Portable Custom Built Device for Thermal Sensitivity Assessment
An Auxiliary Tool to Characterize the Neuropathic Pain following Spinal Cord Injury

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Abstract: Neuropathic pain is characterized to arise without stimulation of nociceptors, but due to injury or dysfunction of Peripheral and Central Nervous Systems. It involves altered mechanisms of impulse transmission in somatosensory pathways, causing abnormal sensations. Quantitative sensory testing, by the detection of thermal stimuli, is a method used to characterize and study the neuropathic pain. Therefore, this work describes the development and application of portable custom built device for cutaneous thermal sensitivity assessment in spinal cord injured subjects (SCIS). Using method of levels, the assessment was applied in healthy subjects and SCIS with and without neuropathic pain. The thresholds determined for healthy subjects during thermal sensitivity assessment are consistent and other results provided by clinical trials are according to previous works, demonstrating the device feasibility as an auxiliary tool for neuropathic pain study.

1 INTRODUCTION

Spinal cord injury (SCI) causes disruption of nerve fibres that transmit ascending sensory and descending motor information. This disruption causes losses in the transmission of sensory-motor information across the site of the lesion, resulting in considerable physical and emotional consequences for individual (Maynard Jr. et al., 1997); (Eng and Miller, 2006). Sensory-motor dysfunctions occur in the parts of the body innervated by areas below the site of the lesion, being characterized by paralysis, altered sensation and weakness (Raineteau and Schwab, 2001).

Spinal cord injured subjects (SCIS) also suffer other disorders and numerous secondary pathologies such as losses of bowel and bladder functions, pressure ulcers, spasticity, gastrointestinal and sexual dysfunctions and heterotopic ossification (Kaplan et al., 1991); (Eng and Miller, 2006); (Verschueren et al., 2011). However, one of the major problems following SCI is the neuropathic pain (Bonica, 1991).

Neuropathic pain is characterized to arise without stimulation of nociceptors (sensory pain fibres that detect tissue damage by physical, chemical or thermal phenomena), but due to injury or dysfunction of Peripheral and Central Nervous Systems. Thus, neuropathic pain is an aggravating for the already weakened patient, imposing severe limitations in performing the activities of daily living (Richards et al., 1980); (Summers et al., 1991).

The pathophysiology of neuropathic pain involves altered mechanisms of impulse transmission in somatosensory pathways, so that axonal injury leads to a gain in excitatory transmission, in other words, there is a massive axonal input. It results from an axonal hyperexcitability, with the generation of ectopic electrical impulses, causing abnormal sensations (Catafau and Bosque, 2003).

In SCIS, partially preserved pathways spinothalamic tract may be the local generator of pain (Wasner et al., 2008). Fibres Aδ and C present little myelin and follow the column via anterolateral spinothalamic tract. These fibres are the main components of the fibres that lead thermal sensitivity (Kirillova et al., 2011) Thus, the thermal sensitivity

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follows the same neurological path of the pain.

Some methods are applied to characterize and study the neuropathic pain, for example, McGill Pain Questionnaire, quantitative sensory testing (QST) and somatosensory evoked potential (Finnerup et al., 2003).

The McGill Pain Questionnaire is an instrument that evaluates qualitatively and quantitatively pain, providing quantitative measures of clinical pain that can be treated statistically (Melzack, 1975). Pimenta and Teixeira (1996) adapted (translation and validation) the questionnaire to Portuguese. The present pain intensity (PPI) is the number chosen by the subject at the time of administration of the questionnaire, ranging from 0 (no pain) to 5 (excruciating). The pain rating index based on the subjects' mean scale values (PRI(S)) obtained by Melzack and Torgerson (1971) is described as the sum of all values of words chosen by subject for all categories (sensory, affective, evaluative, motor and miscellaneous). And other important value is the number of words chosen (NWC) that is the sum of all words chosen by the subject (Melzack, 1975).

QST assess and quantify sensory function in subjects with losses in the neurological system, measuring the detection threshold of tactile, vibratory, thermal or painful stimuli (Shy et al., 2003); (Finnerup et al., 2003). Especially for thermal stimuli, some equipments utilize the Peltier effect, in which the intensity and direction of electrical current controls the surface temperature of a test electrode. The skin was touched by the electrode and the subject reports the sensation in relation to the temperature (Shy et al., 2003); (Kenshalo and Bergen, 1975); (Finnerup et al. 2003).

This paper describes the development and application of portable custom built device for cutaneous thermal sensitivity assessment based on Peltier effect. This device is designed for quick and practice assessment of thermal sensitivity in SCIS, representing an auxiliary tool for neuropathic pain study. Using method of levels, the device was used in healthy subjects and SCIS with and without neuropathic pain. In general, the obtained results were compared with previous works to verify the device feasibility.

2 MATERIALS AND METHODS

About this work, instrumentation development was done at Laboratory of Biocybernetics and Rehabilitation Engineering - USP, and clinical application was performed at Laboratory of Biomechanics and Rehabilitation of the Locomotor System – UNICAMP.

Basically, portable custom built device is composed by microcontroller, thermoelectric module and temperature transducer. The microcontroller associated with amplifier circuits offers electrical energy to supply the thermoelectric module and provides information about device operation condition. Furthermore, it allows setting the probe operating temperature (Figure 1).

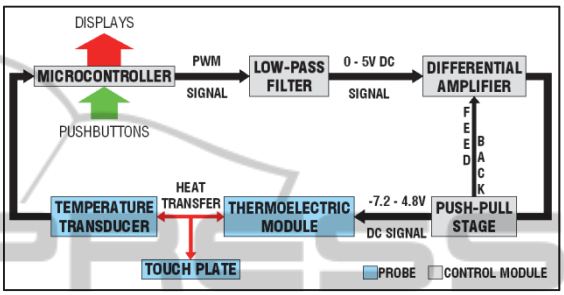

Figure 1: Block diagram of the device.

2.1 Thermoelectric Module, Temperature Transducer and Probe Assembly

The thermoelectric module used was a solid state heat pump (Melcor Corporation, Trenton, NJ, USA), based on Peltier effect. This heat pump contains 66 thermocouples, being able to transfer until 3.56W of heat from cold to hot faces (Q_{max}); it results in the maximum temperature difference of the 67°C between two faces (ΔT_{max}) with low power consumption - input electrical current (I_{max}) of 0.8A and dc voltage (V_{max}) of 7.98V – to achieve ΔT_{max}.

Temperature transducer with analog output based on semiconductor junctions was used to monitor the temperature of thermoelectric module. The transducer used was LM35 (National Semiconductor Corporation, Santa Clara, CA, USA) that is a precision integrated-circuit temperature transducer, whose output voltage is linearly proportional to the Celsius temperature. The LM35 does not require external calibration to provide readouts with accuracies of ±0.75°C over a range -55 to +150°C. Other important features of LM35 make it suitable for control circuits as low output impedance, very low self-heating and sensitivity of 0.01V/°C.

The probe is composed by aluminium touch plate (16x16mm), thermoelectric module, LM35 transducer, heat sink and auxiliary fan. In the first stage of probe assembly, LM35 was coupled to the touch plate by aluminium clamp, and the

thermoelectric module was fixed on heat sink (Figure 2). Touch plate with LM35 was fixed on thermoelectric module by thermal compound, in the second stage. Moreover, the assembly was placed in a suitable case.

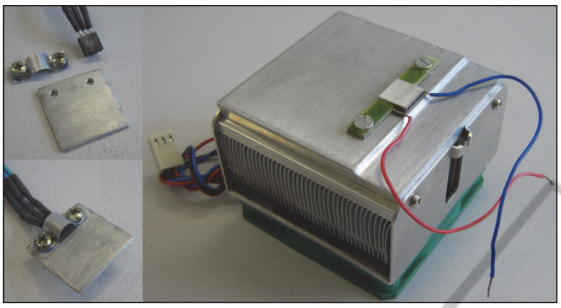

Figure 2: First stage of probe assembly.

2.2 Electronic Apparatus

The microcontroller used was PIC18F252 (Microchip Technology Inc., Chandler, AZ, USA) and it was programmed to use pulse-width modulation (PWM) as technique for controlling power to thermoelectric module. It compares the desired temperature of the probe with the actual temperature and, in accordance with this difference, adjusts the duty cycle of PWM signal.

An active low-pass filter was used to generate a dc signal from 0 – 5V PWM signal. This filter was configured in Sallen-Key topology of second order with cut-off frequency of approximately 35 Hz and quality factor of 0.5.

During bench tests with the probe, dc voltages of thermoelectric module to ensure that the temperature probe reached 0 and 60°C were determined. The voltage polarity was defined so that a negative voltage decreases the probe temperature and a positive one would increase the temperature. These voltages were -7.2V and 4.8V, respectively.

Therefore, it was necessary to convert 0 – 5V dc signal (Vin) obtained from PWM into asymmetric bipolar dc signal (-7.2V – 4.8V) (Vout) required by thermoelectric module. This conversion was done by differential amplifier using an operational amplifier as active component, whose inverting input was held at 5V. Thus, an amplifier with linear transfer characteristic was developed (1), resulting in proper range of signal.

$$Vout=2.435*Vin - 7.353 \quad (1)$$

Although the range of signal was appropriate, the differential amplifier was not able to provide the required electrical power (up to 5.76W). Thus, a push-pull stage with MOSFETs was applied. These components exhibit a negative thermal coefficient, in other words, its electrical conductivity decreases with increasing temperature, protecting the electronic circuit.

The output of push-pull stage with unitary gain was also used as feedback signal to differential amplifier. This strategy reduces signal distortion, providing a linear signal to thermoelectric module. Whole electronic circuit including the thermoelectric module is powered by two batteries (12V, 5Ah).

2.3 Clinical Trials

Twenty SCIS were recruited to participate in this work, and they were divided into two groups, pain SCIS (P) and non-pain SCIS (NP). Subjects were classified according to the American Spinal Cord Injury Association (ASIA) Impairment Scale (AIS) (Maynard Jr. et al., 1997); (Dahlberg et al., 2005); (Wolfe and Hsieh, 2006); (Kirshblum et al., 2011). Control group (CT) was formed by 10 healthy subjects (Table 1).

Table 1: Subjects characteristics.

	P	NP	CT
Age (year)*	39.3(12.1)	35.4(12.9)	27.2(10.6)
Gender (Male/Female)	9/1	7/3	9/1
Body mass (kg)*	69.2(10.1)	71.5(14.7)	77.6(13.6)
Height (m)*	1.74(0.07)	1.72(0.09)	177.3(4.8)
Neurological lesion level (Cervical/ Thoracic)	7/3	3/7	-
AIS (A/B/C/D)	8/2/0/0	7/2/1/0	-

*Values in mean(SD)

Inclusion criteria for P group were lesion level above T12 with central neuropathic pain after traumatic SCI. Exclusion criteria were based on the presence of any other pain different from central neuropathic pain such as nociceptive or peripheral neuropathic pain; or subjects that were under analgesic treatment.

In relation to NP group, inclusion criteria were lesion level above T12 without central neuropathic pain and spontaneous dysesthesia.

To study the sensitivity of pain and losses of sensory pathways following SCI, McGill Pain Questionnaire (Portuguese version) and thermal sensitivity assessment were applied.

For McGill Pain Questionnaire, the values used

for data analysis were PRI, NWC and PPI.

The thermal stimuli were applied to the dominant leg at a point 100mm distal from the patella, in the anterolateral side of the leg, corresponding to the L5 dermatome. For temperature range from 30°C to 60°C, with increment of 5°C, the skin was stimulated by probe (aluminium touch plate, specifically) by over 3s. Subsequently, the temperature range was from 30°C to 0°C, with decrement of 5°C. Warm and cold thresholds (temperature at which the patient feels the stimulus) and pain thresholds were recorded using the method of levels (Shy et al., 2003). For each subject, three measurements with interstimulus interval of 3 – 6s were used to calculate the thresholds.

3 RESULTS

Figure 3 shows portable custom built device for thermal sensitivity assessment; probe and control module.

Figure 3: Portable custom built device for thermal sensitivity assessment.

On the front panel, the control module has two pushbuttons that set the desired probe temperature; the red pushbutton (+) increases probe temperature of 1°C while the black one (-) decreases it of 1°C, at range of 0°C to 70°C. This desired probe temperature and the instantaneous one are shown on the smaller green display and larger red display, respectively. When temperatures become equal, LED turns on, indicating that probe is ready to use. Besides, the front panel has a toggle switch for the auxiliary fan and a DB9 connector for the probe cable.

According to the McGill Pain Questionnaire applied to the P group, half of subjects feel pain at injury level and half of them below the injury level. Figure 4 shows the relation between reported words and number of subjects for each group of questionnaire; and table 2 presents the scores for each variable.

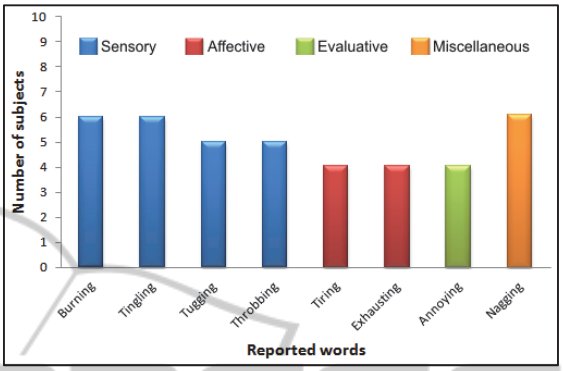

Figure 4: Relation between reported words and number of subjects for each group of McGill Pain Questionnaire (Portuguese version).

Table 2: McGill pain questionnaire scores.

Variables	McGill Pain Questionnaire scores
PRI	28.5(13.7)
NWC	12.7(3.0)
PPI	3.2(1.4)

*Values in mean(SD)

During thermal sensitivity assessment, three subjects detected cold, two detected warm and one detected pain due to heat, in the NP group (Table 3). Furthermore, none reported pain due to cold and one subject (AIS C) presented muscle spasms with stimulus of 50°C.

Table 3: Thermal sensitivity in the NP group.

Subjects (AIS)	Detected threshold ▲			
	Cold	Pain due to cold	Warm	Pain due to heat
1(A)	-	-	-	-
2(B)	-	-	-	-
3(B)	▲	-	▲	▲
4(A)	-	-	-	-
5(A)	▲	-	-	-
6(A)	-	-	-	-
7(A)	-	-	-	-
8(A)	-	-	-	-
9(A)	▲	-	▲	-
10(A)	-	-	-	-

In the P group, four subjects detected cold, one detected pain by cold at 5°C and seven subjects detected warm. Four subjects detected pain due to heat and heat pain tolerance, with three subjects (all

AIS A) presenting muscular spasms at 55°C (Table 4). One subject (AIS B) felt dysesthesia at the stimulation site with stimuli of 0ºC and 45°C. Another subject (AIS A) detected warm all around the knee (not only at the stimulation site) detecting warm at 0°C. And one subject (AIS A) felt a non specific vibration in the L5 dermatome with 45°C in the right leg.

Table 4: Thermal sensitivity in the P group.

Subjects (AIS)	Detected threshold ▲			
	Cold	Pain due to cold	Warm	Pain due to heat
1(A)	-	-	▲	▲
2(B)	-	-	▲	-
3(B)	▲	-	▲	▲
4(A)	-	-	-	-
5(A)	-	-	▲	-
6(A)	▲	-	▲	▲
7(A)	▲	-	▲	-
8(A)	-	-	-	-
9(A)	-	-	-	-
10(A)	▲	▲	▲	▲

Table 5 indicates cold (C), warm (W), pain due to heat (HP) and heat pain tolerance (HPT) thresholds for each group.

Table 5: Temperature thresholds for each group.

Threshold(°C)	Group		
	P	NP	CT
C	15(9.8)	20.6(9.5)	19.2(5.2)
W	38.3(11.9)	38.3(2.6)	36.4(3.3)
HP	47.9(5.4)	50(0)	50.8(2.6)
HPT	48.3(4.9)	50(0)	52.8(3.1)

Values in mean(SD)

4 DISCUSSION

For touch plate construction, aluminium, copper and stainless steel were available. The choice was based on coefficient of thermal conductivity and oxidation resistance of metals. According to the coefficient of thermal conductivity, copper (398W/mK) is a better conductor than aluminium (247W/mK) and stainless steel (15.9W/mK), but stainless steel presents high oxidation resistance. Therefore, aluminium was chosen because presents high coefficient of thermal conductivity and intermediate oxidation resistance (Callister Jr., 2001).

These properties associated to the low mass and small dimension of touch plate (0.7g) enabled a fast thermal equilibrium between both plate surfaces. Thus, the surface temperature acquired by the transducer is the same of surface dedicated to the touch.

Reach and stabilization of desired probe temperature can be attributed to the technique for controlling power to thermoelectric module and the use of heat sink and auxiliary fan. For each increment or decrement of 5°C, this strategy allowed temperature stabilization in around 5s during clinical trials.

In relation to the technique for controlling power to thermoelectric module, another alternative based on the use of PWM signal and an H-bridge can be applied, replacing low-pass filter and differential amplifier. However, this configuration provides a dc voltage range from -12V to 12V for the PWM duty cycle of 0 and 100%, respectively; values which are not in accordance with the asymmetric bipolar dc signal (-7.2V – 4.8V) required by the thermoelectric module to operate in proper temperature range (0 – 60°C). Thus, the PWM duty cycle should be limited between values of 20% and 70%, also avoiding damage to the module since this operates at a maximum dc voltage of 7.98V. Therefore, the use of the low-pass filter and the differential amplifier is more appropriate to the objectives of this work.

Generally, in healthy subjects, the activity of cold-sensitive neurons increases below 35°C, and maximum cutaneous cold sensitivity is around 25°C, while cold fibre activity is ceased at temperatures below 12°C. The firing rates of warm-sensitive neurons increase above 25°C, and their range of thermosensitivity extends from 35°C to 43°C. Temperatures above 43°C and below 12°C cause pain, whose stimulus is transmitted by Aδ and C fibres. Furthermore, nociceptive heat activates Aδ fibres around 43°C, while temperatures above 52°C activate C fibers. Cold stimuli below 12°C also cause pain and, in addition, nociceptives heat and cold are transmitted by polymodal C fibers (Nomoto et al., 2004; Schepers and Ringkamp, 2010). Therefore, the thresholds determined for CT group during thermal sensitivity assessment using portable custom built device are consistent (Table 3).

In relation to SCIS, P group was more sensitive to thermal stimuli than NP group, where 70% of subjects in P group detected some kind of thermal sensitivity against 30% of NP group (Tables 3 and 4). This difference between P and NP groups is in agreement with the study of Wasner et al. (2008). In this study, it was reported that there is some preservation of the spinothalamic tract in pain SCIS greater than in non pain SCIS, which may be involved in the development of neuropathic pain.

From the three subjects who experienced thermal stimuli in NP group, only one presents complete injury. For the P group, two subjects are AIS B and five are AIS A.

This finding can be justified through theories that explain why subjects with complete SCI have some sensibility, characterizing the discomplete injury. Dimitrijevic (1988) and Sherwood, Dimitrijevic and Mckay (1992) found motor remnants in complete SCIS due to a neural control. Thus, discomplete injury is an incomplete injury that fits the AIS criteria for grade A. Moreover, some subjects with complete SCI can present some semblance of sensibility, which can be evoked below the level of injury due to incomplete injuries in the spinothalamic tract. These subjects have subclinical functions of ascending and descending tracts (Finnerup et al., 2004).

5 CONCLUSIONS

Due to feedback control, the custom built portable device provides easy temperature control with resolution of 1°C. The device is simple to build and can stabilize its temperature in about 5s for a 5°C temperature change, therefore representing a simple alternative for quick and practical assessment. It can provide quantified information about sensory performance of subjects, and the results obtained from clinical trials are in accordance to previous works, thus demonstrating the device feasibility for thermal sensitivity assessment. Spinal cord injured subjects that refer neuropathic pain are more sensitive to thermal stimuli than patients do not present neuropathic pain.

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REFERENCES

Bonica, J. J., 1991. Introduction: semantic, epidemiologic, and educational issues. In: Casey, K. L. *Pain and Central Nervous System Disease: the Central Pain Syndromes*. Raven Pr. New York: Raven Pr, pp 13–29.

Callister Jr., W. D., 2001. *Fundamentals of Material Science and Engineering*. 5th ed. New York: John Wiley & Sons, Inc.

Catafau, S., Bosque, Q., 2003. *Mecanismos fisiopatológicos da dor neuropática*, 1st ed. Madrid: Medica Panamericana.

Dahlberg, A., Alaranta, H., Sintonen, H., 2005. Health-related quality of life in persons with traumatic spinal cord lesion in Helsinki. *Journal of Rehabilitation Medicine*, 37, pp. 312–316.

Dimitrijevic, M. R., 1988. Residual motor functions in spinal cord injury. *Advances in Neurology*, 47, pp. 138–155.

Eng, J. J., Miller, W. C., 2006. Rehabilitation: from bedside to community following spinal cord injury (SCI). In: Eng, J. J., Teasell, R. W., Miller, W. C., Wolfe, D. L., Townson, A. F., Aubut, J., Abramson, C., Hsieh, J. T. C., Connolly, S. *Spinal Cord Injury Rehabilitation Evidence*. Vancouver, pp. 16–29.

Finnerup, N. B., Johannesen, I. L., Fuglsang-Frederiksen, A., Bach, F. W., Jensen, T. S., 2003. Sensory function in spinal cord injury patients with and without central pain. *Brain*, 126, pp. 57–70.

Finnerup, N. B., Gyldensted, C., Fuglsang-Frederiksen, A., Bach, F. W., Jensen, T. S., 2004. Sensory perception in complete spinal cord injury. *Acta Neurologica Scandinavica*, 109, pp. 194–199.

Kaplan, S. A., Chancellor, M. B., Blaivas, J. G., 1991. Bladder and sphincter behavior in patients with spinal cord lesions. *Journal of Urology*, 146, pp. 113–117.

Kenshalo, D. R., Bergen, D. C., 1975. A device to measure cutaneous temperature sensitivity in humans and subhuman species. *Journal of Applied Physiology*, 39, pp. 1038–1040.

Kirillova, I., Rausch, V. H., Baron, R., Jänig, W., 2011. Mechano- and thermosensitivity of injured muscle afferents. *Journal of Neurophysiology*, 105, pp. 2058–2073.

Kirshblum, S. C., Burns, S. P., Biering-Sorensen, F., Donovan, W., Graves, D. E., Jha, A., Johansen, M., Jones, L., Krassioukov, A., Mulcahey, M. J., Schmidt-Read, M., Waring, W. 2011. International standards for neurological classification of spinal cord injury (Revised 2011). *The Journal of Spinal Cord Medicine*, 34, pp. 535–546.

Maynard Jr., F. M., Bracken, M. B., Creasey, G., Ditunno Jr, J. F., Donovan, W. H., Ducker, T. B., Garber, S. L., Marino, R. J., Stover, S. L., Tator, C. H., Waters, R. L., Wilberger, J. E., Young, W., 1997. International standards for neurological and functional classification of spinal cord injury. *Spinal Cord*, 35, pp. 266–274.

Melzack, R., 1975. The McGill Pain Questionnaire: major properties and scoring methods. *Pain*, 1, pp. 277–299.

Melzack, R., Torgerson W. S., 1971. On the language of pain. *Anesthesiology*, 422, pp. 50–59.

Nomoto, S., Shibata, M., Iriki, M., Riedel, W., 2004. Role of afferent pathways of heat and cold in body temperature regulation. *International Journal of Biometeorology*, 49, pp. 67–85.

Pimenta, C. A. de M., Teixeira, M. J., 1996. Questionário

de dor McGill: proposta de adaptação para a língua portuguesa. *Revista da Escola de Enfermagem da USP*, 30, pp. 473–483.

Raineteau, O., Schwab, M. E., 2001. Plasticity of motor systems after incomplete spinal cord injury. *Nature reviews. Neuroscience*, 2, pp. 263–273.

Richards, J. S., Meredith, R. L., Nepomuceno, C., Fine, P. R., Bennett, G., 1980. Psychosocial aspects of chronic pain in spinal cord injury. *Pain*, 8, pp. 355–408.

Schepers, R. J., Ringkamp, M., 2010. Thermoreceptors and thermosensitive afferents. *Neuroscience and Biobehavioral Reviews*, 34, pp. 177–184.

Sherwood, A. M., Dimitrijevic, M. R., Mckay, W. B., 1992. Evidence of subclinical brain influence in clinically complete spinal cord injury: discomplete SCI. *Journal of the Neurological Sciences*, 110, pp. 90–98.

Shy, M. E, Frohman, E. M., So, Y. T., Arezzo, J. C., Cornblath, D. R., Giuliani, M. J., Kincaid, J. C., Ochoa, J. L., Parry, G. J., Weimer, L. H., 2003. Quantitative sensory testing. *Neurology*, 60, pp. 898–904.

Summers, J. D., Rapoff, M. A., Varghese, G., Porter, K., Palmer, R. E., 1991. Psychosocial factors in chronic spinal cord injury pain. *Pain*, 47, pp. 183–189.

Verschueren, J. H. M., Post, M. W. M., de Groot, S., van der Woude, L. H. V., van Asbeck, F. W. A., Rol, M., 2011. Occurrence and predictors of pressure ulcers during primary in-patient spinal cord injury rehabilitation. *Spinal Cord*, 49, pp. 106–112.

Wasner, G., Lee, B. B., Engel, S., Mclachlan, E., 2008. Residual spinothalamic tract pathways predict development of central pain after spinal cord injury. *Brain*, 131, pp. 2387–2400.

Wolfe, D. L., Hsieh, J. T. C., 2006. Rehabilitation practice and associated outcomes following spinal cord injury. In: Eng, J. J., Teasell, R. W., Miller, W. C., Wolfe, D. L., Townson, A. F., Aubut, J., Abramson, C., Hsieh, J. T. C., Connolly, S. *Spinal Cord Injury Rehabilitation Evidence*. Vancouver, pp. 44–90.