Journal of Sex & Marital Therapy, 38:418–435, 2012
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ISSN: 0092-623X print / 1521-0715 online
DOI: 10.1080/0092623X.2011.606887

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Neural Correlates of Sexual Arousal in the Spinal Cords of Able-Bodied Men: A Spinal fMRI Investigation

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The purpose of this study was to determine whether spinal cord functional magnetic resonance imaging could be used to map neural activity throughout the lower thoracic, lumbar, and sacral spinal cord regions during sexual arousal in healthy men. The authors found that viewing erotic films and genital self-stimulation elicited predominantly increased signal, indicative of amplified neuronal input to the dorsal and ventral horns and in the autonomic preganglionic nuclei of the lower thoracic, lumbar, and sacral spinal cord. In addition, linear regression analyses revealed a number of robust correlations ($|R| \geq 0.7$) between signal intensity changes in these spinal cord regions and self-reported ratings of mental and physical sexual arousal. Taken together, these results demonstrate that spinal cord functional magnetic resonance imaging is an effective and sensitive technique for mapping the neural correlates of sexual arousal in the spinal cords of able-bodied men. Most important, the results from this study indicate that spinal cord functional

This project was funded by the Craig H. Neilsen Foundation, The Canada Research Chairs Program, and the Canadian Institutes of Health Research Canada Graduate Scholarships Program.

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magnetic resonance imaging may have important applications as a clinical tool for assessing and mapping the changes that occur in the spinal cords of men suffering from sexual dysfunction as a result of spinal cord trauma.

Current knowledge of the spinal cord mechanisms regulating sexual responses in able-bodied men is remarkably incomplete, and the effects of spinal cord trauma on sexual function are even less understood. It is known that the spinal cord is the site of centrally mediated control of sexual function, including erection and ejaculation in male rodents (McKenna, 2000; Pescatori et al., 1993; Rampin, Bernabe, & Giuliano, 1997; Truitt & Coolen, 2002), canines (Lue, Schmidt, & Tanagho, 1985; Miyamoto, Yonezawa, Tadano, Kisara, & Kimura, 1986), and men (Sipski, 1998). Moreover, in men, spinal cord trauma (SCT) typically leads to devastating deficits in erectile and ejaculatory control, indicating that an intact spinal cord is required for normal sexual functioning (Chapelle, Durand, & Lacert, 1980; Comarr & Gunderson, 1975). However, the inaccessibility of the spinal cord in humans presents a significant challenge for research into how sexual responses are controlled. Here, we present a new method for studying sexual responses in the intact human spinal cord, on the basis of functional magnetic resonance imaging (fMRI), and demonstrate its effectiveness for detecting areas of the cord involved with different aspects of sexual arousal in a group of healthy male volunteers.

At present, the majority of knowledge regarding the spinal cord control of sexual function in healthy men is derived from studies in rodents and clinical assessments of men after having experienced SCT. On the basis of this body of knowledge, the sympathetic preganglionic neurons in the thoracolumbar spinal cord mediate *psychogenic* (mentally derived) penile erection in men after experiencing SCT but are believed to be primarily antierectile in healthy men (Giuliano & Rampin, 2000). A decrease in the ability to perceive sensation in the thoracolumbar segments (T11-L2) correlates with a decrease in psychogenic penile erection in men after having experienced SCT. The cell bodies of these sympathetic neurons modulating psychogenic penile erection are localized to the dorsal commissural nucleus and the intermediolateral cell column of segments T11-L2 of the spinal cord (Giuliano & Rampin, 2000). In contrast, *reflexogenic* penile erection in men after having experienced SCT is believed to be modulated by parasympathetic preganglionic neurons, which are thought to be pro-erectile in healthy men (Giuliano & Rampin, 2000). The cell bodies of these parasympathetic preganglionic neurons are localized to the sacral parasympathetic nucleus in the sacral spinal cord (S2-S5). It is not surprising that trauma to the sacral segments (S2-S5) affects parasympathetic transmission regulating sexual function and, as a result, diminishes physically evoked (reflexive) penile erection (Johnson, 2006; Sipski, 1998; Sipski, Alexander, Gomez-Marin, & Spalding, 2007).

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Although clinical studies of men after having experienced SCT provide invaluable insights into the spinal cord mechanisms that control sexual responses in able-bodied men (Chapelle et al., 1980; Comarr, 1970; Comarr & Gunderson, 1975; Courtois, Charvier, Leriche, & Raymond, 1993; Courtois, Goulet, Charvier, & Leriche, 1999; M. Sipski et al., 2007; Sipski, Alexander, & Gomez-Marin, 2006), their conclusions are limited by indirect measurements of neurological function in the spinal cord (pinprick sensation tests) that are further confounded by the presence of considerable variability in the extent and level of injuries studied. Similarly, deducing the neuronanatomical and neurophysiological correlates of sexual function in healthy humans from animal studies is complicated by interspecies differences that exist between rodents and humans. More important, SCT-induced neuroplasticity has been observed in the human brain (Henderson, Gustin, Macey, Wrigley, & Siddall, 2011) and likely also alters the structure and function of spinal cord centers salient to sexual responses in men after having experienced SCT. Therefore, it becomes increasingly difficult to study the neural correlates of sexual responses in the intact spinal cord on the basis of neurological assessments of men after having experienced SCT alone. Instead, healthy, able-bodied men without a history of sexual dysfunction must be studied directly to investigate the neural responses associated with sexual arousal in the intact spinal cord. In turn, improved understanding of the spinal cord neurophysiology pertinent to sexual function in healthy individuals will provide important information about the changes that occur in spinal cord function and the accompanying alterations in sexual responses in men after having experienced SCT.

Before the advent of fMRI (Menon et al., 1992; Ogawa et al., 1992) and its specific adaptation for use in the spinal cord (Kornelsen & Stroman, 2007; Stroman, Kornelsen, & Lawrence, 2005), noninvasive in vivo studies of sexual responses in the human spinal cord were not possible. However, owning to recent methodological advances (Leitch, Figley, & Stroman, 2010), the goal of this study was to use spinal cord fMRI to noninvasively visualize the neural responses associated with sexual arousal in the spinal cords of healthy men. Given the importance of the thoracolumbar and sacral regions of the spinal cord to male sexual function, as evidenced from studies in rodents and in men who have experienced SCT, we hypothesized that these spinal cord regions would show changes in signal intensity in response to sexual stimuli in able-bodied men. In particular, we expected to observe fMRI signal intensity changes (ΔS) in the intermediolateral cell column and dorsal commissural nucleus in response to visual erotic cues and in the sacral parasympathetic nucleus and dorsal gray commissure in response to genital self-stimulation. To test these hypotheses and determine which particular regions/nuclei of the spinal cord show signal changes in response to different types of sexual stimuli, we divided the study into two sequential components. The two parts of the study were designed to target regions of the spinal cord

involved in (a) viewing erotic films and (b) genital self-stimulation, for the purpose of investigating the psychogenic and reflexogenic components of the human sexual response, respectively.

To examine the relation between ΔS in the spinal cord and sexual function in men, we performed voxelwise correlation analyses between measures of sexual function and maps of mean percentage signal intensity changes. The measures of sexual function included reported levels of physical and mental sexual arousal. Similar regression analyses have been performed previously, for example, between perceived sexual arousal and regional cerebral blood flow in the brain (Redoute et al., 2000). Here, we show, for the first time, specifically which regions of the spinal cord are activated in response to distinct components of sexual arousal in healthy men. In addition, this spinal fMRI study provides valuable insight into the individual differences of sexual arousal in able-bodied men, giving rise to potential applications of spinal fMRI as a clinical tool for the assessment of altered spinal cord function in men presenting with sexual dysfunction.

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METHODS

Study Participants

Participants were 10 healthy men recruited from the local community who gave informed consent. The study was approved by the Queen's University Health Sciences Research Ethics Board. Of these volunteers, 8 were heterosexual and 2 were homosexual, with a mean age of 22.1 ($SD = 4.2$ years). All but 1 participant completed a medical/sexual history checklist and the International Index of Erectile Function (Rosen et al., 1997). The participants had no history of (a) sexual dysfunction or (b) central nervous system injury or disease, and all underwent screening before testing to ensure that they generally found erotica to be sexually arousing and were comfortable with genital self-stimulation.

Study Design

Studies on fMRI have been carried out in the Queen's University MRI facility, with a 3 Tesla MRI system (Magnetom Trio, Siemens, Erlangen, Germany). Lying in the supine position on top of the MRI phase-array spine coil, each participant was carefully aligned, and the initial imaging volume was centered at the base of the xiphoid process, approximately at the T12 vertebra. Visual stimuli, including written instructions and videos, were projected onto a screen located outside of the MRI system and were visible to participants in an overhead mirror. We used an optical sensor, attached to the second digit of the nonstimulating hand of each volunteer, to record the peripheral pulse throughout the study. We acquired initial localizer images in three planes

(sagittal, coronal, and transverse), followed by higher resolution coronal and sagittal images to determine the proper slice alignment and positioning for the subsequent fMRI studies.

Functional Imaging Protocol

We carried out fMRI in the spinal cord using the Signal Enhancement by Extravascular Water Protons contrast (Figley, Leitch, & Stroman, 2010; Stroman, Kornelsen, Lawrence, & Malisza, 2005; Stroman, Lee, Pitchers, & Andrew, 2008). Therefore, all functional imaging data were acquired by means of a proton-density-weighted, half-Fourier single-shot fast spin-echo sequence (Stroman, Figley, & Cahill, 2008) to image the lower thoracic, lumbar, and sacral spinal cord with a resolution of (1.5 mm × 1.5 mm × 2 mm), in nine contiguous 2-mm sagittal slices. The images spanned a 280 mm × 140 mm field of view (head/foot × anterior/posterior) centered at the T12 vertebrae and encompassed the seventh thoracic (T7) to the fourth lumbar (L4) vertebral bodies. The echo time was 38 ms and the repetition time was 9 s (i.e., 1000 ms per slice). A spatial saturation pulse was applied to eliminate signal from regions anterior to the spine, and flow compensation gradients were applied in the head/foot direction to reduce image artifacts produced by flow of cerebrospinal fluid. With these acquisition parameters, the 3D volume spanning the lower thoracic, lumbar, and sacral spinal cord was imaged every 9 s to measure the signal time course in response to each stimulus paradigm. After conducting the fMRI scans, we acquired high-resolution (1 mm × 1 mm × 2 mm) T1-weighted anatomical images with an inversion-recovery turbo spin-echo pulse sequence (echo time = 12 ms; repetition time = 2 s; number of averages = 2).

Stimulation Paradigms

The study consisted of two sequential parts. The first part of the study involved audiovisual stimulation (AVS) and was designed to detect spinal cord activity in response to viewing erotic films. The films, depicting heterosexual couples engaged in sex play, vaginal sexual intercourse, and oral sex, were presented in two 5-min blocks, separated by a baseline condition (blank screen) for 3 min. Because the stimulation blocks were also preceded and followed by two baseline conditions of 1.5 min each, the AVS paradigm lasted 16 min (Figure 1A). The selected films were chosen by the investigators and were all very highly rated (on a scale of 1 to 10) by independent viewers. Only films that received a minimum score of 8 out of 10 were shown to participants. The homosexual and heterosexual men were shown the same erotic films to maintain consistency of the visual stimuli. This fact is not expected to confound the results of the study as the heterosexual and

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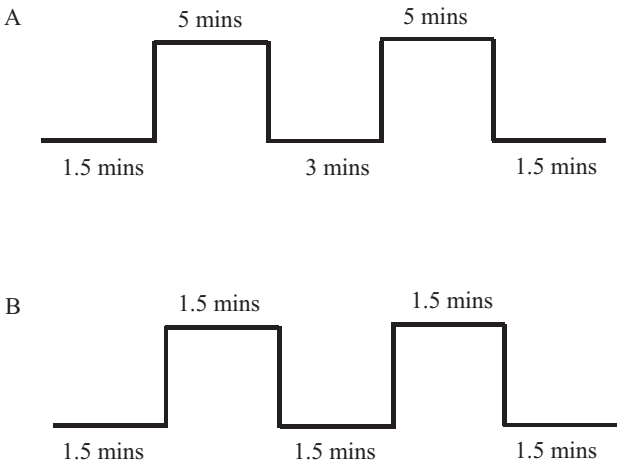

FIGURE 1. Experimental design: Imaging paradigms. Temporal periods of baseline and stimulation for (A) intermittent audiovisual stimulation and (B) intermittent genital self-stimulation.

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homosexual men reported comparable levels of mental and physical sexual arousal in response to viewing the films.

The second part of the study involved genital self-stimulation (GSS). Participants received written instructions superimposed onto a rear-projection screen, indicating whether to rest or to perform penile self-stimulation. The GSS paradigm comprised two equal blocks of 1.5 min of stimulation that were separated by a 1.5-min block of rest and interleaved between 1.5-min initial and final rest (baseline) periods. Therefore, the GSS component lasted 7.5 min (Figure 1B). A shorter duration was selected for the second (compared to the first) part of the study in order to avoid overstimulation of the penis and/or ejaculation. All participants manually performed stimulation of the penis. After we administered each part of the study, we obtained participants' self-reported ratings of mental and physical sexual arousal on a scale ranging from 1 (*very little or no sexual arousal*) to 10 (*greatest possible sexual arousal*).

fMRI Data Analysis

Using a general linear model, we analyzed data from each participant. We then spatially normalized data to a standard spinal cord template (Stroman, Figley, & Cahill, 2008) using custom-made software written in MATLAB (The MathWorks, Inc., Natick, MA). Although cardiac-related spinal cord motion is problematic throughout the cervical and upper thoracic spinal cord (Figley & Stroman, 2007; Piche et al., 2009) in comparison with lower thoracic, lumbar, and sacral regions (Figley, Yau, & Stroman, 2008), we used the

RESPITE basis set (Figley & Stroman, 2009) to compensate for any remaining spinal cord motion, which may have been exacerbated in this study because both conditions—genital self-stimulation in particular—substantially increased subjects' heart rates. The output of the analysis included the magnitudes of the signal changes (beta values: ΔS) corresponding to each function in the basis set, and a test for the significance of the value of $\beta 1$, which corresponds to the magnitude of the component of the response that matched the stimulus paradigm.

We subsequently carried out a random effects analysis across the group of participants on the basis of the mean and standard error of the mean of the $\beta 1$ values in each voxel (McGonigle et al., 2000) to identify consistent regions of activity. Group responses were taken to be significant at a t value greater than 2.5 or less than −2.5 ($p < .04$).

Measures of Sexual Arousal

The measures of sexual function included participants' ratings of perceived physical sexual arousal (PPSA) and perceived mental sexual arousal (PMSA) obtained after each of the two experimental conditions. Before we conducted the study, participants were given a detailed explanation about what we meant by physical and mental sexual arousal. We defined *physical sexual arousal* as physiological changes involving the swelling and erection of the penis and *mental sexual arousal* as feelings and mental imagery associated with the desire and motivation to engage in sexual behaviors. We calculated mean PPSA and PMSA scores across each experimental condition and tested for differences using a two-tailed, unpaired Student's t test ($p < .05$).

Neural Correlates of Sexual Responses

To supplement the group fMRI data, we also investigated subject-by-subject correlations between fMRI activity and ratings of PPSA and PMSA that were collected after each experimental condition was conducted. It is notable that the group fMRI data identified the consistent features of the responses across participants. The regression analyses performed between fMRI ΔS and measures of sexual function (PMSA and PPSA) provided insight into individual differences in sexual responses in the spinal cord. For this regression analysis, we first generated fMRI t value maps to identify voxels that were correlated ($r \geq 0.5$) with specific measures of sexual function. We generated a separate t value map for each comparison and applied Bonferroni correction for multiple comparisons. In addition, we performed regression analyses between maps of mean percentage ΔS and PPSA and PMSA ratings. In the resultant t value maps for each comparison, we selected only regions of ΔS

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that demonstrated consistent patterns of activity across several segments of the spinal cord.

RESULTS

fMRI Signal Intensity Changes

Here, we describe the fMRI group results obtained with a random effects analysis in 10 healthy, able-bodied men. Detailed analysis of fMRI activity maps spanning the lower thoracic, lumbar, and sacral regions demonstrated the presence of consistent patterns of activity in response to AVS and GSS in each of the 10 able-bodied men. Positive and negative ΔS were observed upon stimulation (Figure 2), which are expected to reflect increased or decreased neuronal input, respectively (Figley & Stroman, 2011; Logothetis, Pauls, Augath, Trinath, & Oeltermann, 2001; Stroman, Kornelsen, Lawrence et al., 2005). Throughout AVS, we detected ΔS– (i.e., signal decreases) in the intermediolateral cell column in the lower thoracic spinal cord, and ΔS+ (signal increases) in both the ventral horn and sacral parasympathetic nucleus in the lumbosacral spinal cord (Figure 2A and Table 1). During GSS, ΔS+ were found in the intermediolateral cell column of the lower thoracic spinal cord, while ΔS– were observed in the dorsal gray commissure, sacral parasympathetic nucleus, and dorsal horn of the lumbosacral spinal cord (Figure 2B and Table 1).

All spinal cord nuclei described herein are based on visual comparisons with neuronanatomical drawings from various sources, including neuroanatomy atlases and previously published journal articles (Afifi & Bergman, 1998; Coolen, Allard, Truitt, & McKenna, 2004; Giuliano & Clement, 2005; McKenna, 2000; Swigart, 2000). Therefore, the spinal cord regions discussed

TABLE 1. Summary of Signal Intensity Changes in the Spinal Cord During Audiovisual Stimulation (AVS) and Genital Self-Stimulation (GSS)

Spinal level	(+) Activity	(−) Activity
Intermittent audio-visual stimulation		
Lower thoracic/upper lumbar	Left intermediolateral cell column and ventral horn	Left intermediolateral cell column, right ventral horn
Sacral	Left sacral parasympathetic nucleus, dorsal gray commissural, right dorsal horn	Left dorsal horn
Intermittent genital self-stimulation		
Lower thoracic/upper lumbar	Left intermediolateral cell column	Bilateral dorsal horn, dorsal commissural nucleus
Sacral	None	Dorsal gray commissure, bilateral ventral horn and sacral parasympathetic nucleus, right dorsal horn

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here are approximations of the known location of neuroanatomical structures and are not exact because of the limited spatial resolution.

Perceived Sexual Arousal

Perceived levels of physical and mental sexual arousal (PPSA and PMSA, respectively) were compared across the two experimental conditions (AVS and GSS). There was no significant difference between PPSA scores in response to AVS compared with GSS. Similarly, there were no significant differences between PMSA scores in response to AVS compared with GSS. These results are presented in Figure 3.

Neural Correlates of Audiovisually Evoked Stimulation

In the first part of the study, we investigated correlations between spinal cord ΔS and measures of sexual function during audiovisual stimulation. The intermediolateral cell column and dorsal commissural nucleus ΔS in the upper lumbar segments were positively correlated with PPSA ($r = .76$; Table 2). Similarly, dorsal commissural nucleus and ventral horn ΔS in the lumbar spinal cord were positively correlated with PMSA ($r = .95$; Figure 4A, Table 2).

Neural Correlates of Genital Self-Stimulation

Next, we performed a regression analysis between maps of ΔS corresponding to GSS and measures of sexual function. In particular, we were interested in any associations between signal intensity changes in the GSS condition and physical sexual arousal. It was observed that ΔS in the sympathetic nuclei of the thoracolumbar cord, the dorsal commissural nucleus and intermediolateral cell column, were positively correlated with PPSA ($r = .86$;

TABLE 2. Neural Correlates of Physical and Mental Sexual Arousal

Spinal segment	Spinal regions	Score	*r*
Audiovisual stimulation			
Upper lumbar	IML, DCN	Physical sexual arousal	0.76
Lumbar	DCN, VH	Mental sexual arousal	0.95
Genital self-stimulation			
Upper lumbar	IML, DCN	Physical sexual arousal	0.86
Lower lumbar/upper sacral	DH	Mental sexual arousal	−0.76

DH = dorsal horn. DCN = dorsal commissural nucleus. IML = intermediolateral cell column. VH = ventral horn.

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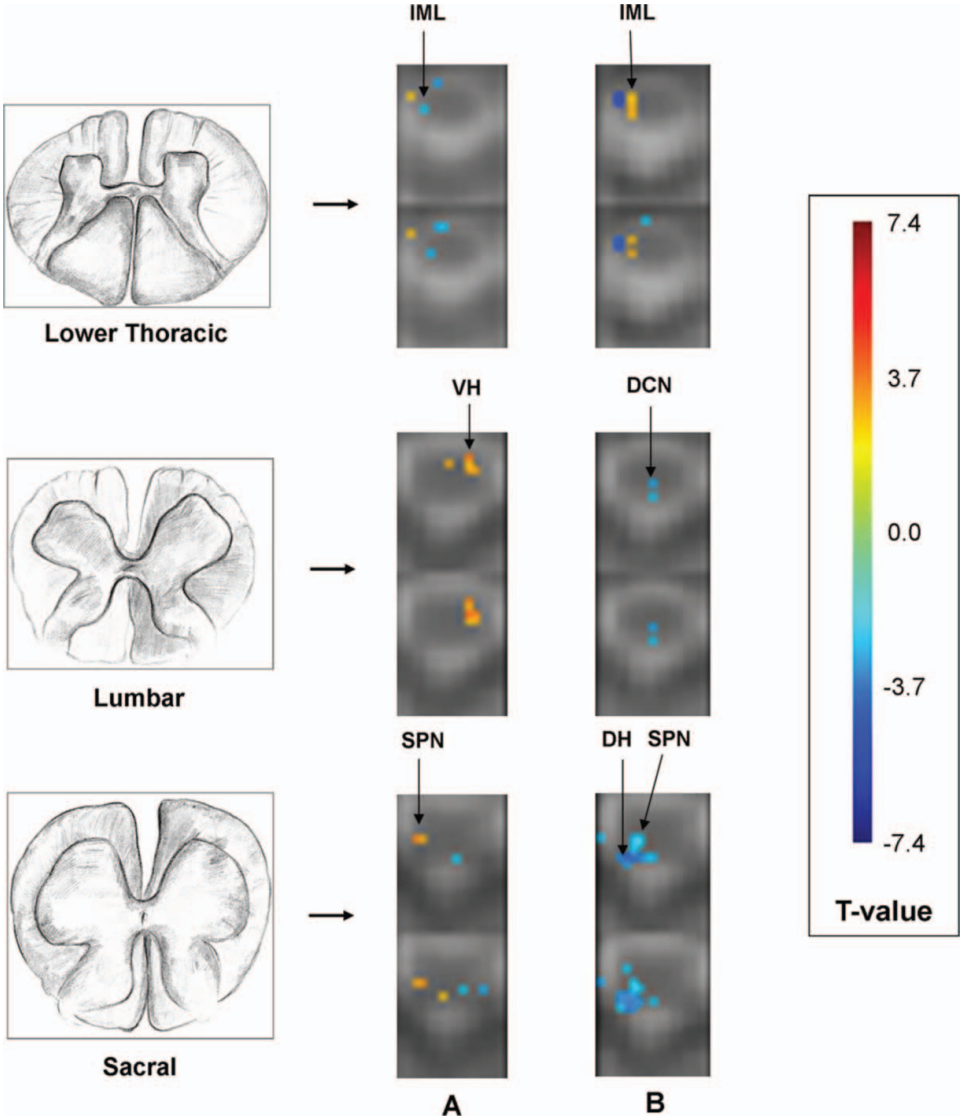

FIGURE 2. Signal intensity changes (ΔS) in the spinal cord during audiovisual and genital stimulation. Signal intensity changes during (A) audiovisual stimulation; and (B) genital self-stimulation in the lower thoracic, lumbar, and sacral spinal cord of 10 able-bodied men (combined group data). Each transverse segment of the spinal cord is 18 mm in the horizontal plane and 3 cm in the vertical plane. Regions of interest are displayed in adjacent anatomical drawings and are presented in radiological orientation. Arrows indicate corresponding regions of interest in the transverse magnetic resonance image of the spinal cord. IML = intermediolateral cell column; DCN = dorsal commissural nucleus; DH = dorsal horn; SPN = sacral parasympathetic nucleus; VH = ventral horn. (Color figure available online).

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Figure 4B, Table 2). Last, in the sacral spinal cord, ΔS in the dorsal horn were negatively correlated with PMSA ($r = -.76$; Table 2).

DISCUSSION

This study represents the first successful attempt to map neural activity associated with sexual responses in the healthy human spinal cord. Using spinal fMRI, we have described the areas of neuronal activity in the spinal cord that mediate sexual responses elicited by AVS and GSS in able-bodied men. In addition, to the best of our knowledge, this is the first time that autonomic responses have been successfully mapped in the healthy human spinal cord, as indicated by the extensive pattern of ΔS detected in the lateral horn of the thoracolumbar and sacral segments (Figure 2 and Table 1).

In line with our first hypothesis, ΔS were observed in the thoracolumbar and sacral regions of the spinal cord in response to sexual stimulation in men. However, contrary to our hypothesis that fMRI ΔS would be present only in the intermediolateral cell column and dorsal commissural nucleus of the thoracolumbar spinal cord, ΔS were also detected in the ventral horn and sacral parasympathetic nucleus of the sacral spinal cord in response to AVS. This sacral cord recruitment can most likely be explained by the high level of physical sexual arousal experienced in response to the films and is reflected in the PPSA scores (Figure 3A), which suggest that most individuals developed some degree of penile tumescence during the AV stimulation. Moreover, the observed activity in the sacral cord is in line with previous studies that have implicated parasympathetic neurons in the sacral parasympathetic nucleus in triggering penile erection in response to supraspinal influences (viewing erotic films; Giuliano & Rampin, 2004; Rampin et al., 1997).

In contrast with our hypothesis that ΔS would only be observed in the sacral parasympathetic nucleus and dorsal gray commissure of the lumbosacral spinal cord, indicative of a reflexogenic response, ΔS were also found in the intermediolateral cell column of the thoracolumbar spinal cord during GSS. These changes may have occurred because individuals were fantasizing during the genital self-stimulation, contributing to the elevated PMSA scores in response to GSS (Figure 3B), and in the absence of spinal cord injury, it is impossible to completely block psychogenic spinal cord responses during manual genital self-stimulation.

Because the participants in this experiment were able-bodied, it is not surprising that the observed ΔS in spinal cord did not selectively involve areas ascribed only to psychogenic (thoracolumbar) or reflexogenic (sacral) functions. Instead, the two components of the autonomic nervous system (sympathetic and parasympathetic) necessarily feed into each other throughout the sexual response in able-bodied men. The integration of psychogenic

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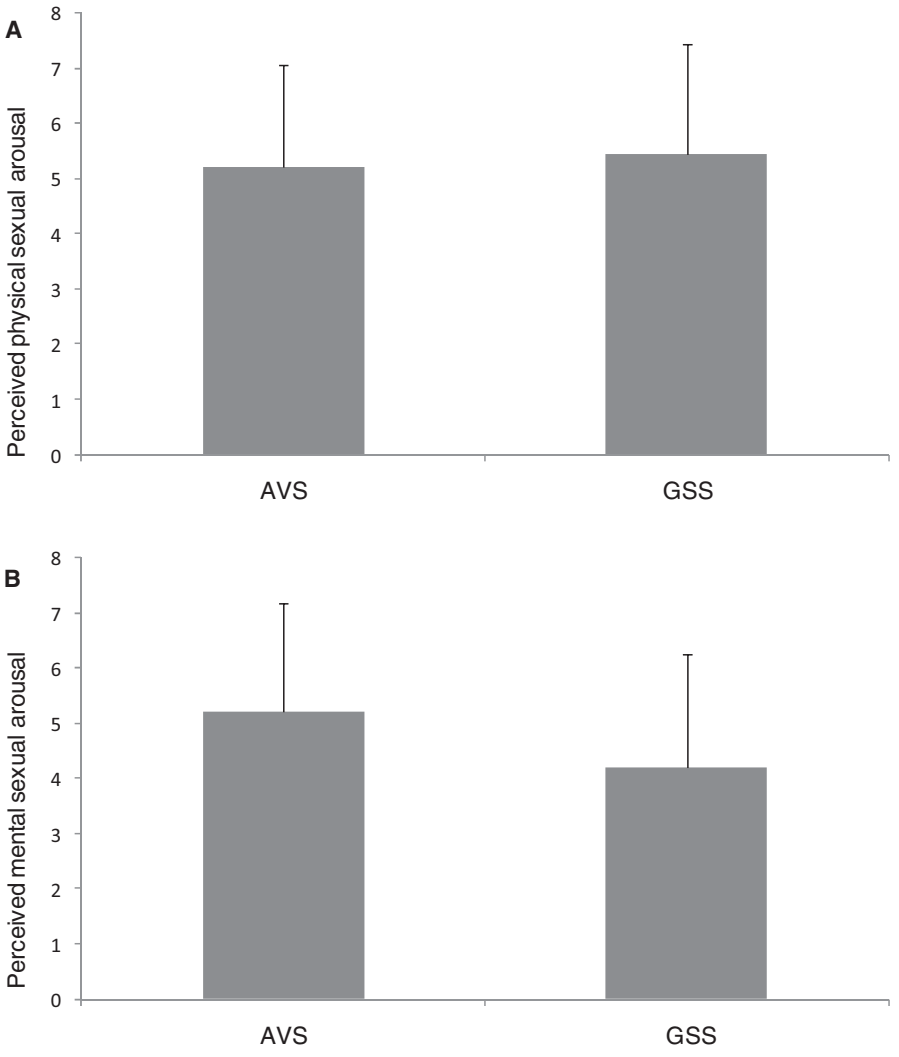

FIGURE 3. Perceived levels of (A) physical sexual arousal and (B) mental sexual arousal in response to AVS and GSS in 10 able-bodied men. Participants reported levels of physical and mental sexual arousal on a scale ranging from 1 (*very little or no sexual arousal*) to 10 (*greatest possible sexual arousal*) in response to AVS and GSS. Perceived levels of physical and mental sexual arousal were compared across the two experimental conditions (AVS and GSS). There were no significant differences observed between perceived physical sexual arousal scores in response to AVS compared with those in response to GSS ($p = 1.00$). Similarly, there were no significant differences found between perceived mental sexual arousal scores in response to AVS compared with those in response to GSS ($p = .28$). Error bars denote the standard error of the mean. AVS = audiovisual stimulation; GSS = genital self-stimulation.

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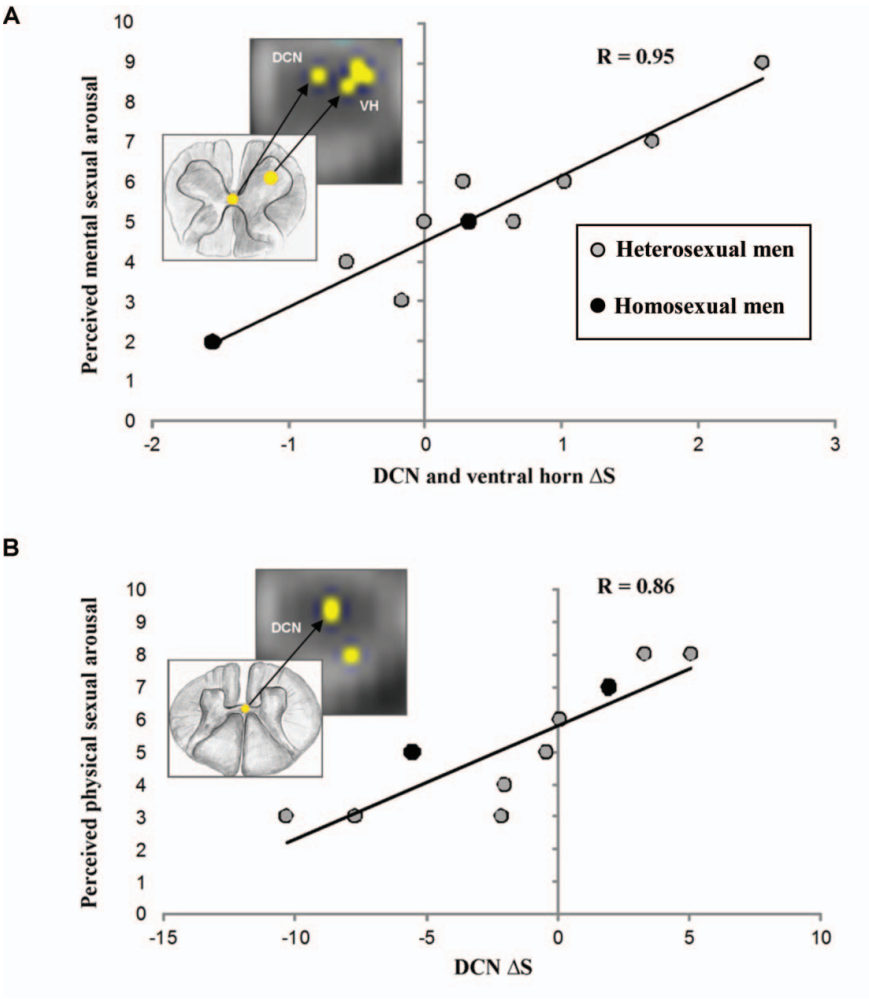

FIGURE 4. Correlations between signal intensity changes (ΔS) in the spinal cord and measures of sexual function in able-bodied men. (A) Positive correlation between (ΔS) in the DCN and ventral horn of the lumbar spinal cord during audiovisual stimulation and perceived mental sexual arousal in 10 able-bodied men (r = .95), and (B) positive correlation between (ΔS) in the DCN of the thoracolumbar spinal cord during genital self-stimulation and perceived physical sexual arousal in 10 able-bodied men (r = .86). Inset: representative magnetic resonance image of the spinal cord (transverse section) with selected ΔS. Anatomical sections, presented in radiological orientation, show the identical spinal nuclei/regions with arrows pointing to the corresponding regions in the adjacent magnetic resonance image. DCN = dorsal commissural nucleus. VH = ventral horn. (Color figure available online).

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and reflexogenic pathways naturally occurs in able-bodied individuals because the spinal cord is intact, and, therefore, spinal centers involved in sexual function receive uninterrupted descending input from supraspinal regions as well as afferent inputs from the sexual organs (McKenna, 2001). However, there is a possibility of order effects because GSS was always preceded by AVS. Thus, it is probable that the effects of viewing erotic film clips during AVS contributed to the spinal cord ΔS observed in response to GSS.

It is noteworthy that the majority of fMRI ΔS in the spinal cord were observed in regions of the spinal cord corresponding to sympathetic and parasympathetic preganglionic nuclei, indicating that in men, as in males of other species, the autonomic nervous system plays an important role in the regulation of sexual responses. In addition, dorsal and ventral horn ΔS were observed across each experimental condition, indicative of ascending and descending neuronal input, respectively. Taken together, our findings indicate that the integration of sensory, motor, and autonomic neural signals occurs during sexual responses in the intact, human spinal cord in able-bodied men.

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Neural Correlates of Sexual Responses in Men

On the basis of fMRI ΔS maps alone, it is not necessarily possible to delineate the functional significance of neural input to a particular region. However, performing regression analyses allowed us to infer whether neural input to a specific region facilitated or blocked sexual responses on the basis of whether activity in a given region was positively or negatively correlated with a specific measure of sexual function. Several regions of the spinal cord involved in sexual function in men revealed ΔS that were correlated with mental and physical sexual arousal, at the time of each experimental condition (Figure 4 and Table 2). In general, the results from AVS indicate that viewing erotic films activates the psychogenic (sympathetic) and reflexogenic (parasympathetic) pathways in the spinal cord. This idea is supported by the positive correlations found between ΔS in sympathetic nuclei and perceived mental and physical sexual arousal. In contrast, the negative correlation between ΔS in the dorsal commissural nucleus and erectile function may be attributed to the antierectile properties of the thoracolumbar spinal cord.

Results from GSS indicate increased sympathetic tone in response to penile stimulation and a decrease in parasympathetic tone (a switch from AVS). This finding may be the result of marked increases in cardiovascular function (reflected by an increase in heart rate) observed during GSS. Similarly, penile vibratory stimulation in men after having experienced SCT frequently triggers autonomic dysreflexia, a condition characterized by episodic increases in blood pressure that is caused by sudden spikes in sympathetic nervous system function and the absence of inhibitory supraspinal control

(Comarr, 1984; Comarr & Eltorai, 1997; Sonksen, Biering-Sorensen, & Kristensen, 1994). It is interesting that throughout the GSS condition, activity in the dorsal commissural nucleus and intermediolateral cell column, which is psychogenic in nature, was predominantly positively correlated with PPSA. This finding is consistent with a previous psychophysiological study that reported a strong correlation between male sexual arousal and penile circumference (Chivers & Bailey, 2005).

Conclusions and Clinical Implications

This study has advanced the understanding of the spinal cord circuitry involved with sexual responses in able-bodied men in several important ways. First, we have shown that spinal fMRI can be used to noninvasively observe the neural correlates of sexual responses in the human spinal cord. Second, on the basis of the extensive number of ΔS detected in the lateral horns of the thoracolumbar and sacral regions, this study represents the first successful observation and mapping of autonomic nervous system function in humans. Third, we have shown that the psychogenic and reflexogenic components of sexual responses are integrated and cannot be functionally separated in able-bodied men. Last, linear regression analyses between fMRI ΔS and measures of sexual function permitted the functional inference of specific spinal cord nuclei regulating sexual responses and shed light on individual differences in sexual function in able-bodied men.

The success of this study, in detecting spinal cord activity elicited by psychogenic and reflexogenic sexual stimulation and the observed individual differences related to levels of sexual arousal, strongly implies that spinal fMRI might be useful for investigating altered sexual function in male SCT patients. Future research will also be required in order to examine sexual responses in the spinal cords of able-bodied women so that gender comparisons can be made. Furthermore, it will be necessary to investigate the functional connectivity between the spinal cord, brainstem, midbrain, and cortical regions modulating human sexual responses. A clearer understanding of the functional connectivity in regions of the central nervous system modulating sexuality in able-bodied humans will enable researchers and clinicians to identify the changes that occur to sexual responses after traumatic spinal cord injury.

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