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Characterization of the motor units of the external anal sphincter in pregnant women with multichannel surface EMG

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ABSTRACT

Introduction. Locating the innervation zones (IZs) of the external anal sphincter (EAS) is helpful to obstetricians to identify areas particularly vulnerable to episiotomy in pregnant women. The aim was to investigate the motor unit (MU) properties of the EAS during voluntary contractions.

Methods. EMG signals were detected, from 478 pregnant women, by means of an intra-anal cylindrical probe carrying a circumferential array of 16 electrodes. The signals were decomposed into the constituent MU action potential trains and 5947 templates were extracted and analyzed in order to identify the IZ position.

Results. MUs innervated at one end are concentrated in the dorsal portion of the sphincter, while MUs innervated in the middle are distributed symmetrically in the left and right portion of the EAS. The angular propagation velocity wasestimated for each MU resulting in 260±45 rad/s, corresponding to 1.8 m/s on the probe surface and to about 4 m/s at a radial depth of 10mm from the probe surface.

Conclusions. A novel method for identification and classification of MUs of the EAS is proposed and applied to a large-scale study. It is possible to distinguish MUs of the EAS in a minimally invasive way and identify their IZs. This information should be used to plan episiotomies and minimize risks of EAS denervation.

INTRODUCTION

Childbirth is one of the major risk factors for anal incontinence in women (Sultan et al., 1993; Sartore et al., 2004). In healthy young women, the occurrence of anal sphincter tears at vaginal delivery is the most common precursor of faecal incontinence and could be a cause of subsequent pelvic dysfunction. Women with anal sphincter lacerations are more likely to report postpartum faecal incontinence than women without sphincter tears (Borello-France et al., 2006). Anal sphincter lacerations occur in 2–19% of vaginal deliveries (Fenner et al., 2003). In addition, lack of recognition immediately post delivery can occur because of blood and tissue edema, and a lack of training in the clinical identification of muscle tears.

The reduction of the external anal sphincter (EAS) muscle thickness following child delivery is likely a consequence of denervation due to pudendal nerve damage. Quantitative needle EMG has been used in a limited number of studies (Podnar et al., 2000; Gregory et al., 2008) because of the large variability of the results and of the pain that is involved.

The surface EMG signal is the summation of electrical contributions from individual muscle motor units (MUs) detected with minimally invasive electrodes (rectal probes) as opposed to needles.

The most used montage for surface EMG signal detection is the bipolar configuration, which records the difference between signals detected by two electrodes placed over the same muscle at a certain distance from each other, usually along the fiber direction. This detection modality has been used in many studies for the assessment of the EAS functions, with a variety of electrode shapes, sizes, and locations. The considerable improvement in EMG acquisition technology of the last decades allows at the moment the detection of EMG signals with large 2D electrode arrays from skeletal muscles (Prutchi 1995; Lapatki et al., 2006; Holobar et al. 2009; Merletti et al., 2010).

Three-dimensional (3D) intra-anal ultrasound scans and Magnetic Resonance Imaging (MRI) are the most commonly used techniques that provide detailed images of the anatomy of the pelvic floor. The anatomical images obtained with these techniques, however, do not provide any indication about sphincter innervation. Recent signal processing techniques allow the extraction of information regarding innervation zone location from multichannel EMG signals (Cescon et al., 2013).

Visual identification of innervation zone (IZ) distribution was observed to be repeatable between measurements performed in different days (Enck et al., 2010). Preliminary clinical assessment indicated that it is possible to identify the IZs of the EAS and PR muscles and study their asymmetry through electrophysiological observations (Cescon et al., 2008; Merletti et al., 2004). Very large inter-individual variability has been observed. No standard innervation pattern has been found (Enck et al., 2004). Lesions of nerve fibers innervating the EAS are common during childbirth and are caused either by spontaneous lacerations or surgical interventions such as episiotomy. Depending on the innervation modalities of the sphincter, the consequences of episiotomy or laceration may be very different. No study exists on the IZ distribution in nulliparous women. Knowledge of such innervation pattern would reduce the likelihood of damage by guiding the incision away from the IZs, when possible.

The aim of the present study is to investigate the motor unit (MU) properties of the external EAS of nulliparous pregnant women during voluntary contractions.

MATERIALS & METHODS

Subjects

Four hundred seventy eight pregnant women participated to the study. Mean and stand. dev. of age, weight , height and duration of gestation where 30 ± 9 years, 70 ± 8 kg, 165 ± 9 cm, 31 ± 2.5 weeks respectively. Nine clinical partners from five European Countries (Germany, Italy, Latvia, Slovenia, Ukraine) were involved in the study. Each clinical partner obtained the approval from the local ethical committee. The inclusion criteria were: nulliparous, no episodes of anal incontinence before pregnancy, no previous pelvic disorders, no presence of neuropathies affecting pelvic innervation, no planned Caesarean section, no 3^{rd} degree hemorrhoids. Each subject was informed about the study protocol and gave written informed consent prior to the test.

EMG signal detection and Acquisition System

Signals were detected using the rectal probe shown in Figure 1a. The probe is a plastic support of 14 mm diameter holding a flexible printed circuit with 16 equally spaced electrodes. During the EMG measurements each subject was sitting in a gynecologic chair with legs spread while a trained doctor or midwife was holding the EMG probe in place. The probe was inserted in the anal canal in order to have the electrode array in correspondence of the anal verge. The orientation of the electrodes was always the same, with the midline between the first and the 16^{th} electrode in ventral position (Figure 1e).

Three acquisitions of 10 seconds were performed without the subject contracting the sphincter (Rest) with two minutes pause in between. The subjects were then asked to perform three maximal voluntary contractions (MVC) of the EAS for 10s. The MVCs were preceded and followed by phases of progressive increase and decrease of contraction force (up and down ramps) of 5s each in order to avoid movement artefacts due to sudden force changes.

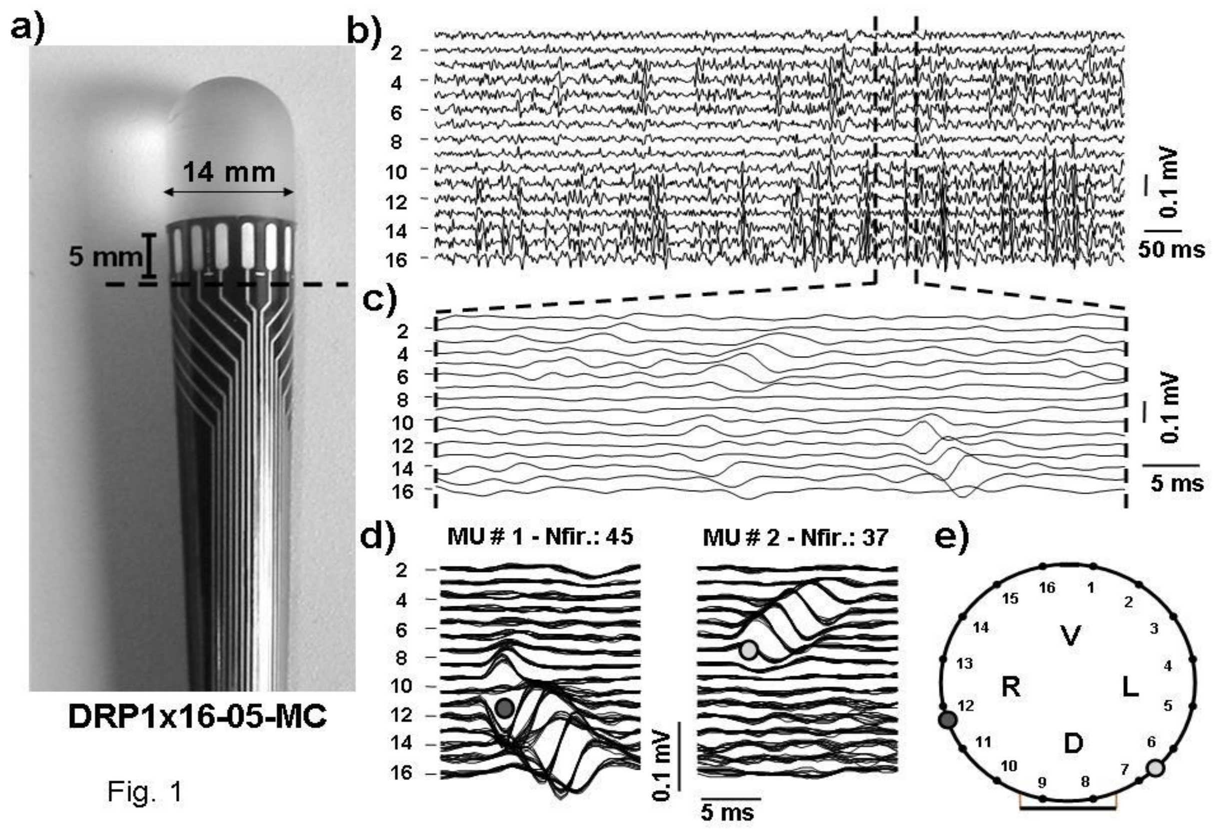

Fig. 1

Figure 1. a) *Probe used for EMG measurements on the external anal sphincter. The probe is composed of 16 silver electrodes equally spaced around the circumference of a plastic support.* ***b, c)*** *Example of EMG signals detected in single differential mode.* ***d)*** *Two motor units identified with the CKC decomposition algorithm. Nfir = number of firings (superimposed).* ***e)*** *Representation of the position of the electrodes along the probe circumference (**V:** Ventral, **D:** Dorsal; **R:** Right, **L:** Left) and location of the two innervation zones of MU#1 and MU#2 (gray and black circles).*

The 16 surface EMG signals were acquired in single differential derivation (Figure 1b,c) with an EMG-USB amplifier (LISiN and OT-Bioelettronica, Torino, Italy, with gain variable from 100 to 10,000 in seven steps, 10-500 Hz 3dB bandwidth, roll-off of 40 dB/decade, noise level lower than 1μV_{RMS}), sampled at 2048 Hz, and stored on a PC after 12bit A/D conversion. Slow signals produced by active smooth muscles (if any) were rejected because of the high pass filter at 10 Hz.

Signal Processing

Single MUAPs (Figure 1d) were identified from surface EMG signals detected during rest and during MVC by the decomposition method based on the Convolution Kernel Compensation (Holobar et al., 2007). Such a method has already been applied to EMG signals from EAS muscle and proved to be robust to noise, allowing the identification of up to 10 concurrently active MUs (Holobar et al., 2008). The IZCorr2 algorithm (Cescon, 2006; Cescon et al., 2013) was applied to the MU templates to identify the innervation zone of each motor unit (Figure 2a). The algorithm is based on the bidimensional correlation between the MU template and its mirrored versions. The parameters extracted for each identified MU template were: peak amplitude (PK), angular conduction velocity (CV), innervation zone position (IZ position), innervation zone position as a percentage of the MU length, (IZ perc), and MUAP width (W). The procedure to compute the MUAP width from a template is performed as follows: The channels where the MUAP is present are identified with the IZCorr2 algorithm (Cescon et al., 2013). For each channel the MUAP width is computed as the width of the signal portion including 50% of the ARV of the template ând the average of these widths is W. The parameters extracted for each identified MU firing pattern were: minimum firing rate (min FR) and maximum firing rate (max FR). The procedure to compute min FR and max FR is performed as follows. The spline curve passing through the points corresponding to the instantaneous firing rates was computed and then filtered with a low-pass Butterworth anticausal filter (2^{nd} order, cut-off frequency 0.5 Hz) in order to reduce the bias due to the presence of instantaneous discharges with high firing rate (real doublets or errors in the decomposition algorithm). The minimum and maximum values of the filtered curve were the min FR and max FR respectively.

The motor units were divided, by the IZCorr2 algorithm, in two groups according to the position of the innervation zone along the fibers: Unidirectional: when the innervation zone was at one extremity of the MU length: Bidirectional: when the IZ position was between the two fiber ends. Unidirectional MUs were divided in two groups: with clockwise propagation and counterclockwise propagation.

RESULTS

In total 7980 MUs (4384 during rest and 3596 during MVC) were identified in the 478 subjects and correspond to approximately nine and seven MUs per subject for rest and MVC respectively. The number of active and detectable MUs is a fraction of the total number of MUs active in the muscle. Some of the MUs detected in repeated contractions are the same, some are not.

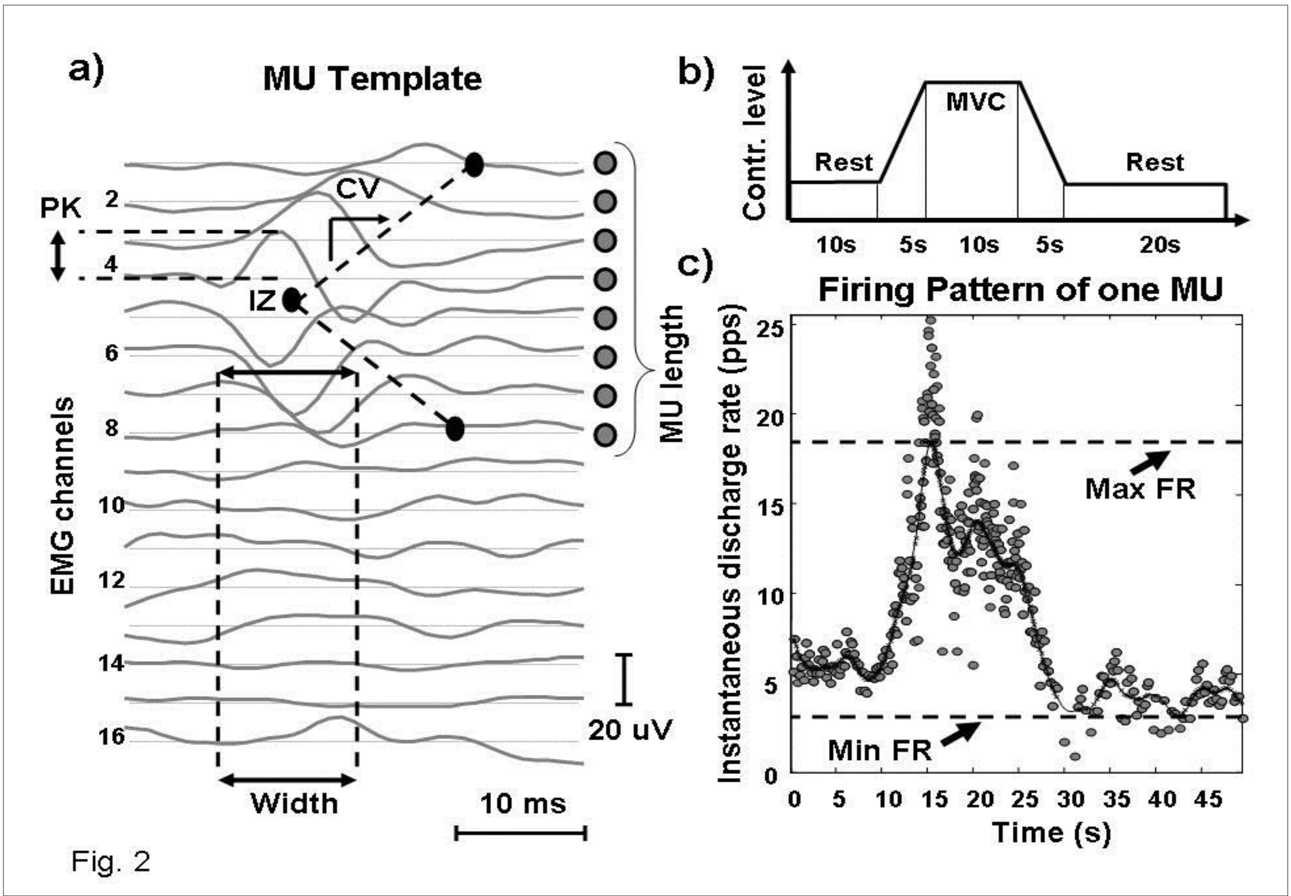

Figure 2. ***a)*** *Example of a MU template and representation of extracted parameters: MUAP Width (see text for definition) , Conduction Velocity, Peak amplitude, MU Length, IZ position,* ***b)*** *pattern of contraction level required to the subject,* ***c)*** *Firing pattern of the MU (see text for definition) represented in* ***a)*** *and representation of extracted parameters. Minimum and maximum firing rate are indicated (see text for definition).*

The decomposition algorithm was applied to the signals of the six acquisitions (three Rest and three MVC) and the
results were merged in order to count only one time a MU identified in more than one acquisition. The decomposition algorithm identified 5947 different MUs in total (3199 during rest and 2748 during MVC). 43% of the MUs were classified as unidirectional by the IZCorr2 algorithm.

The distribution of the IZ of the identified MUs are shown as circular histograms in Figure 3. The mean, and standard deviation of the parameters extracted from the total group of identified MUs are shown on Table 1.

Table 1. Descriptive statistics of the 5947 MUs in total
(3199 during rest and 2748 during MVC)

Variable	**REST**	**MVC**
	Mean ± St. Dev	**Mean ± St. Dev**
Peak amplitude (μV)	38 ± 16	86 ± 31
Length (rad)	2.1 ± 0.7	1.9 ± 10
MUAP Width (ms)	5.6 ± 2.1	5.2 ± 1.8
CV (rad/s)	247 ± 87	293 ± 59
Minimum Firing Rate (pps)	3.9 ± 1.6	8.3 ± 3.5
Maximum Firing Rate (pps)	5.4 ± 2.1	16.2± 6.8

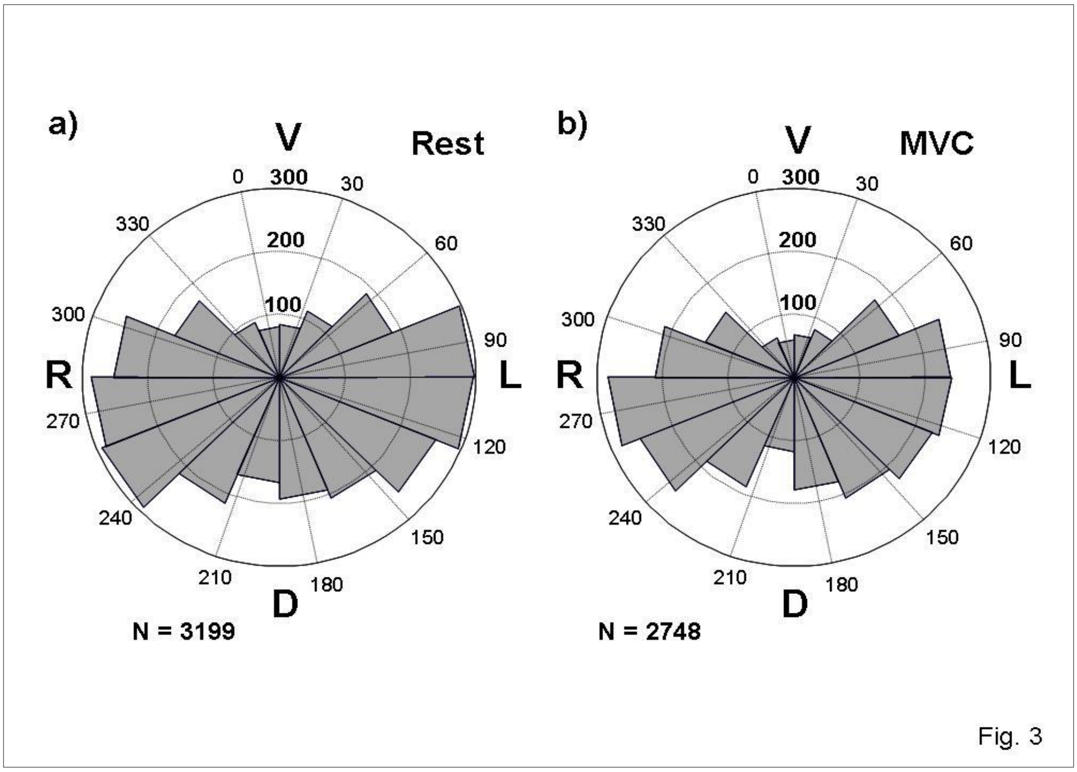

Figure 3. *Circular histograms of the IZ of the MUs identified during Rest and during MVC conditions (panels* ***a)*** *and* ***b)*** *respectively). The radial height of each bin corresponds to the number of MUs that are innervated under the corresponding electrodes considering all 478 subjects (3199 motor units during rest and 2748 during MVC).*

Figure 4 shows the scatter plot of peak amplitude of MUs versus IZ position. Unidirectional and bidirectional MUs are shown in separate panels to underline the differences between the two populations of MUs. The IZs of the unidirectional MUs are mostly concentrated under electrodes 6-12, in the dorsal portion of the sphincter, while the bidirectional MU's innervations show a bimodal distribution with peaks under electrodes 3-8 and 9-14.

Figure 5 summarizes the spatial distribution of IZ of unidirectional and bidirectional MUs identified during Rest and during MVC respectively. As shown in figure 3 and 4 the innervation of bidirectional MUs is approximately in the middle of the two hemi sphincters, confirming anatomical studies, while unidirectional MUs are innervated mostly in the dorsal position.

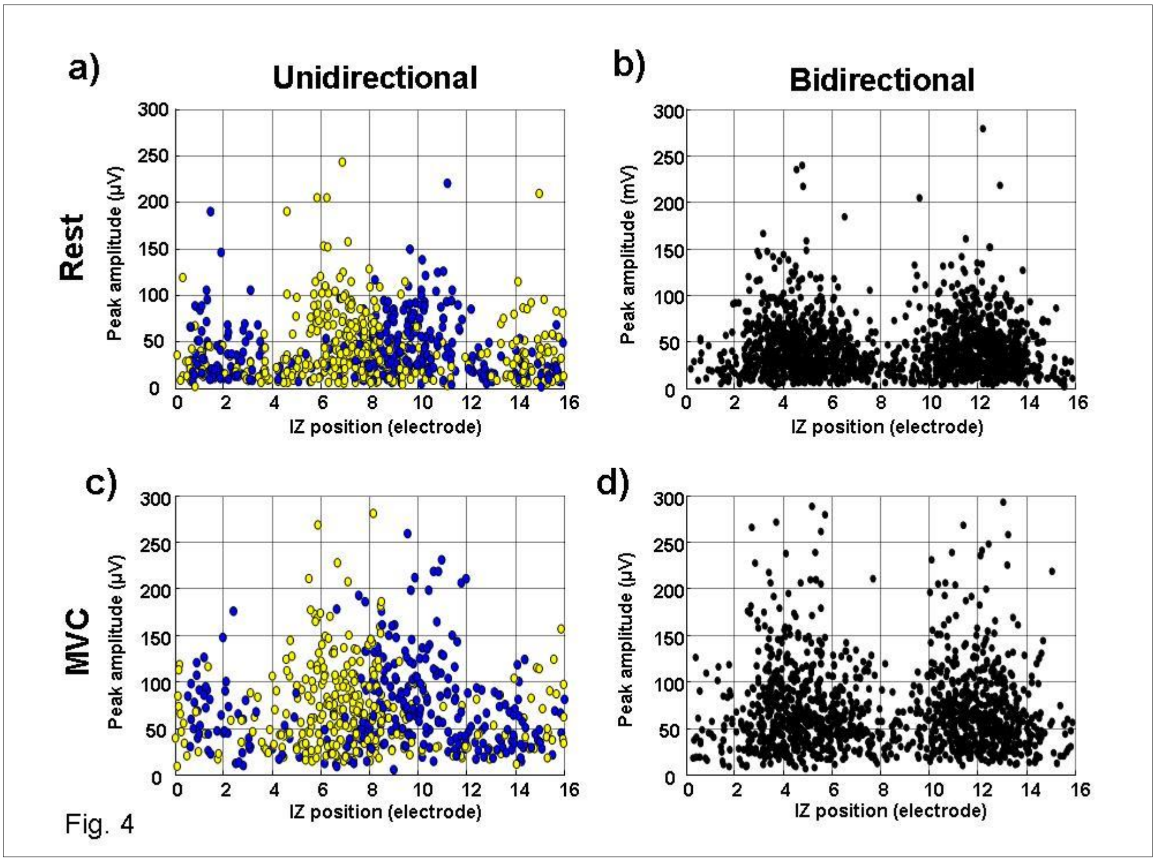

Figure 4. *Scatter plot of MU peak amplitude with respect to MU innervation positions along the probe electrodes for unidirectional and bidirectional MUs during rest (panels **a)** and **b)** respectively) and during MVC (panel **c)** and **d)** respectively). The x-axis represents the MU innervation positions along the probe electrodes. Unidirectional MUs (panels **a)** and **c)** were separated in two groups: 1) showing clockwise propagation (dark circles) and 2) showing counterclockwise propagation (light circles).*

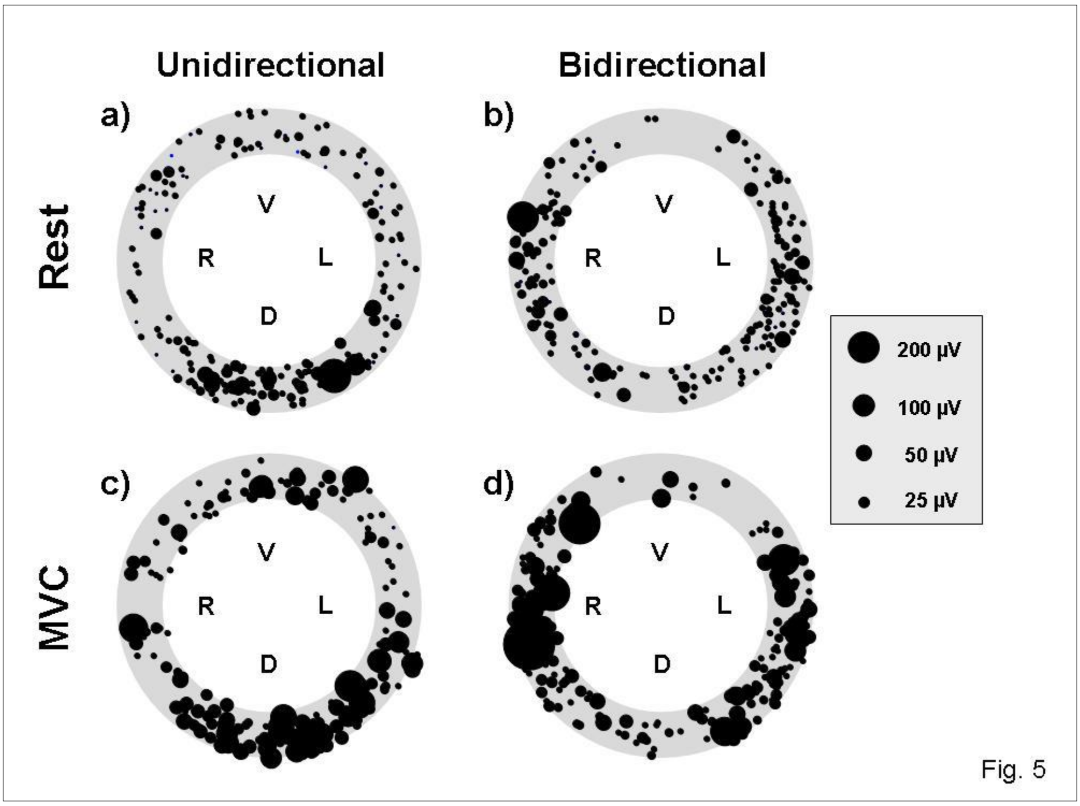

Figure 5. Distribution of the innervation zones in the external anal sphincter for unidirectional and bidirectional motor units during rest (panels **a)** and **b)** respectively) and during MVC (panel **c)** and **d)** respectively). The size of the circles represents the range of amplitude of the motor unit action potential. (**V:** Ventral, **D:** Dorsal; **R:** Right, **L:** Left)

DISCUSSION

Limitations and weaknesses of the study.

The number of different MUs that can be identified by the CKC decomposition algorithm in repeated EAS contractions is about 5-6 either during rest or during MVC. This is a relatively small fraction of the total number of motor units of the EAS, which is likely much higher (but currently unknown). According to the Hennemann recruitment principle the MUs which are active during rest should be the smallest and be active also at higher contraction levels. With increasing number of active MUs the surface EMG signal becomes more interferent, thus the MUs with small action potentials are hidden by the MUs with larger amplitude and may not be detected any longer.

This is the reason why the analysis was conducted at two contraction levels (Rest and MVC) and, in general, the MUs identified at the MVC were not those identified at rest.

Strengths of the study.

This study considerably extends previous works (Enck et al 2004, Merletti et al 2004, Enck et al. 2010) and presents new findings concerning the innervation of the EAS in women, providing a basis for the pre- and post-partum investigation presented in the companion article.

The distributions of IZs of unidirectionally and bidirectionally propagating MUs are clearly different. Some MUs with unidirectional propagation might belong to the puborectalis (Cescon et al., 2008) and the smallest unidirectional MUAPs detected by the probe might be due to crosstalk from this muscle. This issue requires further investigation.

The unidirectional MUs showed potentials propagating in clockwise direction on the right side and counter clockwise direction on the left side of the anal canal according to the propagation of potentials observed in previous studies (Cescon et al., 2008) from the puborectalis muscle. Many MUs are symmetrically innervated in the middle portion of the two hemi-sphincters and their action potentials propagate in two directions, while others are innervated dorsally and have unidirectional propagation of action potentials.

The minimum discharge rate of the identified MUs is lower than in other muscles and is similar for unidirectional and bidirectional potentials.

The angular propagation velocity of about 250 rad/s corresponds to a peripheral propagation velocity of 2m/s at the surface of the probe and of ~4m/s at a radial distance of about 5-10 mm from the probe surface, in agreement with anatomical studies.

Unanswered questions and future research.

The results presented in this work have applications in the study of the effect of episiotomy and other interventions in either male or female subjects on EAS denervation and re-innervation processes. Applications in EMG biofeedback for strengthening voluntary control of the EAS provide material for further research. The issue of cross-talk between pelvic floor muscles remains to be investigated.

CONCLUSION

The MUs of the EAS were analyzed and characterized in a large scale study, for the first time, using a minimally invasive multichannel intra-anal probe. The anatomical and electrophysiological properties were described both during rest and during MVC. Individual MUs of the EAS can be identified with multichannel EMG obtained from the disposable intra-anal probe.

The location of the IZs of motor units innervated in the middle and showing bidirectional propapagation is distributed symmetrically in the two hemi-sphincters. The location of the IZs of MUs showing innervation at one end is mostly dorsal and ventral. The probability of finding innervations in the right or left hemi-sphincter is about the same, while IZs are more likely in the dorsal rather ventral portion of the EAS. The distribution of IZs shows a very high intersubject variability, confirming previous results (Enck et al., 2004). The information concerning the innervation of a specific individual could be useful to obstetricians to choose the side with fewer IZs (for the specific subject) where to perform episiotomy, when necessary, with minimal risk of EAS damage.

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