2014

Characterization Of Sex-Based Differences In The Mechanical Properties Of Human Finger Glabrous Tissue Using A Fiberoptic Sensor

Lalit Venkatesan
University of Nebraska - Lincoln

Steven M. Barlow
University of Nebraska-Lincoln, steven.barlow@unl.edu

PMCID: PMC4075340

Published in final edited form as:
J Biomech. 2014 July 18; 47(10): 2257–2262. doi:10.1016/j.jbiomech.2014.04.044.

CHARACTERIZATION of SEX-BASED DIFFERENCES IN THE MECHANICAL PROPERTIES OF HUMAN FINGER GLABROUS TISSUE USING A FIBEROPTIC SENSOR

Lalit Venkatesan[1,*] and **Steven M. Barlow**[1,2,3]

[1]Communication Neuroscience Laboratories, University of Nebraska, Lincoln, NE 68583, USA

[2]Department of Special Education & Communication Disorders, University of Nebraska, Lincoln, NE 68583, USA

[3]Center for Brain, Biology and Behavior, University of Nebraska, Lincoln, NE 68583, USA

Abstract

TAC-Cell is a custom-built somatosensory stimulator that delivers pneumatic cutaneous tactile inputs to virtually any skin target on the body and by virtue of its non-ferrous materials is compatible with functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG) brain scanners. In this study, we describe the method to measure apparent skin displacement induced by TAC-Cell stimulation of the glabrous surface of the distal phalanx of the index finger. Specifically, we studied the effect of four servo controller input voltages (0.4V to 1.0V) on resultant skin displacement among eighteen, neurotypical adult male and female participants. A fiberoptic displacement sensor, commonly used in industrial applications, was coupled to the TAC-Cell to measure the glabrous skin's kinematic response to different stimulus amplitudes. Skin displacement was significantly dependent on stimulus amplitudes and sex ($p < 0.0001$). Power spectrum and kinematic analysis of skin displacement showed that the pneumatic TAC-Cell stimulus consists of a spectrally rich, high velocity signal. In related work, we have shown that this dynamic pneumocutaneous stimulus is highly effective in evoking a cortical brain response for neurodiagnostic applications and somatosensory pathway analysis in health and disease.

[*]Steven M. Barlow, Ph.D. Corwin Moore Professor Department of Special Education and Communication Disorders, Center for Brain, Biology & Behavior, Professor (affiliate) Biological Systems Engineering, Director, Communication Neuroscience Laboratories, University of Nebraska, 272 Barkley Memorial Center, Lincoln, NE 68583, TL 402 472 6395, FX 402 472 7697, steven.barlow@unl.edu.
Lalit Venkatesan, Ph.D., Communication Neuroscience Laboratories, University of Nebraska, 141 Barkley Memorial Center, Lincoln, NE 68583, TL 402 472 6395, FX 402 472 7697, lalit.venkatesan@gmail.com

Financial Disclosure
There are no additional conflicts of interest with any of the commercial manufacturers listed in this research paper.

Keywords

tactile; pneumatic; glabrous skin; stimulation; human; somatosensory

1. Introduction

Human skin is a highly organized, multilayered organ that covers the body. The skin has the ability to endure large deformations due to its anisotropic, viscoelastic, nonlinear, and non-homogenous properties. Study of the mechanical properties of skin is important, but challenging given its complex structure and characteristics. As a result, development of a real-time system to quantify skin displacement becomes a formidable task. In this study we describe a novel, unconventional technique that utilizes a reflection-dependent fiber-optic displacement sensor coupled to a pneumatic stimulator to characterize skin displacement.

Many studies have illustrated sex-related differences in the mechanical properties and thickness of the skin. Optical coherence tomography studies (Fruhstorfer et al., 2000) have shown that the thickness of the stratum corneum in female fingertips is thinner when compared to males, thus making the tissue more compliant. There are significant sex-related differences in collagen and elastic fiber density (Vitellaro-Zuccarello et al., 1994). Skin thickness is greater in younger males (27–31 years) when compared to age-matched females across the entire body except for the lower back (Seidenari et al., 1994; Tur, 1997). Skinfold thickness (Davies et al., 1988) and compression (Hattori and Okamoto, 1993) of cutaneous surfaces on the limbs is lower in young female subjects. A lower rate of arterial inflow through the fingers has been observed in females (Bollinger and Schlumpf, 1976), and this rate decreases more in response to cooling resulting in lower limb temperatures. Finger blood flow and skin perfusion increases by two- and three-fold respectively in males when compared to females (Cooke et al., 1990). There are differences in skin temperature and hydration between males and females (Verrillo et al., 1998), but the effects of these variables on the extent to which the skin is displaced is unknown. Women manifest significantly lower thresholds to vibrotactile stimuli (Bhattacharjee et al., 2010) and tactile acuity detection tasks (Peters et al., 2009) compared to men when the finger was used as the target for stimulation. This performance difference in tactile perception tasks between males and females is presumed to occur because of higher densities of Meissner’s corpuscles (Dillon et al., 2001) and Merkel disks (Peters et al., 2009), respectively, in the fingers of female subjects.

A force-controlled stimulus causes greater deformation in skin that is more compliant. Thus, differences in skin compliance and thickness between males and females may result in varying degrees of skin displacement to the same stimulus amplitude. Quantitative studies aimed at mapping the relation between applied force and resulting deflection of the skin among male and female subjects are lacking. This is due, in part, to limitations in suitable transduction methods to measure the resultant deflection in tissue conformation in the presence of a pneumatic ‘force’ field. A comprehensive understanding of tissue compliance and modes of displacement during pulsatile pneumatic stimulation of the tactile field in glabrous and non-glabrous tissues will enhance functional neuroimaging studies on

somatosensory function in humans across the lifespan in health and disease. Non-invasive tactile somatosensory stimulation has numerous applications, both in neurorehabilitation and neurological assessments in patients with progressive brain disease, or those suffering from a cerebral infarct due to neurovascular disease or injury. The physical properties of the skin appear to be dependent on characteristics inherent to the subject (e.g., sex and age), along with environmental factors (e.g., skin temperature, and hydration). These variables not only affect tissue compliance, but also influence the somatosensory percept. Thus, the intensity of these non-invasive stimulation modalities during motor rehabilitation and neurological assessments should be scalable to accommodate for these inter-subject differences to achieve an ideal therapeutic or neural response. Currently, there are no systems available for real-time measurement of skin displacement actuated by pneumatic inputs.

A new, open-chamber pneumatic stimulator known as the TAC-Cell was developed in our laboratory to deliver punctate mechanical stimuli to any cutaneous target on the face, trunk, upper or lower limbs, and distal extremities. In a recent functional brain imaging study, we characterized the response of the human face and hand somatosensory cortical network using a repeating 6-pulse pneumatic stimulus train delivered using a single-channel TAC-Cell device (Venkatesan et al., 2010). The control signal voltage for the pneumatic servo was held constant for all test subjects without regard for the actual displacement generated at the skin surface. This was due to the absence of an integral skin displacement sensor in the TAC-Cell device. In the present study, we present a fiberoptic displacement sensor-based real-time solution to digitize glabrous skin deflection on the index finger in response to a servo-controlled pneumatic pulse train. A reflectance-dependent fiberoptic displacement sensor, commonly used in industrial applications to measure the distance from an object that is moving parallel to the axis of the fiberoptic tip, was adapted to the TAC-Cell to quantify the dynamics of glabrous skin deflection in the presence of pneumatic pulsatile inputs among age-matched male and female participants. The corresponding biophysical skin deflection responses were analyzed to measure stimulus pressure, rise-fall time, mechanical response time, and the power spectrum at four different servo motor excitation levels. In addition to testing the feasibility of integrating an optode-detector within the TAC-Cell, we hypothesized that the dynamics of glabrous skin deflection would scale in a nearly monotonic fashion from 40 to 100 cmH_2O as a function of servo motor excitation level, with the glabrous skin of female participants showing significantly greater deflections compared to age-matched males.

2. Methods

2.1. Participants

Eighteen neurotypical young adults (9 male [mean 24.44 (SD=2.27) years] and 9 female [mean 23.11 (SD=1.93) years]) were recruited for this study without exclusions based on race or ethnicity. Written informed consent, approved by the University of Kansas Human Subjects Institutional Review Board, was obtained from all participants. Inclusion criteria: Right-handed according to the Edinburgh handedness scale (Oldfield, 1971) with no report of neurological or psychiatric illness, and not taking regular medication. Exclusion criteria:

Neurological, sensory and/or muscular deficits, psychiatric abnormalities, or abnormal skin sensitivity on face or hand.

2.2. TAC-Cell

The TAC-Cells (**Error! Reference source not found**.1a) used in the present study were custom machined from Delrin (O.D. = 15mm, I.D. = 6mm, H = 6mm) with a 10/32" barb-fitting at the posterior surface of the stimulator. A custom non-commutated linear motor (H2W Technologies, Inc., Serial number: I 1101) coupled to a custom Airpel® *Anti-Stiction*® glass cylinder (Airpot Corporation) operating under position feedback (Biocommunication Electronics, LLC, model 511 servo controller), and computer control was used to modulate the air pressure within the TAC-Cell with pneumatic pressure pulses. The computer was equipped with a 16-bit multifunction card (PCI-6052E, National Instruments). Stimulus control signals were programmed with LabVIEW® software (National Instruments, v11.0), and served as the input to the servo controlled pneumatic amplifier. Pressure pulses were conducted within a polyurethane line (1/4" OD, 7/64″ ID) from the servo motor to the TAC-Cell coupled on the participant's skin using double-adhesive tape collars and tincture of Benzoin (10–90% intercept rise time = 8.5 ms).

2.3. Characterization of TAC-Cell stimulus

The TAC-Cell was modified to accept a non-contact fiberoptic displacement sensor (PHILTEC, Model D170) at an end-gap distance (end-end distance between the active-surface of the fiberoptic sensory and the skin surface) of 8 mm. As shown in Figures 1b and 1c, the fiberoptic sensor was mounted on a linear translation stage and optical mount (Newport optics, Model M-423 and Model 45) to permit precise placement of the TAC-Cell on each subject. Stimulus pressure (calibrated in cmH_2O) was measured using a pressure transducer (Honeywell, 5 psi full scale). A stainless steel reflective marker (diameter = ¼") was adhered to the glabrous skin overlying the distal interphalangeal joint of the right index finger using mastic (Figure 2a). The reflective marker was aligned and centered within the lumen of the TAC-Cell such that its deflection under pneumatic load was parallel to the axis of the sensor. The linear stage containing the TAC-Cell was lowered and the TAC-Cell attached to the finger using a double-adhesive collar (Figure 2b).

Stimulus amplitude was systematically varied and counterbalanced among subjects using four different motor inputs (1V, 0.8V, 0.6V, 0.4V). The corresponding skin displacement peaks were measured. The input stimuli consisted of ten 50-ms pulses that were generated at 2 Hz. Peak values for skin displacement were averaged over the 10 pulses for each input stimulus. LabChart Pro (*v 7.3*, ADInstruments) was programmed to digitize (1k samples/s @ 16-bits vertical resolution ± 5V) the skin displacement signal output from the fiberoptic sensor, TAC-Cell air pressure signal, and the input voltage to the linear motor (Figure 3). The Peak Analysis Module in LabChart was used for off-line analysis of the peaks and 10–90% rise and fall times in the recorded data (displacement in mm, pressure in cmH_2O). LabChart was subsequently utilized in order to perform the power spectrum analysis on the digitized skin displacement and stimulus pressure waveforms for the four different motor inputs.

2.4. Calibration

Distance between the stainless steel reflective marker and the surface of the fiber optic sensor was varied in increments of 0.5 mm and the corresponding outputs from the sensor were recorded. It was determined that the linear operating range of the sensor was between 3 and 13 mm ($R^2 = 0.99$) (Figure 4). The TAC-Cell was affixed at an end-gap distance of 8 mm, so that the range of motion of the stainless-steel marker is centered at mid-range and well within the linear-operating range of the sensor. A simple linear regression model was used to fit these variables (sensor output, distance from the marker). LabChart's multi-point calibration was used to scale the output variables based on the values obtained using the regression model (Figure 4).

2.5. Statistical Analysis

An Analysis of Variance (ANOVA) was performed using the Minitab® v16 statistical analysis software to estimate the effect of different stimulus input amplitudes (independent variable) on skin displacement (dependent variable) as a function of participants' sex, and their interactions.

3. Results

3.1. Skin displacement as a function of sex of the subject

The displacement peaks at the finger due to TAC-Cell stimulation are significantly dependent on the sex of the participant ($F=279.71$, $p<.0001$) for all servo motor inputs ($F=542.97$, $p<.0001$) (Figure 5b). The average displacement peak values for both males and females are shown in Table 1.

3.2. Stimulus Pressure and Apparent Glabrous Tissue Deflection

Stimulus pressure is controlled by the linear motor and servo controller. Stimulus pressure apparent at the TAC-Cell increases in monotonic fashion as motor-input increases (Figure 5a), and is nearly identical among male and female participants. However, the resultant glabrous tissue deflection on the index finger differs, with females manifesting larger deflections (Figure 5b). Average stimulus pressure and tissue deflection peak values for both males and females are summarized in Table 1.

3.3. Power Spectrum Analysis

The power spectra was calculated for displacement and stimulus pressure waveforms for each of the four different motor inputs between male and female participants. A graphical comparison of TAC-Cell pressure and resultant skin displacement power spectra among males and females is shown in Figure 6. Plot panels 6a and 6c reveal virtually identical pressure spectra as a function of linear motor excitation voltage (0.4, 0.6, 0.8, and 1.0 volts). By contrast, plot panels 6b and 6d show differences in tissue displacement spectra with females having larger spectral peaks at each of the linear motor excitation levels when compared to the male response. A two-way ANOVA revealed significant differences for peak components in the tissue displacement spectra ($F\ [3,71]=12.66$, $p<.001$) and sex ($F\ [1,71]=24.13$, $p<.001$) at a linear motor excitation of 1 volt. Similar results were found at

lower levels of linear motor excitation and are summarized in Table 2. Figure 7 shows a direct comparison of male and female tissue compliance at each of the four linear motor excitation voltages (panels 7a – 7d) to further highlight the sex difference. This analysis confirms the observation of higher glabrous skin compliance when TAC-Cell pressure is comparable for male and female participants.

4. Discussion

This study has shown a new method using a fiberoptic sensor for real-time characterization, data acquisition and analysis of glabrous tissue displacement dynamics in neurotypical adult males and females. Systematic changes in linear motor excitation (e.g., 1V, 0.8V, 0.6V, 0.4V) resulted in proportional and predictable change in stimulus pressure peaks at the TAC-Cell skin interface. Although stimulus pressure was clearly comparable for both the sexes at corresponding motor inputs, resultant glabrous skin displacement peaks on the index finger were significantly higher for females when compared to males.

Power spectrum analysis of the resultant skin displacement and stimulus pressure signal reveals a spectrally rich signal with a clearly visible fundamental frequency and several harmonics with significant energy. The signal consists of a broad power spectrum with complex harmonic energy up to 20 Hz. Higher displacement peak power for all linear motor excitation levels (1V, 0.8V, 0.6V, 0.4V) in females indicates greater skin displacement amplitudes compared to males. The spectral energy in these high frequency components contribute to the punctate nature of the TAC-Cell stimulus and makes it a highly effective means of activating the human somatosensory nervous system for neurodiagnostic and neurotherapeutic applications in adult cerebrovascular stroke, and neurosensory integrative disorders (e.g., autism spectrum disorder) (Finan and Barlow, 1998; Venkatesan et al., 2010).

The differences in skin displacement are likely attributable to sex-dependent differences in skin compliance and conformance. An individual’s occupation also may play a role in modifying the viscoelastic properties and thickness of the skin as an adaptation to the functional use of the hand (e.g., manual labor). This experiment was limited in the fact that the effect of physical properties of the skin [e.g. skin temperature (Verrillo et al., 1998), hydration (Verrillo et al., 1998), thickness (Fruhstorfer et al., 2000; Seidenari et al., 1994; Tur, 1997)] on skin displacement was not studied. Future studies could utilize durometers (measures skin compliance), skin hydration and temperature measures in order to ascertain the extent to which the differences in skin displacement between males and females is dependent on these variables.

Integration of an optode-detector within the TAC-Cell has demonstrated the possibility of real-time measurement of skin deflection during pulsatile pneumatic inputs. The enhanced TAC-Cell with an optode-detector will make it possible for the first time to determine if the evoked brain response to punctate pneumatic inputs scales to the amplitude and dynamics (velocity, acceleration) of skin indentation in males and females. A non-ferrous housing that encapsulates a fiberoptic sensor bundle will be considered in future designs of the TAC-Cell to allow for real-time monitoring and control of tissue displacement in the functional

neuroimaging environment. Careful monitoring of the resultant skin displacement using a pneumatic cell such as the TAC-Cell with an integrated optode and detector will make it possible to scale cutaneous stimulus amplitude in a consistent manner at various skin sites across male and female test subjects over the lifespan. Moreover, a well-controlled pneumatic stimulus which can be monitored in real time for apparent skin displacement has added value in neurotherapeutic applications where stimulus scale is a key variable in mapping the plasticity and recovery of function in adult stroke.

Acknowledgments

This work was supported by grants NIH R01 DC003311 (SM Barlow), NIH P30 DC005803, and the Sutherland Family Foundation (SM Barlow).

Drs. Barlow and Venkatesan are the inventors of the TAC-Cell which is registered and licensed by the University of Kansas to Epic Medical Concepts & Innovations, Incorporated (Olathe, Kansas USA).

References

Bhattacharjee A, Ye AJ, Lisak JA, Vargas MG, Goldreich D. Vibrotactile masking experiments reveal accelerated somatosensory processing in congenitally blind braille readers. J Neurosci. 2010; 30:14288–14298. [PubMed: 20980584]

Bollinger A, Schlumpf M. Finger blood flow in healthy subjects of different age and sex and in patients with primary Raynaud's disease. Acta chirurgica Scandinavica. Supplementum. 1976; 465:42–47.

Cooke JP, Creager MA, Osmundson PJ, Shepherd JT. Sex differences in control of cutaneous blood flow. Circulation. 1990; 82:1607–1615. [PubMed: 2225365]

Davies BN, Greenwood EJ, Jones SR. Gender difference in the relationship of performance in the handgrip and standing long jump tests to lean limb volume in young adults. European journal of applied physiology and occupational physiology. 1988; 58:315–320. [PubMed: 3220073]

Dillon YK, Haynes J, Henneberg M. The relationship of the number of Meissner's corpuscles to dermatoglyphic characters and finger size. J Anat. 2001; 199:577–584. [PubMed: 11760888]

Finan DS, Barlow SM. Intrinsic dynamics and mechanosensory modulation of non-nutritive sucking in human infants. Early Hum Dev. 1998; 52:181–197. [PubMed: 9783819]

Fruhstorfer H, Abel U, Garthe CD, Knuttel A. Thickness of the stratum corneum of the volar fingertips. Clin Anat. 2000; 13:429–433. [PubMed: 11111894]

Hattori K, Okamoto W. Skinfold compressibility in Japanese university students. Okajimas Folia Anat Jpn. 1993; 70:69–77. [PubMed: 8247474]

Oldfield RC. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia. 1971; 9:97–113. [PubMed: 5146491]

Peters RM, Hackeman E, Goldreich D. Diminutive digits discern delicate details: fingertip size and the sex difference in tactile spatial acuity. J Neurosci. 2009; 29:15756–15761. [PubMed: 20016091]

Seidenari S, Pagnoni A, Di Nardo A, Giannetti A. Echographic evaluation with image analysis of normal skin: variations according to age and sex. Skin pharmacology : the official journal of the Skin Pharmacology Society. 1994; 7:201–209. [PubMed: 8024801]

Tur E. Physiology of the skin--differences between women and men. Clin Dermatol. 1997; 15:5–16. [PubMed: 9034651]

Venkatesan L, Barlow S, Popescu M, Popescu A, Auer ET. TAC-Cell inputs to human hand and lip induce short-term adaptation of the primary somatosensory cortex. Brain research. 2010; 1348:63–70. [PubMed: 20550944]

Verrillo RT, Bolanowski SJ, Checkosky CM, McGlone FP. Effects of hydration on tactile sensation. Somatosens Mot Res. 1998; 15:93–108. [PubMed: 9730110]

Vitellaro-Zuccarello L, Cappelletti S, Dal Pozzo Rossi V, Sari-Gorla M. Stereological analysis of collagen and elastic fibers in the normal human dermis: variability with age, sex, and body region. Anat Rec. 1994; 238:153–162. [PubMed: 8154602]

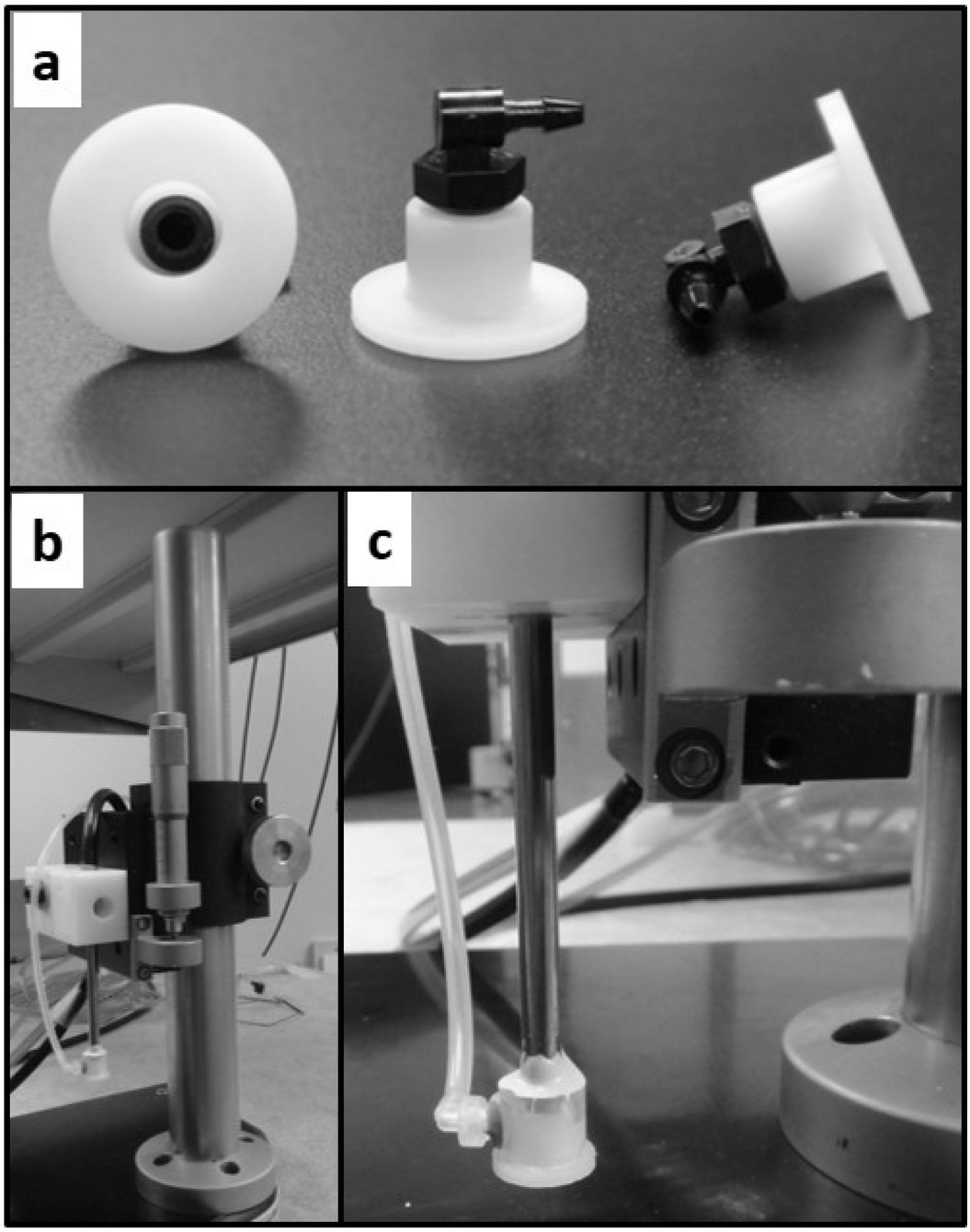

Figure 1.
(**a**) TAC-Cell in 3 views, (**b** and **c**) TAC-Cell attached to fiberoptic displacement sensor and mounted on a Newport linear micrometer stage.

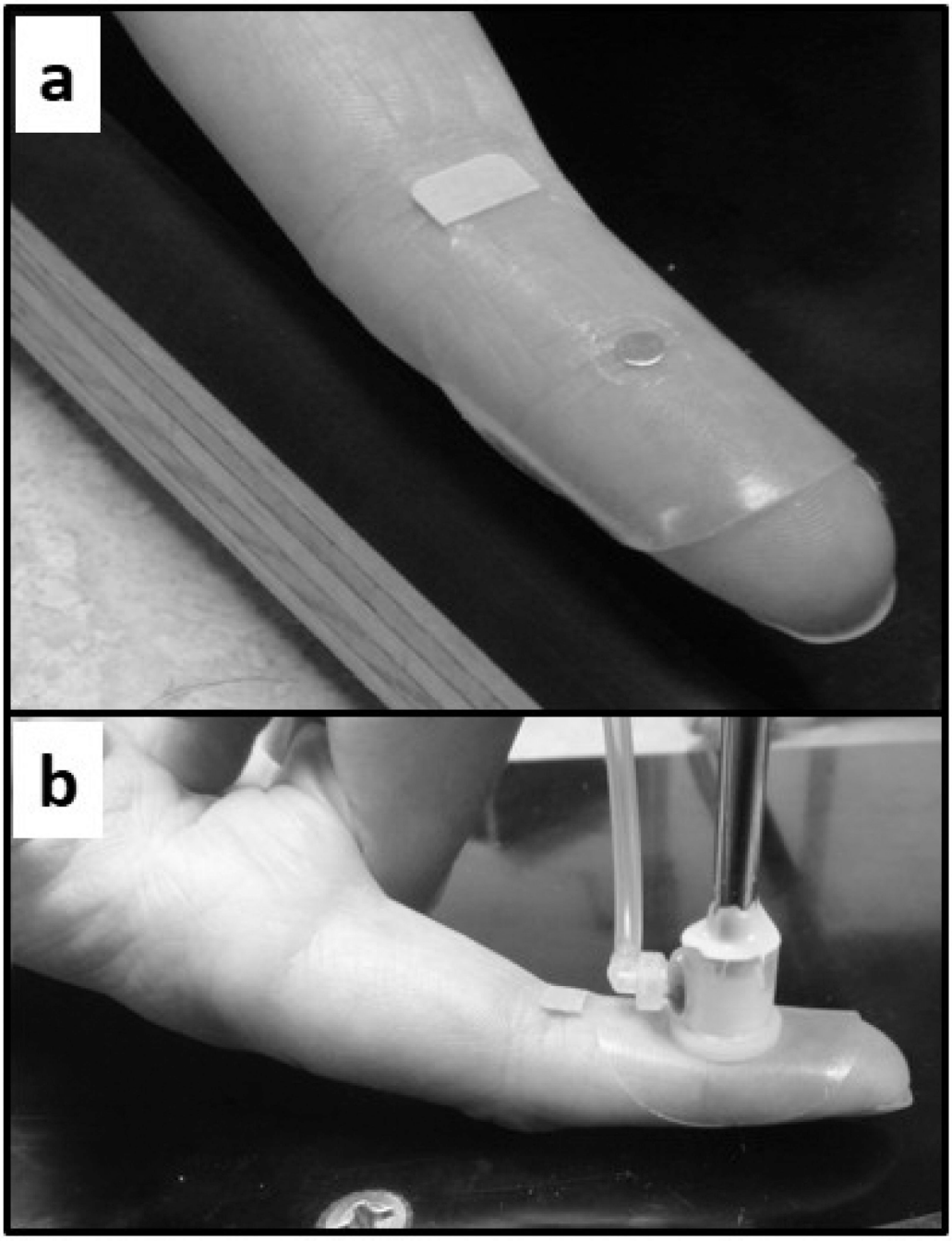

Figure 2.
(**a**) Placement of the stainless-steel marker and double-adhesive collar on the index finger, and (**b**) placement of the TAC-Cell on the index finger.

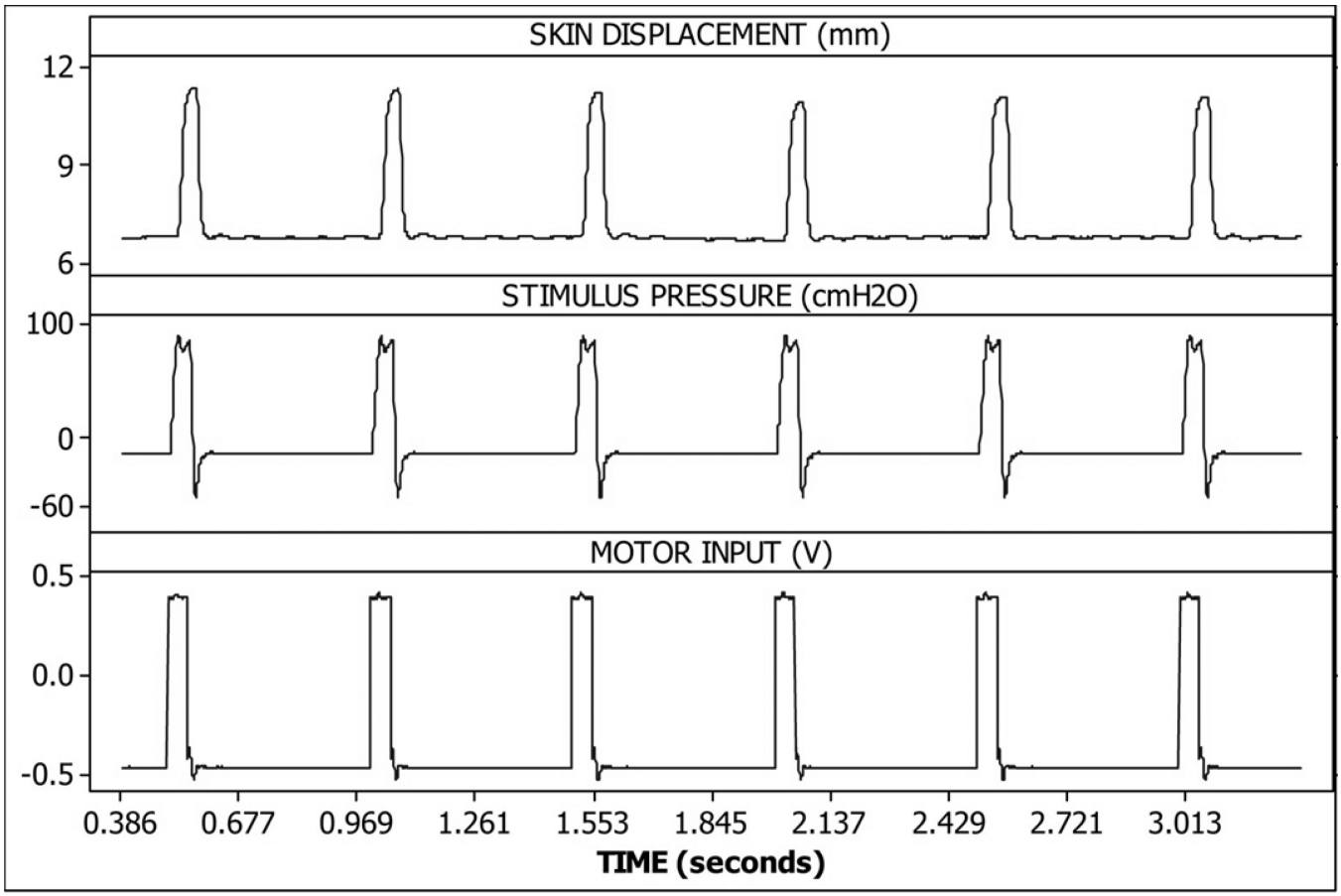

Figure 3.

Sample record of skin displacement and stimulus pressure data for 6 input pulses at 2 Hz when motor input from baseline was +1V.

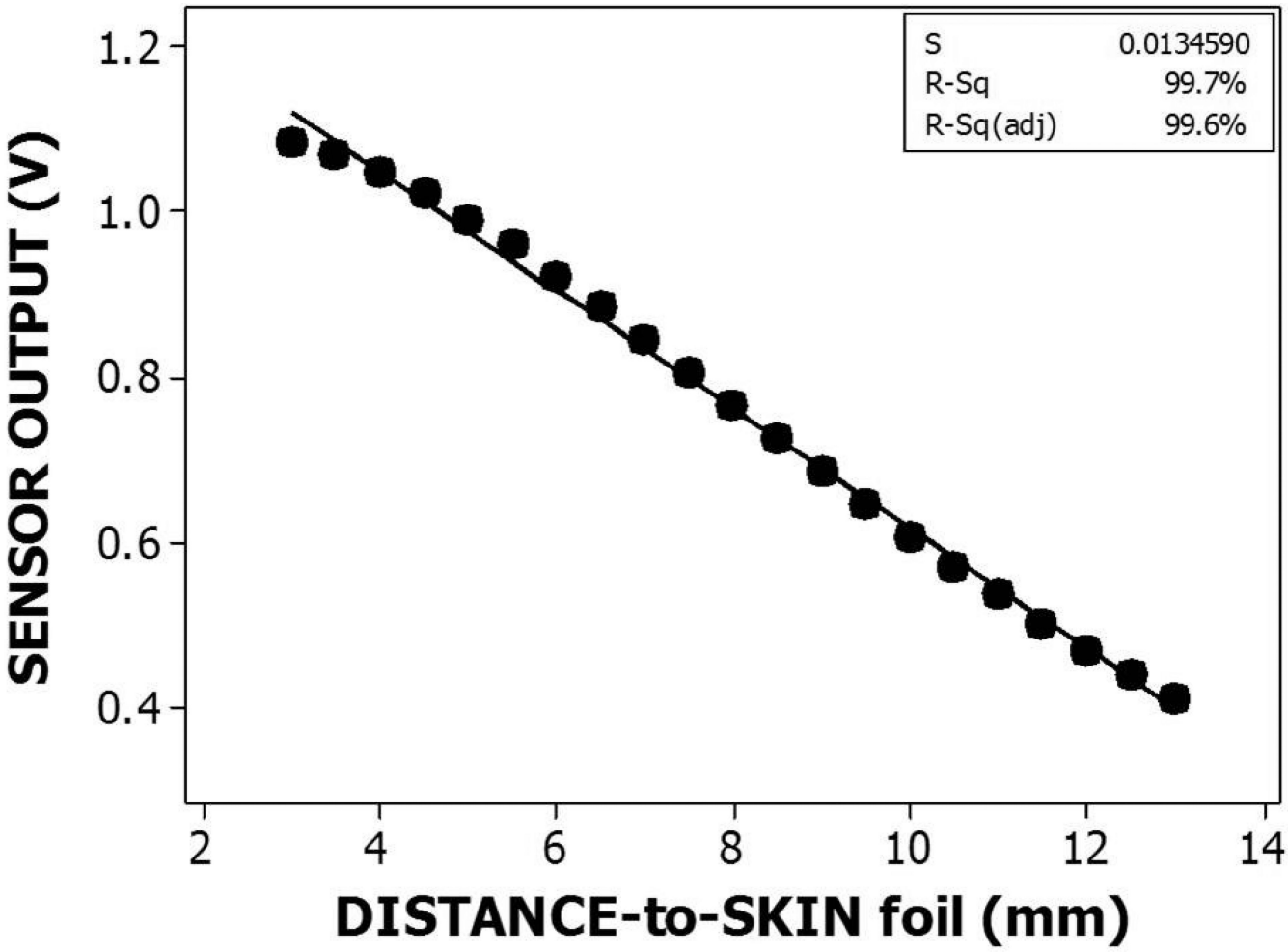

Figure 4.

Fiberoptic sensor calibration and associated simple linear regression fit described by the equation: **Sensor_Output** = 1.338 – 0.07209 × **Distance-to-Skin**.

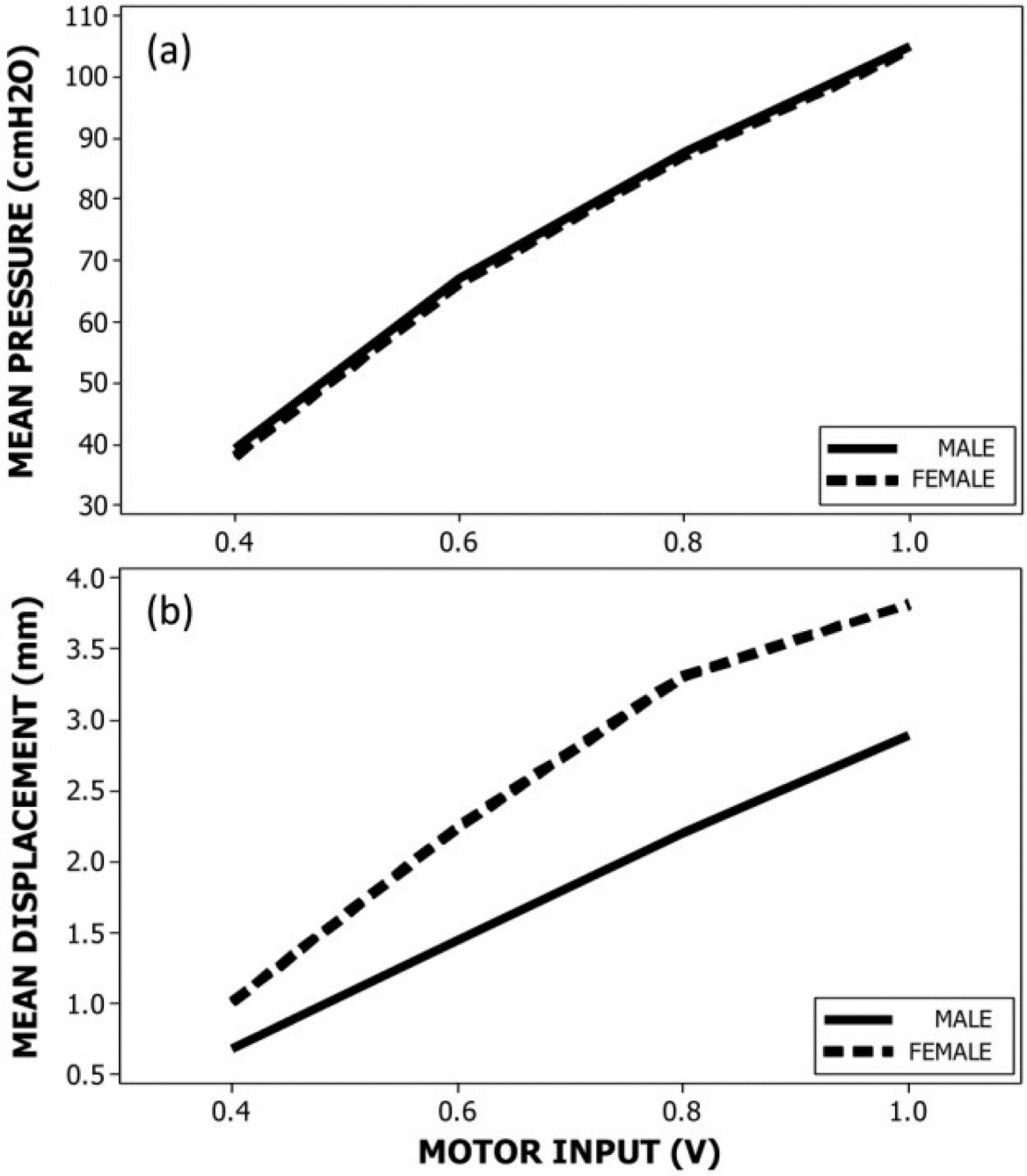

Figure 5.

(**a**) Comparison of mean pressure peaks, (**b**) and mean stimulus displacement peaks between males and females.

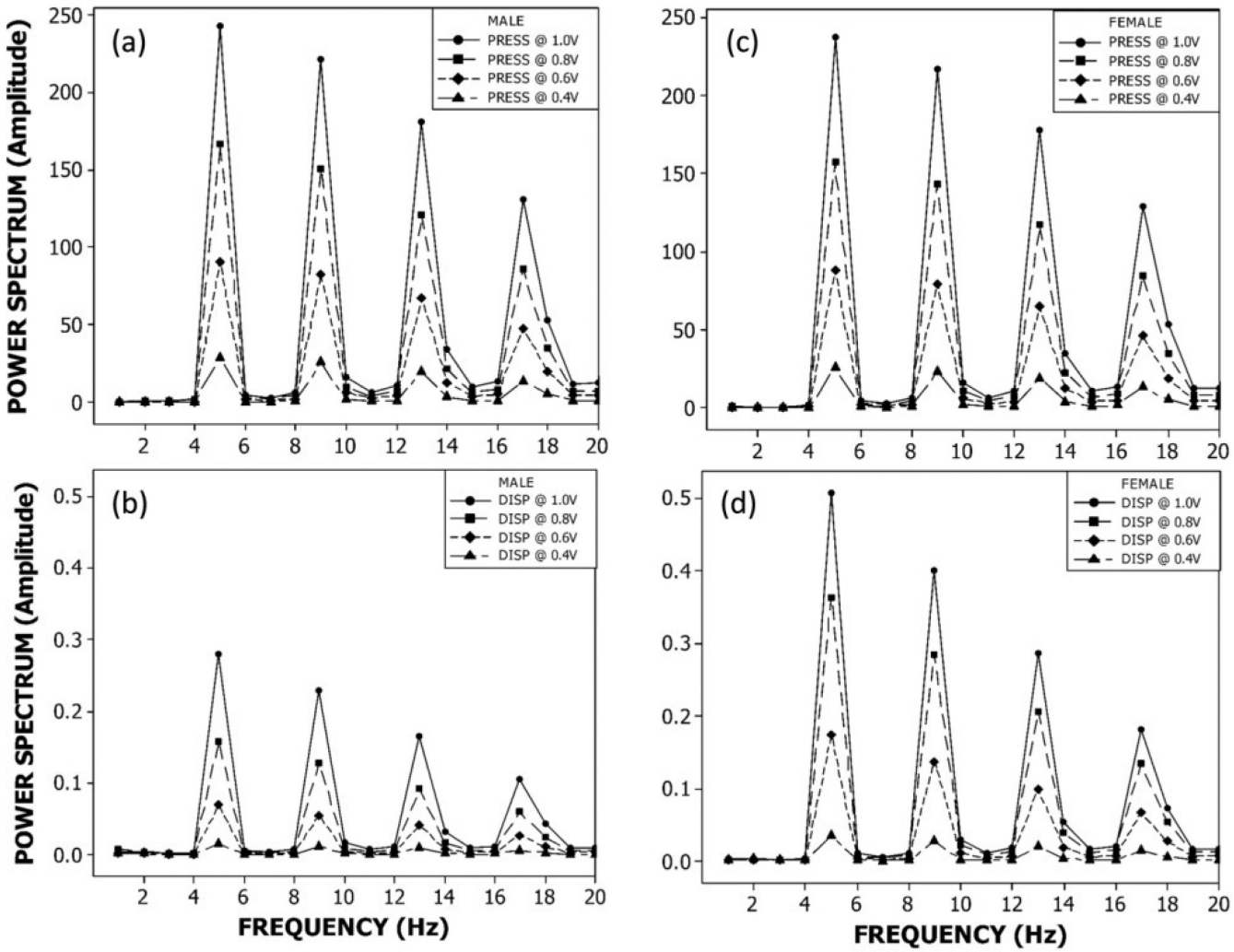

Figure 6.

Comparison of TAC-Cell pressure peak (plot panels **a** and **c**) and resultant skin displacement (plot panels **b** and **d**) power spectra, among males and females when servo controller input voltage to the linear motor was 1.0V, 0.8V, 0.6V, and 0.4V.

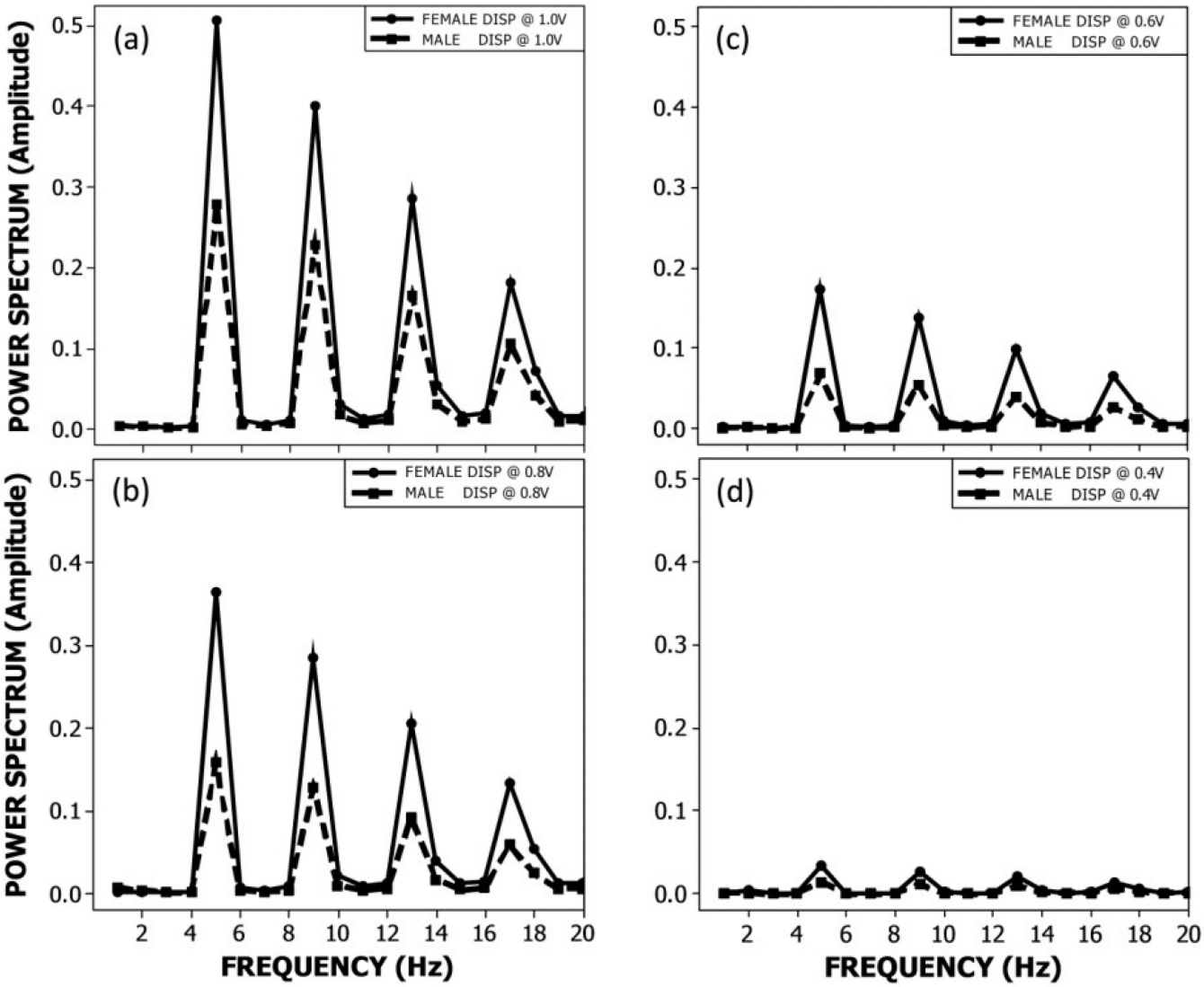

Figure 7.

Comparison of displacement peak power spectrums between males and females when servo controller input voltage to the linear motor was (**a**) 1.0V, (**b**), 0.8V, (**c**), 0.6V, and (**d**) 0.4V.

Table 1

Mean displacement and pressure peaks, and 10–90% rise/fall times among females (♀) and males (♂).

	Motor Input (V)	Displacement Peak (mm) $x \pm s$	Pressure Peak (cmH_2O) $x \pm s$	10–90% Rise Time (ms) $x \pm s$	10–90% Fall Times (ms) $x \pm s$
♀	1.0	3.82 ± 0.63	104.60 ± 2.14	15.30 ± 1.95	14.65 ± 2.92
	0.8	3.31 ± 0.68	87.30 ± 1.18	15.45 ± 2.12	13.18 ± 2.73
	0.6	2.24 ± 0.75	66.40 ± 1.09	13.37 ± 1.60	15.80 ± 3.21
	0.4	1.00 ± 0.50	38.25 ±1.26	8.45 ± 1.30	22.41 ± 3.86
♂	1.0	2.90 ± 0.82	105.08 ± 2.20	19.44 ± 3.01	14.81 ± 3.17
	0.8	2.20 ± 0.70	87.85 ± 1.23	18.28 ± 2.21	15.01 ± 3.83
	0.6	1.45 ± 0.50	67.09 ± 1.13	13.70 ± 1.70	17.57 ± 3.30
	0.4	0.67 ± 0.28	39.32 ± 1.02	8.49 ± 1.30	24.40 ± 5.49

Table 2

ANOVA summary for glabrous tissue spectral peaks and sex as a function of TAC-Cell linear motor excitation voltage.

	Glabrous tissue spectral peaks		Sex	
TAC-Cell linear motor excitation (Volts)	**F-score [3,71 *d.f.*]**	***p*-value**	**F-score [1,71 *d.f.*]**	***p*-value**
1.0	12.66	<.001	24.13	<.001
0.8	8.47	<.001	31.70	<.001
0.6	3.89	.013	19.11	<.001
0.4	1.90	.139	9.34	.003