Nerve Cuff Recordings of Muscle Afferent Activity from Tibial and Peroneal Nerves in Rabbit During Passive Ankle Motion

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***Abstract*—Activity from muscle afferents regarding ankle kinesthesia was recorded using cuff electrodes in a rabbit preparation in which tactile input from the foot was eliminated. The purpose was to determine if such activity can provide information useful in controlling functional electrical stimulation (FES) systems that restore mobility in spinal injured man. The rabbit's ankle was passively flexed and extended while the activity of the tibial and peroneal nerves was recorded. Responses to trapezoidal stimulus profiles were investigated for excursions from 10° to 60° using velocities from 5°/s to 30°/s and different initial ankle positions. The recorded signals mainly reflect activity from primary and secondary muscle afferents. Dorsiflexion stretched the ankle extensors and produced velocity dependent activity in the tibial nerve, and this diminished to a tonic level during the stimulus plateau. The peroneal nerve was silent during dorsiflexion, but was activated by stretch of the peroneal muscles during ankle extension. The responses of the two nerves behaved in a reciprocal manner, but exhibited considerable hysteresis, since motion that relaxed the stretch to the driving muscle produced an immediate cessation of the prior stretch induced activity. A noted difference between the tibial and peroneal nerve responses is that the range of joint position change that activated the flexor afferents was greater then for the extensor afferents. Ankle rotation at higher velocities increased the dynamic stretch evoked responses during the stimulus ramp but showed no effect on the tonic activity during the stimulus plateau. Prestretching the muscles by altering the initial position increased the response to the ramp movement, however, for the peroneal nerve, when the prestretch brought the flexor muscles near to their maximal lengths, the response to additional stretch provided by the ramp movement was diminished. The results indicate that the whole nerve recorded muscle afferent activity may be useful for control of FES assisted standing, because it can indicate the direction of rotation of the passively moved ankle joint, along with coarse information regarding the rate of movement and static joint position.**

***Index Terms*—Functional electrical stimulation (FES), muscle afferents, natural sensors, nerve cuff recordings.**

I. Introduction

FUNCTIONAL electrical stimulation (FES) can be used to restore function in individuals with paralysis [48]. While the forces generated in muscles activated using FES can be graded by varying the intensity, duration and repetition of the stimulus pulses, the relationship of the force to these parameters varies in a complex manner which depends on, for example, muscle length, electrode-nerve coupling and activation history. Several studies [4], [8], [31], [33], [48] have shown that the application of closed loop control techniques can improve the regulation of the muscle activation. These demonstrations have been limited to laboratory environments because of a lack of physically small and cosmetically acceptable sensors required to provide the feedback signals [7]. Natural sensors [13], [14], [16], [17], [42], [44], [47] such as those found in the skin, muscles, tendons and joints present an attractive alternative to artificial sensors for FES purposes because they are present throughout the body and should contain information useful for feedback control. Moreover, preliminary studies have indicated that much of the peripheral sensory apparatus below the level of the spinal lesion in spinal injured man is viable.

Presently, the major challenges for utilizing natural sensors is to develop techniques to interface with the peripheral sensory nerves and to extract the relevant information. In a series of studies performed in the cat, Yoshida and Horch [53] successfully demonstrated that signals recorded from muscle spindles via intrafascicular electrodes could be used as feedback to control ankle joint position in an FES paradigm. Among the various approaches used to record from peripheral nerves, however, including nerve cuffs, fine wire intrafasicular electrodes, wire (e.g., "hat pin") microelectrodes and silicon probes, only nerve cuff electrodes have thus far been demonstrated to provide adequate stability for practical neuroprostheses [15], [19], [25], [43].

The objective of the present study was to record information regarding ankle joint kinesthesia (flexion–extension) from muscle afferents using whole nerve cuff electrodes in a rabbit model of human peripheral nerves. Both animal and human studies [2], [5], [6], [9]–[11], [36]–[38], [45], [51] have suggested that muscle stretch receptors contribute to joint position and movement sensibility. We recorded the neural activity simultaneously from the tibial and peroneal nerves during passive trapezoidal ankle movements.

While there have been numerous studies reported regarding the characteristics of isolated muscle afferent responses [20], [21], [23], [27]–[29], [37], [39], [49], the present studies are unique because they consider the ensemble afferent responses as recorded directly from intact whole peripheral nerves.

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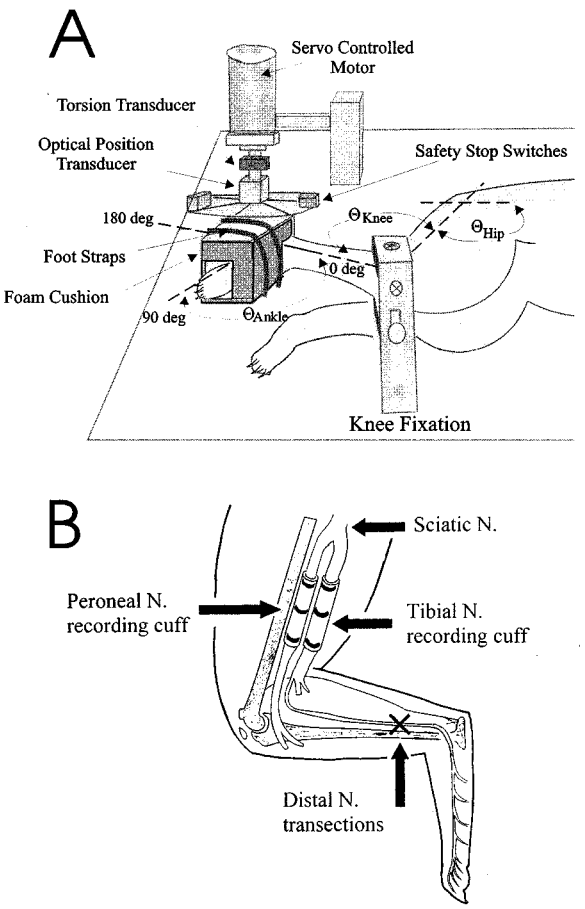

Fig. 1. (a) Illustrating the apparatus used to rotate the rabbit's ankle. The ankle and the knee are fixed in atraumatic clamps. The "shoe" holding the rabbit's foot is rotated by a velocity-controlled servo motor. A torque sensor is positioned in series with the motor shaft and the foot. The coordinate system used to describe the ankle joint position is illustrated. Under that system, 90° represents the angle between the foot and the tibia when the foot is at right angles to the shank. With the animal lying on its side, a neutral position (100°) was found where the passive forces acting at the ankle are balanced. For additional details refer to the text. (b) Illustrating the placement of the nerve recording cuffs on the tibial and peroneal components of the rabbit sciatic nerve. Also indicated are the distal nerve transections performed to exclude cutaneous activity from the foot and joint activity from the ankle from being recorded by the nerve cuffs.

II. Methods

A. Apparatus

The experimental apparatus consisted of a computer controlled position servo system to rotate the rabbit's ankle at programmable rates through the full range of flexion and extension in the saggital plane. Throughout the studies, the animal was placed on its side, and the knee was fixated in the apparatus with the angle between the tibia and femur adjusted to be 85° [Fig. 1(a)]. The trunk was aligned so that the angle at the hip between the femur and the spine was 80°. The motor shaft was coupled via a torque transducer to a "shoe" that cradled the rabbit's foot. The torque transducer consisted of a double bending beam cage containing eight strain gauges connected in a full bridge configuration and providing a sensitivity of 0.1 mNm. Low friction instrumentation bearings were employed to minimize the errors in measuring the torque during the passive ankle motion. The angular position of the ankle joint was continuously monitored using an optical based rotation transducer (sensitivity = 0.05°). Trapezoidal waveforms to control the ankle rotation movements (described below) were provided by a 386-based PC using a 12-bit D/A board and custom software.

B. Preparation

Acute experiments were conducted on five New Zealand White adult female rabbits (3–5 kg, age 10–14 months). Animals were initially injected intramuscularly with *Midazolam* (Dormicum[1] , (2.0 mg/kg) and then anesthetized with an intramuscular injection of *Fentanyl/Fluanison*, (Hypnorm[2] , (0.095 mg/kg and 0.30 mg/kg, respectively).

Supplemental doses of Hypnorm and Dormicum (0.13 mg/kg and 0.5 mg/kg, respectively) were administered every 20 min throughout the surgery and the data collection session. An incision was made on the lateral side of the left hind limb to expose the sciatic nerve approximately 3 cm above the knee. As illustrated in Fig. 1(b), the tibial and the peroneal nerves were carefully separated from each other and mobilized proximally to create enough length (approximately 28 mm) to install 22 mm long spiral cuff electrodes around each nerve. The sural nerve which remained attached to the peroneal nerve while traveling through the cuff, was separated and transected just distal to the cuff to eliminate its cutaneous input from the recordings. The muscles and the skin were then closed at the incision site. Two more incisions were made 2–3 cm proximal to the ankle on the lateral and medial sides of the shank to expose the descending branches of the tibial nerve (proximal to its division into the medial and lateral planter nerves) and the peroneal nerve (i.e., which becomes the superficial peroneal nerve) that innervate the foot and the ankle (see [35, pp. 128 and 131]). Both branches were transected to eliminate sensory inputs from the ankle joint and foot. Finally, the incisions were closed. Throughout the surgery and data collection session, the animal's temperature was continuously monitored and maintained at 37 °C with a heating pad. All of the experimental procedures used in this investigation were reviewed and fully approved by the Danish Committee for the Ethical Use of Animals in Research.

C. Stimuli

The stimuli used in this study consisted of "ramp and hold" rotations of the ankle joint. Several series of trapezoidal command profiles were designed which moved the ankle either in the flexion direction or in the extension direction to predetermined target positions ("onset ramp") using constant velocities of either 5, 10, 20, or 30°/s. The new position was then maintained for 2 s ("plateau phase"), and finally, the trial was completed by returning the ankle to the start position ("return ramp") using the same velocity as the onset ramp. In one series of trials, the start position of the ankle was a neutral position midway between the range from full extension to full flexion. At the neutral position the passive intrinsic flexion and extension torques acting about the ankle were balanced so that no net torque was

[1]Dormicum is a trademark of Alpharma A/S, Oslo, Norway.)

[2]Hypnorm is a trademark of Janssen Pharmaceutical, Beerse, Belgium and contains Fentanyl and Fluanison.)

present. We defined the neutral position as 100° using a coordinate system in which 90° would correspond to the foot being at right angles to the shank. Thus, full extension was represented by 130° and full flexion by 70°. In another series of trials, the ankle starting position was full extension and the onset and return ramps traversed the full 60° joint rotation range that was possible.

Finally, we also utilized a stimulus series that produced three stepwise changes from the neutral position to full extension ("extension staircase") followed by stepwise changes back to neutral. In a complimentary study, 3 stepwise changes from neutral to full flexion ("flexion staircase") were employed, again followed by stepwise changes back to neutral. In all cases we delivered five trials in a block with a 1 s pause between trials. Two such blocks of trials were collected for each unique stimulus profile to allow response averaging during off-line analysis.

We found that the response from the first trial in a block produced a higher response in comparison to the remaining four trials. Differences between the response to an initial stretch and succeeding stretches have been noted previously for primary spindle afferents [40]. As will be shown later, an analysis of the joint torque recorded during the movements in the present study suggests that this difference in afferent activity was due to changes in the visco-elastic properties of the muscular system during the initial trial. Whenever our analysis made use of averaged responses, we excluded such "first trials" from the averaged results. Once the preparation was ready, the actual data collection for each experimental session (each animal) required approximately 2 h to complete.

D. Nerve Recording

The nerve activity was recorded using self coiling spiral design tripolar nerve cuffs. Such a cuff was developed based on prior designs for fabricating self coiling nerve cuffs for stimulating nerves for FES applications [32]. Basically, the recording cuff consisted of three equally spaced strips of platinum foil (thickness = 7.5 μm) sandwiched between two layers of 100-μ m-thick silicone sheeting which are glued together. The dimensions of each of the three rectangular windows were 1 mm by 3 mm. The overall cuff length was 22 mm and the center to center separation of each of the electrodes was 9 mm. The cuff's self coiling feature and high mechanical compliance allow the electrode faces to fit in close apposition to the encircled nerve with little risk (in our experience) of impeding the blood supply. The closeness of the fit in no cases produced any apparent visual deformation of the underlying nerve as viewed during the installation through the surgical microscope. As an insurance that the cuff would not become dislodged during the wound closure procedure and subsequent positioning of the leg into the experimental apparatus, the cuff installation was completed by applying a circumferential suture over each of the underlying electrode regions taking care not to produce any visible tightening of the cuff. For these experiments, the end electrodes were shunted together before being led to one input of a differential preamplifier (gain = 80) while the middle electrode was connected to the other preamplifier input; however, other recording configurations are possible [34]. The reference terminal of the preamplifier was connected to a 19-gauge needle inserted under the skin of the rabbit's back. The preamplified signal was then bandpass filtered (1–5 kHz) and further amplified (gain = 1000) before being recorded. The impedance between the cuff center electrode and each one of the end electrodes (before shunting) was measured at 1 kHz after being installed acutely around the nerve. The values were between 1.5–2.0 kΩ (mean 1.7) at 1 kHz.

E. Data Acquisition and Processing

The activity from the tibial and peroneal nerves and the mechanical signals from the position and torque transducers were digitally sampled and stored directly on magnetic disk with the nerve channels sampled at 10 kHz and the mechanical signals sampled at 625 Hz. The data were analyzed off-line using custom software (SC-ZOOM; Umeå University, Sweden). The nerve activity was digitally rectified and then bin integrated using a symmetrical moving window of $\pm$20 ms. The torque signal was low pass filtered at 32 Hz. Time derivative functions were computed for both the position and torque signals by computing the difference of seven previous and seven following samples. Average responses were computed using linear superposition of successive trials obtained for each stimulus type.

III. Results

The activity of the tibial and peroneal nerves during movement of the ankle joint was mainly reciprocal. During ankle flexion, the extensor muscle group was stretched and most of the recorded activity was from the tibial nerve. Conversely, during ankle extension, the flexor muscle group was stretched and the recorded activity was mainly from the peroneal nerve. This reciprocal behavior is best illustrated from the data in which full excursion movements from flexion to extension and return were performed as shown in Fig. 2. The records shown are excerpted from a series of ten repetitive movements in which the ankle was passively rotated at a velocity of 30 deg/s through a 60° excursion. Each of the movement trials was started from the position where the foot was fully extended (130°). The foot was then moved to the fully flexed position (70°); held at the new position for 2 s and finally returned (30°/s) to the fully extended position. A pause of one second separated successive trials. Both the unprocessed nerve activities and the rectified and integrated signals are shown in Fig. 2.

At the onset of the extension plateau (static position) phase of the motion as denoted by point ***1*** in traces in Fig. 2(a)–(e), there was ongoing activity in the peroneal nerve recording. This activity ceased abruptly as soon as the ankle began to move in the flexion direction (point ***2***). There was only a very weak driven activity for either nerve during the interval when the ankle was rotated from 130° until just beyond 100° (neutral). Once the flexion motion crossed the neutral position, however, a strong response was evoked in the tibial nerve (point ***3***). The tibial nerve continued to show substantial activity during the sustained flexion position associated with the flexion plateau (point ***4***). Finally, this activity ceased abruptly as soon as the ankle began to be rotated in the extension direction (point ***5***), (a similar effect was observed with the peroneal activity at the end of the extension plateau phase when the returning movement was commenced).

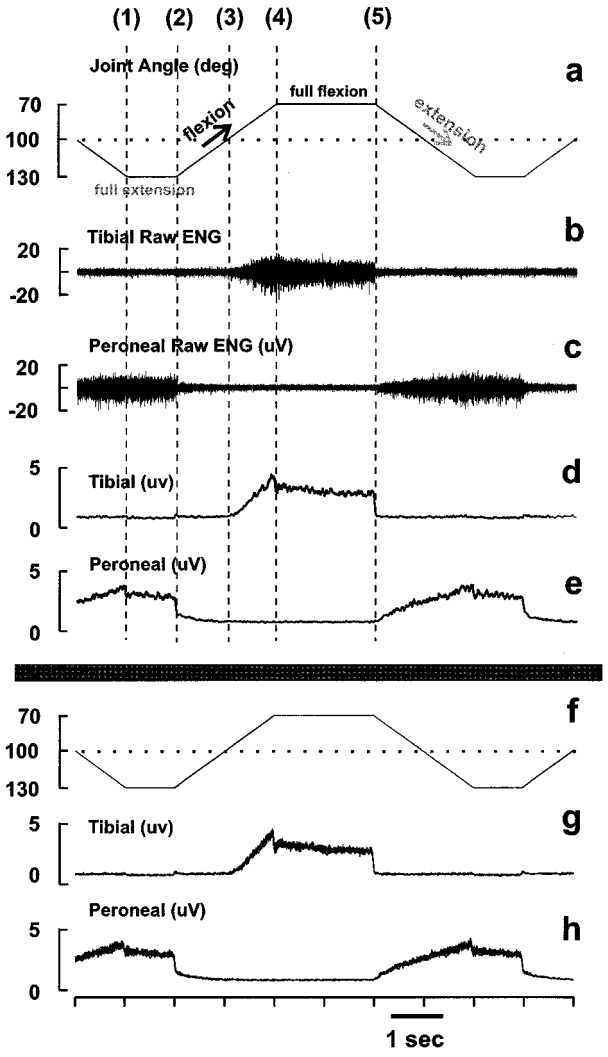

Fig. 2. Recorded tibial and peroneal nerve activity during passive rotation of the ankle joint in an anesthetized rabbit. The ankle was alternately flexed and extended at a velocity of 30°/s, with the position held constant for 2 s at the extreme flexion position (70°) and 1 s at the extreme extension position (130°) as indicated in trace (a). The dotted line at 100° indicates the neutral position where there was no net torque at the ankle from passive forces. (b), (c) nerve activity recorded from the tibial and peroneal nerves, (bandpass filtered at 1–5 kHz). (d), (e) rectified and integrated nerve activity. (f), (g), (h) showing eight superimposed responses from successive flexion–extension cycles to demonstrate the consistency of the responses. Data from rabbit 5.

A difference was observed with regard to the operating ranges of the tibial and peroneal nerves such that the peroneal response was present during the full excursion from 70° to 130° during extension, while the response from the tibial nerve was present only over the more narrow range from 100° to 70° during ankle flexion. Thus, during flexion motion there was a "dead band" between 130° and 100° where there was no driven activity from either nerve.

In all of the preparations, visual examination of the rectified and integrated afferent responses showed a remarkable consistency for successive trials that employed the same stimulus profile. This is demonstrated in the records shown in Fig. 2(f)–(h), where the stimulus position records and neural responses from eight trials have been superimposed. (Note that the eight trials represent trials two through five from the first series of five trials

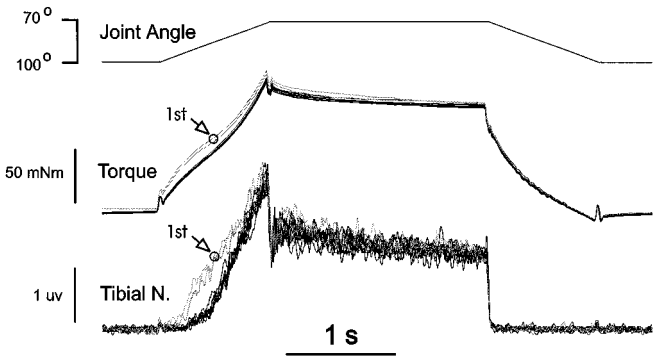

Fig. 3. Comparing the responses obtained for the "first movement trials" from two separate series of five ramp and hold ankle rotations with the remainder of the trials. A total of ten responses are superimposed in the figure. Details see text.

and trials two through five from a second series of five trials. The first trials from each series were not included because they exhibit "warm up effects" as discussed below.

A. Enhanced Sensitivity of Responses Following a Period of Movement Inactivity

When the nerve responses to the first movement ramp in a series of five stimulus trials is compared with the successive ramps, we consistently observed that the initial trial response was greater in amplitude. This is shown in Fig. 3 where the first trial responses from two separate stimulus series are superimposed along with the remaining stimulus trials from each set. Note that the responses from trials 2 through 5 from each of the remaining data sets have about the same amplitudes indicating that the one second delay between the consecutive ramps is not long enough to restore the sensitivity enhancement. During the present studies the delay between presentations of each series of (five) ramps was not controlled because the stimulus series were restarted or substituted by manual input at the computer keyboard. The between trial delay, however, was programmed and always equal to one second. As was stated in SectionII, when performing analyzes, we routinely excluded the responses from the 'first trial' of every series.

B. Verification of the Proprioceptive Origin of the Recorded Activity

We performed a series of tests during ankle flexion-extension at different velocities to ensure that the recorded activity was afferent in nature and not efferent, and that the majority of the activity was coming from muscle afferents and not from other sensory sources such as joint or skin afferents.

At the conclusion of two experimental sessions (rabbits 3 and 5), we studied the activity recorded from the tibial and peroneal nerves before and after transecting them first proximal and then distal to the nerve cuffs. An example of the results is shown in Fig. 4. With either preparation there was no visually observable change in the responses subsequent to transecting the nerves just proximal to the cuffs [compare records Fig. 4(b) and (c)], indicating the absence of any possible efferent component. The afferent nature of the evoked responses was clearly substantiated

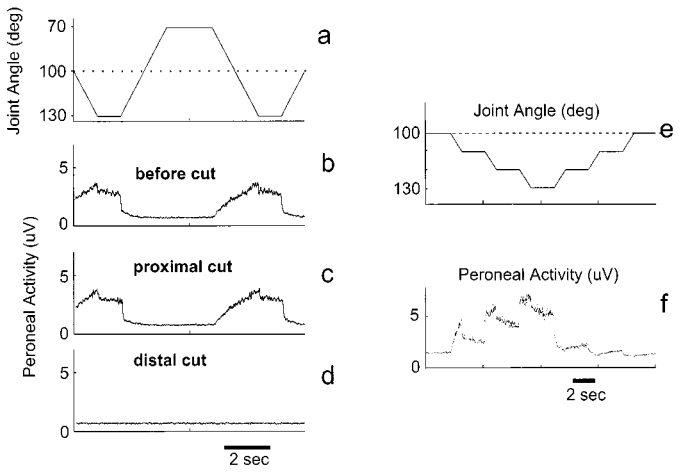

Fig. 4. Studies to verify the afferent origin of the recorded responses to ankle movement. ***Left***—The example recordings are from the peroneal nerve. As depicted in the position record in (a), the ankle was rotated at 30°/s throughout its full range to obtain the control data shown in (b). Cutting the peroneal nerve proximal (c) to the cuff resulted in no apparent decrease in the response, indicating that there was little or no influence from efferent activity within the nerve. Cutting the nerve distally, in contrast (d), completely eliminated the nerve activity demonstrating the afferent nature of the response to joint rotation. ***Right***—Superimposed responses from averaged data recorded from the peroneal nerve before and after injecting Lidocaine around the ankle joint capsule (f). The similarity of the activity before and 30 min after administration of the drug demonstrates a lack of possible input from joint receptors at the ankle. In each case, the extension movement was evoked by the staircase position changes shown in (e) (10° excursions at 10°/s with 2-s plateau periods).

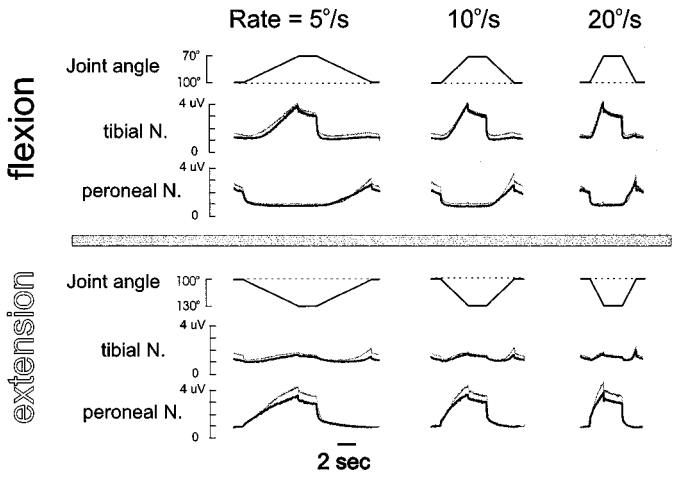

Fig. 5. Depicting the afferent responses to the ankle rotation before and after the cutaneous nerves of the foot were transected. Each trace represents the superposition average of eight successive trials. (Light traces—with cutaneous innervation intact; bold traces—after cutaneous innervation was removed.)

since the activity was eliminated when the recorded nerves were sectioned just distal to the recording cuffs [record Fig. 4(d)].

In another animal, without performing nerve transections at the level of the cuff, we injected lidocaine (10 mg/mL) into the capsule of the ankle joint (1 mL) and knee joint (2 mL) (even though the knee was fixated) in an effort to eliminate activity that might arise from joint afferents. Results from that investigation are shown to the right in Fig. 4. A "staircase" position profile was used to extend the ankle from neutral to full extension while the activity from the peroneal nerve was recorded. The ankle movements using the staircase profile were then repeated 30 min following the injection of the drug. The records shown in Fig. 4(f) are two superimposed responses each representing the average of ten stimulus trials before and ten trials after the application of the drug. Only minor differences can be discerned between the averaged responses before and after Lidocaine, suggesting that there was no appreciable contribution from the ankle joint afferents in the recorded nerve responses to the ankle rotation.

To determine the extent to which cutaneous and muscle afferents from the foot and around the ankle could contribute to the evoked responses, we also obtained successive recordings in two preparations (rabbit 2 of the present study and another rabbit from a related study) before and after we transected the sural nerve just distal to the cuff; and the descending branches of the peroneal and tibial nerves (transected ca. 2 cm above the ankle) which innervate the foot. With the foot both out of the "shoe" and later also fixed within the shoe, we stroked the skin over the foot while monitoring the nerve cuff activity. Performing the three nerve transections stated above effectively eliminated all neural activity evoked by stroking or lightly tapping the skin over the foot. We did note, however, that moving the toes evoked a modest neural discharge even after the nerves to the foot were transected. We expect that this response was caused by stretch applied to the leg muscles situated in the calf (cf., flexor digitorum longus and extensor digitorum longus) whose tendons insert on the toes and which are innervated proximal to the nerve transections [35]. We then carefully checked the fixation of the rabbit's foot in our experimental apparatus and confirmed that the toes were not being moved relative to the rest of the foot during the experimental trials that rotated the ankle. Such motion of the toes was adequately precluded by the design of the foot fixation, so that the toes were free at the front of the "open shoe" and did not contact the shoe.

Fig. 5 presents an additional control study performed with another rabbit used in a related set of experiments. The figure presents a comparison between the activity recorded during ankle movement when the nerves from the foot were intact and after they were transected as described in Section II. The data show that a modest input to the overall ankle rotation response arises from the nerves of the foot when this innervation is left intact. However, the contribution is small in magnitude in comparison to the activity that remains after the afferents from the foot are removed.

C. Hysteresis Effects During Ankle Flexion-Extension

A salient characteristic of the recorded nerve activity during alternating flexion–extension motion of the ankle is a prominent hysteresis as shown in Fig. 6. This derives from a primary attribute of muscle spindle organs in that they increase their activity when subjected to stretch, but they stop discharging abruptly when the direction of the ankle rotation is reversed and the previously stretched muscle is allowed to shorten slightly. While a modest rate dependency of the stretch evoked activity is clearly evident from the data shown in the figure, there appears to be no difference in the characteristic course with which the afferent activity diminishes when the direction of ankle motion is changed.

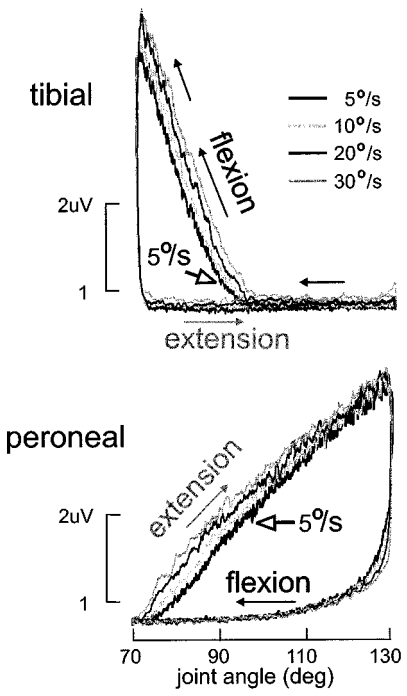

Fig. 6. Showing the pronounced hysteresis that exists for the positional dependence of the nerve activity recorded from the tibial and peroneal nerves when the ankle joint is alternately rotated from full flexion to extension and returned to flexion using a symmetric trapezoidal position profile. The recorded afferent activity is present only during stretch of the appropriate muscle groups and becomes silent as soon as the stretch begins to be released. Each set of traces corresponds to a different velocity (as indicated) and the response is seen to be systematically greater when the rotational velocity was greater. The nerve activity has been rectified and integrated, and each trace represents the superposition average of eight successive trials.

D. Effect of Rate of Ankle Rotation

The rate dependence of the muscle afferent activity was investigated using a series of 20° excursions from the neutral position in both the flexion and extension directions for rates of ankle rotation of 5, 10, 20, and 30°/s. Ten stimulus trials were collected at each velocity before the next velocity was tested. To illustrate the general findings, an example of the results from one preparation are given in Fig. 7. The upper part of the figure shows the superimposed responses derived from the tibial and peroneal nerves during ankle flexion ramps at each of the four velocities while the lower part of the figure shows the responses during extension ramp rotation.

Both the tibial and peroneal nerves showed substantial increases in activity during the onset (muscle stretch phase) of the appropriate stimulus. In some other regards, however, there were differences between the two nerves: The onset of the tibial response was delayed until well after the start of the flexion movement, and this latency was greater as the ankle rotation velocity was reduced. Also, the tibial responses were diminished at the slower velocities. In contrast, the peroneal response was more immediate at the onset of the extension movement; the response latencies were essentially unchanged by the slower velocity stimuli; and there was much less influence of the stimulus velocity on the peak amplitude of the response. A difference was also noted in that the onset of the peroneal response during extension directed movements became more "step like" as the stimulus velocity was increased (i.e., a steep response onset occurred). This transition to a steeper onset was not observed for the tibial responses during corresponding flexion movements.

Another striking difference between the tibial response to flexion and the peroneal response to extension, respectively, was that the tibial response showed a gradual acceleration during the stimulus onset ramp while the peroneal response was markedly steep at the onset, but then gradually decelerated. This effect suggests that the tibial innervated muscles are in a slackened state at the neutral position, whereas the peroneal muscles are not. Thus, a position threshold appears to exist, whereby, the muscles innervated by the tibial nerve must be stretched enough for their spindle afferents to begin to respond. For one of the rabbits, measurements of the ankle position that corresponded to the onset of the muscle stretch response from the tibial nerve during ankle rotation revealed that the position was approximately constant across velocities and corresponded to 5°–6° extension from the neutral position.

Finally, another difference between the nerve responses during the ramp phase is that the tibial nerve showed a higher "gain" than the peroneal nerve (i.e., the increase in nerve activity for a given rate of rotation was greater for the tibial response in comparison to the peroneal response). This effect was not due to differences in the gain characteristics of the two recording cuffs, because the amplitude relationship of the tibial and peroneal nerve responses actually reversed during the static phase of the trapezoidal stimulus where the peroneal activity was greater.

Fig. 8 presents the results of the effect of ankle rotation rate on the nerve activity obtained from each of the different preparations so that the consistency of the behavior can be assessed. For each recorded nerve, the responses to the preferred rotation direction at each velocity are shown as two curves. One curve gives the peak nerve activity (which always occurred near the end of the stimulus onset ramp), while the other curve gives the average activity (slope) of the response to the ramp onset phase. The average activity during the duration of the rotation onset ramp was computed between an upper and lower boundary where the upper boundary was the peak nerve response, and the lower boundary referred to the nerve activity measured at the response onset. For this purpose, the response onset was determined to be the point in time when the nerve activity exceeded the highest level of (background) nerve activity measured within a 100-ms window that immediately preceded the stimulus onset ramp.

In each case, a linear relationship provides a reasonably good fit of the data. There are differences, however, in the gain factors between the results from each rabbit. These differences are thought to be attributable to the recording characteristics of each cuff electrode and its particular installation in each different preparation, rather then reflect any physiological differences among the animals. Mean values and dispersions (± 1 stdev) for both the peak activity and the slope of the average nerve activities during the onset ramp (stretch phase) of the stimulus are given in Table I along with measures of the "Goodness of Fit" (r^2) for the linear regression lines (analyzes performed using PRISM Software—GraphPad Inc. San Diego, Ca, USA). For

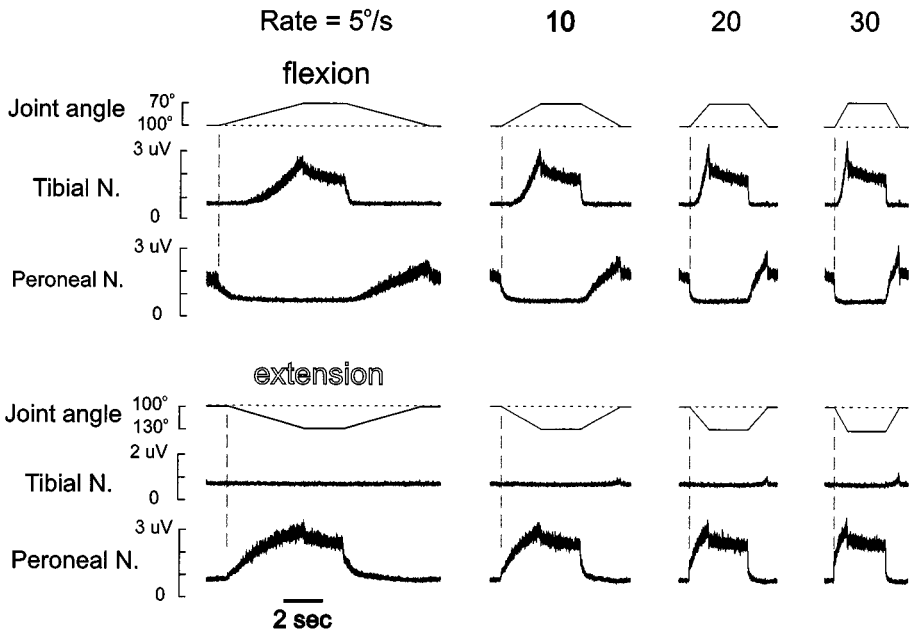

Fig. 7. Showing the effects of different velocities of ankle rotation on the afferent responses. In each case eight successive responses are superimposed. Note that the peroneal nerve has a wider "working range" in that it shows a response during the return phase (i.e., extension directed movement) of the flexion stimulus trials, whereas, the tibial nerve responds only during a part of the range during the flexion trials and has essentially no response during the return phase of the extension movements. Further details see text.

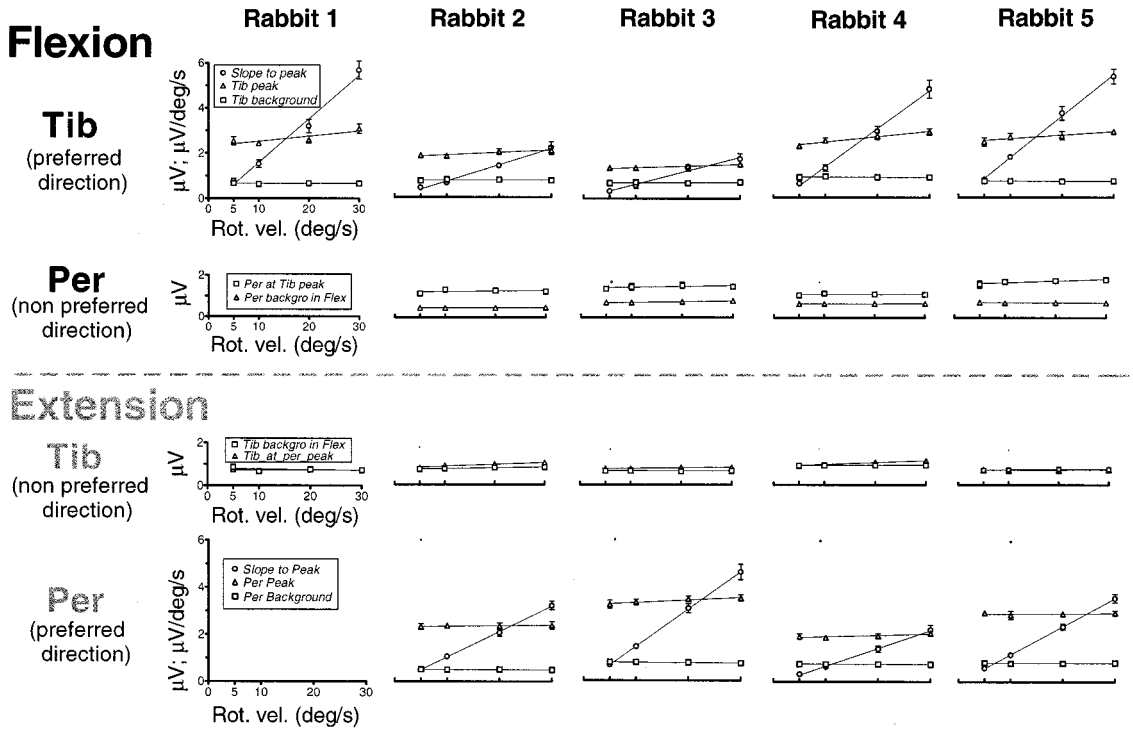

Fig. 8. Showing the effects of velocity on the afferent responses from the different preparations. The average tibial and peroneal nerve responses verses rotation velocity are compared for each rabbit preparation as indicated. One set of peroneal nerve data (rabbit 1) is not displayed because the activity diminished midway through the experimental session and later recovered only partly. (It is thought that the animal's knee was clamped too tightly in the fixation and this applied undue pressure to the underlying nerve, because the response returned after the rabbit's knee was released from the apparatus and then fixated again.) The data displayed represent the mean parameters from all eight trials, and in most cases the error bars ($\pm$ stdev) are too small to be visible behind the plotting symbols. Linear regression curves are fitted for the peak data and average activity during the stimulus onset ramp data. (Details see text.)

the tibial nerve, the slopes of the regression lines for average activity ranged from 0.19 to 0.06 μv/deg (mean $= 0.132$) with values of (r^2) between 0.98 and 0.93 (mean $= 0.96$). For the peroneal nerve, the slope for the average activity ranged from

TABLE I

ENTRIES INDICATE THE SLOPES OF TWO OF THE LINEAR REGRESSION LINES PLOTTED IN FIG. 8. THIS INCLUDES THE SLOPE OF THE REGRESSION LINE THROUGH THE MEAN PEAK RESPONSES TO MUSCLE STRETCH AS A FUNCTION OF ANKLE ROTATION VELOCITY AND THE SLOPE OF THE REGRESSION LINE THROUGH THE MEAN AVERAGE ACTIVITY DURING THE ROTATION OF THE ANKLE JOINT. ONLY DATA FROM THE PREFERRED DIRECTIONS FOR THE TIBIAL AND PERONEAL NERVE RESPONSES ARE INCLUDED AS INDICATED. THE SECOND SET OF TABLE ENTRIES GIVES THE GOODNESS OF FIT PARAMETER FOR EACH OF THESE REGRESSION LINES FROM FIG. 8. FOR FURTHER DETAILS—SEE TEXT

		Slope of Ave. Activity	Goodness of Fit	Slope of Peak Activity	Goodness of Fit
Rab 1	Tibial (flexion)	0.19	0.97	0.02	0.54
		non-zero p<.0001		non-zero p<.0001	
	Per (extension)	.....		.....	
		.....		.....	
Rab 2	Tibial (flexion)	0.07	0.96	0.015	0.39
		non-zero p<.0001		non-zero p<.0001	
	Per(extension)	0.11	0.99	0.002	0.02
		non-zero p<.0001		Not different from zero p<.0001	
Rab 3	Tibial (flexion)	0.06	0.93	0.007	0.55
		non-zero p<.0001		non-zero p<.0001	
	Per (extension)	0.16	0.99	0.01	0.36
		non-zero p<.0001		non-zero p<.0003	
Rab 4	Tibial (flexion)	0.16	0.98	0.02	0.75
		non-zero p<.0001		non-zero p<.0001	
	Per (extension)	0.08	0.97	0.006	0.27
		non-zero p<.0001		non-zero p=.0023	
Rab 5	Tibial (flexion)	0.18	0.98	0.015	0.48
		non-zero p<.0001		non-zero p<.0001	
	Per (extension)	0.12	0.99	0.001	0.01
		non-zero p<.0001		Not different from zero p=0.57	

0.16 to 0.08 μV/deg (mean $= 0.115$) with values of (r^2) from 0.99 to 0.97 (mean $= 0.98$).

With regard to the slope of the regression line fitted to the peak activity during the stretch phase of the movement ramp, the tibial N. showed marginally higher slopes (ranging from 0.02 to 0.007 μV/deg/s; mean $= 0.015$), then was the case for the peroneal N. which produced slopes between 0.01 and 0.006 μV/deg/s (mean $= 0.0048$). Moreover, two of the four rabbits (Rabbits 2 and 5) for which the slope of the regression line for the peroneal peak responses was studied, had slopes that were statistically indistinguishable from zero.

In applying a test of the residuals from the regression analysis to determine the suitability of the linear model for the average response data, it was found that only one case out of the nine available data sets showed a statistically significant deviation from linear behavior (Tibial N. rabbit 1 $p = 0.0046$). Despite this fact, the computed value of r^2 for this linear regression was still high at 0.97, indicating that linear modeling of the afferent sensitivity to rotation velocity is well justified overall.

1) Afferent responses to movement in the "nonpreferred direction": The responses of the recorded nerves during the nonpreferred rotation direction (i.e., the direction that acts to allow the relevant muscles to be less stretched) are also presented in Fig. 8. For the peroneal nerve data during the nonpreferred flexion ramps, the values plotted were measured at the point in time when the tibial nerve response was at its peak. Similarly, for the tibial nerve during the nonpreferred extension rotation direction, the values plotted were measured at the point in time when the corresponding peroneal response was at its peak.

It can be seen that the peroneal activity during the nonpreferred direction movements is substantially lower than the background activity that was measured before the start of each movement ramp. This occurs as a result of the static sensitivity of the peroneal muscle afferents since the peroneal muscles are less stretched at the end of the flexion directed ramp. In contrast, this consistent effect is not seen for the tibial nerve data. For that case, a comparison of the background activity and the onset ramp activity reveals essentially no change because the tibial muscles are presumed to be slack throughout the entire (nonpreferred) movement.

2) Effect of Starting Position on Afferent Responses to Ankle Rotation: In this investigation we examined the influence of the starting position of the ankle on the rotation evoked afferent responses. This was studied by using a complimentary pair of stimulus profiles referred to as the 'flexion staircase' and the 'extension staircase' which provided movement in the direction of ankle flexion and extension, respectively. In every staircase trial, the ankle started from the neutral position and was rotated through three successive 10° steps until the full excursion was attained. The movement was held steady for 2 s following each step of the staircase and finally a mirror symmetric series of decreasing steps returned the ankle to the neutral position, as shown in Fig. 9(a) and (d). For this study, all of the rotation during a single staircase was performed using a single velocity of $\pm 10°$/s. Data from two blocks of five flexion staircase trials were collected after which two blocks of five extension staircase trials were collected. As before, the initial trials from each block were not included in the averaged results which are presented.

Examining the data from the flexion staircase, we observed that the increase in the tibial nerve activity in response to a step change of 10° was higher if the position of the ankle was already in a more flexed position [compare points ***1***, ***2*** and ***3*** in Fig. 9(b)].

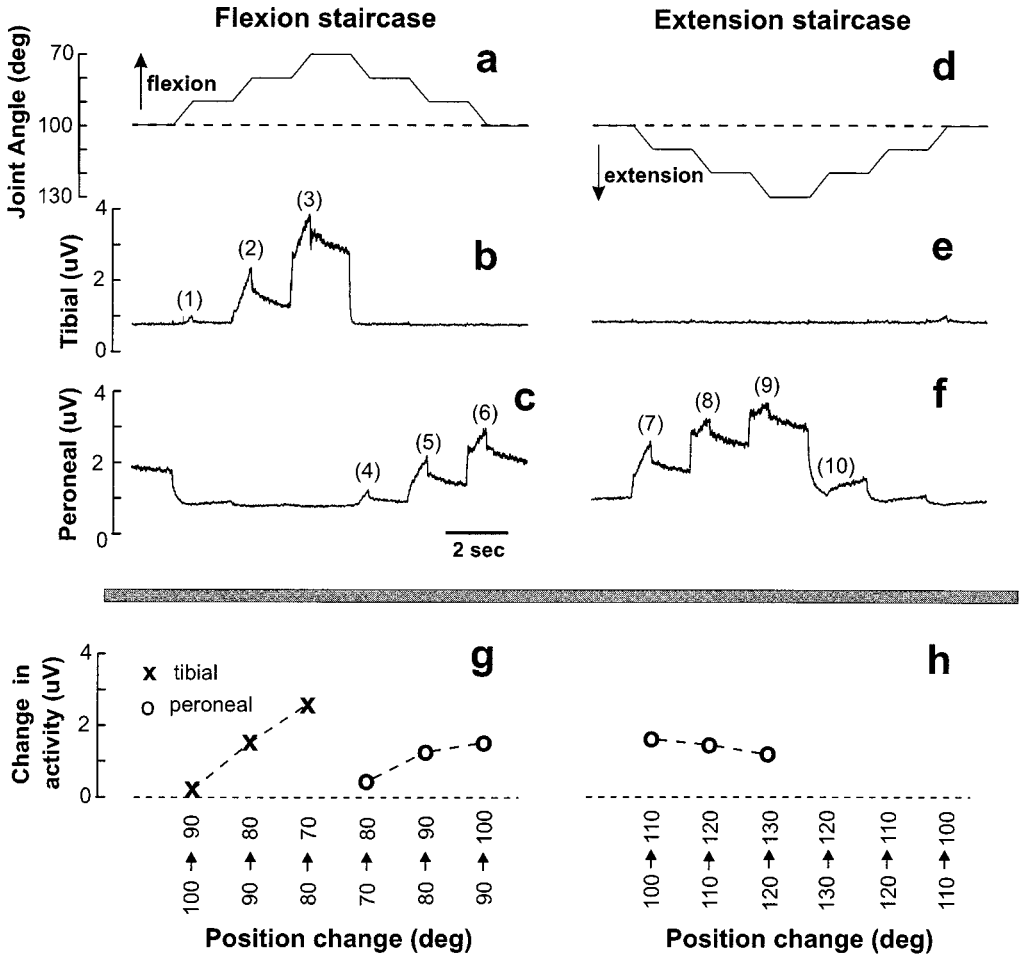

Fig. 9. Depicting stimulus profiles and nerve responses for the investigation of fixed amplitude changes in ankle position when the starting position was systematically varied. Each staircase profile (a) and (d) consisted of three 10° step position changes separated by a 2-s duration plateau. All movement ramps had a constant velocity of 10°/s. (b), (c) and (e), (f) are the averaged integrated responses obtained from 10 stimulus repetitions for the flexion and extension staircases, and tibial and peroneal nerves, respectively. The changes in activity from the level of the preceding plateau to the peak of the current step of the staircase are presented in (g) and (h) for the flexion and extension staircase trials, respectively.

Fig. 9(g) shows the magnitudes of the responses to each successive step of the staircase with the amplitudes expressed as the change in activity from the previous plateau to the peak value for the respective step. It is clear that the transient increase of the nerve activity in response to a fixed amplitude step is greater when the starting position of the ankle is more flexed. This effect of increasing sensitivity is also visible (comparing ***4***, ***5*** and ***6***) when the same analysis is applied to the response from the peroneal nerve during the return direction from the flexion staircase. For the case of the peroneal nerve during the onset phase of the extension staircase, however, the response to further increases in extension diminished as the starting position for the step change brought the ankle closer to the extreme extension position [compare ***7***, ***8*** and ***9*** of Fig. 9(h)]. Thus, the peroneal nerve initially showed an increasing sensitivity over the starting positions from 70° to 100°, but the sensitivity then decreased as the starting position changed from 100° to 130°.

Another feature of the data that merits some comment is the apparent discrepancy between the level of peroneal activity at the conclusion of the flexion staircase data and the activity measured at the onset of the extension staircase data. Before the flexion staircase trials were begun, the peroneal activity level was about 1.3 μV lower (the first trial data is not shown), however, the activity is elevated to about 2 μV at the end of flexion staircase return phase by the stretching of the peroneal muscles. (The activity at the start of Fig. 9(c) is the same as the end of Fig. 9(c) because the data are the superposition of successive trials). The activity is declining at the end of the data displayed and would eventually approach the activity level seen at the start of the extension staircase data, however the next flexion staircase steps are commenced before this can occur.

E. Tonic Response

The plateau phase for each of the trapezoidal movement trials had a fixed duration of 2 s and consisted of a hold period at 80° for the flexion plateau and a hold period at 120° for the extension plateau. Fig. 10 shows superimposed data from each set of averaged trials computed for each of the four rotation velocities tested. Also, shown are the periods 500 ms before the start of the hold phase and 500 ms after the hold phase. It is evident from these data that the tonic afferent activity [Fig. 10(c) and (f)] from either nerve during the corresponding plateau phases is independent of the preceding rate of ankle movement. Some accommodation of the response during the plateau was observed

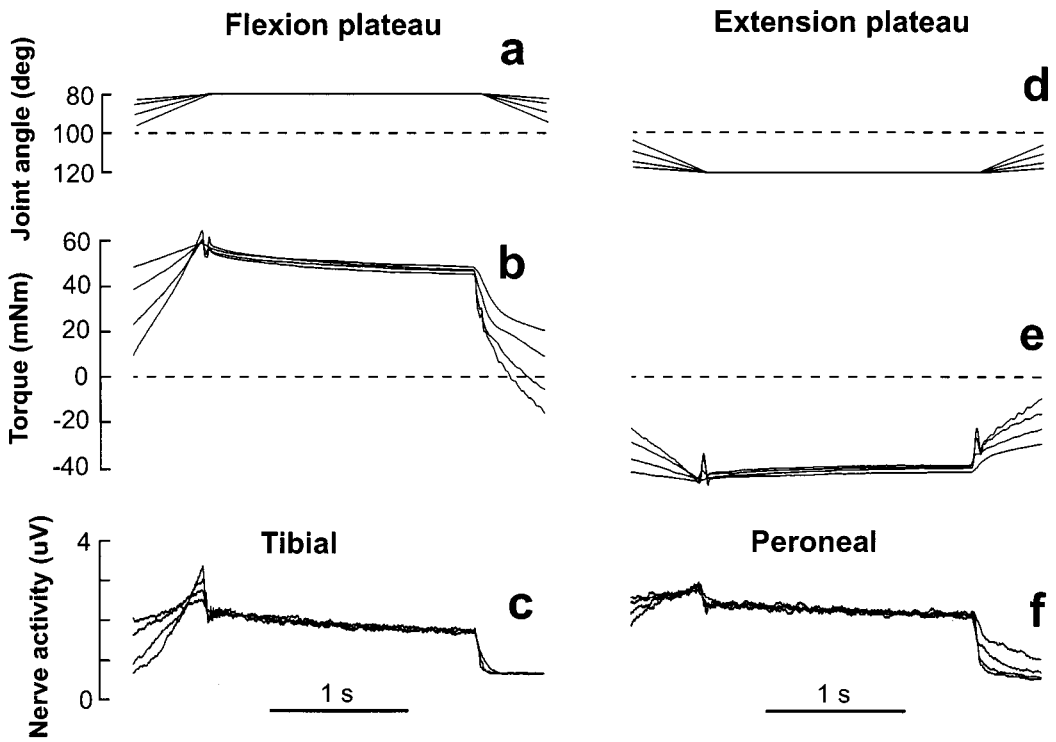

Fig. 10. Showing tonic muscle afferent responses during sustained positions of the ankle at 80° flexion (left) and at 120° extension (right). Each trace is the superimposed average of eight consecutive trials where the preceding movement ramp had a velocity of either 5, 10, 20, or 30°/s. In all cases, the trials were begun with the ankle at the neutral position (100°). All of the flexion trials were given first and then the extension trials were executed. To illustrate the independence of the tonic response with regard to the velocity of the preceding movement ramp, the time period 500 ms before and 500 ms after the plateau are also displayed. Ankle position shown in (a) and (d); passive torque at the ankle shown in (b) and (e); and neural activity shown in (c) and (f). Note the lack of influence of the preceding movement rate on the activity during the static plateau period. Note also, the correspondence between the decline in passive torque and the decline in the nerve activity during the plateau period.

in all of the trials. The accommodation appears to be related to slow changes in the mechanical forces applied to the muscle receptors rather than to a true neural accommodation of the receptors themselves. This is deduced from examining the torque records during the plateau [Fig. 10(b) and (e)], and noting that the decline in neural activity tracks the decline in magnitude of the passive torque at the ankle joint. To illustrate this point, the gain of the torque records was adjusted so that the torque traces and the neural activity records appear to parallel each other.

Just at the onset of the stimulus plateau, it can be seen that the neural activity declines transiently to a level that is lower than the activity briefly thereafter, (i.e., there is a transient depression of activity followed by a partial recovery). Furthermore, the magnitude of the depression was greater when the preceding ramp rate was higher. This effect has been described in other reports as a "deceleration response" or transient decrease of the nerve activity following passive muscle shortening [3], [23].

Finally, it can be noted that the tonic responses for the peroneal nerve are higher, relative to the background then those of the tibial nerve for the 20° extension and 20° flexion positions that were tested.

IV. Discussion

A. Origins of the Evoked Afferent Activity

The signal obtained from a neural recording cuff represents an ensemble average of the massed discharge activity within the nerve, and this provides both advantages and disadvantages. An advantage is that this averaging effect provides a margin of safety against capricious and inconsistent discharge behavior that might be associated with the responses of individual afferent fibers. A major drawback however, is that the modality specificity of different mechanoreceptor afferents present in a motor nerve is lost. Thus, the responses of the primary and secondary muscle spindle afferents, Golgi tendon afferents, and joint receptor afferents are all mixed together. The ability to interpret the composite signal may well require an empirical characterization of the recorded responses to known stimuli, but even then, considerable ambiguity may remain.

There are, however, some properties of the recording cuffs that bias the types of afferents that are registered. For example, larger myelinated fibers in contrast to smaller fibers, present stronger electrical fields during discharging which are more readily picked up by the cuff electrodes. Since muscle afferents are among the largest (and therefore also the fastest conducting) myelinated nerve fibers (group Ia) [22], followed by Golgi tendon organs (group Ib), the activity recorded from a mixed nerve is dominated by any activity present from these large afferents [19].

While afferent fiber discharge rate is presumed to be an important feature in the neural encoding of mechanical events, the discharge rates of cuff recorded afferents can not be recovered from the nerve cuff signal. Instead, for FES applications [16] the average energy associated with the massed activity has usually

been extracted by first rectifying and then low pass filtering the recorded signal.

The recorded activity evoked by the passive trapezoidal ankle motion was mainly derived from muscle afferents by several criteria. First, the afferent origin was demonstrated by transecting the recorded nerves immediately distal to the cuff and noting that the evoked activity was totally eliminated. Second, we eliminated cutaneous activity as a source of input by routinely transecting the distal projections of the recorded nerves in the calf region, and we verified that thereafter, there was no response to stroking and touching the skin around the ankle joint and at the foot. Third, the recorded responses to the ramp and hold stimuli exhibited three behaviors which have been well studied and described by others as characteristics of muscle spindles, as follows: The response during ramp stretch was phasic and increased for higher rates of stretch; an initial transient burst was usually seen at the ramp onset; and there was also present a temporary decrease (deceleration) when the stimulus plateau was begun. It can be argued that the initial phasic response, and the response decrease at the start of the plateau phase are also properties of cutaneous afferents, however, there was never present an "off-response" at the start of the unloading phase of the ramp stimulus. Such an off-response would have been present if the responses were of cutaneous origin [12], [44], [47]. Furthermore, the amplitude of the static response during the plateau was appreciable and much larger then what would be expected from cutaneous responses. Finally, there was an abrupt pause in the activity when the stretched muscle was made to relax passively as has been described for muscle afferents [23]. The activity during the plateau phase (see Fig. 10) could derive from the length dependent properties of the muscle spindle Ia and II afferents as well as from the force sensitive Golgi tendon afferents. From the current experiments, it is not possible to determine the contributions from these alternative sources, although Golgi afferents are considered to have low activity in passively stretched muscle.

B. Phasic Verses Tonic Activity

Both the tibial and peroneal nerves exhibited combinations of phasic and tonic activity in response to the ramp and hold stimuli. The presence of an initial burst at the ramp onset, was dependent on the initial length and velocity of the stretched muscle. This length dependence was most apparent in the case of the staircase investigation, where in Fig. 9(b) and (c), the responses to the first step in the flexion direction (point ***1***) and the first step in the extension direction (point ***4***), did not result in an initial burst for the tibial and peroneal nerves, respectively. Successive steps, however, which further stretched the driving muscles (points ***2***, ***3*** and ***5***, ***6***) elicited initial bursts of increasing amplitude. Such initial burst activity is thought to arise from primary spindle afferents and has been characterized as an acceleration response that might be useful for signaling motion onset [21].

Following the initial burst is a velocity sensitive increase in activity that tracks the increased length changes in the stretched muscles. Over the range of velocities tested (5–30°/s), the relation between the rate of change of the recorded activity and the velocity of angular rotation of the ankle was approximately linear. The linearity between ramp velocity and afferent dynamic response is similar to what has been described by Houk and his colleagues [21] from recordings of isolated muscle spindle afferents. It should also be pointed out that some deviation from linear behavior would be expected from our data regardless of the intrinsic properties of the spindle receptors, since no corrections were applied in our analysis to account for the fact that changes in ankle rotation do not relate linearly to changes in muscle length because of the cam action of the muscle attachments at the ankle. This simple treatment of the data reflects the fact that we wish to relate the neural activity to the kinematics of the ankle joint (for future FES control) and not to length changes of individual muscles.

It might be questioned why we do not seek to record the activity from joint afferents as a more direct way to obtain joint angle information. The major reason is that the small nerves that innervate the joint capsules are less readily accessible to install cuff recording electrodes [18]. Secondarily, some controversy still exists as to whether joint receptors respond throughout the entire joint range of motion or only at the extreme ends of the joint range, and this may be dependent on whether or not the joint is moved through active muscle contraction or only via passive forces [reviewed in [41].

C. Differences Between the Tibial and Peroneal Responses

Three differences were noted between the tibial and peroneal responses to the ramp stimuli. The first is the more limited range of ankle motion over which the tibial nerve showed a response (cf., Figs. 2, 6, and 7). For the tibial nerve no responses occurred until the ankle was flexed beyond the neutral position whereas the peroneal nerve (during extension) responded over the full 60° range. Second, the responses for 30° flexion and 30° extension from the neutral position for the tibial and peroneal nerves were qualitatively different (Fig. 7) in that the peroneal responses included a more pronounced initial burst. Both of these observation can be understood if the extensor muscles are more slackened at the neutral position then is the case for the peroneal muscles. It should be noted, however, that the tendency for the peroneal responses to have steeper onsets at the higher velocities was seen during the return phase of the flexion trials as well as during the onset ramps of the extension trials. Thus, the condition of muscle prestretch may not wholly explain the occurrence of the steeper onsets of the peroneal responses (in relation to the corresponding tibial responses), since the peroneal innervated muscles are much less stretched during the flexion motion trials (70°–100°) in comparison to the extension motion trials (130°–100°), yet the phenomenon of the steep responses is still evident.

Finally, the phasic response from the peroneal nerve became less as the starting position for the ramp stimulus was closer to the end of the joint range of motion, but this "response compression" was not observed to occur for the tibial nerve. It is possible that this effect was also caused by the presumed differences in the state of initial tension present in the tibial and peroneal nerves at the neutral position. If the tibial nerve was not slack at the onset of the flexion ramps, a response compression might also have occurred when the initial position of the ankle was brought nearer to the extreme flexion position.

Differences were also noted in that the ratio of the tonic response (at the ramp plateau) from the peroneal nerve in relation to its phasic peak response (at the end of the onset ramp) was higher than was seen with the tibial nerve. This might represent a difference in the afferent populations which are contained within the two nerves. The peroneal innervated muscles may have a larger proportion of Golgi afferents or static spindle afferents than is the case of the tibial innervated muscles. Another possible influence might be that the tibial innervated muscles collectively may have more dynamic spindle afferents then do the peroneal innervated muscles, and if that were the case, then the larger size of the dynamic afferents would allow those dynamic fibers to contribute more effectively to the recorded compound activity than the Golgi and static afferent fibers.

D. Accommodation During the Static Phase

The neural activity during the 2-s duration of the stimulus plateau phase declined modestly. This was seen (e.g., Fig. 10) to closely parallel a decline in the passive torque around the ankle joint suggesting that the decline in activity is due to a relaxation of the stretch forces acting on the muscle receptors. This observation held for both the tibial and peroneal nerves.

E. A Perspective Regarding the Use of Muscle Afferents for FES Control

1) Expected Complications of Active Muscles: The present study was performed in an anesthetized preparation which has the effect of minimizing any effects from fusimotor activation and thus simplifying the interpretation of the stretch evoked responses. It is largely unknown, however, to what extent fusimotor activity will be present in the muscles below the injury level in paraplegic individuals who will utilize FES systems. Furthermore, the effects of intrinsic muscle activity caused by spasticity will have to be studied.

Even though we expect to use afferent signals from muscles that will not be stimulated during FES but which are subjected to passive stretch and relaxation because of their attachments at important joints such as the ankle and knee, there will still be the possibility of pick up of EMG and FES artifacts from nearby active muscles. Mechanisms to exclude such artifacts will have to be employed to avoid contamination of the muscle afferent control signals. Several techniques such as anticipatory blocking of the input data (synchronized with the delivery of the FES pulses) have been successfully employed during the use of cutaneous afferent activity for the control of a drop foot stimulator [14], [15]. Also, advances are being made in the design of the cuff recording devices and signal processing techniques to improve the ability to reject artifacts [12], [34], [50], [51].

a) Practicality of instrumenting various nerves in human subjects: An important attribute of an FES controller is that it be reliable. A technique to improve the reliability of a controller that is based on signals from natural afferents is to instrument several muscle nerves so that additional and redundant information can be gathered. Constraints regarding this are the increased expense and bulkiness of the lead wires from multiple cuffs, and the size limitations of the nerves which are candidates for nerve cuff recording. The development of leadless cuffs which utilize RF or optical telemetry, would be helpful for the former issue, as would multichannel cuffs that could record from different compartments (fasicules) within a trunk nerve. Fortunately, nerve size is not expected to present a major obstacle since nerves as fine as 0.5 mm are able to be recorded from chronically using cuffs. Moreover, a bonus of obtaining higher signal amplitudes is gained when appropriately sized cuffs are installed around fine nerves verses large nerves [19]. Recent advances in cuff technology include the fabrication of extremely thin cuffs made from metalized polyimide films having integral leads (see [46]). These will be ideal for use in restrictive areas and around fine nerves.

In the present studies, input from cutaneous receptors was eliminated by direct transection of the nerves to the rabbit's foot. Since such nerve transection would not be desirable in the case of FES patients, any attempt to record from large trunk nerves such as the tibial and peroneal components of the sciatic nerve would include considerable activity from the skin and joints of the lower leg and foot. The resulting signals would be complex and might be difficult to interpret. However, for the case of using afferent control for FES-assisted standing in paraplegic individuals, it should be possible to apply separate cuffs and obtain afferent recordings from individual nerve branches that innervate the calf and thigh muscles. Such information could be utilized in combination with foot contact information from the mixed nerves of the foot (e.g., medial and lateral plantar nerves and the medial calcaneal branch of the tibial nerve).

b) Type of controller to be employed for FES: A number of issues regarding the consistency of the recorded afferent signals are noted in the findings described in this paper. These issues include the influence of: a period of joint stationarity; the starting position; the velocity of the movement; spasticity; activation of the gamma system; and the effect of muscle contraction. While some success was demonstrated by Yoshida *et al.* [53] in utilizing recorded muscle afferent signals and a "look-up table" approach to achieve closed loop FES control of joint position in an anesthetized cat, we feel that that approach by itself would not succeed over the range of velocities and movement excursions that we have investigated. In particular, the effect of the initial position and movement velocity on the afferent response sensitivity would make the application of the muscle afferent signals for control of FES walking unlikely without an independent measure of joint ankle.

In the case of FES-assisted quiet standing for paraplegia, however, the ankle excursions are small, centered at a middle position, and the velocity of the postural sway is on the order of only a few degrees per second making this a plausible application for natural sensor technology [24]. Furthermore, we envision using a Fuzzy or NeuroFuzzy-based controller. The development of the NeuroFuzzy control depends only on the input of empirical data rather than analytical formulas (for an overview of Fuzzy Modeling and Control see [1]). Thus, it is unnecessary to describe a precise mathematical function relating the joint kinematics to the ENG. Once an appropriate algorithm has been set up it should be possible to extract joint position and torque information from the nerve activity. In particular, the recorded activity is seen to be highly related to the passive joint torque (in Fig. 10, compare the end of the

onset ramp for the flexion movement B and C with the end of the extension ramp E and F), and preliminary work in our lab to establish a NeuroFuzzy model seems encouraging [30]. Thus, to the extent that knowledge of joint torque can be used by the controller, some of the envisioned complications that arise from the response variability attributable to different joint starting positions may become less troublesome.

V. Conclusion

Several conclusions may be derived from this study of the activity from the hind limb nerves in an anesthetized rabbit preparation as follows.

1) The nerve responses that were evoked during passive joint motion are sufficiently robust to be able to be recorded using cuff electrodes.
2) The cuff recorded nerve responses evoked during passive joint movements that stretch the innervated muscles are mainly driven by muscle afferents.
3) The responses of the peroneal component of the sciatic nerve are present only during ankle extension movements but are elicited over the full range of joint motion (i.e., 70° to 130°).
4) The responses from the tibial component of the sciatic nerve are present only during dorsiflexion movements, but are elicited only over a restricted range of joint motion—from the neutral position (100°) to full flexion (70°).
5) For the ramp excursions from the neutral position which were studied (i.e., ±30°) faster rates of movement result in an approximately linear increase in the evoked responses, as measured by the average rate of change in activity during the motion. Moreover, the effect of velocity is more pronounced for the tibial nerve in comparison to the peroneal nerve.
6) The sustained response of the peroneal nerve during the plateau phase of the trapezoidal extension stimulus is greater then the sustained response from the tibial nerve during the corresponding plateau phase of the flexion stretch stimulus.
7) The evoked responses are influenced by the initial position of the ankle before the motion.
8) The tonic response during a sustained position after a ramp movement is not influenced by the rate of the preceding movement.
9) The findings from these studies suggest that signals derived from muscle afferents (in nonstimulated muscles) using cuff electrodes may be useful for the control of FES systems. This, however, will likely require control strategies that do not require precisely calibrated sensors because of the history dependencies of the muscle afferents (muscle prestretch, initial position and time delay since the preceding motion) that we observed. More detailed studies to access the impact of these influences are required. Presently, it would be possible to know when an innervated muscle is subjected to added stretch by the increased neural activity, and conversely, it would be possible to deduce that such stretch has begun to relax if there is an abrupt halt in the ongoing activity. Some rate information is also clearly present in the responses to movement, and this may be useful in grading an appropriate correction factor during closed loop control of FNS systems.

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