Local Loss of Proprioception Results in Disruption of Interjoint Coordination During Locomotion in the Cat

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Abelew, Thomas A., Melissa D. Miller, Timothy C. Cope, and T. Richard Nichols. Local loss of proprioception results in disruption of interjoint coordination during locomotion in the cat. J Neurophysiol 84: 2709–2714, 2000. To investigate the role of localized, proprioceptive feedback in the regulation of interjoint coordination during locomotion, we substantially attenuated neural feedback from the triceps surae muscles in one hindlimb in each of four cats using the method of self-reinnervation. After allowing the recovery of motor innervation, the animals were filmed during level and ramp walking. Deficits were small or undetectable during walking on the level surface or up the ramp, behaviors that require a large range of forces in the triceps surae muscles. During walking down the ramp, when the triceps surae muscles normally undergo active lengthening, the ankle joint underwent a large yield and the coordination between ankle and knee was disrupted. The correlation of the deficit with the direction of length change and not muscle force suggested that a loss of feedback from muscle spindle receptors was primarily responsible for the deficit. These results indicate an important role for the stretch reflex and stiffness regulation during locomotion.

INTRODUCTION

Loss of proprioception has recently been shown to have dramatic and deleterious effects on the control of upper limb movement in humans (Ghez et al. 1995; Gordon et al. 1995; Sainburg et al. 1995) and on locomotion (Bishop et al. 1997) or intersegmental dynamics (Koshland and Smith 1989) in cats. In these studies, which were based on subjects afflicted with severe joint stiffness, animals injected with pyridoxine or animals subjected to dorsal rhizotomy, respectively, the deficits presumably resulted from the widespread loss of sensory feedback and malfunctions of many associated neural subsystems. In the studies reported here, we evaluated motor function following the disruption of neural pathways that arise predominantly from the most rapid and localized spinal pathways associated with the triceps surae muscles.

Localized feedback from primary afferents has been shown to play a significant role in the regulation of muscular stiffness (Houk et al. 1981; Nichols and Houk 1976). Because muscles yield more during active lengthening than shortening, intrinsic muscular stiffness is greater during shortening. Action of the stretch reflex results in a larger contribution of motor unit recruitment during active lengthening and tends to equalize net muscular stiffness in the two directions. It would therefore be expected that disruption of the stretch reflex would lead to greater deficit during behaviors that involve active lengthening.

Cope and Clark (1993) found that the stretch reflexes in the medial gastrocnemius muscles (MG) of cats were significantly reduced following surgical self-reinnervation. Stretch-evoked motor-unit recruitment during in situ experiments with decerebrate cats 16 mo postreinnervation was drastically reduced when compared with the recruitment typically seen in the stretched MG. One of the primary conclusions from this work was that the efferent pathways had re-established themselves and were functioning in an expected manner while the afferent pathways involved in the normal stretch reflex had either not been re-established or were not functional. Subsequently, Cope et al. (1994) showed that self-reinnervation led to a loss of stretch reflexes and stiffness regulation in two other muscles, lateral gastrocnemius (LG) and soleus (S).

This study was undertaken to test the hypothesis that disruption of the major sources of feedback from the muscle spindles for the triceps surae of a cat would interfere with the normal interjoint coordination during locomotion. Since the triceps surae muscles receive the strongest monosynaptic feedback from within the group (Eccles et al. 1957), we performed self-reinnervation of this muscle group. Although self-reinnervation leads to the loss of most proprioceptive feedback from a given muscle (Cope et al. 1994), we reasoned that the treatment of a limited number of muscles would influence local pathways more than more widely distributed and redundant pathways (Nichols et al. 1999). Preliminary results have been presented in abstract form (Abelew et al. 1997; Nichols et al. 1998) and in a recent review (Nichols et al. 1999).

METHODS

Reinnervation

Four adult cats were used for the experimental (reinnervation) procedure. Two of the four served as presurgical controls. One additional control cat was used. Each experimental cat was anesthetized using isoflurane and continuously monitored. Under strict sterile conditions, an incision was made in the popliteal space of the right hindlimb of each cat to expose the tibial nerve and its branches. The individual nerve branch to the MG muscle and the nerve trunk supplying the LG and S muscles were subsequently cut and immediately reattached using 10.00 suture. As a result, the MG was self-reinnervated, while the LG and S were reinnervated with an unknown degree of cross-reinnervation. Following surgery, cats were placed in an incubator, administered antibiotics and analgesics and closely

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monitored while they recovered from surgery. Once they were able to stand, eat, and use the litterbox, they were returned to the colony (~4 × 20 ft) where they were able to freely run, jump, climb, and interact with other cats.

**Kinematics**

Throughout recovery, the cats were monitored and videotaped for qualitative analysis as they moved around the room. Within 4–6 mo following surgery there was little sign of impairment in any of the cats. At 9 mo, quantitative video analysis began. Both hindlimbs of each experimental and control cat were shaved. Reflective markers were placed over the iliac crest, greater trochanter, lateral femoral epicondyle, lateral malleolus, 5th metatarsophalangeal joint, and the distal toe of both limbs to approximate the endpoints of each hindlimb segment. Two-dimensional videotape images of the markers were acquired at 60 Hz using an S-VHS camera placed orthogonal to the cat. Each cat walked across a level ramp as well as up and down an inclined ramp (43% grade or ~23.3°). Six conditions were obtained (3 ramp conditions for each limb) for each cat. One trial consisted of a complete step (1 complete stance phase) that was selected from the middle of a series of steps to avoid any steps that were transitional. Sequences of steps where clear changes in speed were observed or steps taken at the beginning or ending of the walkway were not used. Paw contact and lift-off were identified visually on the videotapes. Cats were enticed across the walkway with affection and/or food rewards. Cats were allowed to walk at their own pace, so no control for velocity was attempted.

Videotaped trials were digitized using NIH Image software to obtain a complete set of coordinate data for each trial. The raw coordinates were smoothed using a fourth-order, zero-lag Butterworth filter with cutoff frequencies ranging from 2 to 15 Hz. The coordinates were subsequently used to calculate intersegmental joint angles for the hip, knee, ankle, and metatarsophalangeal (MTP) joints.

Plots of joint angle as a function of time (angle-time) and joint angle as a function of joint angle (angle-angle) were constructed to

![Representative stance phase plots displaying joint angle vs. time for 1 cat, prereinnervation (A and B) and postreinnervation (C and D). Level and down-ramp stance phases for 4 individual trials are shown. The joint angle convention used for the knee (θ_k) and the ankle (θ_a) is shown in the bottom left corner. Closed circles represent the knee joint while open circles represent the ankle joint. Trial codes represent the cat identification initials, limb of interest (R or L), walking condition (L, level; U, up-ramp; D, down-ramp), and trial number.](image-url)
detect differences in knee and ankle coordination between experimental and control animals. Reference angles used for the analysis are shown in Fig. 1.

**RESULTS**

Representative angle-time plots of the knee and ankle joints are presented in Fig. 1 for typical trials for cat 5 during the stance phase of level (Fig. 1, A and C) and down-ramp walking (Fig. 1, B and D) conditions. These four individual trials represent both pre- and postreinnervation data from one cat. Trial codes have been included to assist in comparisons across figures and represent the cat identification number, the limb of interest, the walking condition, and the trial number.

Knee and ankle curves in Fig. 1, A–C, show a coordinated pattern as changes in each joint angle occurred together during level walking. The slopes of the curves within a trial are almost parallel through most of the stance phase. In Fig. 1D, this pattern is absent, and a significant decrease in ankle angle (ankle flexion) occurred with a concurrent increase in knee joint angle (knee extension) throughout midstance. This increased ankle flexion during stance represents a loss of coordination that was consistently observed in the reinnervated hindlimb during the down-ramp trials following surgery.

Angle-angle plots of individual trials for four different cats are presented in Fig. 2 and show the interaction between the ankle and knee joints that was typical for these cats during
level and up-ramp walking. In these plots, a positive slope represents a simultaneous increase or decrease in each joint, while a negative slope represents an inverse relationship where one angle increased as the other decreased. Vertical and horizontal relationships represent changes in the knee joint and ankle joint alone, respectively.

Level and up-ramp angle-angle plots of the knee and ankle were very consistent and characterized by a linear pattern with a positive slope (Fig. 2). During level walking, a yield in the ankle and knee joints was usually observed at the onset of stance (Figs. 1A and 2, A, C, E, and G), although this yield was usually smaller than that observed during treadmill walking (Buford and Smith 1990; Buford et al. 1990). During up-ramp walking, this initial yield was often absent (compare Fig. 2, B, D, F, and H), in agreement with previous findings (Carlson-Kuhta et al. 1998). This linear pattern was observed in the control (Fig. 2, A–D) and reinnervated (Fig. 2, E–H) cats during level and up-ramp walking trials. Stance times in these trials ranged from 300 to 566 ms, indicating that the linear pattern displayed by these cats is most likely independent of velocity.

Down-ramp angle-angle data displayed in Fig. 3 show the contrast between prereinnervation (A–D) and postreinnervation trials (E–H) in two animals that showed differing severity of the motor deficit. In both animals, the stance phase began with larger than normal yield of the ankle joint (Fig. 3, E–H). In the most severely affected animal, the kinematic pattern was characterized by sequential rather than concurrent changes in knee and ankle joint angles (Fig. 3, F and H). In the less severely affected animal, there were significant periods of concurrent

**Fig. 3.** Representative stance phase angle-angle plots of knee vs. ankle angle for 2 cats during the stance phase of down-ramp walking. Ankle and knee angles are displayed along the x and y axes, respectively. Individual pre- and postreinnervation trials are displayed for both cats. A, C, E, and G are trials for cat 4 and B, D, F, and H are trials for cat 5. Note that Fig. 3B corresponds to Figs. 1B and 3; F corresponds to Fig. 1D. Paw contact (PC) and paw-off (PO) are indicated by bold arrows while the time course is indicated by lighter arrows. Trial codes represent the cat identification initials, limb of interest (R or L), walking condition (L, level; U, up-ramp; D, down-ramp), and trial number.
change in ankle and knee, but the initial ankle yield and final knee yield were consistently greater than in the presurgical state (Fig. 3, E and G). Therefore the reinnervated cats showed an altered pattern that is characterized by complete, nearly closed, loops. Sections of many of these curves were almost vertical. The pronounced loops and the distinct vertical slope sections are only present in the data from the reinnervated cats and never appear in any of the control data. Loops that appear in some of the control trials (Fig. 3, A and C) are narrower than those seen in the reinnervated data and never formed complete circles. These animals were studied for several months in the manner described in the preceding text and continued to show the motor deficit throughout the period of study.

DISCUSSION

The purpose of this study was to address the changes in interjoint coordination that result following reinnervation of selected hindlimb muscles of a cat during slope and level walking. Comprehensive comparisons of hindlimb kinematics during slope and level walking have been reported (Buford and Smith 1990; Buford et al. 1990; Carlson-Kuhta and Smith 1998; Smith et al. 1998). While some variability in kinematic patterns exists, our control and prereinnervation data are in general agreement with previous studies.

The results of this study reveal a disruption of interjoint coordination during the stance phase of down-ramp locomotion in cats with local loss of proprioreception following surgical self-reinnervation of the triceps surae muscle group. Angular displacement patterns at the knee and ankle reflect the trajectory of the limb and the coordination between joints. The pronounced kinematic alterations during down-ramp walking suggest a possible link to motor behaviors that require deceleration and eccentric muscle activity.

The stiffness regulation hypothesis predicts that the largest contribution of the stretch reflex to the mechanical responses of a muscle occur during eccentric contractions (Nichols and Houk 1976). Hoffer et al. (1989) has shown during locomotion in cats that eccentric activity in the MG muscle fibers was present only during down-ramp walking. During level and up-ramp walking muscle fibers shortened or remained at a constant length while the tendon shortened. Whole muscle-tendon unit-length changes were considerably larger in down-ramp walking when compared with up-ramp or level walking (Nichols et al. 1999), and it was during these trials that the loss of coordination was most pronounced in our cats. It is likely that lengthening of the muscle fibers occurred during down-ramp walking and that the larger than normal yield of the ankle occurred in the treated cats because the stretch reflexes of the triceps surae muscles were essentially absent. In addition, forces were recorded from buckle transducers on the tendons of reinnervated and untreated soleus muscles in one cat with reinnervated muscles (Nichols et al. 1998). These measurements indicated that fluctuations in force were somewhat larger during ramp walking in the reinnervated muscle than in the untreated muscle but not in proportion to the increased length changes in these muscles. This observation supports our interpretation that the increased length excursion of the soleus observed during down-ramp walking resulted from a reduction in the stiffness of the soleus muscle.

A loss of stiffness regulation in all three reinnervated muscles was confirmed in situ during terminal experiments in which the animals were decerebrated (Huyghues-Despointes 1998). Comparisons of the mechanical behavior between self-reinnervated and control muscles demonstrated a loss of stretch reflexes in the reinnervated muscles. There was also significant disruption of heterogenic reflexes arising from these muscles, including the heteronymous Ia pathways (cf. Cope et al. 1994). Pathways arising from Golgi tendon organs were also disrupted in these preparations, suggesting that group I excitation (Guertin et al. 1995) and inhibitory force feedback (Nichols et al. 1999) would have also been impaired. However, deficits during level or up-ramp walking were minimal or undetected even though forces in the triceps surae were substantial (Nichols et al. 1998). This finding implies that these pathways were compromised to a lesser extent than the monosynaptic pathways, perhaps because they are more widely distributed and therefore redundant (Guertin et al. 1995; Nichols et al. 1999).

Since the deficit was correlated with the direction of length change and not with force, we conclude that the impaired coordination resulted primarily from the loss of the stretch reflex, and therefore stiffness regulation, in the triceps surae muscles. Although results of the terminal experiments implicated the loss of monosynaptic excitation in contributing to the deficit (Huyghues-Despointes 1998), the loss of pathways from group II afferents cannot be excluded (Sinkjaer et al. 2000). Among the constellation of deficits exhibited by patients afflicted by large fiber sensory neuropathy (Sainburg et al. 1995) was the failure of the patients to regulate intersegmental dynamics. These authors discussed the roles of descending feed-forward mechanisms and spinal propriocceptive pathways in the regulation of intersegmental dynamics. Since our results indicate that local, rapid feedback in the spinal cord contributes importantly to the regulation of limb mechanics and interjoint coordination, it is probable that these pathways are also essential to the regulation of intersegmental dynamics for a large repertoire of voluntary movement.

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REFERENCES


