



Neuromechanical Strategies for Obstacle Negotiation during Overground Locomotion following Incomplete Spinal Cord Injury in Adult Cats

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Following incomplete spinal cord injury in animals, including humans, substantial locomotor recovery can occur. However, functional aspects of locomotion, such as negotiating obstacles, remains challenging. We collected kinematic and electromyography data in 10 adult cats (5 males, 5 females) before and at weeks 1–2 and 7–8 after a lateral mid-thoracic hemisection on the right side of the cord while they negotiated obstacles of three different heights. Intact cats always cleared obstacles without contact. At weeks 1–2 after hemisection, the ipsilesional right hindlimb contacted obstacles in ~50% of trials, triggering a stumbling corrective reaction or absent responses, which we termed Other. When complete clearance occurred, we observed exaggerated ipsilesional hindlimb flexion when crossing the obstacle with contralesional Left limbs leading. At weeks 7–8 after hemisection, the proportion of complete clearance increased, Other responses decreased, and stumbling corrective reactions remained relatively unchanged. We found redistribution of weight support after hemisection, with reduced diagonal supports and increased homolateral supports, particularly on the left contralesional side. The main neural strategy for complete clearance in intact cats consisted of increased knee flexor activation. After hemisection, ipsilesional knee flexor activation remained, but it was insufficient or more variable as the limb approached the obstacle. Intact cats also increased their speed when stepping over an obstacle, an increase that disappeared after hemisection. The increase in complete clearance over time after hemisection paralleled the recovery of muscle activation patterns or new strategies. Our results suggest partial recovery of anticipatory control through neuroplastic changes in the locomotor control system.

Key words: locomotion; neuroplasticity; obstacle recovery; reflex; spinal cord injury

Significance Statement

Most spinal cord injuries (SCIs) are incomplete and people can recover some walking functions. However, the main challenge for people with SCIs that do recover a high level of function is to produce a gait that can adjust to everyday occurrences, such as turning, stepping over an obstacle, etc. Here, we use the cat model to answer two basic questions: How does an animal negotiate an obstacle after an incomplete SCI and why does it fail to safely clear it? We show that the inability to clear an obstacle is because of improper activation of muscles that flex the knee. Animals recover a certain amount of function thanks to new strategies and changes within the nervous system.

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Introduction

Animals, including humans, must adjust their gait pattern in a changing environment. For instance, stepping over obstacles requires modifying limb trajectory and coordinating the other limbs for balance. Safely negotiating obstacles involves several levels of the nervous system. When anticipating an obstacle, the visual cortex receives information and sends signals to motor and premotor areas (Sherk and Fowler, 2001; Mohagheghi et al., 2004; Wilkinson and Sherk, 2005; Patla and Greig, 2006; Volgushev et al., 2022). In turn, corticospinal and rubrospinal tracts signal spinal motor circuits to activate muscles and alter limb trajectory (Beloozerova and Sirota, 1993; Widajewicz et al.,

1994; Drew et al., 1996; Lavoie and Drew, 2002). Without anticipatory control, the foot dorsum contacts the obstacle and a reflex, triggered by cutaneous afferents, which modifies limb trajectory to step away from and over the obstacle to prevent stumbling, termed the stumbling corrective reaction (SCR) (Prochazka et al., 1978; Forssberg, 1979; Wand et al., 1980; Buford and Smith, 1993; Schillings et al., 1996, 2000; Zehr et al., 1997; Quevedo et al., 2005; McVea and Pearson, 2007a). The SCR occurs in low-thoracic spinal-transsected cats, consistent with a spinal mechanism (Forssberg et al., 1974, 1975).

Following incomplete spinal cord injury (SCI) in humans, although substantial walking recovery can occur, notable deficits persist in features critical for community ambulation, including obstacle negotiation (Musselman and Yang, 2007; Musselman et al., 2011). People categorized as American Spinal Injury Association Impairment Scale D, the highest level of recovery, fail to properly negotiate obstacles (Amatachaya et al., 2010). Despite the importance of negotiating obstacles after SCI, few studies have investigated it. Drew et al. (1996) showed that corticospinal and/or rubrospinal tracts were involved in obstacle negotiation during treadmill locomotion by performing dorsolateral spinal lesions at low thoracic levels (T13) in cats. An SCR emerged after the lesion because cats could not anticipate and avoid the obstacle (Drew et al., 2002). Another study conducted during overground locomotion after a T10 lateral hemisection in cats showed that the ipsilesional hindlimb contacted the obstacle in ~90% of trials 2 weeks after SCI (Doperalski et al., 2011). Despite some recovery over the course of 8 weeks before a plateau, limb contact persisted in ~50% of trials (Doperalski et al., 2011). However, they did not record muscle activity, although they highlighted the importance of doing so in future studies, focusing on some kinematic adjustments of the ipsilesional hindlimb.

An important aspect to consider when negotiating an obstacle is the limb that crosses the obstacle first (the leading limb) because biomechanical demands differ. In humans, the strategy for the trailing limb allows sufficient time after limb elevation to decelerate the limb for a smooth foot contact (Patla et al., 1996), while the leading limb strategy prevents slipping at contact (Patla and Rietdyk, 1993). For the leading and trailing limbs, foot elevation is mainly driven by hip/knee and knee/ankle flexion, respectively (Patla et al., 1996). In cats and humans, knee flexion is always the main contributor in vertical foot elevation (McFadyen et al., 1993; Lavoie et al., 1995).

The purpose of the present study was to characterize neuro-mechanical strategies used by adult cats when negotiating obstacles of different heights during overground locomotion before and after a lateral hemisection on the right side of the spinal cord at mid-thoracic levels to determine disruptions in voluntary/anticipatory control and neuroplastic changes in spared structures/pathways over time. We recorded EMG and kinematic data before (intact) and at 1–2 and 7–8 weeks after hemisection, separating trials with right (ipsilesional) and left (contralesional) limbs leading. We mainly focused on kinematic changes in the right ipsilesional hindlimb and its clearance strategies. We hypothesize that disrupting commands from the brain impairs activation of muscles that flex the ipsilesional right hindlimb, particularly knee flexors. However, over time, neuroplastic changes allow for some recovery. We also expect different strategies to clear an obstacle based on whether the ipsilesional right hindlimb is the leading or trailing limb because of different biomechanical constraints.

Materials and Methods

Animals and ethical information. The Animal Care Committee of the Université de Sherbrooke approved all procedures in accordance with the policies and directives of the Canadian Council on Animal Care (Protocol 442-18). In the present study, we used 10 adult cats (>1 year of age at the time of experimentation), 5 females and 5 males, with a mass between 3.8 and 6.1 kg. We followed the ARRIVE guidelines for animal studies (Percie du Sert et al., 2020). To reduce the number of animals used in research, cats participated in other studies to answer different scientific questions, some of which have been published (Lecomte et al., 2022; Merlet et al., 2022). Cats were housed in individual cages in the same room of the animal care facility. Cats were kept in their cages for 3–4 d after surgeries, but otherwise they were free to move in the room for a few hours during the day, with access to toys, food, and water. Cats were also free to move in the laboratory for several hours each week and frequently interacted with laboratory personnel.

Surgical procedures and electrode implantation. We performed surgeries under aseptic conditions with sterilized instruments in an operating room. Before surgery, the cat was sedated with an intramuscular injection of a cocktail containing butorphanol (0.4 mg/kg), acepromazine (0.1 mg/kg), and glycopyrrolate (0.01 mg/kg) and induced with another intramuscular injection (0.05 ml/kg) of ketamine (2.0 mg/kg) and diazepam (0.25 mg/kg) in a 1:1 ratio. The fur overlying the back, stomach, forelimbs, and hindlimbs was shaved and the skin was cleaned with chlorhexidine soap. The cat was then anesthetized with isoflurane (1.5%–3%) and O₂ using a mask for a minimum of 5 min and then intubated with a flexible endotracheal tube. Isoflurane concentration was confirmed and adjusted throughout the surgery by monitoring cardiac and respiratory rates, by applying pressure to the paw to detect limb withdrawal and by assessing muscle tone. A rectal thermometer was used to monitor body temperature and keep it within physiological range ($37 \pm 0.5^\circ\text{C}$) using a water-filled heating pad placed under the animal and an infrared lamp positioned ~50 cm above the cat. We inserted a 24–26G catheter in the left or right cephalic vein to give cats a continuous infusion of lactated Ringer's solution (3 ml/kg/h, i.v.).

We directed pairs of Teflon-insulated multistrain fine wires (AS633; Cooner Wire) subcutaneously from two head-mounted 34-pin connectors (Omnetics Connector) and sewn them into the belly of selected forelimb and hindlimb muscles for bipolar recordings, with 1–2 mm of insulation stripped from each wire. Wires are threaded through the muscle using a 21G \times 1½ inch needle, and then tied together. The head connector was secured to the skull using dental acrylic and six screws (Fig. 1A). We verified electrode placement by electrically stimulating each muscle through the appropriate head connector channel. The skin was closed using subcuticular sutures (monocryl 4–0, Ethicon) followed by cutaneous sutures (monocryl 3–0, Ethicon).

At the end of surgery, we injected an antibiotic (cefovecin, 8 mg/kg) subcutaneously and taped a transdermal fentanyl patch (25 µg/h) to the back of the animal 2–3 cm rostral to the base of the tail, which was removed 5–7 d later. We injected buprenorphine (0.01 mg/kg, s.c.), a fast-acting analgesic, during surgery and ~7 h after. Following surgery, we placed the cats in an incubator until they regained consciousness.

Lateral hemisection. We performed a lateral hemisection on the right side of the spinal cord at thoracic levels T5–T6. A small laminectomy was performed between the fifth and sixth thoracic vertebrae. After exposing the spinal cord, lidocaine (xylocaine, 2%) was applied topically and injected intraspinally (two or three 1 ml injections) on the right side of the cord using a 25G \times 5/8 inch needle. The spinal cord was then hemisected laterally from the midline with surgical scissors. The dura was cut as part of the hemisection and was left open. Hemostatic material (Spongostan, Ethicon) was inserted within the gap, and muscles and skin were sewn back to close the opening in anatomic layers. The same preoperative and postoperative treatments were administered as for the implantation surgery. In the days following the hemisection, cats were carefully monitored for voluntary bodily functions. The bladder was expressed manually if needed.

Experimental protocol. We trained cats to step on an overground walkway with a straight path 207 cm long and 32 cm wide between two Plexiglas walls with food and affection as reward (Fig. 1B). The walkway

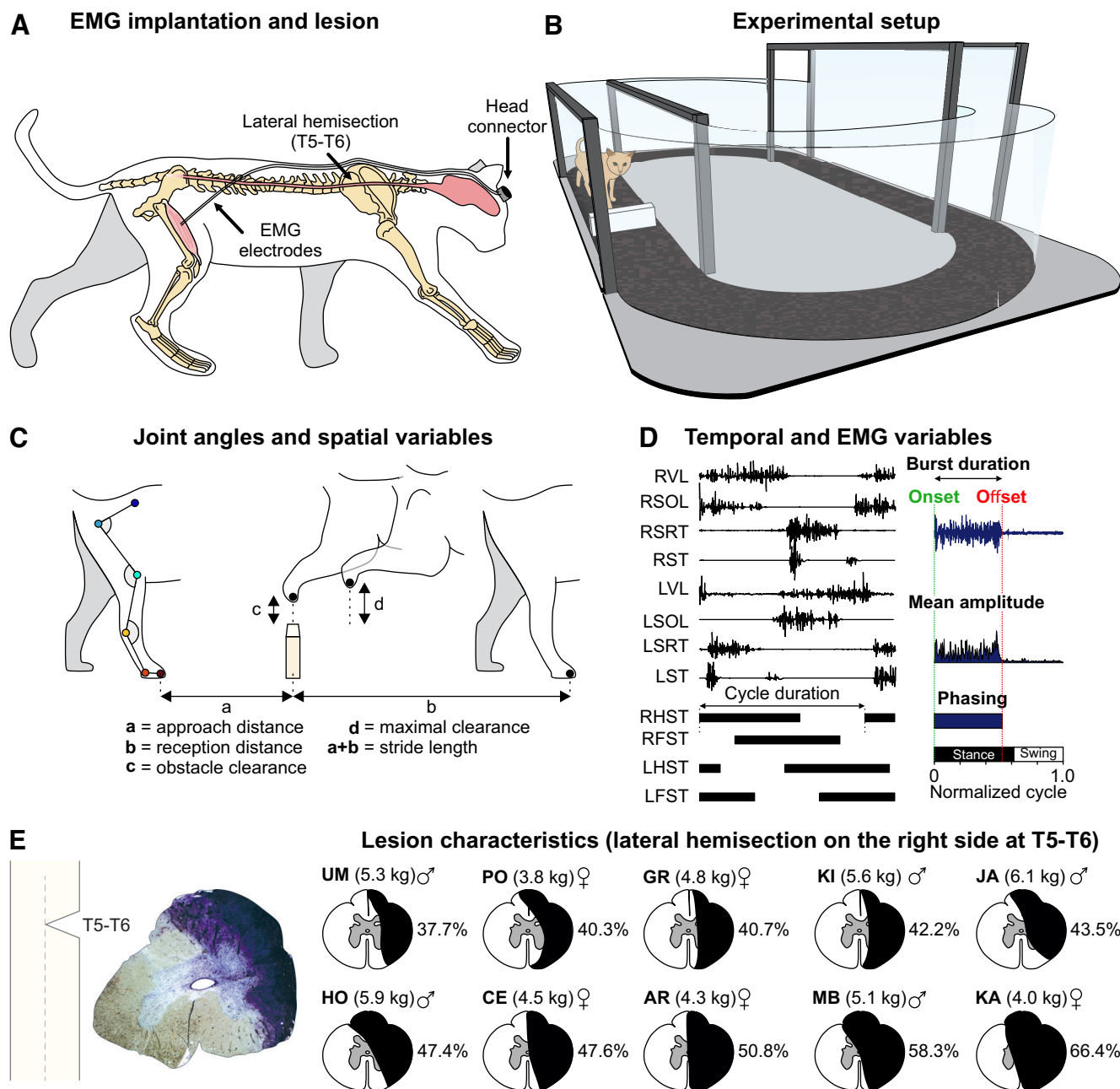


Figure 1. Experimental design, data analysis, and lesion characteristics. **A**, Experimental design showing EMG electrodes directed subcutaneously to muscles from a head connector and the site of spinal lesion. **B**, Walkway with an obstacle in the straight path. **C**, Joint angles and spatial variables. **D**, Measures of EMG variables. EMG activity is shown for 4 muscles of the left (L) hindlimb and 4 muscles of the right (R) hindlimb. VL, Vastus lateralis; SOL, soleus; SRT, anterior sartorius; ST, semitendinosus. Thick horizontal lines indicate right hindlimb (RHST), right forelimb (RFST), left hindlimb (LHST), and left forelimb (LFST) stances phases. **E**, Spinal lesion site with cresyl violet staining (Cat JA). Darker area represents the lesioned area. The estimated lesion percent is indicated for each cat to the left of their representative lesion schematic.

is oval-shaped, and the animals have sufficient room to turn around at the two ends of the straight path. The surface of the walkway is made of black rubberized material. To assess obstacle negotiation, cats stepped in the walkway with an obstacle placed in the middle of the straight path. The three obstacles used were white plastic objects 2.5 cm wide and 1, 5, and 9 cm in height that could easily be knocked over if contacted by the cat's limb to avoid injury. From the first training session, cats negotiated all obstacle heights without contact. Experiments began after a minimum of 2 weeks of familiarization where cats performed sessions lasting 20–30 min, 3 times a week.

Each cat performed one session that consisted of negotiating the three obstacle heights. Cats were given a few seconds of rest and a food reward between each negotiation (a trial) to obtain ~20 trials for each obstacle height where we could analyze the step before, during, and after

crossing the obstacle. A session lasted ~25–30 min. Before and after hemisection, cats stepped at a self-selected speed. Intact cats stepped at speeds ranging from 0.36 to 0.84 m/s with a mean of 0.62 ± 0.13 m/s. At weeks 1–2 after hemisection, cats stepped at speeds ranging from 0.24 to 0.77 m/s with a mean of 0.53 ± 0.15 m/s. At weeks 7–8 after hemisection, cats stepped at speeds ranging from 0.36 to 0.77 m/s with a mean of 0.53 ± 0.11 m/s. The trials where cats were running, jumping, or pausing between different steps were not analyzed.

Data acquisition and analysis. We collected kinematic and EMG data before and 1–2 weeks and 7–8 weeks after hemisection. Two cameras (Basler Aca640-100 G) captured videos of the left and right sides at 60 frames per second with a spatial resolution of 640×480 pixels. A custom-made program (LabView) acquired the video images and synchronized them with EMG data. We analyzed each video offline

using a deep-learning approach, DeepLabCut (Mathis et al., 2018; Nath et al., 2019), as recently described (Lecomte et al., 2021, 2022; Merlet et al., 2022). DeepLabCut allows motion tracking without requiring placing reflective markers. The images were captured with the same cameras mentioned above. We specified the points of interest that trained the software. The output provided was in the form of an Excel spreadsheet with x and y coordinates of all points of interest for each video frame. We measured kinematic variables from these coordinates.

We determined the contact and liftoff of each limb by visual inspection. We defined contact as the first frame where the paw made visible contact with the walking surface while liftoff corresponded to the frame with the most caudal displacement of the toe. Based on contacts and liftoffs for each limb, we measured individual periods of support (double, triple, and quad) and expressed them as a percentage of cycle duration (Frigon et al., 2014; Lecomte et al., 2022). During a normalized cycle, defined from successive right hindlimb contacts, we identified nine periods of limb support (Gray, 1968; Wetzel and Stuart, 1976; Hildebrand, 1989; Frigon et al., 2021). We measured various spatial parameters for the right ipsilesional hindlimb (Fig. 1C), including stride length, defined as the distance traveled by the limb between two consecutive contacts. We measured the animal's speed during a cycle by dividing the horizontal displacement of the right hip between two consecutive right hindlimb contacts by cycle duration. We obtained the height of the right hindpaw as it traveled over the obstacle by measuring the distance between the base of the fifth metatarsal and the top of the obstacle when the paw is directly above the obstacle (obstacle clearance) and when it reaches its maximum height (maximal clearance). We measured two other distances horizontally from the base of the fifth metatarsal and the obstacle. The approach distance was measured at the time of right hindlimb contact before the obstacle. The reception distance was measured at right hindlimb contact after the obstacle. We measured right hip, knee, and ankle angles throughout the step cycle.

EMG signals were preamplified ($\times 10$, custom-made system), band-pass filtered (30–1000 Hz), and amplified ($100\text{--}5000\times$) using a 16-channel amplifier (AM Systems model 3500). As we implanted >16 muscles per cat, we obtained data for each obstacle height twice, one for each connector, as our data acquisition system does not currently allow us to record >16 channels simultaneously. EMG data were digitized (2000 Hz) with a National Instruments card (NI 6032E), acquired with a custom-made acquisition software and stored on a computer. Although several muscles were implanted in the forelimbs and hindlimbs, we focused our analysis on 10 muscles of the left (L) contralesional and right (R) ipsilesional hindlimbs: vastus lateralis (knee extensor, LVL, $n=8$; RVL, $n=9$), biceps femoris anterior (hip extensor, LBFA, $n=8$; RBFA, $n=9$), lateral gastrocnemius (ankle extensor/knee flexor, LLG, $n=7$; RLG, $n=8$), medial gastrocnemius (ankle extensor/knee flexor, LMG, $n=7$; RMG, $n=7$), soleus (ankle extensor, LSOL, $n=8$; RSOL, $n=9$), anterior sartorius (hip flexor/knee extensor, LSRT, $n=7$; RSRT, $n=6$), iliopsoas (hip flexor, LIP, $n=3$; RIP, $n=3$), biceps femoris posterior (hip extensor/knee flexor, LBFP, $n=8$; RBFP, $n=8$), semitendinosus (hip extensor/knee flexor, LST, $n=9$; RST, $n=6$), and tibialis anterior (ankle flexor, RTA, $n=4$). Burst onsets and offsets were determined visually by the same experimenter (Lecomte) from the raw EMG waveforms using a custom-made program. Burst duration was determined from onset to offset while mean EMG amplitude was measured by integrating the full-wave rectified EMG burst from onset to offset and dividing it by its burst duration (Fig. 1D). Joint angles were low-pass filtered (fourth-order Butterworth filter, zero-lag, cutoff frequency 6 Hz).

Histology. To determine the extent of the spinal lesion, spinal cords were prepared for histologic staining and evaluation. After the experiments, under general anesthesia (same as above), cats received a lethal dose of pentobarbital (120 mg/kg) through the left or right cephalic vein, and we collected spinal cord tissue for histologic analysis. Briefly, after confirming euthanasia (i.e., no presence of heartbeat and respiratory function), we dissected a 2-cm-long segment of the spinal cord centered around the injury site and placed it in 25 ml of 4% PFA solution (0.1 M PB, 4°C). After 5 d of immersion, the spinal cord was cryoprotected in PB 0.2 M containing 30% sucrose for 72 h at 4°C and snap frozen in isopentane maintained at -50°C . We then sliced the spinal cord into 50 μm

coronal sections using a cryostat (Leica CM1860, Leica Biosystems). Sections were mounted on gelatin-coated slides, dried overnight, and stained with an acidic solution containing 0.1% cresyl violet acetate (Sigma-Aldrich) for 12 min. The slides were then washed once in distilled water for 3 min before being dehydrated in successive baths of ethanol 50%, 70%, and 100%, 5 min each, before being transferred in xylene for 5 min. Slides were finally mounted with dibutylphthalate polystyrene xylene (Sigma-Aldrich) and coverslips, and dried before being scanned using a Nanozoomer (Hamamatsu). We then performed qualitative and quantitative evaluations of the lesioned area using ImageJ (developed by National Institutes of Health) by taking the slide with the largest visible damaged area. The area of the lesion, the darkened area, was calculated and then divided by total area of the slice to obtain lesion percentage (Fig. 1E). The percent value is an estimate of lesion extent based on the scarring tissue stained with cresyl violet acetate in cross sections.

Statistical analysis. We performed statistical tests with SPSS Statistics 20.0 (IBM). We separated trials with Left and Right limbs leading. When the right forelimb stepped over the obstacle first, it was followed by the left forelimb, right hindlimb, and left hindlimb. We termed these trials Right limbs leading. The same applies to Left limbs leading (left forelimb followed by right forelimb, left hindlimb, and right hindlimb). For each animal and a given obstacle height, we averaged Left and Right limbs leading trials separately. To assess the evolution of the proportions of each type of negotiation after hemisection, as well as potential preferred leading limbs, we performed a χ^2 test. We performed a two-factor mixed-effects model ANOVA with the cat as the experimental unit to determine main effects and possible interactions on dependent variables for the following factors: (1) negotiation \times obstacle height, (2) step \times obstacle height, and (3) clearance \times obstacle height. For each two-factor ANOVA, the interaction between the two parameters determines whether one factor influences the other. For EMG data, we performed a two-factor repeated-measures ANOVA for individual cats to determine individualized strategies. If there was a main effect of the ANOVA, we performed Dunnett's test to compare post-hemisection values with intact values. The normality of each variable was assessed by the Shapiro–Wilk test. Although we did not correct for multiple comparisons to avoid Type II errors (Rothman, 1990; Hurteau and Frigon, 2018), we used a CI of 99% or a $p \leq 0.01$ to determine significance for each test. This increases the probability that significant differences correspond to robust and physiological/functional changes in the gait pattern.

Results

Different types of obstacle negotiations after lateral hemisection

In the intact state, the right hindlimb of all cats cleared the obstacles at all three heights without contact, which we term complete clearance (CC), while after hemisection other negotiation types appeared in the ipsilesional right hindlimb (Fig. 2A). After hemisection, we observed CC, an SCR, where the right hindlimb contacts the obstacle and evokes a reflex response to move it away and over the obstacle, as well as an absence of response following contact, which we term “Other,” as in Doperalski et al. (2011). In the intact state, CC represented 100% of trials. After hemisection, the proportion of CC significantly decreased at all three obstacle heights, even for obstacles of 1 cm ($\chi^2_{(9)} = 32.59$, $p = 0.0002$; χ^2). At 1–2 weeks after hemisection, CC and SCR represented 39.8% and 39.6% of trials, respectively, while 20.6% were Other. At weeks 1–2, considering only obstacles of 5 and 9 cm, 56.1% were SCR while the proportion of CC and Other were similar at 21.8% and 22.0%, respectively. At weeks 7–8 after hemisection, the amount of CC significantly increased to 62.9% ($\chi^2_{(9)} = 23.67$, $p = 0.0049$; χ^2) in favor of Other ($\chi^2_{(9)} = 25.12$, $p = 0.0013$; χ^2), which almost disappeared with only 3.0% of trials. At weeks 7–8, considering only obstacles of 5 and 9 cm, CC represented 46.1% of trials

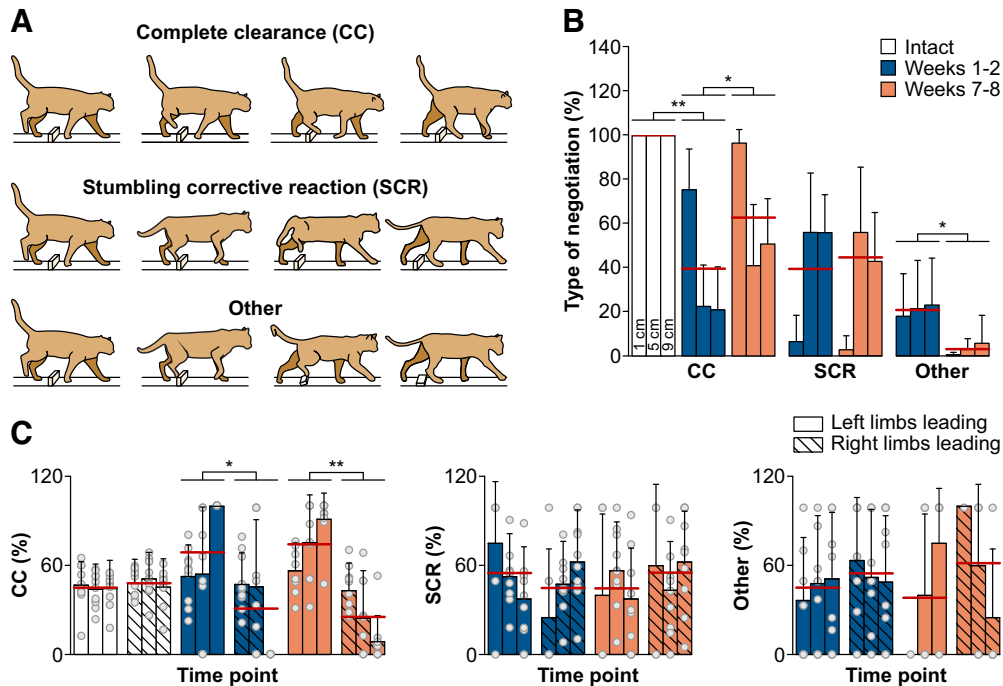


Figure 2. Different types of obstacle negotiations and their proportions. **A**, Schematic illustration of the three obstacle negotiations. **B**, Proportion of each negotiation type for the ipsilesional right hindlimb. Red line indicates mean for the three obstacle heights. **C**, Percentage of each negotiation type according to leading limbs. Error bars indicate mean \pm SD for the group. Gray circles represent individual data points (mean for each cat). For each obstacle height, we averaged between 3 and 25 trials per cat ($n = 10$ cats; 5 females and 5 males). Thick red line indicates the mean of the three obstacle heights. We performed χ^2 tests to assess differences between proportions. Significant difference between sides: $*p < 0.01$; $**p < 0.001$; $***p < 0.0001$.

and SCR 47.1%. The proportion of CC at weeks 7–8 was not significantly different from that of the intact state ($\chi^2_{(9)} = 20.18$, $p = 0.0168$; χ^2). The proportion of Other remained low at 4.4% of trials (Fig. 2B). Thus, Other trials will not be discussed further at weeks 7–8. Table 1 summarizes the negotiation types made by each cat at the two post-injury time points.

For CC of the right hindlimb in intact cats, we observed no clear side preference, with both Left and Right limbs leading showing similar proportions ($\chi^2_{(9)} = 10.24$, $p = 0.3314$, χ^2) (Fig. 2C, left). However, after hemisection, the proportion of CC was significantly greater with Left limbs leading compared with Right limbs leading, at weeks 1–2 ($\chi^2_{(9)} = 156.6$, $p < 0.0001$, 102.7%; χ^2) and 7–8 ($\chi^2_{(9)} = 114.1$, $p < 0.0001$, 202%; χ^2) (Fig. 2C, left). Importantly, no cat performed CC of the right ipsilesional hindlimb with Right limbs leading for the 9 cm obstacle height at weeks 1–2. After hemisection, we observed no side preference in limbs leading with SCR at weeks 1–2 ($\chi^2_{(9)} = 13.36$, $p = 0.1432$; χ^2) and 7–8 ($\chi^2_{(9)} = 13.89$, $p = 0.1169$, χ^2) (Fig. 2C, middle). The Other type of negotiation also did not show a side preference in limbs leading at weeks 1–2 ($\chi^2_{(9)} = 10.36$, $p = 0.3122$, χ^2) and 7–8 ($\chi^2_{(9)} = 19.98$, $p = 0.0232$, χ^2) after hemisection. After hemisection, the contralesional left hindlimb never contacted the obstacle. For all negotiation types pooled, we observed no side preference in the intact state ($\chi^2_{(9)} = 10.24$, $p = 0.3314$; χ^2) and at weeks 1–2 after hemisection ($\chi^2_{(9)} = 15.62$, $p = 0.0753$; χ^2). However, 7–8 weeks after hemisection, 62.8% of negotiations were with Left limbs leading, which was significantly greater compared with the proportion of Right limbs leading ($\chi^2_{(9)} = 118.2$, $p < 0.0001$; χ^2).

Altered and less optimal limb trajectories when negotiating obstacles after hemisection

After hemisection, right ipsilesional hindlimb trajectory was altered compared with the intact state and depended on the type

of negotiation, as shown in Figure 3 for a single cat crossing a 5 cm obstacle with Left and Right limbs leading before and at weeks 1 and 7 after hemisection. In the intact state, with Right limbs leading, the right hindlimb begins its swing phase further away from the obstacle compared with Left limbs leading. These distances of the right ipsilesional hindlimb from the obstacle at swing onset were maintained after hemisection. When an SCR occurred after hemisection, we observed that the right hindpaw was closer to the obstacle at liftoff with Left limbs leading and not sufficiently lifted during swing with Right limbs leading. An absence of an SCR following contact with the obstacle characterized the Other type of negotiation. With Other, right ipsilesional hindlimb trajectory remained unchanged as it contacted the obstacle, knocking it over. At week 7 after hemisection, right ipsilesional hindlimb trajectory during CC was exaggerated, with increased paw height, with Left limbs leading but relatively similar to the intact state with Right limbs leading. The SCR at week 7 displayed a noticeable elevation of the right ipsilesional hindpaw with Left and Right limbs leading.

When animals step over an obstacle, they must consider various factors, such as the distance between the hindpaw and the obstacle at liftoff (approach distance) and where it lands after clearing it (reception distance). With Left limbs leading (Fig. 4A, left), right ipsilesional hindlimb approach distance was shorter ($F_{(2.488, 39.81)} = 12.56$, $p < 0.0001$; ANOVA) for CC at weeks 1–2 ($p = 0.0011$, -43.7% ; Dunnett) and 7–8 weeks ($p < 0.0001$, -47.6% ; Dunnett) after hemisection compared with intact CC, indicating that the right hindpaw was closer to the obstacle. For reception distance, we found a significant main effect ($F_{(2.262, 36.20)} = 10.50$, $p = 0.0032$; ANOVA), but a significant difference was only observed for SCR at weeks 1–2 ($p = 0.0013$, -11.8% ; Dunnett) with the right ipsilesional hindlimb landing closer to the obstacle. With Right limbs leading (Fig. 4A, right), we found no significant differences for approach

Table 1. Type of obstacle negotiation of the ipsilesional right hindlimb after lateral hemisection^a

	Height (cm)	1–2 weeks after hemisection						7–8 weeks after hemisection					
		CC		SCR		Other		CC		SCR		Other	
		LLL	RLL	LLL	RLL	LLL	RLL	LLL	RLL	LLL	RLL	LLL	RLL
AR	1	8/23	6/23	9/23				14/28	14/28				
	5	5/21		7/21	6/21	3/21		13/30	5/30	4/30	5/30		3/30
	9	6/21		2/21	9/21	4/21		17/31	3/31		8/29	3/31	
CE	1	6/23	11/23			3/23	3/23	10/25	15/25				
	5	5/27	6/27	4/27	6/27	3/27	3/27	14/24	4/24	6/24			
	9	3/24	3/24		10/24	5/24	3/24	16/23			4/23	3/23	
GR	1	17/32	9/32			3/32	3/32	23/31	8/31				
	5	4/21		9/21	3/21		5/21	18/27		7/27	2/27		
	9	10/28		4/28	14/28			25/32		4/32	3/32		
HO	1	12/22	3/22			3/22	4/22	10/33	11/33		12/33		
	5		3/25	13/25	3/25	3/25	3/25	7/25	3/25	9/25	3/25	3/25	
	9			3/21	7/21	7/21	4/21	12/28	3/28	3/28	10/28		
JA	1	10/31	11/31	3/31	3/31		4/31	13/29	13/29	3/29			
	5	6/27	3/27	3/27	7/27	5/27	3/27	8/32	3/32	11/32	7/32		3/32
	9	6/26		6/26	9/26	5/26		13/37	3/37	10/37	8/37	3/37	
KA	1	18/35	11/35		3/35		3/35	19/29	6/29	4/29			
	5	6/23		8/23	9/23			4/26		18/26	4/26		
	9	11/31		10/31	6/31		3/31	19/37		15/37	3/37		
KI	1	15/24	6/24			3/24		16/25	6/25		3/25		
	5	3/29	3/29	8/29	12/29		3/29	5/35		13/35	17/35		
	9	8/31		11/31	10/31		2/31	12/23		3/23	8/23		
MB	1	4/24	14/24	3/24			3/24	25/40	12/40				3/40
	5		5/23	5/23	7/23	3/23	3/23	6/40		15/40	16/40	3/40	
	9				14/21		7/21	9/37	3/37	7/37	15/37	3/37	
PO	1	3/25	8/25			10/25	4/25	8/28	20/28				
	5	8/21	4/21			6/21	3/21	10/29	10/29	3/29	3/29		3/29
	9	10/22		3/22	3/22	3/22	3/22	5/25	6/25		5/25		9/25
UM	1	15/33	12/33	3/33			3/33	17/34	17/34				
	5		6/30	14/30	7/30		3/30	4/33	9/33	17/33	3/33		
	9	3/29		17/29	3/29	3/29	3/29	7/27		12/27	8/27		

^aThe number of negotiation types/total number of cycles made by the ipsilesional right hindlimb of individual cats (cat identification, first column) at both time points after hemisection at the three obstacle heights (1, 5, and 9 cm, second column). LLL, Left limbs leading; RLL: Right limbs leading.

distance ($F_{(2,276, 32.78)} = 1.031, p = 0.3761$; ANOVA). The only significant difference was a greater reception distance ($F_{(2,758, 39.72)} = 6.312, p = 0.0017$; ANOVA) for SCR at weeks 7–8 after hemisection ($p = 0.0007, 24.4\%$; Dunnett), indicating that the right ipsilesional hindpaw landed further away from the obstacle.

When stepping over an obstacle, humans and cats will use a minimal clearance height and optimal limb flexion that prevents contact with the obstacle and minimizes energy expenditure (Doperalski et al., 2011). To assess this and how it might be impaired after hemisection, we measured the difference between the maximal clearance and obstacle clearance for the right ipsilesional hindlimb for each type of negotiation and compared it with intact CC (Fig. 4B). Smaller values reflect a more efficient or optimal obstacle crossing. With Left limbs leading, the difference between maximal and obstacle clearance significantly increased ($F_{(2,027, 30.81)} = 41.3, p < 0.0001$, ANOVA) after hemisection for all negotiations at weeks 1–2 (CC: $p = 0.0002, 184.6\%$ and SCR: $p < 0.0001, 530.9\%$; Dunnett) and weeks 7–8 (CC: $p < 0.0001, 298.7\%$ and SCR: $p < 0.0001, 686.7\%$; Dunnett) compared with CC intact, except for the Other type of negotiation. With Right limbs leading, we observed a significant increase [$F_{(2,655, 36.64)} = 39.17, p < 0.0001$, ANOVA] for SCR at weeks 1–2 ($p < 0.0001, 1918.4\%$; Dunnett) and 7–8 ($p < 0.0001, 2283.3\%$; Dunnett) compared with CC intact.

Negotiating obstacles mainly involves a knee and ankle strategy before and after hemisection

To determine the different strategies used to negotiate obstacles after hemisection, we measured joint angles of the right

ipsilesional hindlimb throughout the cycle, as shown for a single cat before and at weeks 1 and 7 after hemisection at an obstacle height of 5 cm (Fig. 5). We compared the step before and when crossing the obstacle. Smaller angle values correspond to greater flexion. In the intact state for this cat, with Left and Right limbs leading, we observed greater angular excursion at the knee and ankle, particularly flexion, in the obstacle step while hip joint excursions were similar. At week 1 after hemisection with Left limbs leading, we observed smaller hip excursion but similar knee and ankle excursions for CC in the obstacle step. With Right limbs leading, all three joints showed greater excursions for CC at week 1 after hemisection in the obstacle step. The SCR at week 1 after hemisection was mainly characterized by greater knee joint excursion in the obstacle step with Left and Right limbs leading. The Other type of negotiation shows little modulation in excursion for all three joints in the obstacle step for Left limbs leading but considerably greater excursions at the hip, knee, and ankle with Right limbs leading. At week 7, CC and SCR show increased excursions at all three joints in the obstacle step for Left limbs leading, particularly at the knee and ankle. With Right limbs leading at week 7, CC and SCR were characterized by a greater excursion for the knee and ankle in the obstacle step but not at the hip.

For the group (Fig. 6, top panels), right hindlimb hip excursion was not significantly different between the control and obstacle step before or after hemisection in Left and Right limbs leading except for CC at weeks 1–2 in Right limbs leading ($F_{(1,12)} = 35.59, p < 0.0001, 22.6\%$, ANOVA). For the knee joint,

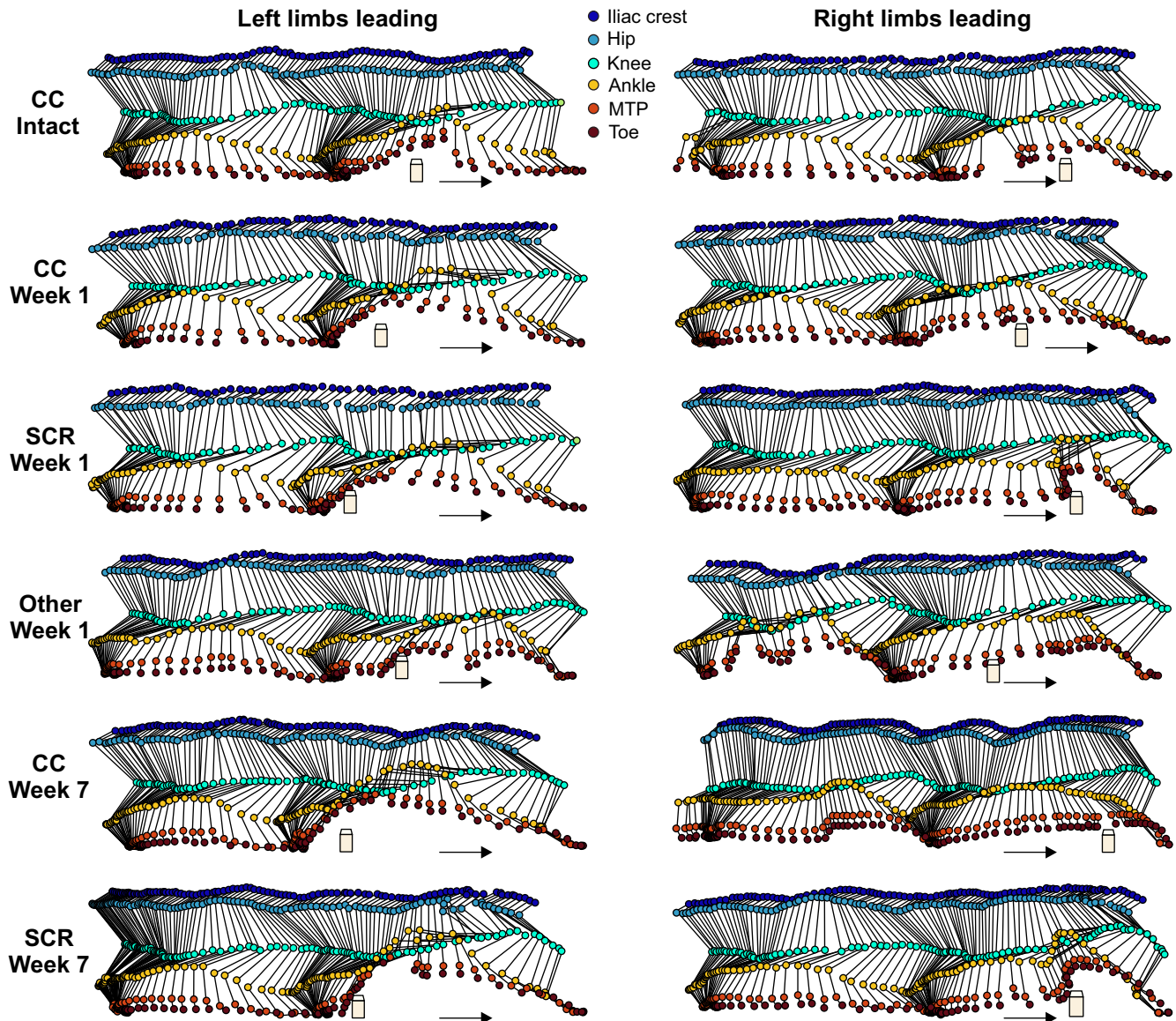


Figure 3. Kinematics of the right hindlimb during obstacle negotiation before and after a spinal hemisection. Figure represents stick figure diagrams of the right ipsilesional hindlimb for representative cycles for the step before and the obstacle step for the six types of negotiation before and at weeks 1 and 7 after hemisection for Left (left panels) and Right (right panels) limbs leading. All figures are from Cat JA with a 5 cm obstacle. Arrows indicate direction of movement.

angular excursion was significantly greater in the obstacle step compared with the control step for all negotiation types before and at weeks 1–2 and 7–8 after hemisection in Left and Right limbs leading (Fig. 6, middle panels). For Left limbs leading, we observed significant increases (ANOVA) for intact CC ($F_{(1,54)} = 337.2$, $p < 0.0001$, 67.3%), CC at weeks 1–2 ($F_{(1,17)} = 85.15$, $p < 0.0001$, 44.9%), SCR at weeks 1–2 [$F_{(1,15)} = 21.44$, $p = 0.0003$, 50.0%], Other at weeks 1–2 ($F_{(1,12)} = 30.73$, $p = 0.0001$, 40.9%), CC at weeks 7–8 ($F_{(1,26)} = 91.59$, $p < 0.0001$, 57.9%) and SCR at weeks 7–8 ($F_{(1,10)} = 64.59$, $p < 0.0001$, 76.3%). For Right limbs leading, we observed significant increases (ANOVA) for intact CC ($F_{(1,54)} = 32.02$, $p < 0.0001$, 25.1%), CC at weeks 1–2 ($F_{(1,12)} = 14.58$, $p = 0.0024$, 12.7%), SCR at weeks 1–2 ($F_{(1,17)} = 17.17$, $p = 0.0007$, 41.5%), Other at weeks 1–2 ($F_{(1,12)} = 22.76$, $p = 0.0005$, 12.7%), CC at weeks 7–8 ($F_{(1,14)} = 11.97$, $p = 0.0038$, 17.1%), and SCR at weeks 7–8 ($F_{(1,30)} = 23.07$, $p < 0.0001$, 57.5%). For the ankle joint, angular excursion was significantly greater in the obstacle step compared with the control step for all negotiation types before and at weeks 1–2 and 7–8 after hemisection in Left limbs leading (Fig. 6, bottom

left). We observed significant increases (ANOVA) for intact CC ($F_{(1,54)} = 59.13$, $p < 0.0001$, 23.3%), CC at weeks 1–2 ($F_{(1,17)} = 17.15$, $p = 0.0007$, 16.1%), SCR at weeks 1–2 ($F_{(1,15)} = 19.66$, $p = 0.0005$, 29.6%), Other at weeks 1–2 ($F_{(1,12)} = 28.68$, $p = 0.0002$, 26.6%), CC at weeks 7–8 ($F_{(1,26)} = 34.87$, $p < 0.0001$, 27.9%), and SCR at weeks 7–8 ($F_{(1,10)} = 13.19$, $p = 0.0046$, 36.0%). In Right limbs leading (Fig. 6, bottom right), ankle joint angular excursion was significantly greater (ANOVA) in the obstacle step compared with the control step for intact CC ($F_{(1,54)} = 73.85$, $p < 0.0001$, 35.9%) and SCR at weeks 1–2 ($F_{(1,17)} = 15.55$, $p = 0.0010$, 23.0%) and 7–8 ($F_{(1,15)} = 27.12$, $p = 0.0001$, 33.0%) after hemisection.

The timing of joint flexion depends on the leading limbs after hemisection

To determine whether the timing of hip, knee, and ankle joint flexion of the ipsilesional right hindlimb could explain the different negotiation types after hemisection, we measured their flexion onsets in the different negotiations and compared them with intact CC (Fig. 7). In general, for all negotiation types, the right

hip flexed significantly earlier after hemisection with Left limbs leading ($F_{(2.025, 34.42)} = 9.430$, $p = 0.0005$; ANOVA) and Right limbs leading ($F_{(2.861, 41.78)} = 19.89$, $p < 0.0001$; ANOVA), with the exception of Other at weeks 1–2 with Left limbs leading. With Left limbs leading, the right hip flexed earlier for CC at weeks 1–2 ($p = 0.0053$, -5.9% ; Dunnett) and 7–8 ($p < 0.0001$, -6.0% ; Dunnett) and SCR at weeks 1–2 ($p < 0.0001$, -9.1% ; Dunnett) and 7–8 ($p < 0.0001$, -5.9% ; Dunnett). With Right limbs leading, the right hip flexed earlier for CC at weeks 1–2 ($p = 0.0005$, -9.5% ; Dunnett) and 7–8 ($p < 0.0001$, -10.5% ; Dunnett), SCR at weeks 1–2 ($p < 0.0001$, -14.4% ; Dunnett) and 7–8 ($p < 0.0001$, -13.0% ; Dunnett) as well as Other at weeks 1–2 ($p = 0.0015$, -9.0% ; Dunnett). Right knee flexion onset did not change significantly after hemisection with Left limbs leading ($F_{(2.746, 43.94)} = 3.211$, $p = 0.0357$; ANOVA) and the right ankle joint only flexed significantly earlier ($F_{(2.818, 47.90)} = 5.643$, $p = 0.0026$; ANOVA) for CC at weeks 7–8 ($p = 0.0019$, -3.2% ; Dunnett). However, with Right limbs leading, right knee flexion occurred significantly earlier ($F_{(3.383, 45.33)} = 10.50$, $p < 0.0001$; ANOVA) for all negotiation types after hemisection, including CC at weeks 1–2 ($p = 0.0004$, -9.4% ; Dunnett) and 7–8 ($p = 0.0001$, -7.9% ; Dunnett), SCR at weeks 1–2 ($p < 0.0001$, -10.3% ; Dunnett) and 7–8 ($p = 0.0019$, -8.4% ; Dunnett), as well as Other at weeks 1–2 ($p = 0.0002$, -9.5% ; Dunnett). With Right limbs leading, ankle flexion also occurred significantly earlier ($F_{(3.778, 55.16)} = 9.595$, $p < 0.0001$; ANOVA) for CC at weeks 1–2 ($p = 0.0005$, -6.3% ; Dunnett) and SCR at weeks 1–2 ($p < 0.0001$, -9.8% ; Dunnett) and 7–8 ($p < 0.0001$, -7.9% ; Dunnett).

Reorganization of support periods after hemisection

To determine how the four limbs contribute to dynamic balance when stepping over an obstacle and how this is affected by incomplete SCI, we measured support periods before and after hemisection for each negotiation type and compared them with intact CC (Fig. 8). With Left limbs leading, the triple support period involving the two hindlimbs and the left forelimb (Period 1) decreased for all negotiation types after hemisection ($F_{(3.601, 66.98)} = 18.28$, $p < 0.0001$, ANOVA) compared with intact CC, including CC at weeks 1–2 and 7–8, SCR at weeks 1–2 and 7–8, as well as Other at weeks 1–2. We also observed a significant decrease in period 1 with Right limbs leading ($F_{(2.597, 37.92)} = 27.66$, $p < 0.0001$, ANOVA) compared with intact CC for CC at weeks 1–2 and 7–8, SCR at weeks 1–2 and 7–8, as well as Other at weeks 1–2. We observed a significant decrease in both diagonal support periods, Period 2 ($F_{(2.564, 47.68)} = 12.43$, $p < 0.0001$, ANOVA) and Period 6 ($F_{(3.306, 61.50)} = 32.67$, $p < 0.0001$, ANOVA) for Left limbs leading after hemisection for all negotiation types compared with intact CC with the exception of Other for Period 2. A significant decrease also occurred compared with intact CC with Right limbs leading for Period 2 ($F_{(2.579, 37.65)} = 14.41$, $p < 0.0001$; ANOVA) and Period 6 ($F_{(2.555, 37.31)} = 19.99$, $p < 0.0001$; ANOVA) for all negotiation types after hemisection, with the exception of Other for Period 2. In contrast, both homolateral support periods, Period 4 ($F_{(3.142, 58.45)} = 9.836$, $p < 0.0001$, ANOVA) and Period 8

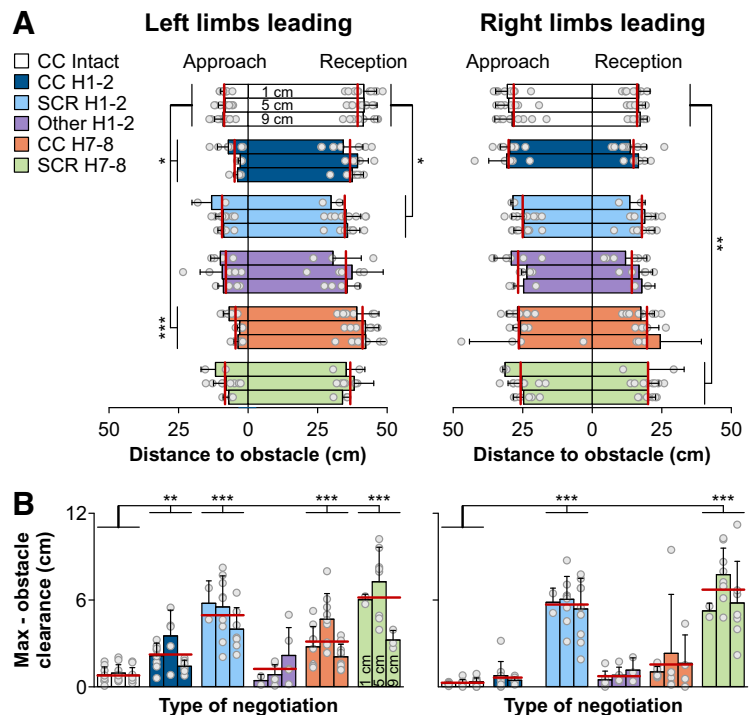


Figure 4. Distances in relation to the obstacle at liftoff and contact and limb elevations before and after a spinal hemisection. **A**, Approach and reception distances of the right ipsilesional hindlimb for each negotiation type before and at weeks 1–2 (H1–2) and 7–8 (H7–8) after hemisection for Left (left panels) and Right (right panels) limbs leading. **B**, Difference between maximal and obstacle clearance of the right hindlimb for each negotiation type for Left (left panels) and Right (right panels) limbs leading. Error bars indicate mean \pm SD for the group. Gray circles represent individual data points (mean for each cat). For each obstacle height, we averaged between 3 and 25 trials per cat ($n = 10$ cats; 5 females and 5 males). Thick red line indicates the mean of the three obstacle heights. When we found a main effect (mixed-effects ANOVA), we performed pairwise comparisons. Significant difference between CC in intact cats and the other negotiation types observed after hemisection: * $p < 0.01$; ** $p < 0.001$; *** $p < 0.0001$.

($F_{(3.704, 68.90)} = 19.05$, $p < 0.0001$, ANOVA), significantly increased after hemisection compared with intact CC with left limbs for all negotiation types after hemisection, with the exception of SCR and Other at 1–2 weeks after hemisection for Period 4. For Right limbs leading, we observed significant increases for Period 4 ($F_{(3.039, 44.37)} = 6.793$, $p = 0.0007$, ANOVA) at weeks 7–8 after hemisection for CC and SCR. For Right limbs leading, left homolateral support (Period 8) increased for all negotiation types ($F_{(2.188, 31.94)} = 28.44$, $p < 0.0001$, ANOVA) compared with intact CC. For Left limbs leading, we observed a significant decrease in triple support involving the two forelimbs and the right hindlimb, Period 3 ($F_{(2.306, 42.88)} = 5.700$, $p = 0.0046$, ANOVA) compared with intact values for CC and SCR at weeks 7–8 after hemisection. This was accompanied with an increase in triple support involving the two hindlimbs and the right forelimb, Period 5 ($F_{(2.884, 53.64)} = 8.210$, $p = 0.0002$, ANOVA) for CC and SCR at weeks 7–8 after hemisection. For Right limbs leading, we observed an increase in quadrupedal support, Period 9 ($F_{(3.354, 48.97)} = 5.211$, $p = 0.0024$, ANOVA), compared with intact CC for SCR at weeks 1–2 as well as CC and SCR at weeks 7–8 after hemisection. Table 2 summarizes significant changes in support periods with percent differences compared with intact CC. Thus, support periods are reorganized after hemisection depending on the type of negotiation and the leading limbs.

Strategies for stepping over an obstacle involve increasing body speed and stride length

To determine some of the strategies used by cats to step over an obstacle, we measured body speed and stride length during the

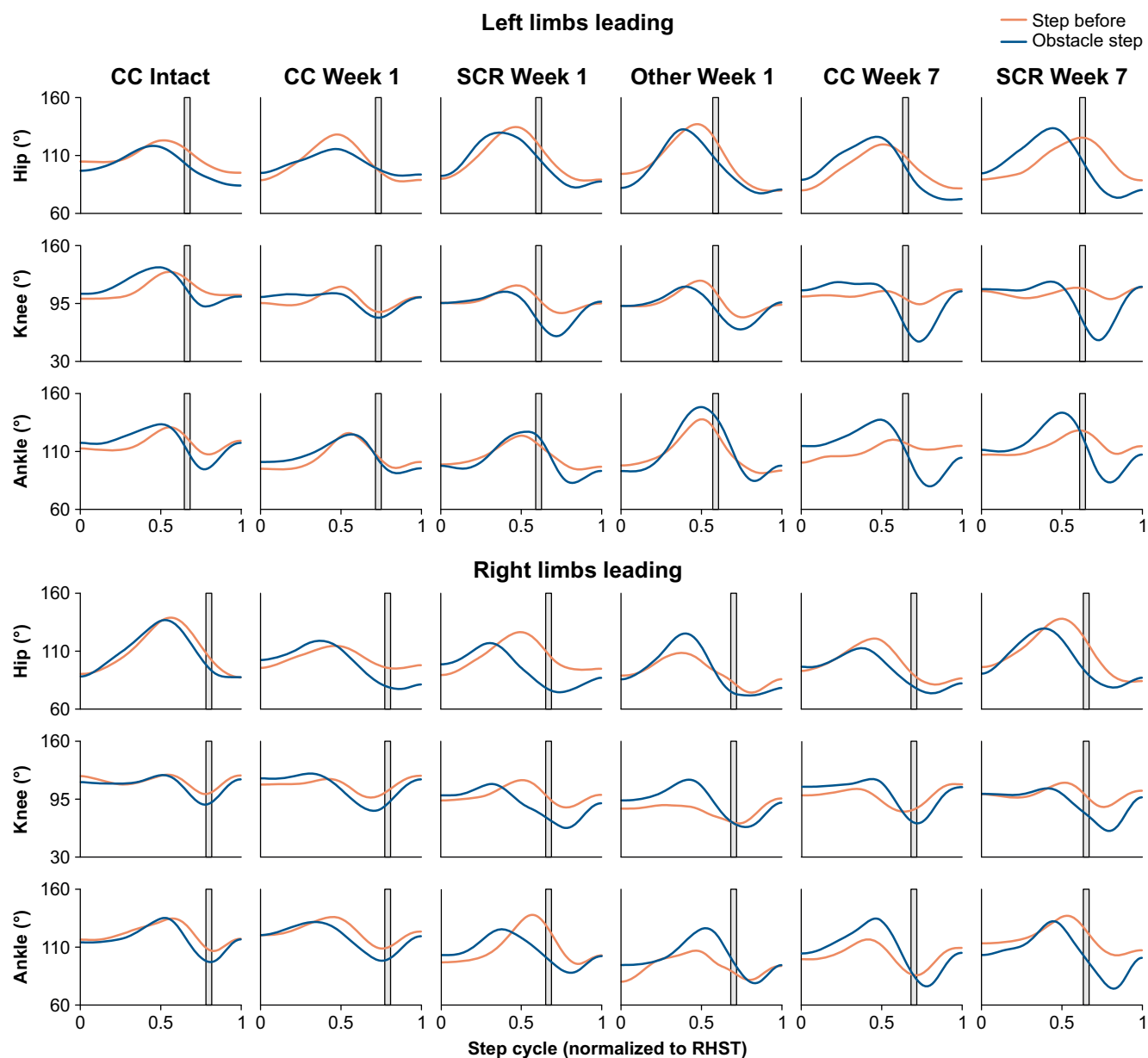


Figure 5. Joint angular excursion of the right hindlimb during obstacle negotiation before and after hemisection in a single cat. Joint angles of the right ipsilesional hip, knee, and ankle for the step before and the obstacle step timed to right hindlimb contact and normalized by interpolating the step cycle into 512 equal bins for Left (top panels) and Right (bottom panels) limbs leading. Each waveform is the average of 3–5 trials from Cat JA with a 5 cm obstacle. Gray area represents the timing of the obstacle.

control and obstacle cycles before and after hemisection. Intact cats performing CC significantly increased their speed when stepping over the obstacle for left ($F_{(1,27)} = 21.12$, $p < 0.0001$, 7.6%; ANOVA) and right ($F_{(1,27)} = 86.59$, $p < 0.0001$, 22.8%; ANOVA) limbs leading (Fig. 9A). In contrast, cats did not increase their speed after hemisection in the different negotiation types.

Intact cats performing CC significantly increased right hindlimb stride length when stepping over obstacles for left ($F_{(1,27)} = 258.8$, $p < 0.0001$, 19.8%; ANOVA) and right ($F_{(1,27)} = 33.65$, $p < 0.0001$, 8.3%; ANOVA) limbs leading (Fig. 9B). At weeks 1–2 after hemisection, right ipsilesional hindlimb stride length did not change significantly when stepping over the obstacle for CC, SCR, and Other negotiation types in Left limbs leading. We observed an increase in right ipsilesional hindlimb stride length at weeks 7–8 for CC ($F_{(1,26)} = 34.30$, $p < 0.0001$, 17.0%; ANOVA). In Right

limbs leading, right ipsilesional hindlimb stride length significantly increased when stepping over the obstacle for all negotiation types at weeks 1–2 after hemisection, including CC ($F_{(1,12)} = 119.3$, $p < 0.0001$, 24.5%; ANOVA), SCR ($F_{(1,17)} = 24.02$, $p = 0.0001$, 18.6%; ANOVA), and Other ($F_{(1,11)} = 15.02$, $p = 0.0026$, 15.5%; ANOVA). At weeks 7–8, right ipsilesional hindlimb stride length increased only for SCR ($F_{(1,15)} = 18.40$, $p = 0.0006$, 11.3%; ANOVA).

Altered muscle activation strategies when negotiating an obstacle after hemisection

To determine how the nervous system adjusts to a lateral hemisection when negotiating obstacles, we analyzed EMG data for each cat separately to assess individualized strategies and group tendencies. We compared the cycle before (control cycle) and when stepping over the obstacle (obstacle cycle). The muscle activation strategies for Left and Right limbs leading differed to

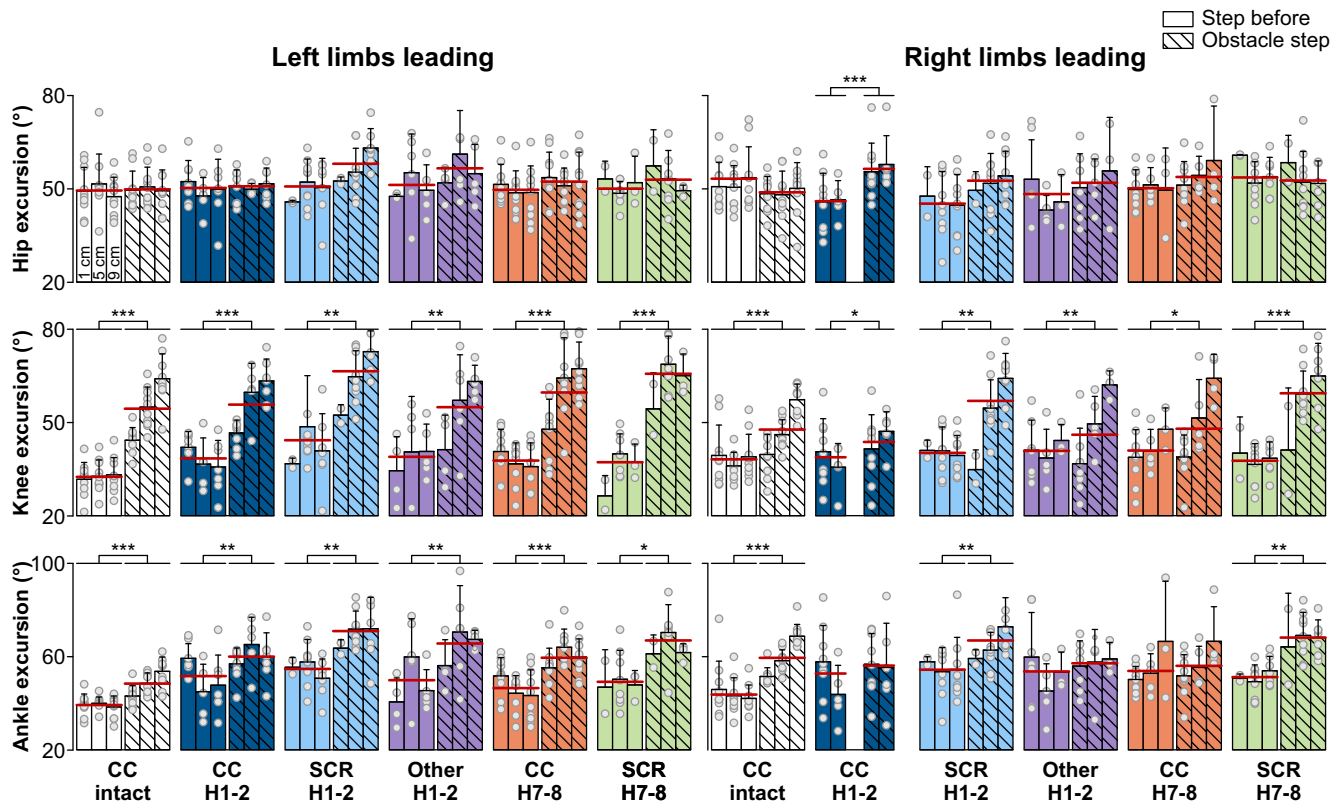


Figure 6. Joint angular excursions of the right hindlimb during obstacle negotiation before and after hemisection for the group. Joint excursions of the right ipsilesional hip, knee, and ankle for the step before and the obstacle step for each negotiation type before and at weeks 1–2 (H1–2) and 7–8 (H7–8) after hemisection for Left (left panels) and Right (right panels) limbs leading. Error bars indicate mean \pm SD for the group. Gray circles represent individual data points (mean for each cat). For each obstacle height, we averaged between 3 and 25 trials per cat ($n = 10$ cats; 5 females and 5 males). Thick red line indicates the mean of the three obstacle heights. When we found a main effect (mixed-effects ANOVA), we performed pairwise comparisons. Significant difference between the step before and the obstacle step: * $p < 0.01$; ** $p < 0.001$; *** $p < 0.0001$.

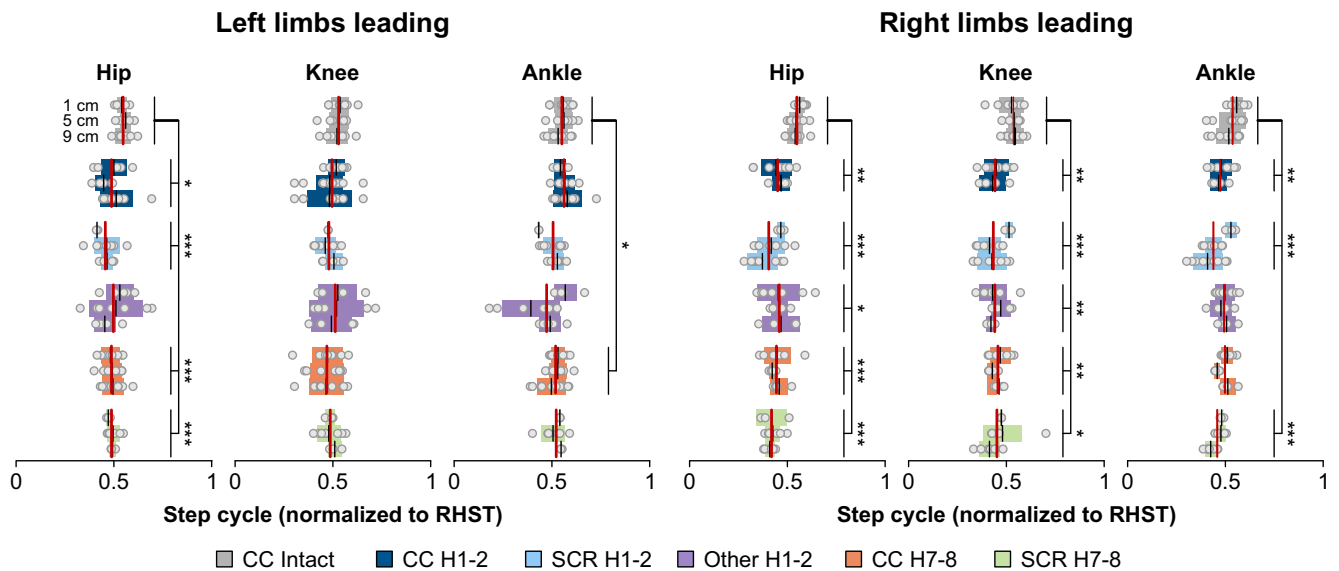


Figure 7. Timing of joint flexions of the right hindlimb during obstacle negotiation before and after hemisection for the group. Timing of flexion onsets of the right ipsilesional hip, knee, and ankle for each obstacle height and negotiation type before and at weeks 1–2 (H1–2) and 7–8 (H7–8) after hemisection for Left (left panels) and Right (right panels) limbs leading. Error bars indicate mean \pm SD for the group. Gray circles represent individual data points (mean for each cat). For each obstacle height, we averaged between 3 and 25 trials per cat ($n = 10$ cats; 5 females and 5 males). Thick red line indicates the mean of the three obstacle heights. When we found a main effect (mixed-effects ANOVA), we performed pairwise comparisons. Significant difference between CC in intact cats and the other negotiation types observed after hemisection: * $p < 0.01$; ** $p < 0.001$; *** $p < 0.0001$.

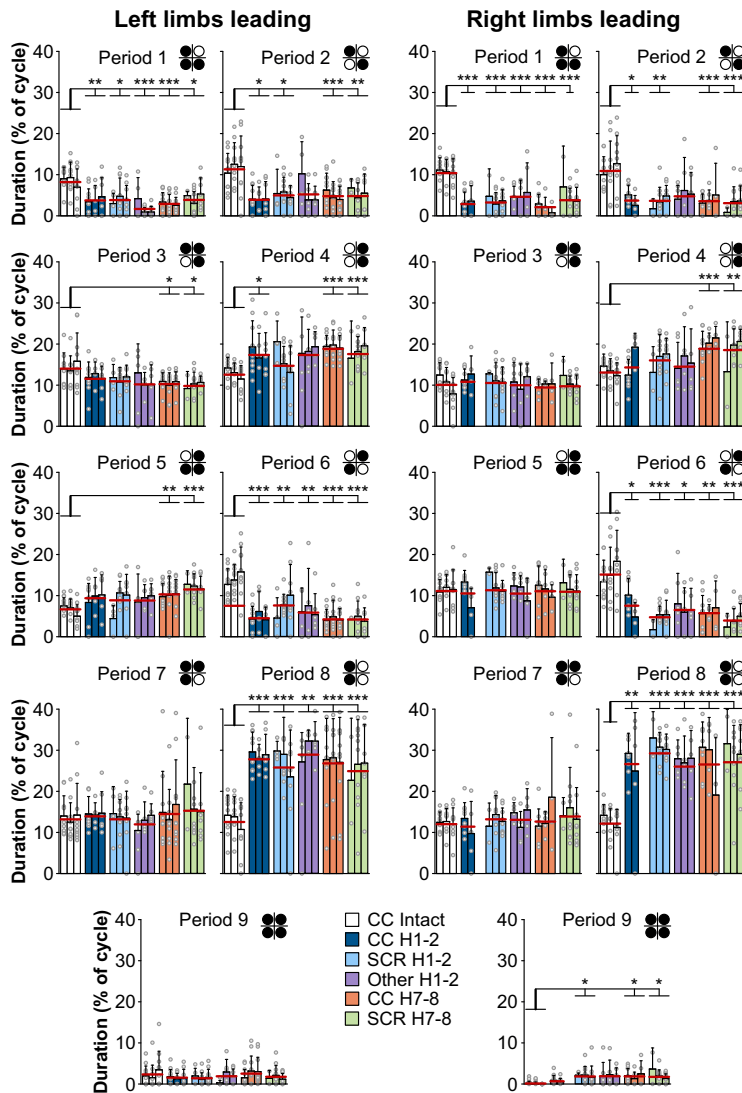


Figure 8. Support periods during obstacle negotiation before and after hemisection for the group. Proportion of each support period normalized to cycle duration for each obstacle height and negotiation type for the obstacle cycle before and at weeks 1–2 (H1–2) and 7–8 (H7–8) after hemisection for Left (left panels) and Right (right panels) limbs leading. The limbs contacting the surface are shown in black in the footfall diagram in each panel. Top left, top right, bottom left, and bottom right circles represent left forelimb, right forelimb, left hindlimb, and right hindlimb, respectively. Error bars indicate mean \pm SD for the group. Gray circles represent individual data points (mean for each cat). For each height, we averaged 3–25 cycles per cat ($n = 10$ cats; 5 females and 5 males). Thick red line indicates the mean of the three obstacle heights. When we found a main effect (mixed-effects ANOVA), we performed pairwise comparisons. Significant difference between CC in intact cats and the other negotiation types observed after hemisection: * $p < 0.01$; ** $p < 0.001$; *** $p < 0.0001$.

allow the right hindlimb to step over the obstacle in intact cats. Figure 10 shows raw EMG waveforms of four hindlimb muscles bilaterally with the stance phases of the four limbs in 1 cat for each type of negotiation before and at weeks 1–2 after hemisection at an obstacle height of 5 cm. With Left limbs leading, we observed a large increase in the RST burst and a delay in the activation of the RSRT along with a small increase in its amplitude, allowing the knee to flex and the hip to extend before flexing the hip. Less visible is an increase in RVL amplitude before the right hindlimb steps over the obstacle. With Right limbs leading, we see an increase in RST amplitude combined with concurrent activation of the RSRT and an increase in its amplitude. For CC at weeks 1–2 after hemisection, the ipsilesional RST burst was longer and more variable in both Left and Right limbs leading.

The onset of the ipsilesional RSRT was also more variable, and we did not observe an increase in its amplitude. As a potential compensatory mechanism, we found a second burst in the contralesional LSRT during left hindlimb stance in Left limbs leading. This coactivation of hip flexor muscles with other extensors can increase stiffness and limb support. For SCR at weeks 1–2 for Left and Right limbs leading, we see an activation of RST before the obstacle, but it was small compared with the intact state. However, following contact, we observed a large spike in amplitude. The onset of RSRT relative to RST is variable. For the Other type of negotiation, we also observe activation of RST before the obstacle in both conditions; but when the right hindpaw contacts the obstacle, we see no spike in its amplitude, consistent with a lack of reflex response.

For the group, muscle activation strategies (onsets and amplitudes) emerged from individual cat data, as summarized in Tables 3 and 4 for eight selected muscles before and after hemisection in Left and Right limbs leading, respectively. For Left limbs leading (Table 3), the muscle strategy to allow the right hindlimb to step over the obstacle for CC in most intact cats consisted of increasing the amplitude of muscles that flex the knee and extend the hip, such as RST (6/6 cats) and RBFP (7/9 cats). RST (6/6 cats) and RBFP (7/9 cats) had also an earlier onset. We also observed a later onset (5/6 cats) and increased amplitude (5/6 cats) of the hip flexor RSRT. The amplitude of RVL, a knee extensor, also increased in the obstacle step (7/9 cats), possibly to provide greater propulsion to step over the obstacle. In the contralesional left hindlimb, we observed an earlier onset of LSOL (6/7 cats). After hemisection, muscle activation strategies were strikingly different. For CC at weeks 1–2, fewer cats showed an increase in the amplitude of RST (2/6 cats), RBFP (3/8 cats), and RSRT (0/5 cats) in the ipsilesional right hindlimb. Fewer cats also showed an increase in RVL (3/7 cats). Instead, we saw a delayed onset for LVL (5/6 cats), LBFA (3/6 cats), and LSOL (5/6 cats). At weeks 7–8 for CC, we observed a return of the increase in amplitude for RST (4/6 cats) and RBFP (6/9 cats) but not in RSRT (0/6 cats) and RVL (2/9 cats). Compared with weeks 1–2, we observed more cats displaying a delayed onset of contralesional extensors, including LVL (7/8 cats), LBFA (7/8 cats), and LSOL (4/8 cats). The SCR at weeks 1–2 was mainly characterized by increased amplitude of RST (4/6 cats), RBFP (4/8 cats), and RTA (2/4 cats) as well as RVL (4/8 cats). We also observed a delayed onset of contralesional extensors, such as LVL (5/6 cats), LBFA (4/6 cats), and LSOL (5/6 cats). The SCR at weeks 7–8 was similar, with an increase in the amplitude of RST (5/5 cats), RBFP (5/6 cats), RTA (2/2 cats), and RVL (3/7 cats). The delayed onset for contralesional extensors was also maintained in about half the animals for LVL (4/6 cats), LBFA (3/5 cats), and LSOL (3/7 cats). For the Other type of negotiation at weeks 1–2, we only observed

Table 2. Support periods before and after a lateral hemisection of the right thoracic cord during obstacle negotiation^a

	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9
Left limbs leading									
CC H1-2	0.0002	0.0012	0.188	0.0059	0.0309	<0.0001		<0.0001	
	–53.1%	–65.2%		37.5%		–65.4%		123.0%	
SCR H1-2	0.0029	0.0017	0.0489	0.4021	0.2737	0.0003		<0.0001	
	–54.9%	–55.4%				–47.7%		111.6%	
Other H1-2	<0.0001	0.042	0.1648	0.1774	0.5351	0.0002		0.0001	
	–76.4%					–55.5%		135.5%	
CC H7-8	<0.0001	<0.0001	0.0020	<0.0001	0.0002	<0.0001		<0.0001	
	–67.7%	–57.8%	–26.7%	50.1%	54.5%	–69.1%		113.9%	
SCR H7-8	<0.0001	0.0002	0.0075	<0.0001	<0.0001	<0.0001		<0.0001	
	–48.0%	–52.4%	–30.6%	39.3%	77.6%	–69.9%		95.6%	
Right limbs leading									
CC H1-2	<0.0001	0.0011		0.7499		0.0035		0.0002	0.2097
	–79.2%	–77.1%				–57.3%		143.6%	
SCR H1-2	<0.0001	0.0009		0.0559		<0.0001		<0.0001	0.0037
	–65.2%	–71.0%				–73.6%		149.2%	1361.6%
Other H1-2	<0.0001	0.0208		0.8472		0.0026		<0.0001	0.1161
	–54.0%					–56.3%		120.0%	
CC H7-8	<0.0001	<0.0001		<0.0001		0.0001		<0.0001	0.0054
	–81.9%	–64.5%		49.7%		–60.3%		112.5%	1357.9%
SCR H7-8	<0.0001	<0.0001		0.0005		<0.0001		<0.0001	0.0022
	–55.6%	–77.0%		31.9%		–76.5%		132.8%	1596.4%

^aThe results of Dunnett's test when a significant main effect was found with the ANOVA along with significant percent differences compared with CC in the intact state.

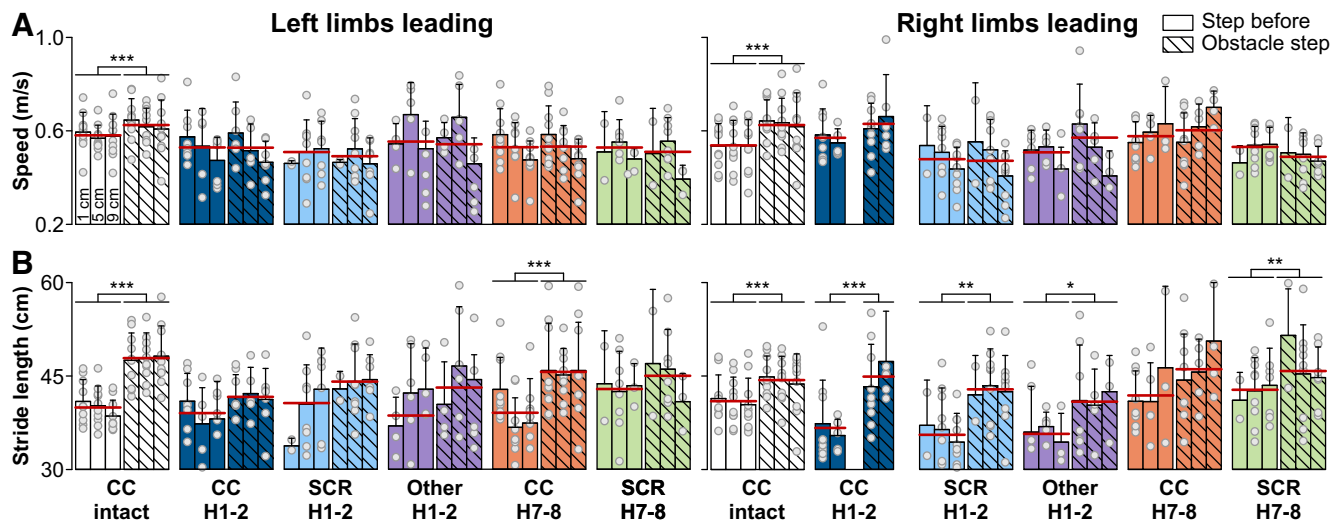


Figure 9. Ipsilesional spatial parameters during obstacle negotiation before and after hemisection. **A, B.** Body speed (**A**) and right ipsilesional hindlimb stride length (**B**) for the step before and the obstacle step for each obstacle height and negotiation type before and at weeks 1–2 (H1–2) and 7–8 (H7–8) after hemisection for Left (left panels) and Right (right panels) limbs leading. Error bars indicate mean \pm SD for the group. Gray circles represent individual data points (mean for each cat). For each height, we averaged 3–25 cycles per cat ($n = 10$ cats; 5 females and 5 males). Thick red line indicates the mean of the three obstacle heights. When we found a main effect (mixed-effects ANOVA), we performed pairwise comparisons. Significant difference between the step before and the obstacle step: * $p < 0.01$; ** $p < 0.001$; *** $p < 0.0001$. Left, Left limbs are leading. Right, Right limbs are leading.

a significant increase in the amplitude of RBF (3/4 cats) and a delayed onset of LVL (4/4 cats) and LBFA (3/3 cats).

For Right limbs leading (Table 4), activation strategies for flexor muscles were similar as Left limbs leading for CC in the intact state with an increase in the amplitude of RST (5/6 cats), RSRT (6/6 cats), and RTA (4/4 cats). RSRT (3/6 cats), RST (4/5 cats), and RTA (3/4 cats) also had earlier onsets in intact CC. Using the RVL for propulsion by increasing its amplitude before stepping over the obstacle was less frequent (2/9 cats). At weeks 1–2 and 7–8 after hemisection, the increase in amplitude for flexors was absent for CC, except for RSRT (1/5 and 3/5 cats at weeks 1–2 and 7–8, respectively). The earlier onset of RSRT, RST, and RTA was also absent. The SCR at weeks 1–2 was mainly

characterized by increased amplitude of RST (3/6 cats) and RTA (3/4 cats) and earlier onsets for RSRT (2/5 cats), RST (3/6 cats), and RTA (3/4 cats). We also observed an increase in the amplitude of contralesional extensors, such as LBFA (3/7 cats) and LSOL (1/6 cats). At weeks 7–8, the increase in the amplitude of RST (6/6 cats) and RTA (4/4) for SCR became more consistent while the increase in LBFA remained similar (3/7 cats). We observed earlier onsets for RSRT (4/5 cats) and RTA (3/4 cats) but not for RST. For the Other type of negotiation at weeks 1–2, we observed no significant modulation of onsets or amplitudes for selected muscles.

In Right limbs leading, we also have information when the left hindlimb stepped over the obstacle for LST and LSRT. For

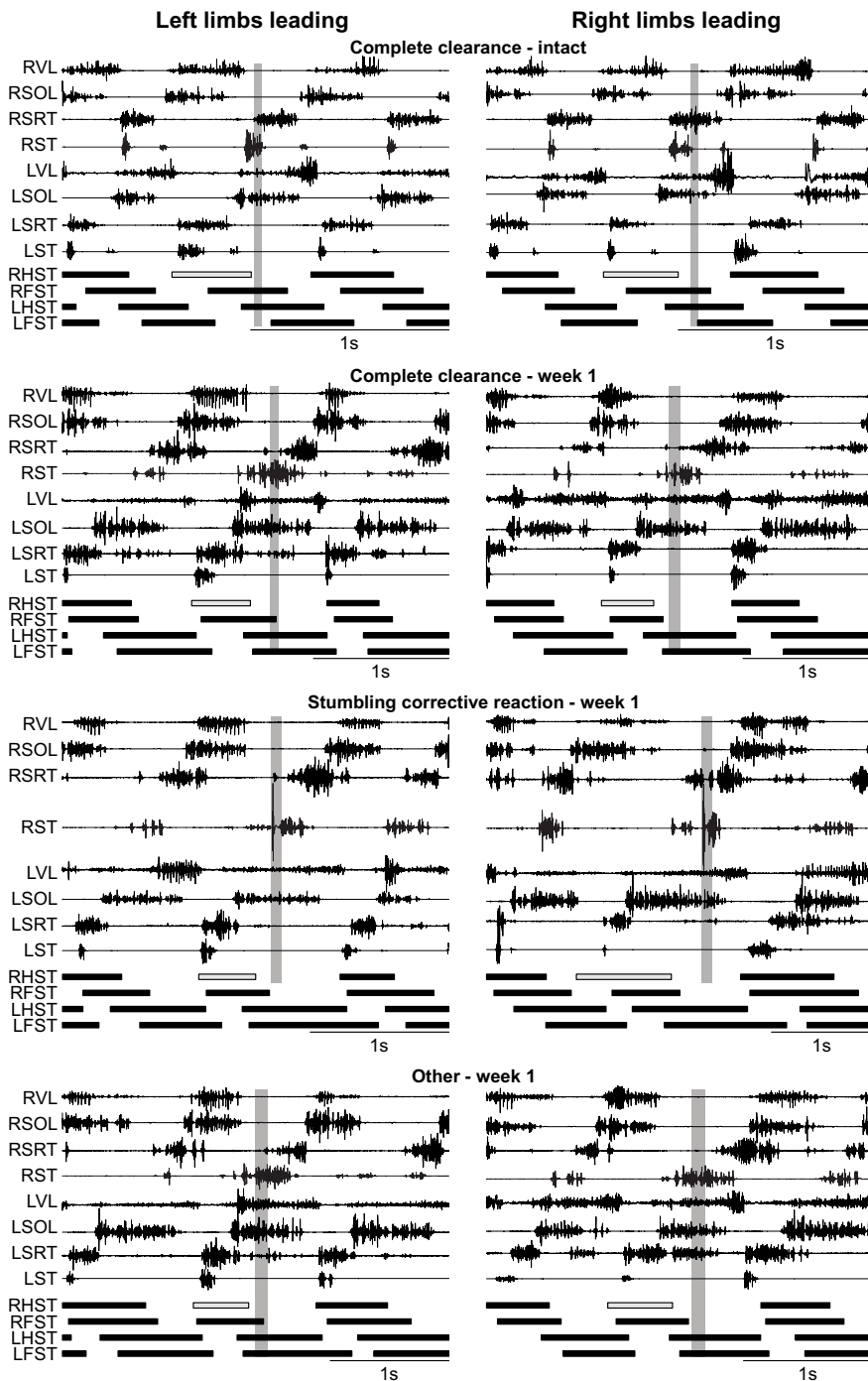


Figure 10. Muscle activity during obstacle negotiation before and after hemisection. Each panel represents the EMG of hindlimb muscles recorded bilaterally (L, left; R, right) along with the stance phases of the four limbs during obstacle negotiation before and at week 1 after hemisection in cat AR at an obstacle height of 5 cm. Gray stance phase represents right ipsilesional hindlimb stance before the obstacle. The vertical scale for each EMG waveform is optimized for viewing. VL, Vastus lateralis; SOL, soleus; SRT, anterior sartorius; ST, semitendinosus.

CC in the intact state, we observed an increase in the amplitude of LST (8/8 cats) and LSRT (6/7 cats). We also observed an earlier onset for LST (3/9 cats) and a delay for LSRT (6/7). For CC at weeks 1–2 after hemisection, the increase in the amplitude of LST (0/8 cats) and LSRT (0/6 cats) and the delayed onset in LSRT (0/6 cats) was absent in all cats. The SCR at weeks 1–2 was mainly characterized by increased amplitude of LST (5/7 cats). For Other, LST increased in amplitude in some cats (3/7 cats) with only 1 cat showing an earlier onset (1/7 cats). At 7–8 weeks

after the hemisection, CC was characterized by an increased amplitude for LST (5/8 cats) only, with an earlier onset observed for LSRT in only 1 cat (1/6 cats). For SCR at weeks 7–8, we found an increase in amplitude for LST (6/8 cats) and LSRT (4/7 cats) in most cats. Changes in onset were rare.

Discussion

We showed that intact cats easily stepped over an obstacle without contact, completely clearing it. However, after mid-thoracic lateral hemisection, cats displayed different negotiation types and neuromechanical strategies. Main results are summarized in Table 5.

Different negotiation types reflect disruption in anticipatory control and reduced neuronal excitability

The proportion of CC decreased in the ipsilesional right hindlimb after lateral hemisection at right T5–T6. Although we did not measure kinematics of the left contralesional hindlimb, the left hindlimb never contacted the obstacle after hemisection, always completely clearing it. At weeks 1–2 after hemisection, CC remained in ~40% of trials, but we also observed a reflex response when the right hindpaw contacted the obstacle, the SCR in ~40% of trials, as well as a lack of response, termed “Other” in ~20% of trials (Fig. 2B). At weeks 7–8 after lateral hemisection, CC increased to ~60% of trials, SCR remained stable at ~40%, and Other decreased to ~5%. Thus, the increase in CC was because of a reduction in Other, consistent with recovery of anticipatory/voluntary control of ipsilesional right hindlimb trajectory. When separating these results in terms of obstacle height (1, 5, and 9 cm), we see that the proportion of CC is much higher at the smallest height of 1 cm at weeks 1–2 and 7–8 after hemisection, whereas the proportion of SCR is considerably higher at heights of 5 and 9 cm at both post-hemisection time points. The proportion of Other did not appear to be influenced by obstacle height.

Cutaneous afferents, particularly from the superficial peroneal nerve, trigger the SCR in cats and humans (Prochazka et al., 1978; Forssberg, 1979; Wand et al., 1980; Buford and Smith, 1993; Schillings et al., 1996, 2000, 2005; van Wezel et al., 1997; Lam et al., 2003; Quevedo et al., 2005; Potocanac et al., 2016; Merlet et al., 2022; McVea and Pearson, 2007b). In our study, cats showed SCR in the ipsilesional right hindlimb in the first 2 weeks after hemisection, as shown by Doperalski et al. (2011). Thus, the SCR is a new strategy to help move the hindpaw over

Table 3. Modulation of EMG burst onset and amplitude before and after lateral hemisection during obstacle negotiation with Left limbs leading^a

Left limbs leading		RVL		RSRT		RST		RBFP	
		Onset	Amplitude	Onset	Amplitude	Onset	Amplitude	Onset	Amplitude
CC	↗	1/9 (1.03%)	7/9 (44.56%)	5/6 (5.32%)	5/6 (14.18%)	0/6	6/6 (180.8%)	0/8	7/9 (48.14%)
intact	=	8/9	2/9	1/6	1/6	0/6	0/6	2/8	2/9
	↘	0/9	0/9	0/6	0/6	6/6 (5.14%)	0/6	6/8 (4.44%)	0/9
CC	↗	0/7	3/7 (25.25%)	0/5	0/5	0/6	2/6 (92.36%)	0/8	3/8 (111.6%)
H1-2	=	7/7	4/7	5/5	5/5	6/6	4/6	7/8	5/8
	↘	0/7	0/7	0/5	0/5	0/6	0/6	1/8 (1.10%)	0/8
SCR	↗	2/8 (2.69%)	4/8 (30.86%)	0/5	0/5	3/6 (9.45%)	4/6 (146.4%)	1/8 (6.55%)	4/8 (67.05%)
H1-2	=	6/8	3/8	5/5	4/5	3/6	2/6	7/8	4/8
	↘	0/8	1/8 (18.25%)	0/5	1/5 (20.36%)	0/6	0/6	0/8	0/8
Other	↗	1/4 (3.32%)	2/4 (79.63%)	1/3 (9.94%)	1/3 (25.45%)	2/3 (9.91%)	2/3 (214.5%)	1/4 (7.59%)	3/4 (116.8%)
H1-2	=	3/4	2/4	2/3	2/3	0/3	1/3	3/4	1/4
	↘	0/4	0/4	0/3	0/3	1/3 (9.44%)	0/3	0/4	0/4
CC	↗	3/9 (2.59%)	2/9 (12.48%)	1/6 (4.16%)	0/6	0/6	4/6 (90.58%)	0/9	6/9 (112.5%)
H7-8	=	6/9	7/9	5/6	6/6	6/6	2/6	7/9	3/9
	↘	0/9	0/9	0/6	0/6	0/6	0/6	2/9 (5.77%)	0/9
SCR	↗	2/7 (4.32%)	3/7 (5.57%)	0/5	0/5	0/5	5/5 (146.3%)	0/6	5/6 (142.9%)
H7-8	=	5/7	4/7	5/5	4/5	5/5	0/5	6/6	0/6
	↘	0/7	0/7	0/5	1/5 (25.90%)	0/5	0/5	0/6	1/6 (2.03%)
Left limbs leading		RTA		LVL		LBFA		LSOL	
		Onset	Amplitude	Onset	Amplitude	Onset	Amplitude	Onset	Amplitude
CC	↗	0/4	1/4 (20.24%)	0/8	0/8	0/8	0/8	0/7	0/7
INTACT	=	4/4	3/4	3/8	8/8	4/8	8/8	1/7	7/7
	↘	0/4	0/4	5/8 (4.01%)	0/8	4/8 (1.74%)	0/8	6/7 (4.03%)	0/7
CC	↗	0/4	0/4	5/6 (7.69%)	0/6	3/6 (4.02%)	0/6	5/6 (6.08%)	2/6 (10.01%)
H1-2	=	4/4	4/4	1/6	5/6	3/6	6/6	1/6	4/6
	↘	0/4	0/4	0/6	1/6	0/6	0/6	0/6	0/6
SCR H1-2	↗	0/4	2/4 (35.41%)	5/6 (9.73%)	0/5	4/6 (6.81%)	0/6	5/6 (9.73%)	0/5
	=	4/4	2/4	1/6	4/5	2/6	6/6	1/6	5/5
	↘	0/4	0/4	0/6	1/5	0/6	0/6	0/6	0/5
Other	↗	0/2	0/2	4/4 (9.21%)	0/4	3/3 (14.81%)	0/3	4/4 (7.89%)	0/4
H1-2	=	2/2	2/2	0/4	4/4	0/3	3/3	0/4	4/4
	↘	0/2	0/2	0/4	0/4	0/3	0/3	0/4	0/4
CC	↗	0/4	2/4 (59.24%)	7/8 (6.89%)	1/8 (9.29%)	7/8 (5.31%)	0/8	4/8 (7.33%)	0/7
H7-8	=	3/4	2/4	1/8	7/8	1/8	8/8	4/8	7/7
	↘	1/4 (9.70%)	0/4	0/8	0/8	0/8	0/8	0/8	0/7
SCR	↗	0/2	2/2 (92.79%)	4/6 (5.17%)	0/6	3/5 (6.07%)	0/5	3/7 (6.51%)	0/6
H7-8	=	2/2	0/2	2/6	6/6	2/5	5/5	4/7	5/6
	↘	0/2	0/2	0/6	0/6	0/5	0/5	0/7	1/6 (7.32%)

^aThe number of individual cats/total number of cats with EMGs available for a given muscle. Up and down arrows indicate significant increases or decreases, respectively. Equals sign indicates no significant change of the obstacle step compared with the control step (two-factor repeated-measures ANOVA). The percent value indicates the average of all cats that showed a significant increase or decrease.

an obstacle after incomplete SCI. Studies have reported depression of SCR and spinal reflexes in general in the ipsilesional hindlimb for a few days after hemisection, with a return in the first 2 weeks as locomotion recovers (Murray and Goldberger, 1974; Helgren and Goldberger, 1993). The SCR probably shares some circuits with the withdrawal reflex, which becomes more variable in terms of latency after lateral hemisection (Vierck et al., 2013).

The appearance of Other in the ipsilesional right hindlimb, mainly at weeks 1–2 after hemisection, is surprising because SCR is found in spinal cats with mechanical contact applied to the hindpaw dorsum during swing (Forssberg et al., 1974, 1975). However, these studies did not assess the proportion of SCR/Other following mechanical contact. Spinal cats might not display an SCR for each contact. The appearance of Other in the present study could be because of reduced spinal neuronal excitability, which can persist for several weeks after hemisection. Studies have shown that supraspinal pathways (e.g., rubrospinal

tract) facilitate SCR in cats (Batson and Amassian, 1986; Amassian and Batson, 1988; Fleshman et al., 1988). The lack of SCR could also be because of the area of the hindpaw making contact with the obstacle, for example toes versus foot dorsum (Hennig and Sterzing, 2009).

Cats also participated in other studies to answer different scientific questions. These included stepping on a split-belt treadmill at different speeds and left-right speeds in tied- and split-belt conditions, respectively. We also electrically stimulated nerves to evoke reflexes during treadmill locomotion. It is possible that these studies produced a training effect that helped cats recover following hemisection. However, we think that these have a standardizing effect across animals because some animals are naturally more active than others before and/or after SCI. Having them perform a variety of tasks provides a better baseline of physical activity, although this remains variable between animals. Compared with all the movements cats do in the laboratory or in the animal care facility (they are free to move for several

Table 4. Modulation of EMG burst onset and amplitude before and after lateral hemisection during obstacle negotiation with Right limbs leading^a

Right limbs Leading		RVL		RSRT		RST		RTA	
		Onset	Amplitude	Onset	Amplitude	Onset	Amplitude	Onset	Amplitude
CC	↗	0/9	2/9 (11.05%)	0/6	6/6 (32.53%)	0/5	5/6 (129.1%)	0/4	4/4 (94.05%)
INTACT	=	7/9	7/9	3/6	0/6	1/5	1/6	1/4	0/4
	↘	2/9 (2.52%)	0/9	3/6 (5.42%)	0/6	4/5 (4.44%)	0/6	3/4 (4.73%)	0/4
CC	↗	0/6	0/6	0/5	1/5 (51.09%)	0/5	0/5	0/3	0/3
H1-2	=	6/6	6/6	5/5	4/5	5/5	5/5	3/3	3/3
	↘	0/6	0/6	0/5	0/5	0/5	0/5	0/3	0/3
SCR	↗	0/7	1/7 (6.19%)	0/5	1/5 (23.17%)	0/6	3/6 (179.5%)	0/4	3/4 (75.63%)
H1-2	=	6/7	6/7	3/5	4/5	3/6	3/6	1/4	1/4
	↘	1/7 (2.43%)	0/7	2/5 (9.22%)	0/5	3/6 (6.11%)	0/6	3/4 (9.15%)	0/4
Other	↗	0/4	0/4	0/5	0/5	0/4	0/4	0/1	0/1
H1-2	=	4/4	4/4	5/5	5/5	4/4	4/4	1/1	1/1
	↘	0/4	0/4	0/5	0/5	0/4	0/4	0/1	0/1
CC	↗	0/9	0/8	0/5	3/5 (45.40%)	0/5	0/5	0/3	0/3
H7-8	=	9/9	8/8	3/5	2/5	5/5	5/5	3/3	3/3
	↘	0/9	0/8	2/5 (7.52%)	0/5	0/5	0/5	0/3	0/3
SCR	↗	0/8	0/7	0/5	1/6 (40.88%)	0/6	6/6 (130.91%)	0/4	4/4 (92.08%)
H7-8	=	8/8	7/7	1/5	5/6	6/6	0/6	1/4	0/4
	↘	0/8	0/7	4/5 (7.62%)	0/6	0/6	0/6	3/4 (11.55%)	0/4
Right limbs Leading		LBFA		LSOL		LSRT		LST	
		Onset	Amplitude	Onset	Amplitude	Onset	Amplitude	Onset	Amplitude
CC	↗	0/8	1/8 (38.74%)	0/7	0/7	6/7 (8.98%)	6/7 (33.17%)	0/9	8/8 (140.7%)
INTACT	=	3/8	7/8	5/7	5/7	1/7	1/7	6/9	0/8
	↘	5/8 (5.46%)	0/8	2/7 (5.03%)	2/7 (11.37%)	0/7	0/7	3/9 (5.25%)	0/8
CC	↗	0/5	0/5	0/5	0/4	0/6	0/6	0/8	0/8
H1-2	=	5/5	5/5	5/5	4/4	6/6	6/6	8/8	8/8
	↘	0/5	0/5	0/5	0/4	0/6	0/6	0/8	0/8
SCR	↗	0/7	3/7 (72.23%)	0/7	1/6 (15.15%)	0/7	2/8 (24.69%)	0/8	5/7 (238.8%)
H1-2	=	4/7	4/7	6/7	5/6	7/7	0/8	5/8	2/7
	↘	3/7 (7.77%)	0/7	1/7 (7.72%)	0/6	0/7	0/8	3/8 (7.09%)	0/7
Other	↗	0/3	0/3	0/3	0/2	0/6	0/6	0/7	3/7 (287.3%)
H1-2	=	3/3	3/3	3/3	2/2	6/6	6/6	6/7	4/7
	↘	0/3	0/3	0/3	0/2	0/6	0/6	1/7 (9.45%)	0/7
CC	↗	0/7	0/7	0/8	1/7 (18.36%)	0/6	0/6	0/8	5/8 (78.15%)
H7-8	=	4/7	7/7	5/8	6/7	5/6	5/6	7/8	3/8
	↘	3/7 (4.89%)	0/7	3/8 (6.20%)	0/7	0/6	1/6 (22.83%)	0/8	0/8
SCR	↗	0/7	3/7 (86.96%)	0/7	0/6	1/7 (8.66%)	4/7 (43.55%)	1/8 (4.79%)	6/8 (148.52%)
H7-8	=	4/7	4/7	5/7	6/6	6/7	3/7	6/8	2/8
	↘	3/7 (9.22%)	0/7	2/7 (7.39%)	0/6	0/7	0/7	1/8 (5.77%)	0/8

^aThe number of individual cats/total number of cats with EMGs available for a given muscle. Up and down arrows indicate significant increases or decreases, respectively. Equals sign indicates no significant change of the obstacle step compared with the control step (two-factor repeated-measures ANOVA). The percent value indicates the average of all cats that showed a significant increase or decrease.

hours each day), the experimental sessions have a negligible effect on overall physical activity and a potential training effect.

Neuromechanical strategies when negotiating obstacles before and after hemisection

Intact cats clear an obstacle by mainly flexing the knee followed to a lesser degree by flexing the ankle with Left and Right limbs leading (Fig. 6), consistent with studies in cats (Lavoie et al., 1995) and humans (McFadyen et al., 1993). The EMG amplitude of knee flexors, such as RST and RBFP, increases when the right hindlimb clears an obstacle with Left or Right limbs leading (Tables 3 and 4). After hemisection, the knee flexion strategy of the ipsilesional right hindlimb was maintained in both conditions for CC trials, whereas additional ankle flexion occurred with Left limbs leading. An SCR appeared in the ipsilesional right hindlimb when the cat's hindpaw contacted the obstacle because of an inability to sufficiently activate muscles that flex the knee before the obstacle and/or improper timing of joint flexions

(Fig. 7). Indeed, fewer cats showed an increase in EMG amplitude of right ipsilesional knee flexors, such as RST and RBFP, with Left and Right limbs leading at weeks 1–2 after hemisection in CC trials (Tables 3 and 4). Earlier hip flexion after hemisection may bring the limb forward prematurely before sufficient elevation occurs. With Right limbs leading, earlier knee flexion may compensate for earlier hip flexion, allowing sufficient elevation in some trials. Increased EMG amplitude of right knee flexors in the obstacle step recovered at weeks 7–8 with Left limbs leading when the right hindlimb cleared the obstacle but not with Right limbs leading.

Cats have a preferred limb when grabbing food, going down stairs or when stepping into a litter box (McDowell et al., 2018) but not when negotiating obstacles, as shown here and in Doperalski et al. (2011). Cats cannot be categorized as right- or left-handed. Lack of side preference persisted at weeks 1–2 after a right lateral hemisection but at weeks 7–8, we observed a clear preference for Left limbs leading (>60% of trials). Functionally,

Table 5. Summary of main results^a

Negotiation types and limbs leading (LL) preference:

- ↓ CC after hemisection
- Weeks 1–2: appearance of SCR and Other in ipsilesional right hindlimb
- Weeks 7–8: ↑ CC, ↓ Other and ≈ SCR relative to weeks 1–2 in ipsilesional right hindlimb
- Intact cats = no side preference in LL
- CC with LLL > CC with RLL after hemisection in ipsilesional right hindlimb
- No side preference in LL before and at weeks 1–2 after hemisection in ipsilesional right hindlimb
- LLL is preferred at weeks 7–8 in ipsilesional right hindlimb

Optimal crossing:

- less optimal for CC and SCR at weeks 1–2 and 7–8 in ipsilesional right hindlimb
- RLL: less optimal for SCR at weeks 1–2 and 7–8 in ipsilesional right hindlimb

Joint angles:





Excursions (control vs obstacle step):

- Almost no change in hip excursion when crossing with LLL and RLL before and after hemisection in ipsilesional right hindlimb
- ↑ knee excursion when crossing with LLL and RLL before and after hemisection in ipsilesional right hindlimb
- ↑ ankle excursion when crossing with LLL and RLL before and after hemisection but some lost with RLL after hemisection in ipsilesional right hindlimb

Flexion onsets:

- Hip flexion occurs sooner with LLL and RLL after hemisection in ipsilesional right hindlimb
- Knee flexion onset unchanged after hemisection with LLL but occurs sooner with RLL in ipsilesional right hindlimb
- Ankle flexion mostly unchanged after hemisection with LLL but occurs sooner with RLL (some exceptions) in ipsilesional right hindlimb

Support periods:

- ↓ in  and  at weeks 1–2 and 7–8 after hemisection
- ↑ in  mainly at weeks 7–8 after hemisection and large ↑ in  at weeks 1–2 and 7–8

Speed and stride length (control vs obstacle step):

- ↑ in speed of intact cats when stepping over obstacle with LLL and RLL; No ↑ in speed after hemisection
- ↑ in stride length of intact cats when stepping over obstacle with LLL and RLL; No ↑ in stride length after hemisection with LLL, except for CC at weeks 7–8; ↑ in stride length after hemisection with RLL, except for CC at weeks 7–8 in ipsilesional right hindlimb

EMG (control vs obstacle step):

- Intact cats with LLL: ↑ amplitude and earlier onset of RST and RBFP; ↑ amplitude and later onset of RSRT; ↑ amplitude of RVL; earlier onset of LSOL
- CC at weeks 1–2 after hemisection with LLL: ↓ in number of cats showing increased amplitude of ipsilesional RST, RBFP, RSRT, and RVL; delayed onset of contralesional extensors (LVL, LBFA, and LSOL)
- CC at weeks 7–8 after hemisection with LLL: return of increase in amplitude of ipsilesional RST and RBFP but not RSRT and RVL
- Intact cats with RLL: ↑ amplitude and earlier onset of RST, RSRT, and RTA
- CC at weeks 1–2 and 7–8 after hemisection with RLL: ↓ in number of cats showing increased amplitude of ipsilesional RST, RSRT, and RTA as well as loss of earlier onset in these muscles

^aSummary of the main findings when cats negotiated obstacles before and after lateral hemisection with left (LLL) and right (RLL) limbs leading. BFA, Biceps femoris anterior; BFP, biceps femoris posterior; SOL, soleus; SRT, anterior sartorius; ST, semitendinosus; TA, tibialis anterior; VL, vastus lateralis.

this is a more stable position because, when the contralesional left hindlimb has cleared the obstacle, it is in a stable support position to allow the ipsilesional right hindlimb to step over the obstacle. This might be a conscious decision/strategy made by cats.

We determined the redistribution of weight support after a right lateral hemisection by measuring support periods (Fig. 8). Generally, triple support involving both hindlimbs and the left forelimb decreased after hemisection as did both diagonal supports for most negotiation types. Diagonal support periods are the least stable support when stepping in the forward direction (Farrell et al., 2014). In contrast, homolateral support periods increased after hemisection, particularly contralesional left homolateral support, approximately doubling in proportion for all negotiation types. Thus, cats shift their weight to the contralesional side after hemisection to negotiate obstacles, consistent with maximizing dynamic balance. A limitation of the present study is that we did not randomize the side of the hemisection, which was performed on the right side at T5–T6 in all cats.

Stepping over an obstacle as an optimization problem

Clearing an obstacle relies on anticipatory control, or planning (Drew, 1993; Patla and Vickers, 1997; Beloozerova and Sirota, 2003; Fowler and Sherk, 2003; Wilkinson and Sherk, 2005; Drew et al., 2008; McVea et al., 2009). Intact cats increased their speed

to clear obstacles in Left and Right limbs leading conditions (Fig. 9). Humans also increase speed before stepping on a curb based on optimization criteria to conserve momentum and minimize energy expenditure by modulating push-off work (Darici and Kuo, 2022). Most cats increased the amplitude of RVL, a knee extensor, in the stance phase preceding stepping over the obstacle in Left limbs leading (Table 3), consistent with increasing push-off work, which was lost after hemisection.

We showed exaggeration of ipsilesional right hindlimb flexion after clearing the obstacle with Left limbs leading after hemisection (Fig. 4B), which has no functional benefit because it increases energy expenditure (Wu and Kuo, 2016), potentially destabilizing the body. We can explain the exaggerated flexion following clearance in Left limbs leading using optimal feedback control (Scott, 2004; Todorov, 2004). In this framework, a state estimator receiving sensory information sends signals to a controller to regulate a cost function (e.g., energy expenditure). The controller sends a motor efference copy to the state estimator and a forward internal model to predict state, allowing online corrections based on available information. After hemisection, we propose that proprioceptive information fails to reach the state estimator/forward internal model, located in the cerebellum for example (Scott, 2004), and the controller in the spinal cord (Ryu and Kuo, 2021) cannot properly correct ipsilesional hindlimb trajectory.

Potential neuroplastic changes and functional recovery

In intact cats, rubrospinal and corticospinal tracts contribute to obstacle negotiation (Beloozerova and Sirota, 1993; Widajewicz et al., 1994; Drew et al., 1996, 2002; Lavoie and Drew, 2002; Beloozerova et al., 2010). A lateral hemisection abolishes all descending and ascending pathways unilaterally. Although we can only speculate, we can attribute the smaller proportion of CC early after hemisection to the loss of supraspinal pathways, reduced spinal neuronal excitability, and/or loss of ascending proprioceptive information. Spared connections from the contralesional corticospinal tract, which has extensive commissural projections throughout the spinal cord in cats, can help maintain obstacle clearance after hemisection (Satomi et al., 1988, 1991). Recovering CC from early to late time points after hemisection can involve a return in spinal neuronal excitability and new or strengthened pathways from the brain (Doperalski et al., 2020). Supraspinal pathways synapse on long and short cervical propriospinal neurons that project to the lumbar region (Alstermark et al., 2007). After incomplete SCI, new or strengthened propriospinal pathways can transmit commands from the brain to lumbar regions (Grill et al., 1997; Bareyre et al., 2004; Zaporozhets et al., 2006; Courtine et al., 2008, 2009; Cowley et al., 2008; Murray et al., 2010; Jefferson et al., 2011). Although reorganized propriospinal circuits might bypass the lesion site by projecting to the other side (Frigon, 2017; Laliberte et al., 2019), whether new connections make functional and meaningful contributions to locomotor control is less clear.

Studies in cats showed that the spinal locomotor network becomes more autonomous following incomplete SCI, with altered sensorimotor interactions (Barrière et al., 2008; Rossignol et al., 2008; Frigon et al., 2009; Rossignol and Frigon, 2011). Spinal interneurons form new connections (Fenrich and Rose, 2009) and excitability returns (Murray et al., 2010). Changes within lumbosacral circuits could make them more responsive to descending inputs, facilitating voluntary commands. Contralesional spinal circuits might also facilitate the recovery of anticipatory control through strengthened commissural interactions (Frigon et al., 2017).

In conclusion, performing locomotor tasks involving voluntary/anticipatory control remains challenging for people with SCI. We showed partial maintenance of anticipatory control after mid-thoracic lateral hemisection and some recovery over time, albeit incomplete. We presented several reasons why cats fail to clear an obstacle after incomplete SCI as well as new neuromechanical strategies. Future studies will need to address how we can measure and promote neuroplastic changes to restore anticipatory control for CC of obstacles after incomplete SCI.

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