting muscles when joints are damaged (92).

The cutaneous receptors best suited to signal position are slowly adapting type II receptors that respond to stretching of the skin, in some cases several centimeters from the point of maximal strain (46, 47, 85). Type I cutaneous receptors respond more locally, fire less regularly, and adapt more rapidly. Finally, there are at least four kinds of hair follicle and glabrous skin receptors that respond to dynamic components of hair deflection or skin stretch (187).

Conclusions on the Sensory Receptors that Contribute to Movement Control

Though there are some lingering uncertainties about fusimotor control and hence the nature of the signals from muscle spindles, the bulk of the available evidence supports the following conclusions:

1. Muscle spindles and cutaneous receptors contribute to the conscious perception of movement (33, 58).

2. Signals from spindle, cutaneous, and tendon organ afferents provide information on muscle displacement, velocity, and force required by the CNS to control these variables and to switch between phases of movement (e.g. stance to swing in locomotion). For example, Figure 3 shows step-cycle averages of actual hind-limb joint angles and those

estimated from the firing of 11 muscle and 6 cutaneous afferents recorded from the dorsal root ganglion during treadmill locomotion in a cat (184, 185). This demonstrated that the afferent signals coded the kinematics accurately. Even better estimates were achieved from the same data with a dynamic fuzzy neural network (149), which incorporates aspects of the way the CNS may decode sensory input.

3. A component of fusimotor action appears to be automatically linked to muscle activation, providing some reinforcement through monosynaptic reflex connections to α-motoneurons. In addition, fusimotor action modulates spindle afferent sensitivity to length changes in ways that depend on the motor task.

Sensory Control of Movement

In the following discussion of the motor effects of sensory input, we will concentrate mainly on the sensory control of locomotion. This was one of the first neural mechanisms to be analyzed in detail (56, 158, 159) and it remains the focus of many motor control studies. Sherrington suggested that locomotion was the result of a chain of proprioceptive reflexes, the end of one movement phase of the step cycle triggering the onset of the next. This was in fact a special case of an earlier hypothesis, that all motor acts are simply sequences of reflexes (153).

The notion that locomotion was the result of a cyclical chain of reflexes was contradicted by the observation that locomotor-like rhythms may still be generated by the mammalian spinal cord after all sensory and descending input has been abolished (24). Brown proposed the existence of an "intrinsic factor" in the spinal cord, capable of producing the basic locomotor rhythm without descending control or sensory input. Subsequently this intrinsic factor was renamed the "central pattern generator" (CPG) (74). It was initially assumed that a single CPG, comprising flexor and extensor "half-centers" controlled each limb, in coordination with the CPGs of the other limbs (e.g. reference 37). It has since been suggested that individual joints are controlled by their own "unit CPGs," functionally coupled to all the other CPGs (72). We will use the term "locomotor CPG" in the general sense of a *system* of coupled oscillators or unit CPGs controlling locomotion.

The behavior of CPGs isolated from sensory or descending inputs has been investigated and modeled in a variety of animals (9, 73, 100, 111, 151, 152, 154, 197). It has been posited that the isolated locomotor CPG comprises a "timing element" or oscillator that generates the basic locomotor rhythm and an interneuronal network called the "pattern formation layer," which selects and grades the activation of individual muscles (103, 129, 131) (151). The brainstem (160, 171), cerebellum (10), and motor cortex (14, 44, 186) all provide inputs to spinal CPGs.
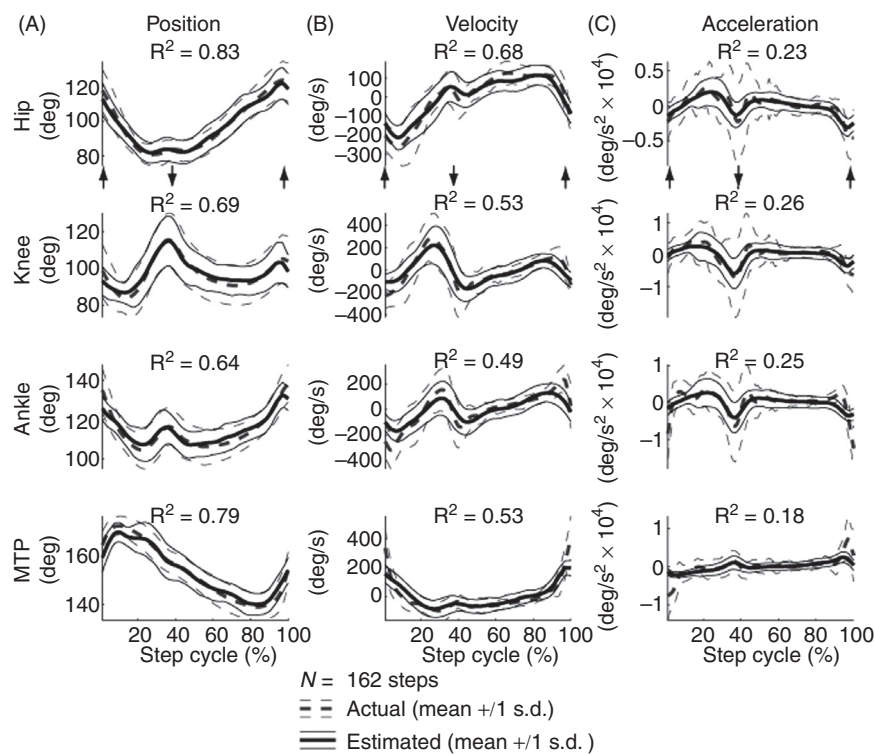
Figure 3 Estimated time course of joint angle variations computed from the firing rates of 47 sensory afferents recorded simultaneously during treadmill locomotion with a microelectrode array implanted in the L7 dorsal root of a cat. This group included five spindle 1^0 and five spindle 2^0 endings, one Golgi tendon organ, four glabrous cutaneous receptors and two hair follicle receptors. Step-cycle averages of the actual and estimated (A) position, (B) velocity, and (C) acceleration in joint-angle coordinates. Each plot shows the mean of 162 steps (toe-off to toe-off). The thin lines represent ± 1 s.d. from the mean of the actual trajectories. The up and down arrows indicate onset of the swing and stance phases, respectively. Reproduced, with permission, from reference 185.

A given cadence and set of activation amplitudes generated by the timing and pattern formation elements of the locomotor CPG would not in general result in stable stepping, because the activation of the numerous segments of the body must be coordinated so as to maintain biomechanical stability in the face of continuous variations in posture, speed, and terrain. This has become abundantly clear in neuromechanical simulations, which have also shown that sensory input is indispensible in this regard (48, 126, 169, 170, 193).

Sensory input may interact with the CPG in at least three ways: (a) stretch reflex control of α-motoneurons (150), (b) triggering step-cycle phase transitions, and (c) varying phase durations continuously.

(a) *Stretch reflex control*

At a constant level of activation, muscles resist stretch through their own intrinsic biomechanical properties, providing length and velocity feedback control. Indeed, all forces generated by muscles act through the biomechanics of the musculoskeleton and any loads borne by or applied to it. This was recognized many years ago (19, 52, 133) and gave rise to the field of "neuromechanics." The spinal

α-motoneurons that activate the muscles are activated or inhibited by the CPG pattern formation network, sensory afferents, and many species of interneurons, including those that mediate sensory input from muscle and cutaneous receptors. Most cutaneous receptors fire only at discrete times in the step cycle, for example, upon ground contact (104). They have polysynaptic reflex actions on α-motoneurons and may influence the timing of locomotor phase transitions (150). They contribute to kinesthesia (33) and they also trigger specific motor programs such as the stumble corrective reaction (55, 78). However, most of the *continuous* reflex control of α-motoneurons and the timing elements of the locomotor CPG during stepping must be attributed to the proprioceptive afferents, muscle spindles, and tendon organs, which fire continuously throughout the step cycle.

Stretch of an actively contracting muscle causes an increase in firing of its muscle spindle Ia and II afferents, increasing the reflex drive to homonymous α-motoneurons and thereby resisting the stretch (157). Therefore, spindle-mediated stretch reflexes are equivalent to negative length and velocity feedback. Golgi tendon organ

Ib afferents respond to the increase in force during the stretch. In static postures, extensor Ib afferents reflexively inhibit extensor α-motoneurons, thereby causing the muscle to yield, that is, resisting the change in force. This is equivalent to negative force feedback, the loop gain of which is probably quite low (83, 89). However, during locomotion, the reflex action of Ib afferents reverses (34, 128), at least in the more distal muscles of the cat (121). Ib afferents now reflexively *excite* α-motoneurons of their parent muscle to produce even more force. This is equivalent to *positive* force feedback (59, 69, 137). In addition, they prolong the stance phase, presumably by modulating the CPG timing element (see below).

The intrinsic mechanical stiffness of muscle increases with the level of muscle activation, whether this originates from descending supraspinal drive or from sensory input. The relative importance of stretch reflexes and the inherent stiffness of active muscle in the control of normal movement depends on factors such as muscle length, activation, and rate of stretch (16,17) as well as the state of interneurons and fusimotor drive. In experiments in the immobile decerebrate cat, stretch reflexes were shown to linearize the force responses to sudden muscle stretch (122). In decerebrate locomotion in cats, Ib input has been estimated to contribute up to 30% of muscle activation (42, 43, 167). Sinkjaer and colleagues compared the stiffness of electrically activated muscles (mimicking steady descending drive without stretch reflex responses) to voluntarily activated muscles with active stretch reflexes. At medium activation levels the stretch reflexes increased the stiffness of muscle by up to 60%, but at low and high levels of activation the reflex contribution dropped to zero (163). Furthermore, the reflex contributions did not develop fully until about 200 ms after the onset of rapid stretch. In related experiments, the maximal loop gain of positive force feedback consistent with stability was explored (137). This revealed an unexpected stabilizing effect of the length and activation dependence of intrinsic stiffness, theoretically allowing large contributions of Ib positive feedback to muscle activation, provided that muscle shortening could occur.

In the normal cat, large, rapid perturbations were required to clearly reveal stretch reflexes electromyographically (64, 76), and even then they had a relatively long latency. This led to some doubt as to their importance in contributing to load bearing during locomotion (119). In humans, it was originally assumed that Ia afferents mediated locomotor stretch reflexes (28), but Sinkjaer and colleagues refuted this, instead proposing that spindle group II afferents were the main contributors (68, 162). This in turn was refuted in more recent experiments that implicated tendon organ rather than muscle spindle afferents (2, 69). Finally, it should be mentioned that the reflex control of γ-motoneurons during locomotion, in contrast to that of α-motoneurons, has not been investigated.

Modeling the sensory contribution to locomotor control. Given the confusing and in some cases contradictory conclusions on the contribution of stretch reflexes to biomechanical responses, neuromechanical modeling has been employed to try to gain insight from a different direction (193). In one such model of the hindquarters of a quadruped, in the absence of stretch reflexes, a set of hand-crafted muscle activation profiles produced by a "CPG" could produce several stable step cycles, but when the activation levels were set to be slightly too low to provide adequate body support and propulsion, stretch reflexes helped "rescue" stability. The addition of the same stretch reflexes to CPG activation profiles that by themselves were sufficient to produce stable locomotion, resulted in more vigorous steps, which in some cases eventually resulted in a fall. It was concluded that stretch reflexes could "rescue" locomotion when CPG activation levels were low and they improved overall stability by a modest amount.

(b) **Triggering step cycle phase transitions**

In the absence of sensory input, the abrupt transitions between the stance and swing phases of the locomotor step cycle are controlled by the timing elements of the CPG. As we have seen, the CPG timer is itself influenced by descending and sensory influences. One possibility is that sensory input overrides or resets the CPG at critical points in the step cycle. It was proposed that the execution of finite state (IF-THEN) rules triggers phase transitions (37, 134, 175, 176). The sensory rules were of the type: IF in stance phase AND ipsilateral hip is extended AND contralateral leg is loaded THEN initiate swing phase. Neuromechanical simulations showed that when rules of this type were used to override and reset the timing of phase transitions generated by a "CPG," the flexibility and stability of overground locomotion was significantly improved (193). The reason for the improvement was that the timing of the transitions was precisely adjusted according to the position and force of each limb at the end of each phase. In another study, locomotion was generated entirely by IF-THEN rules, in the absence of a CPG (48).

(c) **Varying phase durations continuously**

In the above studies, the execution of a sensory rule abruptly overrode the CPG's timing of the next phase transition or determined the timing completely, without a CPG. Another possibility is that sensory input speeds up or slows down the CPG oscillator according to how quickly the displacement and force of the limb are approaching the end of their expected ranges. Artificially stimulating tendon organ afferents that normally signal extensor force delays the transition from stance to swing (127). Artificially stimulating hip muscle afferents that signal hip extension delays the transition from swing to stance (81).

In most animals, the locomotor cycle duration varies mainly as a result of changes in the duration of the extension (stance) phase of the cycle, with much less variation in the flexion (swing) phase (77). In neuromechanical simulations, this relationship between flexion and extension durations emerged in nearly all phases triggered by sensory input, showing that it is biomechanically favorable (142). This is not to deny that with voluntary intervention and practice, long-duration step cycles with equal swing and stance durations can be produced (e.g. goose-step marching), but special effort is then required. Interestingly, in fictive locomotion elicited by stimulation in the midbrain locomotor region (MLR), flexion phases were more often than not longer than extension phases (194). In this preparation, no actual movement occurs, so the sensory input to the CPG that would normally act to trigger phase switching or speed up and slow down phase durations, was lacking.

Velocity Command Signals

One puzzling feature of the neuromechanical modeling was the tendency for the velocity of locomotion to stabilize to a given value, depending on the CPG cadence and activation amplitude parameters. In more recent modeling, we found that by using velocity as the command signal to control not only the cadence of the CPG oscillator, but also the amplitude of muscle activation, a large range of velocities and cadences could be achieved (141). This model, shown schematically in Figure 4B, may provide a useful framework for future studies. It is based on the following relationships. First, in normal animals, as bodily velocity increases, cadence increases linearly and stance and swing phase durations decline hyperbolically (65). In accordance with this, increasing the amplitude of stimulation in the MLR increases the cadence of locomotion in the decerebrate cat (160) (Fig. 4A). The control of cadence and phase durations by a velocity command can be accurately
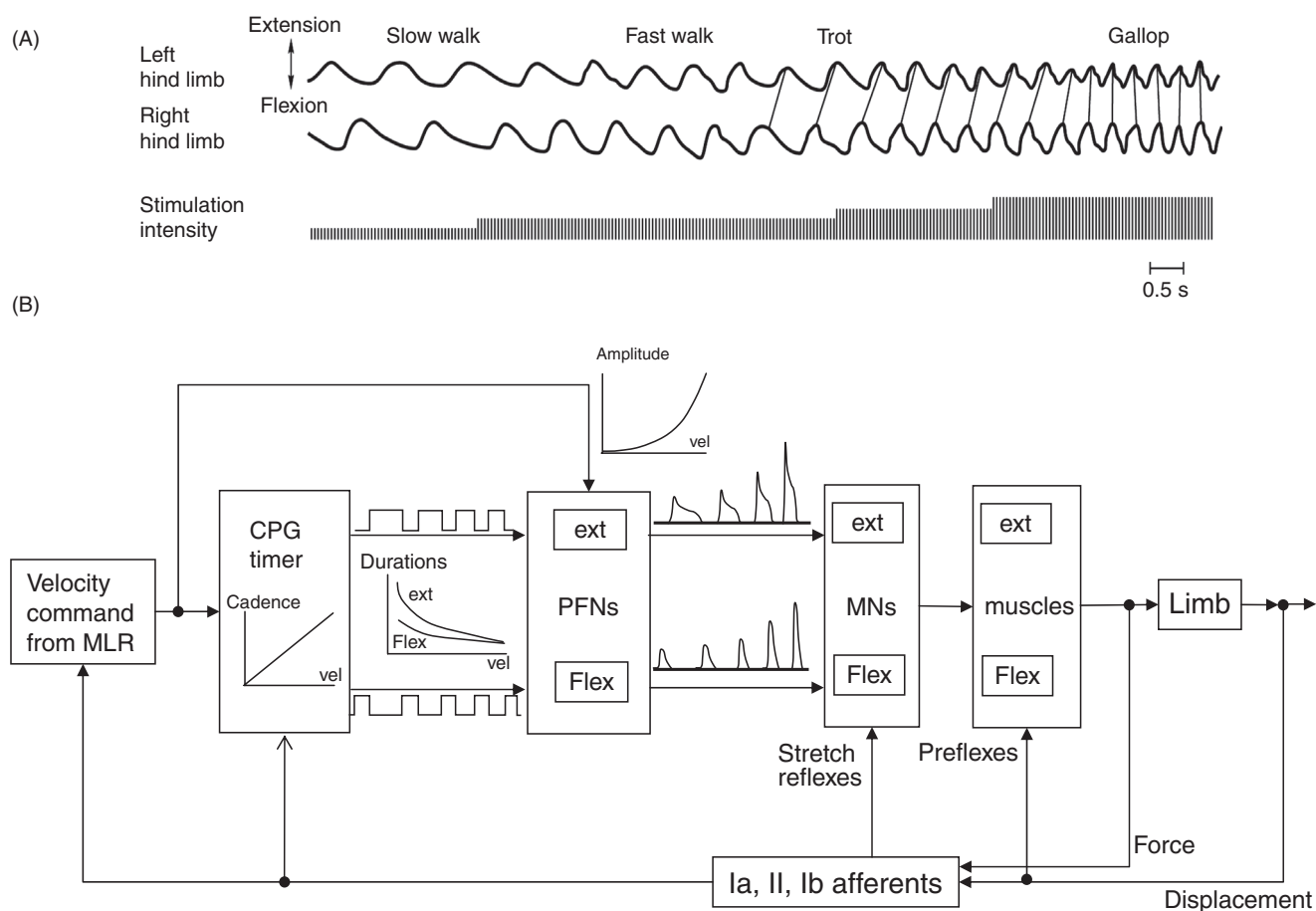
Figure 4 Descending control of the locomotor step cycle. (A) Increments in the intensity of stimulation in the midbrain locomotor region (MLR) in the high decerebrate cat (lower trace) increases the cadence of locomotion (upper traces) (adapted, with permission, from reference 160). (B) Schematic summarizing the velocity command hypothesis: a command signal specifying desired body velocity descends from brainstem and drives the timing element of the locomotor central pattern generator (CPG) to generate cadences with flexor and extensor phase durations that depend in a specific way on cycle duration. The velocity signal also drives the pattern formation network (PFN) to modulate the amplitudes of activation of the flexor and extensor muscles according to a square law relationship. Muscle displacement automatically modulates muscle force through the intrinsic length-tension properties. Muscle force and displacement sensed by spindle and tendon organ afferents elicit continuous stretch reflexes as well as modulating or overriding phase transitions via the CPG timer. Presented at the Society of Experimental Biology Annual General Meeting in 2009 (141).

modeled with a simple oscillator comprising a pair of switching integrators (194), as shown in Figure 4B. Second, if a mass is moved sinusoidally at varying cadences while maintaining a constant amplitude, the peak accelerations and therefore the peak forces required, increase by the square of cadence. Thus, in the model of Figure 4B, velocity^2 is the control signal for the level of motoneuronal activation. Sensory input in this model triggered phase transitions in an all-or-nothing manner. As discussed above, it is possible that the CNS compares the time course of sensory input to an internal model and speeds up or slows down the CPG oscillator to minimize the mismatch (115, 116), but so far our attempts to model this have been unsuccessful.

Sensorimotor Control Involving the Brain and Cerebellum

When animals move, in addition to the proprioceptive information described above, they also take into account global information on the environment and the context of the task from visual and auditory inputs. The greater the motor requirements to maintain stability (e.g. bipedal vs. quadrupedal gait), the more crucial are these inputs, which are used by supraspinal centers to plan movements in advance and possibly to predict their sensory outcomes. The processes involved are clearly extremely complex, as evidenced by recordings of the kinematic and neural correlates of predictive and adaptive responses, for example, references 45, 75, and 192. The following basic concepts regarding prediction and how it is influenced by sensory input have been proposed over the years:

1. "Einstellung," "behavioral set." Animals prepare themselves to initiate movements and to react to impending perturbations (1, 60, 93, 183).

2. "Degrees of freedom." The control of multisegmented limbs is simplified when the number of degrees of freedom is reduced, either by cocontracting antagonist muscles, or by coordinating the activation of synergists (19).

3. "Efference copy." In the 1950s, it was suggested that the cerebral cortex generates a copy of motor commands from which reafferent signals are subtracted (180, 181). Though efference copy makes sense in counteracting the perception of movement of the visual field during eye movements, as von Holst proposed, it makes less sense for limb movements, whose movements need to be perceived (50). A mechanism like efference copy underlies the "Smith predictor," developed to overcome delays in industrial control processes (164). Miall and others suggested that the cerebellum was a Smith predictor, forecasting the kinematic outcomes of movements and the sensory signals associated with them (114,115,116, 155). The general idea of prediction in motor control has been renamed several times, the

most recent example being "internal models" (178, 179, 189, 190). The latest manifestation of the concept is the suggestion that muscle spindles act as "forward sensory models" (41).

4. "Fixed action patterns," "motor programs," "preprogrammed movements," and "movement primitives." Spencer proposed that "instincts" were assemblies of reflexes consolidated by repetition and transmitted in a hereditary manner (165). The idea of stored motor programs or subroutines has been reiterated many times since (80). CPGs are essentially examples of this idea.

The cerebellum is thought to be crucial in nearly all the above operations, in particular generating motor programs, modulating reflex gains and scaling the size of movement sequences (20, 86, 161). It is interesting that spinocerebellar tract neurons evidently signal whole-limb kinematic and kinetic variables rather than raw signals from sensory receptors (21, 22). In human locomotion, subjects plan foot placement one or two steps ahead and avoid obstacles by anticipatory high-stepping (124, 125). In fact the reaction of animals to unpredictable terrain is simply to high step, a gait modification that can be elicited by injecting a droplet of Lidocaine into the interpositus nucleus of the cerebellum (63).

Conclusion

The range of movements that animals are capable of is quite extraordinary. Our ability to probe the flow of information and the neural networks involved in both the peripheral and CNSs during these various movements is quite limited. Taking these factors together, it is not at all surprising that our understanding of how animal movement is controlled is rudimentary and full of controversy. It is clear from this article that Richard Burgess's rubric "you can only control what you sense" serves well as a guiding principle. A corollary is that "what you sense determines what you control." As we have seen, there are numerous sensory channels that, when combined, can sense a large number of variables both within the body and in the external environment. The key sensory inputs are known, the properties of the actuators have been well characterized, and there are useful hypotheses regarding how the inputs and outputs may be combined. Powerful new techniques are either already available or under development, and they will no doubt soon provide fascinating insights in a field that is fundamental to our understanding of motor behavior.

Acknowledgments

References

1. Ach N. *Über die Willenstätigkeit und das Denken*. Göttingen, 1905.

2. af Klint R, Mazzaro N, Nielsen JB, Sinkjaer T, Grey MJ. Load rather than length sensitive feedback contributes to soleus muscle activity during human treadmill walking. *J Neurophysiol* 103: 2747-2756, 2010.

3. al-Falahe NA, Nagaoka M, Vallbo AB. Response profiles of human muscle afferents during active finger movements. *Brain* 113: 325-346, 1990.

4. al-Falahe NA, Nagaoka M, Vallbo AB. Dual response from human muscle spindles in fast voluntary movements. *Acta Physiol Scand* 141: 363-371, 1991.

5. Allum JH, Oude Nijhuis LB, Carpenter MG. Differences in coding provided by proprioceptive and vestibular sensory signals may contribute to lateral instability in vestibular loss subjects. *Exp Brain Res* 184: 391-410, 2008.

6. Amis A, Prochazka A, Short D, Trend PS, Ward A. Relative displacements in muscle and tendon during human arm movements. *J Physiol* 389: 37-44, 1987.

7. Aniss AM, Diener HC, Hore J, Gandevia SC, Burke D. Behavior of human muscle receptors when reliant on proprioceptive feedback during standing. *J Neurophysiol* 64: 661-670, 1990.

8. Appenteng K, Prochazka A. Tendon organ firing during active muscle lengthening in awake, normally behaiving cats. *J Physiol* 353: 81-92, 1984.

9. Arshavsky YI, Deliagina TG, Orlovsky GN. Pattern generation. *Curr Opin Neurobiol* 7: 781-789, 1997.

10. Arshavsky YI, Gelfand IM, Orlovsky GN. *Cerebellum and Rhythmical Movements*. Berlin: Springer, 1986.

11. Barker D, Ip MC, Adal MN. A correlation between the receptor population of the cat's soleus muscle and the afferent fibre diameter spectrum of the nerve supplying it. In: Barker D, editor. *Symposium on Muscle Receptors*. Hong Kong: Hong Kong University Press, 1962, pp. 257-261.

12. Bastian HC. The "muscular sense": Its nature and localisation. *Brain* 10: 1-136, 1888.

13. Bell C. *The Hand. Its Mechanism and Vital Endowments as Evincing Design*. London: William Pickering, 1834.

14. Beloozerova IN, Sirota MG. The role of the motor cortex in the control of accuracy of locomotor movements in the cat. *J Physiol* 461: 1-25, 1993.

15. Bennett DJ. Torques generated at the human elbow joint in response to constant position errors imposed during voluntary movements. *Exp Brain Res* 95: 488-498, 1993.

16. Bennett DJ. Stretch reflex responses in the human elbow joint during a voluntary movement. *J Physiol (Lond)* 474: 339-351, 1994.

17. Bennett DJ, Gorassini M, Prochazka A. Catching a ball: Contributions of intrinsic muscle stiffness, reflexes, and higher order responses. *Can J Physiol Pharmacol* 72: 525-534, 1994.

18. Bergenheim M, Johansson H, Pedersen J, Ohberg F, Sjolander P. Ensemble coding of muscle stretches in afferent populations containing different types of muscle afferents. *Brain Res* 734: 157-166, 1996.

19. Bernstein N. *The Coordination and Regulation of Movements*. Oxford: Pergamon, 1967.

20. Bloedel JR. Task-dependent role of the cerebellum in motor learning. *Prog Brain Res* 143: 319-329, 2004.

21. Bosco G, Eian J, Poppele RE. Kinematic and non-kinematic signals transmitted to the cat cerebellum during passive treadmill stepping. *Exp Brain Res* 167: 394-403, 2005.

22. Bosco G, Poppele RE. Proprioception from a spinocerebellar perspective. *Physiol Rev* 81: 539-568, 2001.

23. Boyd IA, Roberts TDM. Proprioceptive discharges from stretch receptors in the knee joint of the cat. *J Physiol* 122: 38-58, 1953.

24. Brown TG. The intrinsic factors in the act of progression in the mammal. *Proc R Soc Lond, Series B* 84: 308-319, 1911.

25. Burgess PR, Clark FJ. Characteristics of knee joint receptors in the cat. *J Physiol* 203: 317-335, 1969.

26. Burke D, Hagbarth KE, Lofstedt L. Muscle spindle activity in man during shortening and lengthening contractions. *J Physiol* 277: 131-142, 1978.

27. Cabelguen JM. Static and dynamic fusimotor action on the response of spindle primary endings to sinusoidal stretches in the cat. *Brain Res* 169: 45-54, 1979.

28. Capaday C, Stein RB. Amplitude modulation of the soleus H-reflex in the human during walking and standing. *J Neurosci* 6: 1308-1313, 1986.

29. Carli G, Farabollini F, Fontani G, Meucci M. Slowly adapting receptors in cat hip joint. *J Neurophysiol* 42: 767-778, 1979.

30. Clark FJ, Burgess RC, Chapin JW, Lipscomb WT. Role of intramuscular receptors in the awareness of limb position. *J Neurophysiol* 54: 1529-1540, 1985.

31. Cleland CL, Hayward L, Rymer WZ. Neural mechanisms underlying the clasp-knife reflex in the cat. II. Stretch-sensitive muscular-free nerve endings. *J Neurophysiol* 64: 1319-1330, 1990.

32. Cleland CL, Rymer WZ. Neural mechanisms underlying the clasp-knife reflex in the cat. I. Characteristics of the reflex. *J Neurophysiol* 64: 1303-1318, 1990.

33. Collins DF, Prochazka A. Movement illusions evoked by ensemble cutaneous input from the dorsum of the human hand. *J Physiol* 496(Pt 3): 857-871, 1996.

34. Conway BA, Hultborn H, Kiehn O. Proprioceptive input resets central locomotor rhythm in the spinal cat. *Brain Res* 68: 643-656, 1987.

35. Cordo PJ, Flores-Vieira C, Verschueren SM, Inglis JT, Gurfinke lV. Position sensitivity of human muscle spindles: Single afferent and population representations. *J Neurophysiol* 87: 1186-1195, 2002a.

36. Cordo PJ, Flores-Vieira C, Verschueren SM, Inglis JT, Gurfinkel V. Position sensitivity of human muscle spindles: Single afferent and population representations. *J Neurophysiol* 87: 1186-1195, 2002b.

37. Cruse H. What mechanisms coordinate leg movement in walking arthropods? *Trends Neurosci* 13: 15-21, 1990.

38. Day BL, Fitzpatrick RC. The vestibular system. *Curr Biol* 15: R583-R586, 2005.

39. Dimitriou M, Edin BB. Discharges in human muscle receptor afferents during block grasping. *J Neurosci* 28: 12632-12642, 2008a.

40. Dimitriou M, Edin BB. Discharges in human muscle spindle afferents during a key-pressing task. *J Physiol* 586: 5455-5470, 2008b.

41. Dimitriou M, Edin BB. Human muscle spindles act as forward sensory models. *Curr Biol* 20: 1763-1767, 2010.

42. Donelan JM, McVea DA, Pearson KG. Force regulation of ankle extensor muscle activity in freely walking cats. *J Neurophysiol* 101: 360-371, 2009.

43. Donelan JM, Pearson KG. Contribution of force feedback to ankle extensor activity in decerebrate walking cats. *J Neurophysiol* 92: 2093-2104, 2004.

44. Drew T. Motor cortical activity during voluntary gait modifications in the cat. I. Cells related to the forelimbs. *J Neurophysiol* 70: 179-199, 1993.

45. Drew T, Andujar JE, Lajoie K, Yakovenko S. Cortical mechanisms involved in visuomotor coordination during precision walking. *Brain Res Rev* 57: 199-211, 2008.

46. Edin BB. Cutaneous afferents provide information about knee joint movements in humans. *J Physiol* 531: 289-297, 2001.

47. Edin BB. Quantitative analyses of dynamic strain sensitivity in human skin mechanoreceptors. *J Neurophysiol* 92: 3233-3243, 2004.

48. Ekeberg O, Pearson K. Computer simulation of stepping in the hind legs of the cat: An examination of mechanisms regulating the stance-to-swing transition. *J Neurophysiol* 94: 4256-4268, 2005.

49. Elek J, Prochazka A, Hulliger M, Vincent S. In-series compliance of gastrocnemius muscle in cat step cycle: Do spindles signal origin-to-insertion length? *J Physiol* 429: 237-258, 1990.

50. Ellaway PH, Prochazka A, Chan M, Gauthier MJ. The sense of movement elicited by transcranial magnetic stimulation in humans is due to sensory feedback. *J Physiol* 556: 651-660, 2004.

51. Emonet-Denand F, Jami L, Laporte Y. Skeleto-fusimotor axons in the hind-limb muscles of the cat. *J Physiol* 249: 153-166, 1975.

52. Feldman AG. Functional tuning of the nervous system with control of movement and maintenance of steady posture. II. Controllable parameters of the muscle. *Biophysics* 11: 565-578, 1966.

53. Ferrell WR. The adequacy of stretch receptors in the cat knee joint for signalling joint angle throughout a full range of movement. *J Physiol* 299: 85-100, 1980.

54. Ferrell WR, Gandevia SC, McCloskey DI. The role of joint receptors in human kinaesthesia when intramuscular receptors cannot contribute. *J Physiol* 386: 63-71, 1987.

55. Forssberg H. Stumbling corrective reaction: A phase-dependent compensatory reaction during locomotion. *J Neurophysiol* 42: 936-953, 1979.

56. Freusberg A. Reflexbewegungen beim Hunde. *Pflug Archiv Physiol* 9: 358-391, 1874

57. Fukunaga T, Kubo K, Kawakami Y, Fukashiro S, Kanehisa H, Maganaris CN. In vivo behaviour of human muscle tendon during walking. *Proc R Soc Lond B Biol Sci* 268: 229-233, 2001.

58. Gandevia S. Kinesthesia: Roles for afferent signals and motor commands. In: Rowell L, Sheperd JT, editors. *Handbook of Physiology. Section 12. Exercise: Regulation and Integration of Multiple Systems*. New York: American Physiological Society, 1996, pp. 128-172.

59. Geyer H, Seyfarth A, Blickhan R. Positive force feedback in bouncing gaits? *Proc Biol Sci* 270: 2173-2183, 2003.

60. Gibson JJ. A critical review of the concept of set in contemporary experimental psychology. *Psychol Bull* 38: 781-817, 1941.

61. Godwin-Austen RB. The mechanoreceptors of the costo-vertebral joints. *J Physiol* 202: 737-753, 1969.

62. Goodwin GM, Hulliger M, Matthews PB. Studies on muscle spindle primary endings with sinusoidal stretching. *Prog Brain Res* 44: 89-98, 1976.

63. Gorassini M, Prochazka A, Taylor JL. Cerebellar ataxia and muscle spindle sensitivity. *J Neurophysiol* 70: 1853-1862, 1993.

64. Gorassini MA, Prochazka A, Hiebert GW, Gauthier MJ. Corrective responses to loss of ground support during walking. I. Intact cats. *J Neurophysiol* 71: 603-610, 1994.

65. Goslow GE, Jr., Reinking RM, Stuart DG. The cat step cycle: Hind limb joint angles and muscle lengths during unrestrained locomotion. *J Morphol* 141: 1-41, 1973.

66. Goslow GE, Stauffer EK, Nemeth WC, Stuart DG. The cat step cycle: responses of muscle spindles and tendon organs to passive stretch within the locomotor range. *Brain Res* 60: 35-54, 1973b.

67. Gregory JE, McIntyre AK, Proske U. Tendon organ afferents in the knee joint nerve of the cat. *Neurosci Lett* 103: 287-292, 1989.

68. Grey M, Ladouceur M, Andersen JB, Nielsen JB, Sinkjaer T. Contribution of group II muscle afferents to the medium latency soleus stretch reflex during walking in man. *J Physiol* 534: 925-933, 2001.

69. Grey MJ, Nielsen JB, Mazzaro N, Sinkjaer T. Positive force feedback in human walking. *J Physiol* 581: 99-105, 2007.

70. Griffiths RI. Shortening of muscle fibres during stretch of the active cat medial gastrocnemius muscle: The role of tendon compliance. *J Physiol (Lond)* 436: 219-236, 1991.

71. Grigg P, Greenspan BJ. Response of primate joint afferent neurons to mechanical stimulation of knee joint. *J Neurophysiol* 40: 1-8, 1977.

72. Grillner S. Control of locomotion in bipeds, tetrapods, and fish. In: *Handbook of physiology.The nervous system.* Bethesda: American Physiological Society, 1981, sect. 2, pp. 1179-1236.

73. Grillner S, Cangiano L, Hu G, Thompson R, Hill R, Wallen P. The intrinsic function of a motor system–from ion channels to networks and behavior. *Brain Res* 886: 224-236, 2000.

74. Grillner S, Zangger P. How detailed is the central pattern generation for locomotion? *Brain Res* 88: 367-371, 1975.

75. Gritsenko V, Kalaska JF. Rapid online correction is selectively suppressed during movement with a visuomotor transformation. *J Neurophysiol* 2010.

76. Gritsenko V, Mushahwar V, Prochazka A. Adaptive changes in locomotor control after partial denervation of triceps surae muscles in the cat. *J Physiol* 533: 299-311, 2001.

77. Halbertsma JM. The stride cycle of the cat: The modelling of locomotion by computerized analysis of automatic recordings. *Acta Physiol Scand Suppl* 521: 1-75, 1983.

78. Haridas C, Zehr EP, Misiaszek JE. Adaptation of cutaneous stumble correction when tripping is part of the locomotor environment. *J Neurophysiol* 99: 2789-2797, 2008.

79. Herbert RD, Moseley AM, Butler JE, Gandevia SC. Change in length of relaxed muscle fascicles and tendons with knee and ankle movement in humans. *J Physiol* 539: 637-645, 2001.

80. Hermer-Vazquez L, Hermer-Vazquez R, Chapin JK. The reach-to-grasp-food task for rats: A rare case of modularity in animal behavior? *Behav Brain Res* 177: 322-328, 2007.

81. Hiebert GW, Whelan PJ, Prochazka A, Pearson KG. Contribution of hind limb flexor muscle afferents to the timing of phase transitions in the cat step cycle. *J Neurophysiol* 75: 1126-1137, 1996.

82. Hoang PD, Herbert RD, Todd G, Gorman RB, Gandevia SC. Passive mechanical properties of human gastrocnemius muscle tendon units, muscle fascicles and tendons in vivo. *J Exp Biol* 210: 4159-4168, 2007.

83. Hoffer JA, Andreassen S. Regulation of soleus muscle stiffness in premammalian cats: Intrinsic and reflex components. *J Neurophysiol* 45: 267-285, 1981.

84. Hoffer JA, Caputi AA, Pose IE, Griffiths RI. Roles of muscle activity and load on the relationship between muscle spindle length and whole muscle length in the freely walking cat. *Prog Brain Res* 80: 75-85, 1989.

85. Horch KW, Tuckett RP, Burgess PR. A key to the classification of cutaneous mechanoreceptors. *J Invest Dermatol* 69: 75-82, 1977.

86. Horn KM, Pong M, Gibson AR. Discharge of inferior olive cells during reaching errors and perturbations. *Brain Res* 996: 148-158, 2004.

87. Hospod V, Aimonetti JM, Roll JP, Ribot-Ciscar E. Changes in human muscle spindle sensitivity during a proprioceptive attention task. *J Neurosci* 27: 5172-5178, 2007.

88. Houk J, Henneman E. Responses of Golgi tendon organs to active contractions of the soleus muscle of the cat. *J Neurophysiol* 30: 466-481, 1967.

89. Houk JC, Singer JJ, Goldman MR. An evaluation of length and force feedback to soleus muscles of decerebrate cats. *J Neurophysiol* 33: 784-811, 1970.

90. Hulliger M. The mammalian muscle spindle and its central control. *Rev Physiol Biochem Pharmacol* 101: 1-110, 1984a.

91. Hulliger M. The mammalian muscle spindle and its central control. [Review]. *Rev Physiol Biochem Pharmacol* 101: 1-110, 1984b.

92. Iles JF, Stokes M, Young A. Reflex actions of knee joint afferents during contraction of the human quadriceps. *Clin Physiol* 10: 489-500, 1990.

93. James W. *The Principles of Psychology.* New York: Henry Holt, 1890.

94. Jami L. Golgi tendon organs in mammalian skeletal muscle: Functional properties and central actions. *Physiol Rev* 72: 623-666, 1992.

95. Johansson H, Sjolander P, Sojka P. Receptors in the knee joint ligaments and their role in the biomechanics of the joint. *CRC Crit Rev Biomed Eng* 18: 341-368, 1991.

96. Johansson RS, Vallbo AB. Tactile sensibility in the human hand: Relative and absolute densities of four types of mechanoreceptive units in glabrous skin. *J Physiol (Lond)* 286: 283-300, 1979.

97. Jones KE, Wessberg J, Vallbo AB. Directional tuning of human forearm muscle afferents during voluntary wrist movements. *J Physiol* 536: 635-647, 2001.

98. Kakuda N, Vallbo AB, Wessberg J. Fusimotor and skeletomotor activities are increased with precision finger movement in man. *J Physiol* 492(Pt 3): 921-929, 1996.

99. Kennedy WR. Innervation of normal human muscle spindles. *Neurology* 20: 463-475, 1970.

100. Kiehn O. Locomotor circuits in the mammalian spinal cord. *Annu Rev Neurosci* 29: 279-306, 2006.

101. Kniffki KD, Schomburg ED, Steffens H. Effects from fine muscle and cutaneous afferents on spinal locomotion in cats. *J Physiol* 319: 543-554, 1981.

102. Kowalczewski J, Prochazka A. *Interactive Receptor Model.* University of Alberta Libraries, Free Internet Access, www.library.ualberta.ca. 2006.

103. Lafreniere-Roula M, McCrea DA. Deletions of rhythmic motoneuron activity during fictive locomotion and scratch provide clues to the organization of the mammalian central pattern generator. *J Neurophysiol* 94: 1120-1132, 2005.

104. Loeb GE. Somatosensory unit input to the spinal cord during normal walking. *Can J Physiol Pharmacol* 59: 627-635, 1981.

105. Loeb GE, Levine WS, He J. Understanding sensorimotor feedback through optimal control. *Cold Spring Harb Symp Quant Biol* 55: 791-803, 1990.

106. Loram ID, Lakie M, Di Giulio I, Maganaris CN. The consequences of short-range stiffness and fluctuating muscle activity for proprioception of postural joint rotations: The relevance to human standing. *J Neurophysiol* 102: 460-474, 2009.

107. Lund JP, Matthews B. Responses of temporomandibular joint afferents recorded in the Gasserian ganglion of the rabbit to passive movements of the mandible. In: Kawamura Y, editor. *Oral-facial Sensory and Motor Functions.* Tokyo: Quintessence, 1981, pp. 153-160.

108. Maganaris CN, Paul JP. In vivo human tendinous tissue stretch upon maximum muscle force generation. *J Biomech* 33: 1453-1459, 2000.

109. Maganaris CN, Paul JP. Tensile properties of the in vivo human gastrocnemius tendon. *J Biomech* 35: 1639-1646, 2002.

110. Matthews PBC. *Mammalian Muscle Receptors and Their Central Actions.* London: Arnold, 1972.

111. McCrimmon DR, Ramirez JM, Alford S, Zuperku EJ. Unraveling the mechanism for respiratory rhythm generation. *Bioessays* 22: 6-9, 2000.

112. McIntyre AK, Proske U, Tracey DJ. Afferent fibres from muscle receptors in the posterior nerve of the cat's knee joint. *Exp Brain Res* 33: 415-424, 1978.

113. Merton PA. How we control the contraction of our muscles. *Sci Am* 226: 30-37, 1972.

114. Miall C. Motor control: Correcting errors and learning from mistakes. *Curr Biol* 20: R596-598, 2010.

115. Miall RC. The cerebellum, predictive control and motor coordination. *Novartis Found Symp* 218: 272-284; discussion 284-290, 1998.

116. Miall RC, Weir DJ, Wolpert DM, Stein JF. Is the cerebellum a Smith predictor? *J Mot Behav* 25: 203-216, 1993.

117. Murphy PR, Martin HA. Fusimotor discharge patterns during rhythmic movements. *Trends Neurosci* 16: 273-278, 1993.

118. Murphy PR, Stein RB, Taylor J. Phasic and tonic modulation of impulse rates in gamma-motoneurons during locomotion in premammalian cats. *J Neurophysiol* 52: 228-243, 1984.

119. Mushawhar VK, Gillard DM, Gauthier MJ, Prochazka A. Intraspinal micro stimulation generates locomotor-like and feedback-controlled movements. *IEEE Trans Neural Syst Rehabil Eng* 10: 68-81, 2002.

120. Newsom Davis J. The response to stretch of human intercostal muscle spindles stduied *in vitro. J Physiol* 249: 561-579, 1975.

121. Nichols R, Ross KT. The implications of force feedback for the lambda model. *Adv Exp Med Biol* 629: 663-679, 2009.

122. Nichols TR, Houk JC. Improvement in linearity and regulation of stiffness that results from actions of stretch reflex. *J Neurophysiol* 39: 119-142, 1976.

123. Patla AE, Niechwiej E, Racco V, Goodale MA. Understanding the contribution of binocular vision to the control of adaptive locomotion. *Exp Brain Res* 142: 551-561, 2002.

124. Patla AE, Prentice SD, Rietdyk S, Allard F, Martin C. What guides the selection of alternate foot placement during locomotion in humans. *Exp Brain Res* 128: 441-450, 1999.

125. Patla AE, Vickers JN. Where and when do we look as we approach and step over an obstacle in the travel path? *Neuroreport* 8: 3661-3665, 1997.

126. Pearson K, Ekeberg O, Buschges A. Assessing sensory function in locomotor systems using neuro-mechanical simulations. *Trends Neurosci* 29: 625-631, 2006.

127. Pearson KG. Role of sensory feedback in the control of stance duration in walking cats. *Brain Res Rev* 57: 222-227, 2008.

128. Pearson KG, Collins DF. Reversal of the influence of group Ib afferents from plantaris on activity in medial gastrocnemius muscle during locomotor activity. *J Neurophysiol* 70: 1009-1017, 1993.

129. Perret C. Centrally generated pattern of motoneuron activity during locomotion in the cat. *Symp Soc Exp Biol* 37: 405-422, 1983.

130. Perret C, Buser P. Static and dynamic fusimotor activity during locomotor movements in the cat. *Brain Res* 40: 165-169, 1972.

131. Perret C, Cabelguen JM. Main characteristics of the hindlimb locomotor cycle in the decorticate cat with special reference to bifunctional muscles. *Brain Res* 187: 333-352, 1980.

132. Poppele RE, Kennedy WR. Comparison between behavior of human and cat muscle spindles recorded in vitro. *Brain Res* 75: 316-319, 1974.

133. Poppele RE, Terzuolo CA. Myotatic reflex: Its input-output relation. *Science* 159: 743-745, 1968.

134. Prochazka A. Comparison of natural and artificial control of movement. *IEEE Trans Rehab Eng* 1: 7-17, 1993.

135. Prochazka A. Proprioceptive feedback and movement regulation. In: Rowell L, Sheperd JT, editors. *Handbook of Physiology. Exercise: Regulation and Integration of Multiple Systems*. New York: American Physiological Society, 1996, sect. 12, pp. 89-127.

136. Prochazka A. Quantifying proprioception. *Prog Brain Res* 123: 133-142, 1999.

137. Prochazka A, Gillard D, Bennett DJ. Implications of positive feedback in the control of movement. *J Neurophysiol* 77: 3237-3251, 1997.

138. Prochazka A, Gorassini M. Ensemble firing of muscle afferents recorded during normal locomotion in cats. *J Physiol* 507(Pt 1): 293-304, 1998a.

139. Prochazka A, Gorassini M. Ensemble firing of muscle afferents recorded during normal locomotion in cats. *J Physiol* 507: 293-304, 1998b.

140. Prochazka A, Hulliger M, Zangger P, Appenteng K. 'Fusimotor set': New evidence for alpha-independent control of gamma-motoneurones during movement in the awake cat. *Brain Res* 339: 136-140, 1985.

141. Prochazka A, Sorensen C. Biomechanical imperatives in the neural control of locomotion. *Comp Biochem Physiol* 153: S135-S136, 2009.

142. Prochazka A, Yakovenko S. The neuromechanical tuning hypothesis. In: Cisek P, Drew, T, Kalaska, J, editors. *Progress in Brain Research Computational Neuroscience: Theoretical Insights into Brain Function*. NY: Elsevier, 2007, pp. 255-265.

143. Proske U. The Golgi tendon organ. Properties of the receptor and reflex action of impulses arising from tendon organs. In: Porter R, editor. *MTP International Review of Physiology, Neurophysiology IV*. Baltimore: MTP University Park Press, 1981, pp. 127-171.

144. Proske U, Gregory JE. Signalling properties of muscle spindles and tendon organs. *Adv Exp Med Biol* 508: 5-12, 2002.

145. Proske U, Morgan DL. Stiffness of cat soleus muscle and tendon during activation of part of muscle. *J Neurophysiol* 52: 459-468, 1984.

146. Rack PM, Ross HF, Thilmann AF, Walters DK. Reflex responses at the human ankle: The importance of tendon compliance. *J Physiol* 344: 503-524, 1983.

147. Ribot-Ciscar E, Hospod V, Roll JP, Aimonetti JM. Fusimotor drive may adjust muscle spindle feedback to task requirements in humans. *J Neurophysiol* 101: 633-640, 2009.

148. Ribot-Ciscar E, Rossi-Durand C, Roll JP. Increased muscle spindle sensitivity to movement during reinforcement manoeuvres in relaxed human subjects. *J Physiol* 523(Pt 1): 271-282, 2000.

149. Rigosa J, Weber D, Prochazka A, Stein R, Micera S. Neuro-fuzzy decoding of sensory information from ensembles of simultaneously recorded dorsal root ganglion neurons for FES applications. *J Neural Eng* 8(4): 046019, 2011.

150. Rossignol S, Dubuc R, Gossard JP. Dynamic sensorimotor interactions in locomotion. *Physiol Rev* 86: 89-154, 2006.

151. Rybak IA, Shevtsova NA, Lafreniere-Roula M, McCrea DA. Modelling spinal circuitry involved in locomotor pattern generation: Insights from deletions during fictive locomotion. *J Physiol* 577: 617-639, 2006.

152. Rybak IA, Stecina K, Shevtsova NA, McCrea DA. Modelling spinal circuitry involved in locomotor pattern generation: Insights from the effects of afferent stimulation. *J Physiol* 577: 641-658, 2006.

153. Sechenov IM. Reflexes of the Brain, (Refleksy Golovnogo Mozga). In: Subkov AA, editor. *I.M. Sechenov, Selected Works*. Moscow: State Publishing House, 1863, pp. 264-322.

154. Selverston AI. Modeling of neural circuits: What have we learned? *Annu Rev Neurosci* 16: 531-546, 1993.

155. Shadmehr R, Krakauer JW. A computational neuroanatomy for motor control. *Exp Brain Res* 185: 359-381, 2008.

156. Sherrington CS. On the proprio-ceptive system, especially in its reflex aspects. *Brain* 29: 467-482, 1906.

157. Shemmell J, Krutky MA, Perreault EJ. Stretch sensitive reflexes as an adaptive mechanism for maintaining limb stability. *Clin Neurophysiol* 121: 1680-1689, 2010.

158. Sherrington CS. Flexion-reflex of the limb, crossed extension-reflex, and reflex stepping and standing. *J Physiol (London)* 40: 28-121, 1910.

159. Sherrington CS. Further observations on the production of reflex stepping by combination of reflex excitation with reflex inhibition. *J Physiol* 47: 196-214, 1914.

160. Shik ML, Severin FV, Orlovsky GN. Control of walking and running by means of electrical stimulation of the mid-brain. Biophysics 11: 756-765, 1966.

161. Shimansky Y, Wang JJ, Bauer RA, Bracha V, Bloedel JR. On-line compensation for perturbations of a reaching movement is cerebellar dependent: Support for the task dependency hypothesis. *Exp Brain Res* 155: 156-172, 2004.

162. Sinkjaer T, Andersen JB, Ladouceur M, Christensen LO, Nielsen JB. Major role for sensory feedback in soleus EMG activity in the stance phase of walking in man. *J Physiol* 523: 817-827, 2000.

163. Sinkjaer T, Toft E, Andreassen S, Hornemann BC. Muscle stiffness in human ankle dorsiflexors: Intrinsic and reflex components. *J Neurophysiol* 60: 1110-1121, 1988.

164. Smith OJM. A controller to overcome dead time. *Instrum Soc Am J* 6: 28-33, 1959.

165. Spencer H. The principles of psychology. London: Longman, Brown, Green, and Longmans, 1855.

166. St George RJ, Fitzpatrick RC. The sense of self-motion, orientation and balance explored by vestibular stimulation. *J Physiol* 589: 807-813, 2011.

167. Stein RB, Misiaszek JE, Pearson KG. Functional role of muscle reflexes for force generation in the decerebrate walking cat. *J Physiol* 525: 781-791, 2000.

168. Stephens JA, Reinking RM, Stuart DG. Tendon organs of cat medial gastrocnemius: Responses to active and passive forces as a function of muscle length. *J Neurophysiol* 38: 1217-1231, 1975.

169. Taga G. A model of the neuro-musculo-skeletal system for human locomotion. II Real-time adaptability under various constraints. *Biol Cybern* 73: 113-121, 1995.

170. Taga G, Yamaguchi Y, Shimizu H. Self-organized control of bipedal locomotion by neural oscillators in unpredictable environment. *Biol Cybern* 65: 147-159, 1991.

171. Takakusaki K, Oohinata-Sugimoto J, Saitoh K, Habaguchi T. Role of basal ganglia-brainstem systems in the control of postural muscle tone and locomotion. *Prog Brain Res* 143: 231-237, 2004.

172. Taylor A, Cody FW. Jaw muscle spindle activity in the cat during normal movements of eating and drinking. *Brain Res* 71: 523-530, 1974.

173. Taylor A, Durbaba R, Ellaway PH, Rawlinson S. Patterns of fusimotor activity during locomotion in the decerebrate cat deduced from recordings from hindlimb muscle spindles. *J Physiol* 522: 515-532, 2000.

174. Taylor A, Durbaba R, Ellaway PH, Rawlinson S. Static and dynamic gamma-motor output to ankle flexor muscles during locomotion in the decerebrate cat. *J Physiol* 571: 711-723, 2006.

175. Tomovic R, Anastasijevic R, Vuco J, Tepavac D. The study of locomotion by finite state models. *Biol Cybern* 63: 271-276, 1990.

176. Tomovic R, McGhee R. A finite state approach to the synthesis of control systems. *IEEE Trans Hum Fac Electron* 7: 122-128, 1966.

177. Tracey DJ. Characteristics of wrist joint receptors in the cat. *Brain Res* 34: 165-176, 1979.

178. van Beers RJ, Wolpert DM, Haggard P. When feeling is more important than seeing in sensorimotor adaptation. *Curr Biol* 12: 834-837, 2002.

179. Vaziri S, Diedrichsen J, Shadmehr R. Why does the brain predict sensory consequences of oculomotor commands? Optimal integration of the predicted and the actual sensory feedback. *J Neurosci* 26: 4188-4197, 2006.

180. von Holst E. Relations between the central nervous system and the peripheral organs. *Br J Anim Behav* 2: 89-94, 1954.

181. von Holst E, Mittelstaedt H. Das Reafferenzprincip. *Naturwissenschaften* 37: 464-476, 1950.

182. Voss H. Tabelle der absoluten und relativen Muskelspindelzahlen der menschlichen Skelettmuskulatur. *Anatomische Anzeiger* 129: 5562-5572, 1971.

183. Watt HJ. Experimentelle Beiträge zu einer Theorie des Denkens. *Archiv gesamter Psychologie* 4: 289-436, 1905.

184. Weber DJ, Stein RB, Everaert DG, Prochazka A. Decoding sensory feedback from firing rates of afferent ensembles recorded in cat dorsal root ganglia in normal locomotion. *IEEE Trans Neural Syst Rehabil Eng* 14: 240-243, 2006.

185. Weber DJ, Stein RB, Everaert DG, Prochazka A. Limb-state feedback from ensembles of simultaneously recorded dorsal root ganglion neurons. *J Neural Eng* 4: S168-S180, 2007.

186. Widajewicz W, Kably B, Drew T. Motor cortical activity during voluntary gait modifications in the cat. II. Cells related to the hindlimbs. *J Neurophysiol* 72: 2070-2089, 1994.

187. Willis WD, Coggeshalll RE. *Sensory Mechanisms of the Spinal Cord*. N.Y.: Plenum, 1991.

188. Wilson LR, Gandevia SC, Burke D. Discharge of human muscle spindle afferents innervating ankle dorsiflexors during target isometric contractions. *J Physiol* 504: 221-232, 1997.

189. Witney AG, Goodbody SJ, Wolpert DM. Predictive motor learning of temporal delays. *J Neurophysiol* 82: 2039-2048, 1999.

190. Wolpert DM, Ghahramani Z. Computational principles of movement neuroscience. *Nat Neurosci* 3: 1212-1217, 2000.

191. Wolpert DM, Miall RC. Forward Models for Physiological Motor Control. *Neural Netw* 9: 1265-1279, 1996.

192. Yakovenko S, Drew T. A motor cortical contribution to the anticipatory postural adjustments that precede reaching in the cat. *J Neurophysiol* 102: 853-874, 2009.

193. Yakovenko S, Gritsenko V, Prochazka A. Contribution of stretch reflexes to locomotor control: A modeling study. *Biol Cybern* 90: 146-155, 2004.

194. Yakovenko S, McCrea DA, Stecina K, Prochazka A. Control of locomotor cycle durations. *J Neurophysiol* 94: 1057-1065, 2005.

195. Zalkind VI. Method for an adequate stimulation of receptors of the cat carpo-radialis joint. *Sechenov Physiol J USSR* 57: 1123-1127, 1971.

196. Zehr EP, Stein RB. What functions do reflexes serve during human locomotion? *Progress in Neurobiology* 58: 185-205, 1999.

197. Zelenin PV, Deliagina TG, Grillner S, Orlovsky GN. Postural control in the lamprey: A study with a neuro-mechanical model. *J Neurophysiol* 84: 2880-2887, 2000.