Eur Spine J (2009) 18:972–977
DOI 10.1007/s00586-009-0896-x

ORIGINAL ARTICLE

A quantitative skin impedance test to diagnose spinal cord injury

Safak Sahir Karamehmetoglu · Mukden Ugur · Yunus Ziya Arslan · Deniz Palamar

Received: 16 June 2008 / Accepted: 19 January 2009 / Published online: 20 March 2009

Abstract The purpose of this study was to develop a quantitative skin impedance test that could be used to diagnose spinal cord injury (SCI) if any, especially in unconscious and/or non-cooperative SCI patients. To achieve this goal, initially skin impedance of the sensory key points of the dermatomes (between C3 and S1 bilaterally) was measured in 15 traumatic SCI patients (13 paraplegics and 2 tetraplegics) and 15 control subjects. In order to classify impedance values and to observe whether there would be a significant difference between patient and subject impedances, an artificial neural network (ANN) with back-propagation algorithm was employed. Validation results of the ANN showed promising performance. It could classify traumatic SCI patients with a success rate of 73%. By assessing the experimental protocols and the validation results, the proposed method seemed to be a simple, objective, quantitative, non-invasive and non-expensive way of assessing SCI in such patients.

Keywords Spinal cord injury · Skin impedance · Quantitative diagnose

S. S. Karamehmetoglu (✉) · D. Palamar
Physical Medicine and Rehabilitation Department, Cerrahpasa Medical Faculty, Istanbul University, Cerrahpasa, Istanbul 34098, Turkey
e-mail: karamehm@istanbul.edu.tr

M. Ugur
Department of Electric-Electronics Engineering, Faculty of Engineering, Istanbul University, Avcilar, Istanbul 34320, Turkey

Y. Z. Arslan
Department of Mechanical Engineering, Faculty of Engineering, Istanbul University, Avcilar, Istanbul 34320, Turkey

Introduction

Spinal cord injury (SCI), fortunately, has a very low incidence ranging between 6 and 56 per million population [7, 10, 12]. In order to diagnose and assess the level of SCI, clinical neurological examination technique has been widely used by clinicians for years. However, in recent years, a few studies were carried out to assess the level and severity of SCI in quantitative manner [8, 9, 13, 15, 16]. Main motivation of these studies was the relative subjectivity of clinical neurological examination in the assessment and monitoring of neurological changes in patients with SCI [11]. For this purpose, Savic et al. [15] aimed to develop a quantitative sensory test (QST) by using electrical stimulation in patients with SCI. They concluded that electrical perceptual threshold was a simple, reproducible QST that could assess both the level and the severity of SCI. In addition to this study, vibration and thermal sensation thresholds [6, 9, 13] and somatosensory and motor-evoked potentials [3] have been suggested as useful additions to clinical testing in evaluating SCI. Nicotra and Ellaway [13] used thermal perception thresholds to investigate whether QST was able to reveal subclinical deficits at the neurological level of the lesion in subjects with chronic SCI. Despite their promising results, their techniques needed feedback from patients and thus could only be applied to conscious and cooperative patients.

Following SCI, various changes occur throughout the body especially below the level of the injured spinal cord. These are mostly sensory, motor and vegetative system changes [17]. These types of changes may be utilized to diagnose SCI, to determine the level and the degree of SCI and to monitor the neurological changes that would occur in patients with SCI [13, 15].

The purpose of this study was to investigate whether the electrical conductivity of skin tissue was affected by SCI. If so, a method which could be used to diagnose SCI in a quantitative manner would be developed. The main advantage of this technique would be its applicability to unconscious and non-cooperative SCI patients with more objectivity. In order to achieve this goal, skin impedances of SCI patients and control subjects were measured, compared and these impedance values were classified by using a neural network.

Materials and methods

Subjects and methods

Patients with traumatic SCI and control subjects aged between 18 and 55 years were included into the study. The subjects were given sufficient information about the experiments and their informed consents were taken. They were all evaluated by history and physical examination according to The International Standards for Neurological Classification of SCI, American Spinal Injury Association (ASIA), and International Spinal Cord Society (ISCoS) [11].

Skin impedance of the sensory key points was measured in 15 control subjects and in 15 SCI patients (13 paraplegics and 2 tetraplegics), between C3 and S1 bilaterally. The impedances were measured in all dermatomes except C2 (because of hair), L1-3 and S2-5 (because of the refusal of the control subjects). According to the aforementioned booklet of ASIA and ISCoS, 10 pairs of key muscles and 28 pairs of sensory key points were evaluated and the neurological level, completeness and the classification of SCI were determined. For the patients, inclusion criteria were determined as traumatic SCI and both gender; however the exclusion criteria were determined for patients with any other neurological disorder than SCI and also non-traumatic SCI.

Experimental set-up

In order to find out the real impedance value of the human skin, a skin–electrode impedance model presented in Fig. 1 was used for mathematical calculations. Similar circuit models for skin–electrode interface were used in literature [1, 2, 4]. In this model, the skin was represented by pure resistance and capacitance, total resistance of the electrodes was shown by a resistance connected in parallel with a capacitance and liquid gel was represented as a resistance.

The mathematical equation of this model is presented in Eq. 1, which clearly indicates that for DC currents the

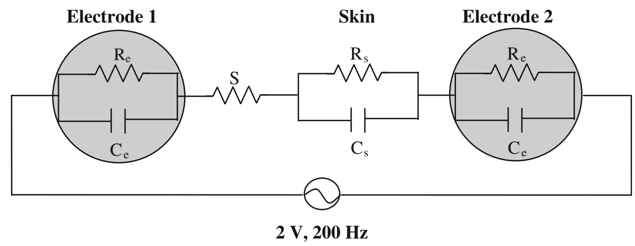

Fig. 1 Electrical equivalent circuit of the skin–electrode impedance model

model might lead to some misleading results due to the stray capacitance and resistance of electrodes. In this case the real skin resistance might be well below the measured value. The total impedance can be defined as,

$$Z=\left[\left(\frac{R_e^2X_r}{R_e^2+X_r^2}+\frac{R_s^2X_s}{R_s^2+X_s^2}\right)^2+\left(S+\frac{R_eX_r^2}{R_e^2+X_r^2}+\frac{R_sX_s^2}{R_s^2+X_s^2}\right)^2\right]^{1/2} \quad (1)$$

where Z is the total impedance, R_s is the resistance of the skin and S is the resistance of the gel. R_e and C_e simulate the transient resistance and the stray capacitance of the electrodes respectively. X_r and X_s represent the transient reactance of electrodes and the transient reactance of the skin respectively.

In order to obtain an accurate value of the skin resistance, AC current with a frequency of 200 Hz was used, which reduced the error in calculating the real skin resistance with respect to the measured value. Obviously, increasing the frequency reduced the reactance of the stray capacitance and hence decreased the total impedance of the parallel circuit which simulated the electrode–skin connection of the test subjects. At higher frequencies stray capacitance behaved as short circuit and the contact resistance became negligible values. However due to the capacitive nature of the human skin, increasing the frequency also reduced the measured total skin impedance and hence might lead to some misleading results. Two hundred Hertz was selected as an acceptable frequency with minimal distortion and high accuracy. Two self adhesive electrodes were placed on the skin of the test group and an AC signal with the amplitude of 2 V was applied. The type of the electrodes was electrocardiography (ECG) electrodes (Unomedical, Unilect). In order to prevent the deterioration of adhesiveness of electrodes which would have affected the skin–electrode impedance, each electrode was only used for once. The distance between the centers of the electrodes was 3 cm. A portable multimeter was placed between one of the electrodes and frequency generator and current values were recorded for each subject respectively (Fig. 2). Since at this frequency the measured impedance (Z), which in fact is a combination of the skin

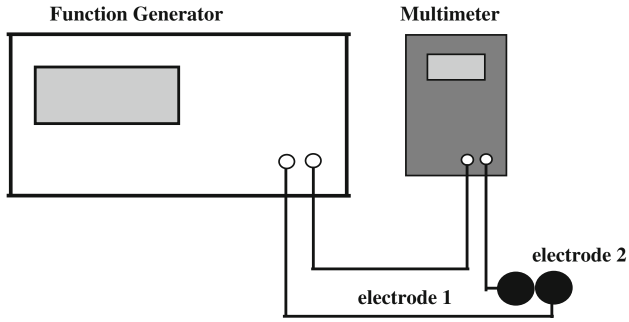

Fig. 2 Measurement set-up used for impedance measurements

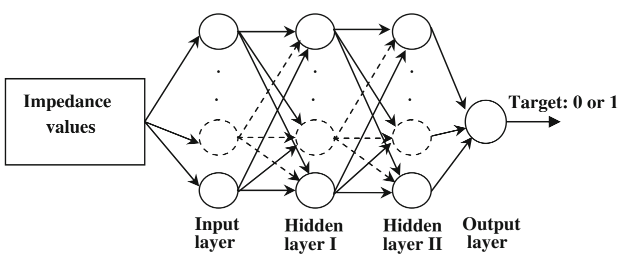

Fig. 3 The structure of the ANN utilized for classification of impedance values

resistance and capacitance, electrode resistance and capacitance, resistance of the conducting gel etc., was close to the real resistance (R_s), further calculations were not made to define the skin resistance.

Artificial neural networks

The artificial neural network (ANN) used in this study had one input layer, two hidden layers, and one output layer (Fig. 3). The input array was constituted from skin impedances and target array was constituted from array of ones (denoted patients) and zeros (denoted subjects).

Impedance values of three patients and three subjects were randomly chosen and used to train the network. The whole of other measures, which were not used during training stage, were employed for validation. Training and test sets were randomly changed for cross validation and performance test was repeated 50 times.

In the network model, one input layer, two hidden layers, and one output layer having 10, 5, 10, and 1 neurons were used respectively. Log-sigmoid transfer function was employed as the transfer function, which was used for calculations between the neurons during the training process. Back-propagation feed-forward algorithm was chosen for the training process. Number of the epoch was limited to 500 for the learning stage of the network. The number of the neurons and epoch, type of the transfer function and training algorithm used in this network were determined in an adaptive manner.

Results

Average and standard deviation (SD) of impedance values of each subject were represented in Fig. 4, which indicated that there was no significant difference between the average values of magnitudes of the patients and the control group. The maximum and minimum values of the skin impedances varied between 22 and 190 kΩ in control subjects, between 17 and 90 kΩ in paraplegic SCI patients and varied between 30 and 350 kΩ in tetraplegic SCI patients.

By analyzing the impedance values in a qualitative manner, a certain correlation between corresponding right and left dermatomes and repeated assessments were not found. In addition, distributions of the magnitudes of the impedances measured from C3 to S1 were irrelevant in patient and control groups. However, after analyzing the distribution of the skin impedance values by using a second order polynomial curve fitting method, strictly similar curve profiles were observed in paraplegics. It could be seen from Fig. 5a that the curves of the impedances of the paraplegic patients had an increasing inclination beginning from the level of the SCI to the lower part of the body. In addition to paraplegics, a certain curve profile could be seen in tetraplegics, namely the impedance values change slightly throughout all dermatomes (Fig. 5b). In the control group, a typical inclination was not observed (Fig. 5c). The impedance values of the both sides of the representative subjects could also be seen in Fig. 5.

In order to classify impedance values and to assess the success of findings as an indicator of SCI in a quantitative manner, employing the ANN was considered. Comparing with the number of paraplegic and control subjects, number of tetraplegic subjects (two patients) was smaller. Therefore, we took the possibility of failure of the ANN in learning phase into account and trained and tested the ANN by using two different data sets. In the first trial (Phase I) we used the data set including the impedance values of paraplegic, tetraplegic and control subjects. In the second trial (Phase II), we excluded data of the tetraplegic subjects from the input of the training and testing arrays of the ANN and hence only used the paraplegic and control subjects data.

In the training and testing stages of the ANN, the training and test sets were changed 50 times randomly. In Phase I, the validation result of the ANN was obtained as a rate of 73% in average. In Phase II, the validation results were better such as 75.4% in average. A statistical representation of the validation results is shown in Fig. 6. Figure 6a indicates the mean and SD of the errors of the testing results obtained in the Phase I. In Fig. 6b, the results for the subjects consisting of paraplegic patients and

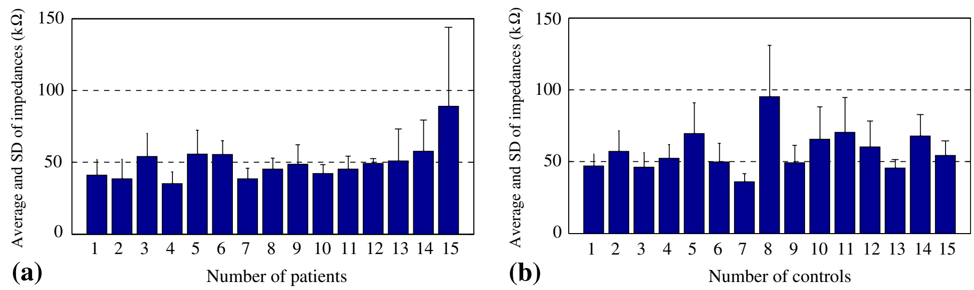

Fig. 4 Average and SD of impedance values of **a** patients (1–13 paraplegics, 14–15 tetraplegics), **b** controls

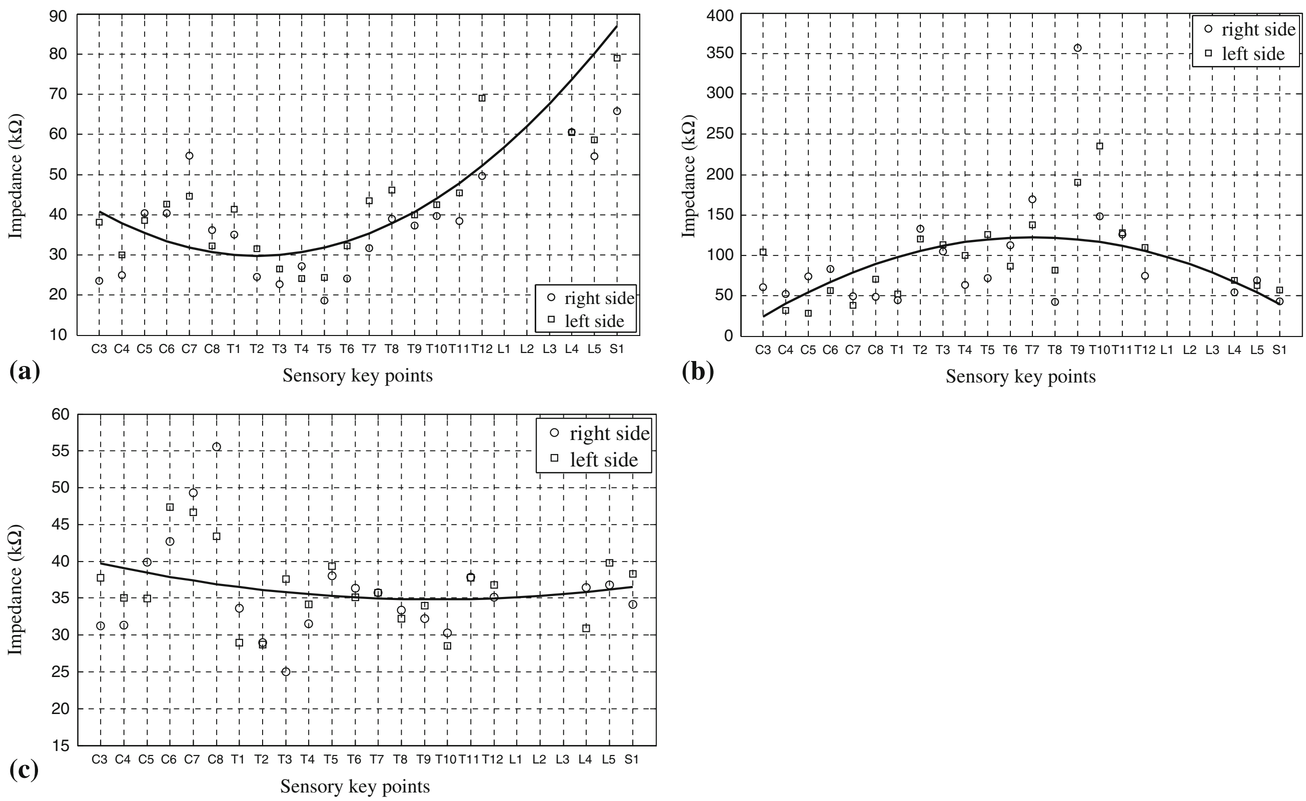

Fig. 5 Curve fitting results of the impedance values obtained from one representative **a** paraplegic subject **b** tetraplegic subject **c** control subject

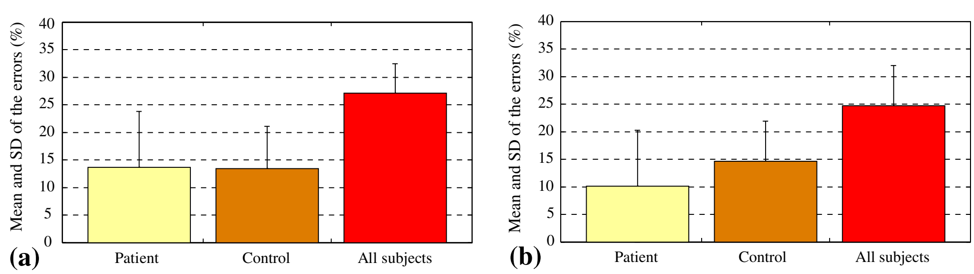

Fig. 6 Mean and SD of the errors obtained from the ANN. **a** Phase I: includes paraplegic, tetraplegics and control subjects **b** Phase II: includes paraplegic and control subjects

control group only (Phase II) are given. First, second and third bars of the each graphs denote the mean and SD of the errors obtained in patients, in controls and in all of the subjects, respectively.

A detailed representation of the mean and SD of the errors can also be seen in Table 1.

Discussion

It is well known that after SCI, atrophy could take place in all kinds of tissue such as the skin, muscle, tendon, and also blood circulation could diminish. The hypothesis that electrical impedance of the skin tissue would be affected by

Table 1 Mean and standard deviations of the errors

Subject	Phase I (paraplegic + tetraplegic + control)	Phase II (paraplegic + control)
Patient		
Mean (%)	13.6	10
SD (%)	10.1	10.1
Control		
Mean (%)	13.4	14.6
SD (%)	7.6	7.2
All subjects		
Mean (%)	27	24.6
SD (%)	5.3	7.2

SCI, was analyzed in this study. It could be said that by comparing the impedance values of SCI patients and control subjects (Fig. 4) a certain change occurred in the electrical conductivity of the skin after SCI. However, it is still not well known whether this change occurred in the superficial skin or deeper tissues yet. Also, it was not so easy to state that the only electrical property changed in the skin tissue was the conductivity. As stated before, increasing the frequency of the test signal reduced the reactance of the stray capacitances of the test electrodes. However, it was found that it was difficult to claim that the AC signal was transferred only on the surface of the skin, in fact it might penetrate through the skin and travel beneath the skin through several tissues. A low frequency electrical current affects superficial tissues whereas a high frequency electrical current affects deep structures, hence several additional tests and measurements needed to be done in order to find out the optimum frequency which minimizes the penetration effect into the deep tissue and also reduced the capacitive reactance up to an acceptable level.

Comparing the validation results obtained from Phase I and Phase II it can be seen that (Table 1), mean and SD errors of the testing performance in Phase II (24.6 ± 7.2%) were less than in Phase I (27 ± 5.3%). Due to the inconvenient and difficult situations in measuring the impedance values of tetraplegic subjects, inadequate number of test results has been obtained and hence tetraplegic impedance values were excluded from the data set (Phase II). In this case ANN showed a superior performance than in Phase I. The prediction of the presence of SCI increased from 86.4 to 90% in patients group and from 73 to 75.4% in all subjects. When excluding the tetraplegic data, the prediction of the absence of the SCI in control groups decreased from 86.6 to 85.4%. This was because of the lacking of total data when calculating the average validation rate.

During measurements, the impedance of the skin could be affected by several factors such as the environmental temperature, wetness, adhesiveness of the electrodes, perspiration, presence or absence of hair, etc. Perspiration as a vegetative system function can directly affect the skin impedance [5]. An increase in perspiration may lower the skin resistance considerably. In addition to perspiration, abrasion of the skin reduces the skin impedance [14]. Therefore in order to measure the skin impedance correctly, these factors should be taken into account prior to measurements. However, in this study in order to simulate the worst case conditions, skin was not prepared artificially by cleaning and abrasion prior to measurements. Thus several factors, such as perspiration, humidity, temperature and skin preparation process could affect success and accuracy of the impedance measurements.

Future studies would be aimed to improve the performance of this technique, to evaluate the validity of the technique in acute patients and to determine the level of the SCI only by using a few of test locations in real time applications. The classification performance of the ANN can be improved by increasing the number of patients and controls. Since SCI has a very low incidence and exclusion criteria were strictly applied, we had difficulty to include more patients. In addition to this, there seemed to be a need for minimizing the effects of environmental factors such as temperature, humidity and pressure. But minimizing the effects of environmental factors could reduce the advantage of this technique in terms of practical application to the patients.

Conclusions

As a quantitative SCI diagnosing method, the proposed technique showed promising performance. The validation result of the ANN was obtained as a rate of 73% in average. According to the experimental procedure and results, proposed skin impedance test seemed to be a simple, objective, quantitative, non-invasive and non-expensive way of assessing the presence of SCI. It could be a useful tool in determining the existence of SCI if any, especially in unconscious and non-cooperative patients. It could also be used for monitoring and research purposes to find out any natural and/or interventional recovery or deterioration in SCI.

Acknowledgments This study was approved by the Ethics Committee of Cerrahpaşa Medical Faculty, Istanbul University and was supported by the Research Fund of Istanbul University, Project Number UDP-1144/09052007.

References

1. Assambo C, Baba A, Dozio R, Burke MJ (2007) Determination of the parameters of the skin-electrode impedance model for ECG measurement. Proceedings of the 6th WSEAS international

conference on electronics, hardware, wireless and optical communications, Corfu Island, Greece, pp 90–95, February 16–19
2. Chizmadzhev YA, Indenbom AV, Kuzmin PI, Galichenko SV, Weaver JC, Potts RO (1998) Electrical properties of skin at moderate voltages: contribution of appendageal macropores. Biophys J 74:843–856
3. Curt A, Dietz V (1999) Electrophysiological recordings in patients with spinal cord injury: significance for predicting outcome. Spinal Cord 37:157–165. doi:10.1038/sj.sc.3100809
4. Dorgan SJ, Reilly RB, Murray CD (1997) A model for human skin impedance during surface functional neuromuscular stimulation. Proceedings of the 19th international conference of the IEEE/EMBS, Chicago, USA, pp 1770–1773 October 30–November 2
5. Gondran C, Siebert E, Fabry P, Novakov E, Gumery PY (1995) Non-polarisable dry electrode based on NASICON ceramic. Med Biol Eng Comput 33:452–457. doi:10.1007/BF02510529
6. Hayes KC, Wolfe DL, Hsieth JT, Potter PJ, Krassioukov A, Durham CE (2002) Clinical and electrophysiologic correlates of quantitative sensory testing in patients with incomplete spinal cord injury. Arch Phys Med Rehabil 83:1612–1619. doi:10.1053/apmr.2002.35101
7. Karamehmetoglu SS, Nas K, Karacan I, Sarac AJ, Koyuncu H, Ataoglu S, Erdogan F (1997) Traumatic spinal cord injuries in Southeast Turkey: an epidemiological study. Spinal Cord 35:531–533. doi:10.1038/sj.sc.3100404
8. Kramer JLK, Moss AJ, Taylor P, Curt A (2008) Assessment of posterior spinal cord function with electrical perception threshold in spinal cord injury. J Neurotrauma 25(8):1019–1026. doi:10.1089/neu.2007.0503
9. Krassioukov A, Wolfe DL, Hsieh JT, Hayes KC, Durham CE (1999) Quantitative sensory testing in patients with incomplete spinal cord injury. Arch Phys Med Rehabil 80:1258–1263. doi:10.1016/S0003-9993(99)90026-6
10. Kraus JF, Franti CE, Riggins RS, Richards D, Borhani NO (1975) Incidence of traumatic spinal cord lesions. J Chronic Dis 28:471–492. doi:10.1016/0021-9681(75)90057-0
11. Maynard FM Jr, Bracken MB, Creasey G, Ditunno JF Jr, Donovan WH, Ducker TB, Garber SL, Marino RJ, Stover SL, Tator CH, Waters RL, Wilberger JE, Young W (1997) International standards for neurological and functional classification of spinal cord injury. American Spinal Injury Association. Spinal Cord 35(5):266–274. doi:10.1038/sj.sc.3100432
12. National Spinal Cord Injury Statistical Center (2008) Spinal cord injury: facts and figures at a glance 2008. National Spinal Cord Injury Statistical Center, Birmingham
13. Nicotra A, Ellaway PH (2006) Thermal perception thresholds: assessing the level of human spinal cord injury. Spinal Cord 44:617–624. doi:10.1038/sj.sc.3101877
14. Rosell J, Colominas J, Riu P, Pallas-Areny R, Webster JG (1988) Skin impedance from 1 Hz to 1 MHz. IEEE Trans Biomed Eng 35(8):649–651. doi:10.1109/10.4599
15. Savic G, Bergström EMK, Frankel HL, Jamous MA, Ellaway PH, Davey NJ (2006) Perceptual threshold to cutaneous electrical stimulation in patients with spinal cord injury. Spinal Cord 44:560–566. doi:10.1038/sj.sc.3101921
16. Savic G, Bergström EMK, Davey NJ, Ellaway PH, Frankel HL, Jamous MA, Nicotra A (2007) Quantitative sensory tests (perceptual thresholds) in patients with spinal cord injury. J Rehabil Res Dev 44(1):77–82. doi:10.1682/JRRD.2005.08.0137
17. Staas WE Jr, Formal CS, Freedman MK, Fried GW, Schmidt Read ME (1998) Spinal cord injury and spinal cord injury medicine. In: DeLisa JA (ed) Rehabilitation medicine principles and practice. Lippincott Raven, Philadelphia