# Effect of Initial Joint Position on Nerve-Cuff Recordings of Muscle Afferents in Rabbits

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Abstract—The objective was to characterize nerve-cuff recordings of muscle afferents to joint rotation over a large part of the physiological joint range. This information is needed to develop control strategies for functional electrical stimulation (FES) systems using muscle afferent signals for sensory feedback. Five acute rabbit experiments were performed. Tripolar cuff electrodes were implanted around the tibial and peroneal divisions of the sciatic nerve in the rabbit's left leg. The electroneurograms (ENG) were recorded during passive ankle rotation, using a ramp-and-hold profile starting at seven different joint positions (excursion  $= 5^{\circ}$ , velocity =  $10^{\circ}$ /s, initial positions  $60^{\circ}$ ,  $70^{\circ}$ ,  $80^{\circ}$ ,  $90^{\circ}$ ,  $100^{\circ}$ ,  $110^{\circ}$ , and 120°). The amplitude of the afferent activity was dependent on the initial joint position. The steady-state sensitivity of both nerve responses increased with increasing joint flexion, whereas the dynamic sensitivity increased initially but then decreased. The results indicate that recordings of the muscle afferents may provide reliable information over only a part of the physiological joint range. Despite this limitation, muscle afferent activity may be useful for motion feedback if the movement to be controlled is within a narrow joint range such as postural sway.

*Index Terms*—Muscle afferents, nerve cuff, peripheral nerve, position, rabbits, sensory feedback.

#### I. INTRODUCTION

CTIVATION of paralyzed muscles using functional electrical stimulation (FES) is useful to restore lost or impaired mobility after spinal cord injury. Closed-loop controlled FES systems depend on feedback to evaluate the current state of the body movement. Ordinarily sensors mounted externally on the body have been used to provide cognitive feedback to a human subject [1] and to provide feedback to a FES control system [2]. As an alternative approach, closed-loop FES systems have been developed using sensory feedback from cuff recordings of peripheral nerve activity in human subjects [3], [4]. The present study is part of a series to evaluate if nerve-cuff recordings of muscle afferents can provide suitable information for control feedback. Our present objective was to examine the effect of initial joint position on muscle afferent recordings from an agonist–antagonist muscle pair during joint rotation.

The muscle spindles and the Golgi tendon organs are the proprioceptive sensors located within the muscles and the tendons. The spindles are innervated by the group Ia (primary) and group II (secondary) afferents which are excited when stretch is applied to the muscle. The primary afferents are sensitive to both

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dynamic and static changes of muscle length, whereas in the secondary afferents the static sensitivity is more pronounced [5]. Muscle afferent responses from single-unit and multi-unit recordings have been studied extensively in the past (see e.g., [5], [6]). The Golgi tendon organs are innervated by the group Ib afferents and they are not very sensitive to passive muscle stretch [7]. The Golgi afferents are, therefore, not likely to contribute significantly to the afferent responses recorded in our present studies.

A cuff electrode registers the compound activity of the nerve fibers [8], but the nerve-cuff recording is biased in favor of the largest axons, which include the group Ia and group II afferents. Properties of whole nerve-cuff recordings of muscle afferents from the tibial and peroneal nerves in rabbit preparations have been characterized in prior studies [9], [10]. One of the most prominent features observed was that the tibial nerve mainly responded during joint flexion and that the peroneal nerve mainly responded during joint extension. It was noted that the afferent responses were dependent on the initial length of the parent muscle and the nerves did not respond to stretch over the entire joint range [10].

The effect of a stationary period on the muscle afferent responsiveness to passive stretch has been studied [9] and it was concluded that the effect was too small to be of consequence in the design of a closed-loop controller. We showed recently, that joint angle information could be predicted from the muscle afferent recordings using a fuzzy model [11]. However, if the muscle afferent activity is absent or if pronounced nonlinear changes in the activity occur over the joint range to be controlled, this must be taken into consideration when inferences are made from the muscle afferent recordings. To address the effect of initial joint position on muscle afferent recordings from an agonist-antagonist muscle pair, we compared the muscle afferent responses to ramp-and-hold perturbations starting at seven different initial joint positions over a large part of the rabbit's physiological joint range. To examine the nonlinear properties in detail, we assessed the steady-state and dynamic sensitivity of the afferent recordings.

#### II. METHODS

#### A. Experimental Setup

All procedures used in the experiments were approved by the Danish Committee for the Ethical Use of Animals in Research. Five acute experiments were performed using adult female New Zealand white rabbits (weight 3–5 g). The anaesthesia was



Fig. 1. (a) Depicting the animal preparation. The implantation sites of the two nerve-cuff electrodes are indicated. (b) Plot of the trapezoidal pertubation used to rotate the rabbit's ankle joint and the range of initial joint positions where the perturbation commenced.

initiated with 2.0 mg/kg Midazolam (Dormicum<sup>™</sup>, Dumex-Alpharma, Alpharma A/S, Oslo, Norway) and 0.095 mg/kg Fetanyl and 3 mg/kg Fluranison (combined in Hypnorm<sup>™</sup>, Janssen Animal Health, Janssen Pharmaceutica, Beerse, Belgium) to relax the animal. Intramuscular injections were repeated every 20 min to maintain the anaesthesia (0.15 mg/kg Midazolam, 0.03 mg/kg Fetanyl and 1 mg/kg Fluranison).

Tripolar cuff electrodes (cuff length = 22 mm, inner diameter = 2 mm) were implanted around each of the tibial and common peroneal nerve divisions of the sciatic nerve in the rabbit's left leg. The implantation sites are indicated in Fig. 1. The cuff electrodes were made according to the procedure described by Haugland in [12], except that a straight longitudinal cut was used to open the cuff. The sural nerve was cut just distal to the cuff electrode implanted around the peroneal nerve to exclude the majority of the cutaneous afferent input from the foot. Furthermore, the tibial and peronal nerve branches were cut just proximal the ankle joint to eliminate sensory inputs from the foot. Riso et al. [10] showed that a transection of these nerves and the sural nerve in similar rabbit preparations eliminated neural activity evoked from stroking or tapping the skin. Moving the toes could evoke an afferent response due to stretch of the attatched muscles, but this was avoided in those and in the present studies by the design of the foot fixation. The impedances between the contacts in the tripolar recording cuffs were measured immediately following the implantation and ranged between 850  $\Omega$ –2.3 k $\Omega$  (mean = 1.6 k $\Omega$ ), measured at 1 kHz. The tibial nerve-cuff impedances did not differ from the peroneal nerve-cuff impedances (*t* test, p = 0.47). The rabbit was placed on its right side and the ankle and knee of the left hind limb were each fixed between pairs of concave cups (diameter = 10 mm,  $\theta_{\text{Knee}} = 65^{\circ}$  and  $\theta_{\text{Hip}} = 55^{\circ}$ ). The rabbit's foot was strapped to a rigid shoe lined with a thin cushioning layer of foam rubber. The shoe was attached to the shaft of a servo-motor, which provided rotational movement. We have used this same preparation in our prior studies (see, e.g., [10], [13] and [14]). Additional details of the experimental apparatus can be found in [10].

The nerve signals were amplified (gain 200 000–300 000) and filtered (second order Butterworth-type filter, with cutoff frequencies at 500 Hz and 5 kHz). The neural signals were then sampled at 10 kHz and stored for off-line analysis, where the nerve-cuff recordings were rectified and bin-integrated in successive 100-ms bins. The nerve-cuff recordings showed large variations among the rabbits, which may be explained by differences in the gain and background noise level of the nerve interface. The background response levels of the rectified, bin-integrated electroneurogram (ENG) signals (RBI-ENG) in these experiments ranged between 0.50  $\mu$ V–1.02  $\mu$ V and the peak response levels ranged between 0.94  $\mu$ V–1.88  $\mu$ V. The background tibial nerve response was assessed at the shortest initial muscle length (60°), and the results for the five rabbits were: Rabbit A = 0.51  $\mu$ V, Rabbit B = 0.56  $\mu$ V, Rabbit C = 0.50  $\mu$ V, Rabbit D = 0.74  $\mu$ V, and Rabbit E = 1.02  $\mu$ V. The background peroneal nerve response were similarly assessed at the shortest initial muscle length (120° in this case), and the individual results were: Rabbit A = 0.52  $\mu$ V, Rabbit B = 0.53  $\mu$ V, Rabbit C = 0.99  $\mu$ V, Rabbit D = 0.64  $\mu$ V, and Rabbit E = 0.63  $\mu$ V. The peak response levels were assessed at the longest muscle length (120°) and the peak responses for the tibial nerve were: Rabbit A = 1.13  $\mu$ V, Rabbit B = 1.13  $\mu$ V, Rabbit C = 0.94  $\mu$ V, Rabbit D = 1.88  $\mu$ V, and Rabbit E = 1.23  $\mu$ V. The peak responses for the peroneal nerve were assessed at 60°, and the results were: Rabbit A = 1.05  $\mu$ V, Rabbit B = 1.15  $\mu$ V, Rabbit C = 1.82  $\mu$ V, Rabbit D = 1.04  $\mu$ V, and Rabbit E = 0.98  $\mu$ V. These ranges are comparable to what has been measured in similar animal preparations [9] and in other studies involving human peripheral nerves [3].

The joint position was measured with an optical transducer. The passive torque imposed by the rabbit's foot on the shoe was measured using a strain gauge based transducer. The mechanical signals were sampled at 625 Hz and lowpass filtered at 18 Hz.

#### B. Movement Trials

A series of six identical and symmetrical ramp-and-hold profiles was used to passively rotate the rabbit's ankle joint [see Fig. 1(b)]. The velocity of the rotation was always  $10^{\circ}$ /s and the duration of the hold phases were always 2 s. Each series of six trapezoidal movements was repeated five times at each of seven initial ankle joint positions ( $60^{\circ}$ ,  $70^{\circ}$ ,  $80^{\circ}$ ,  $90^{\circ}$ ,  $100^{\circ}$ ,  $110^{\circ}$ , and  $120^{\circ}$ ). The response of the first of each set of six trapezoidal movements was routinely discarded to avoid response variability caused by nonuniform delays between successive series and thus nonuniform periods when muscle length was unchanged [9]. The responses from the five repetitions at each initial joint position were averaged for the individual rabbits before any further processing took place.

#### C. Data Analysis

To compare the afferent responses at the seven initial joint positions, three epochs were studied during the trapezoidal movement, as shown in Fig. 3(g). The background activity was taken as the mean response over a 100-ms interval beginning 0.1 s before the onset of the ramp. The peak response was defined to be the maximum value of the afferent response located near the transition point between the ramp and the plateau phases. The ramp-hold activity was measured over a 100-ms interval during the stimulus plateau beginning 1.5 s after the peak. The change in steady-state sensitivity of the afferent responses was assessed by subtracting the background activity from the ramp-hold activity. Correspondingly, a measure of the dynamic sensitivity was found by subtracting the ramp-hold activity from the peak response. This is comparable to the method used to evaluate the dynamic index of primary and secondary afferent responses described by Edin and Vallbo [15].

A working range for each of the two nerves was estimated by evaluating the difference between the response peak and the background activity at each position. If the peak response was not at least 10% greater than the background, the joint position was defined to be outside the particular nerve's "working range." To assess if there was any significant difference between the background nerve responses at initial joint positions of 60° and 120°, an analysis of variance test was performed (ANOVA test  $\mu_{60_{\oplus}} = \mu_{120_{\oplus}}$ ) with joint position and rabbits as factors, p < 0.05).

The joint torque was evaluated during the same epochs as described for the afferent responses and we examined if the changes in joint torque could explain the variations in the afferent responses. This was evaluated by fitting linear regression lines between the two variables. The statistical significance of the regressions were then assessed (t test, p < 0.05), and the correlation coefficients were calculated. The correlation is a measure of how well the regression model describes the data, and a measure close to one indicates that the equation is a good description of the relationship between the variables. The statistical analysis was performed using SigmaStat (SSPS Inc., Chicago, IL).

#### **III. RESULTS**

The responses from one rabbit preparation are plotted in Fig. 2. Each trace represents the mean of five successive repetitions of ramp-and-hold perturbations at each of the seven initial positions tested. The joint torque and position are plotted in the top panels (a and b), and the bottom panels show the corresponding tibial and peroneal nerve recordings (c and d). The joint torque was zero when the ankle was placed at approximately 90°. When the foot was passively moved into flexion, the torque became more negative. If the foot was extended passively from this position, the torque increased toward higher positive torque values. In either case, the afferent activity was evoked during the appropriate muscle's stretch phase. When the rabbits foot was flexed, the ankle extensor muscle group was stretched and the peroneal nerve responded. During the return phase when the motion was in the extension direction, the ankle flexor muscle group was stretched and the tibial nerve responded. The tibial and peroneal nerve activity thus behaved in a reciprocal manner, as observed in previous studies (see e.g., [10], [16], and [17]).

## A. Changes in Tibial and Peroneal Nerve Activity to Passive Joint Rotation

The background, the peak and the ramp-hold responses pooled from the five rabbits are plotted in Fig. 3. The tibial and peroneal nerve responses showed qualitatively similar characteristics for a majority of the initial positions. An abrupt increase in the afferent activity occurred at the ramp onset. The activity peaked at the transition point between the ramp and the following hold phase and then gradually decreased throughout the hold phase. An abrupt decrease was observed when the return ramp began after which the afferent activity approximately diminished to the background level that was present before the perturbation was applied. The most salient difference was a pronounced change in amplitude from the most flexed to the most extended position. The afferent activity from the tibial nerve [Fig. 3(a)] showed the highest amplitude at the most flexed initial joint position (60°) and the response decreased in a monotonic fashion as the initial ankle position



Fig. 2. Results of applying the ramp-and-hold perturbation at seven initial joint positions in one rabbit. (a) The four panels show joint torque. (b) Joint position. (c) Tibial nerve recordings. (d) Peroneal nerve recordings. All responses represent the mean of five repetitions at each initial position. The arrows in panel (c) and (d) indicate the intervals examined.

was less flexed (i.e.,  $70^{\circ}$ ,  $80^{\circ}$ ,  $90^{\circ}$ , and  $100^{\circ}$ ). At initial positions of  $110^{\circ}$  and  $120^{\circ}$ , where the afferent responses from the tibial nerve were very weak. The afferent activity from the peroneal nerve [Fig. 3(a)] showed the highest amplitude at the most extended initial joint position ( $120^{\circ}$ ), and the responses also decreased in a monotonic fashion, however, in this case, the afferent responses decreased as the initial ankle position was less extended.

The peak and the ramp-hold afferent responses were clearly influenced by the change of the initial position. For the tibial nerve, the mean peak response increased from the most extended (120°) to the most flexed position (60°) by 88%  $\pm$  42% (mean  $\pm$  standard deviation). For the peroneal nerve, the increase from the most flexed to the most extended initial position was 81%  $\pm$  37%, similar to the change with the tibial nerve. In the case of the peroneal nerve, the highest value for the peak



(g)

Fig. 3. Results of examining the background activity, the peak activity and the ramp-hold activity of the responses to the movement trials. (a) and (b) Results from the tibial and peroneal nerves. (c) and (d) The joint torque is plotted in the middle panels and was evaluated over the same epochs as the nerve signals. (e) Joint torque are plotted against the tibial nerve activity in and (f) plotted against the peroneal nerve activity in for the three phases examined from the movement trials; background, peak, and ramp-hold activity. All traces in panels (a)–(e) represent the mean ( $\oplus$  std) of the pooled data from the five rabbits. (g) The locations where the neural activity measures and the joint torque measures were derived during ankle flexion and ankle extension.

activity occurred just before the most extended initial position was attained, whereas the peak tibial response continually increased throughout the test range. The change in background activity over the same range was smaller, measuring only 10%



Fig. 4. The steady-state and the dynamic sensitivities of the afferent responses to the ramp-and-hold perturbation at the seven initial joint positions. Each panel shows the results from five rabbits (indicated as A, B, C, D, and E). The dynamic sensitivity was calculated as the difference between the peak response and the ramp-hold response. The two top figures show the results from the tibial and peroneal nerve responses, respectively. The steady-state sensitivity plotted in the bottom panels was calculated as the difference between the ramp-hold and the background.

 $\pm$  8% for the tibial nerve and 11%  $\pm$  8% for the peroneal nerve. The changes in mean ramp-hold responses were 49%  $\pm$  50% for the tibial nerve and 60%  $\pm$  22% for the peroneal nerve. The ramp-hold responses behaved similarly to the peak responses, i.e., the peroneal nerve activity halted its rise before the most extended initial joint position was reached, whereas the tibial response continued to increase.

The working ranges of the individual nerves are indicated in the top panels of Fig. 3(a) and (b). The working range for the tibial nerve was  $60^{\circ}-90^{\circ}$ , with a mean range of  $28^{\circ} \pm 15^{\circ}$ . In the case of the peroneal nerve, the range was  $70^{\circ}-120^{\circ}$ , and the mean operating range was  $46^{\circ} \pm 11^{\circ}$ . The overlap between the working range of the tibial nerve and the peroneal nerve was  $14^{\circ} \pm 23^{\circ}$ . The overlap differed among the rabbits, i.e., in one of the preparations the overlap was  $50^{\circ}$ , whereas in two rabbit preparations the working ranges did not overlap at all (working ranges: Rabbit A =  $0^{\circ}$ , Rabbit B =  $20^{\circ}$ , Rabbit C =  $10^{\circ}$ , Rabbit D =  $50^{\circ}$ , Rabbit E =  $0^{\circ}$ ).

#### B. Changes in Passive Joint Torque

The torque responses were evaluated during the same epochs as the nerve responses and the results are plotted in Fig. 3(c) and (d). The torque values all increased over the joint range tested. A correlation between the joint torque and the nerve response during the rotational movement was observed, whereby these parameters increased simultaneously as shown in Fig. 3(e) and (f). We examined if the joint torque could explain the variation in the nerve responses at the three phases during the ramp-and-hold movement, as we suggested to be the case in our earlier studies [9], [10]. This was assessed by testing if there existed a significant linear regression between torque and tibial nerve activity or between torque and peroneal nerve activity, respectively, over the seven initial joint positions. The results showed that the joint torque contributed to the variation in the afferent responses at the movement ramp peak and at the plateau for both the tibial and peroneal nerve recordings (p < 0.05). However, in all cases the correlation was only in the range from 0.23 to 0.53, indicating that the correlation should be interpreted cautiously.

The proposed linear relationship between joint torque and the background responses at each joint position was not significant (p > 0.05). We compared the background nerve activity at the most flexed (60°) and the most extended (120°) initial joint positions to determine if the background activity was modulated over the joint range. The background activity was measured during a 100 ms epoch prior to the ramp onset. Data pooled from all five preparations showed a range of 0.49–1.01  $\mu$ V for the tibial nerve and 0.47–1.09  $\mu$ V for the peroneal nerve at 60°. At 120° the range of the background activity was 0.50–1.02  $\mu$ V for the tibial nerve and 0.91–1.82  $\mu$ V for the peroneal nerve recordings. The background activity for the peroneal nerve was found to be different at the extreme ends of the joint range (p = 0.005), whereas the difference in the background activity for the tibial nerve was found to be just significant (p = 0.051).

#### C. Steady-State and Dynamic Sensitivity

The steady-state and dynamic sensitivities of the tibial and peroneal nerve responses were calculated and the results are shown in Fig. 4. The steady-state sensitivity of the tibial nerve increased in all five rabbits until the most flexed initial joint position was reached. The steady-state sensitivity for the peroneal nerve increased consistently from  $60^{\circ}$  to approximately  $90^{\circ}$ . Above  $90^{\circ}$ , however, some variation among the rabbits was observed. In two preparations (rabbits B and C) the steady-state re-

sponses of the peroneal nerve peaked and then decreased again. In rabbit D the response approached a plateau. Finally, in the two remaining preparations (rabbits A and E) the steady-state response continued to increase.

In four of the five rabbits the dynamic sensitivity of the tibial nerve increased until a certain point (between  $80^{\circ}$  and  $70^{\circ}$ ) whereafter it decreased again. In the remaining preparation (Rabbit E) the dynamic sensitivity increased over the whole range tested. Similarly, the dynamic sensitivity of the peroneal nerve responses first increased when the initial joint position was more and more extended, reaching a maximum value between  $90^{\circ}$  and  $100^{\circ}$ , whereafter the sensitivity decreased again.

#### **IV. DISCUSSION AND CONCLUSION**

In the present study, cuff recordings of afferent activity from agonist–antagonist muscles in acute rabbit preparations were characterized. The rabbit's ankle joint was passively rotated and  $5^{\circ}$  ramp-and-hold perturbations were applied at seven different initial joint positions over a  $60^{\circ}$  range. The most salient observations were that a shift in initial joint position had a pronounced effect on the muscle afferent recordings and the neural activity was evoked only over a part of the joint range tested. The tibial nerve responses increased in amplitude with increasing joint flexion, whereas the peroneal nerve response amplitude increased with increasing joint extension. This increase in amplitude with increased prestretch of the muscle has been observed in our previous studies using similar rabbit preparations [10], [13].

#### A. Range of Responsitivity to Joint Movements

In the present study, we observed a range between  $90^{\circ}$  and 120° where ankle dorsi flexion failed to evoke a response in the tibial nerve recording. An inactive range between  $60^{\circ}-70^{\circ}$ was also identified for the peroneal nerve recordings. This lack of receptor sensitivity may be explained by a state of slackness of the intrafusal muscle fibers. The cross bridges of the intrafusal and extrafusal muscle fibers constantly detach and reform during stretch or contraction of a muscle [6]. Stable cross bridges form within the intrafusal and extrafusal muscle fibers only when the muscle length is maintained constant. An important consequence of this is that slack muscle fibers can occur. Passive muscle fibers, i.e., muscle fibers that are not under the influence of fusimotor activation, are always in a slackened state if they are held short enough and are always taut if they are stretched sufficiently [6]. A 5° ramp-and-hold perturbation applied to the ankle joint at some positions is not sufficient to take up the intrafusal slack so that no mechanical stretch is applied to the spindles and they fail to increase their activity.

### B. Effect of Initial Joint Position on Steady-State and Dynamic Sensitivities

The steady-state position sensitivity has been reported to increase with mean muscle length [5], [18]. In the present study, the steady-state sensitivity of the tibial nerve response continued to increase when the joint was moved toward more flexed positions, whereas the steady-state sensitivity of the peroneal nerve response first increased and then decreased when the joint was moved toward more extended positions.

Studies have demonstrated, that the dynamic response increase with increasing muscle length. A model of spindle afferent responses was proposed by Hasan [20]. Hasan indicated that the dynamic index increased with increasing length of the parent muscle, but the results were not compared with experimental data. Houk et al. [19] examined the dependence of the dynamic response on muscle length and velocity and showed that the dynamic responses increased with increasing muscle length. In the present study, the dynamic sensitivity increased until a certain point, whereafter the sensitivity decreased (the peroneal dynamic sensitivity increased in three of five rabbits and the tibial dynamic sensitivity increased in four of five rabbits). The increase in dynamic sensitivity over part of the joint range correspond with the observations by Houk et al. [19]. The angular position at which the peak sensitivity occurred appeared to be slightly different among the five preparations. However, this might be because of the fact that we took data only at  $5^{\circ}$ steps so that the actual positions of the peak sensitivities could have been slightly more or less than the sampled positions.

### C. Effect of Joint Position on Passive Joint Torque and Muscle-Tendon Length

Significant linear relationships between the joint torque and both the peak and the ramp-hold afferent responses were shown in the present study. The correlations were low, however, indicating that other factors influence the recorded activity. Factors that may contribute to the nonlinear modulation of the ENG responses with joint position are as follows. First, a given length change of the muscle-tendon unit is not transferred equally to the muscle and to the tendon rather the distribution depends on the current tension. This was examined in rabbit soleus muscles by Herbert and Crosbie [21] who showed that at very low tensions, the tendons undergo large strains in comparison to the muscle fiber length changes. Conversely, at high tensions, the tendon contribution to the total length change of the muscle-tendon unit is smaller than that of the muscle fibers. The intrafusal fibers, where the spindle afferent endings are located, therefore, do not experience a linear length change over the complete joint range. Second, Young et al. [22] showed that for the ankle joint in the cat, the moment arms of the attached muscles change with joint angle. In the case of the soleus and the tibialis anterior muscles, the moment arm is largest in the mid range of the joint and decreases at the extremes of the joint movement. If the moment arm decreases at the extremes of the joint range, this implies that the change in muscle length also decreases with joint rotation away from the mid position. Third, a 5° rotation applied to the ankle joint does not produce the same length change in the lateral gastrocnemius (LG) and tibialis anterior (TA) muscles at the seven initial joint positions. The mean length change of the LG was estimated to be 2.4 mm  $\pm$  0.2 mm (standard deviation) using trigonometric calculations. The length change was 2.47 mm at 60°-70°, 2.58 mm at 70°-80°, 2.61 mm at 80°-90°, 2.56 mm at 90°–100°, 2.43 mm at 100°–110°, 2.24 mm at 110°–120°, and 2.00 mm  $120^{\circ}$ -130°, total length change = 16.89 mm. The moment arm of the LG was taken to be 15 mm (measured in one rabbit preparation). The length of the tibia bone was set to 134 mm (the mean and standard deviation of the five rabbits in the present experiments was 134.3 mm  $\pm$  16.7 mm). These actions may explain the decrease in dynamic sensitivity which we observed at the extremes of the joint range since the relative change in the length of the studied muscles would not have been as great when the 5° perturbation was applied at the extreme positions of the joint range verses the middle range.

#### D. Muscle Afferent Feedback in FES Control

This study shows that the muscle afferent recordings provide qualitative information on flexion-extension of the ankle joint, which is consistent with earlier results (see [9] and [10]). The sensory information from the muscle afferents, however, may only be available over a portion of the physiological movement range in a passively rotated joint. In three of the five rabbit preparations in the present study, there existed a common joint range where both the tibial and the peroneal nerve activities were influenced concurrently. This overlap between the defined working ranges of the afferent responses recorded from the tibial and peroneal nerves was in mean 14°. During the experiments the knee joint was fixed between pairs of concave cups in the position that yielded a passive torque close to zero around the ankle. The hip angles and knee joint were adjusted to be as uniform as possible for each experiment, however, the hip and knee joint angles were positioned by the experimenter only with reference to a protractor. Placement of the knee and the hip joint angles could cause variability in the initial length of the muscles and joint torque, which may explain the differences in the working ranges observed among the rabbits. Since the use of a neuro-fuzzy model to extract quantitative information from the whole nerve-cuff recordings requires reliable information from both signals [11], closed-loop control of paralyzed muscles based on feedback from muscle afferents, may be useful only within a narrow range of joint movement such as is the case with sway during paraplegic FES standing.

It may be argued that the ramp-and-hold movements that we employed do not occur during natural movements, and thus the results obtained may not be directly applicable for FES. The movement profiles that we employed, however, are within the limits of what was observed in quiet standing of normal subjects (see [20], [21]) and in FES assisted standing of a paraplegic subject (see [13] and [22]). The kinematics of the perturbation applied to the rabbit's ankle joint in the present study, therefore, correspond to the kinematics of the type of movements we ultimately want to control.

Another issue concerns the fact that amount of fusimotor drive to the muscles below the level of lesion in spinal cord injured subjects is not known, and this may impact the neural activity. Ongoing work in our laboratory includes the development of methods to extract feedback control signals from the muscle afferent information using both artificial neural networks [23] and neuro-fuzzy approaches [11]. The preliminary outcomes are encouraging, however, validation studies on control of the ankle joint position in rabbits still have to be performed.

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**Thomas Sinkjær** (M\*84), photograph and biograph not available at the time of publication.