University of Wollongong

Research Online

Faculty of Engineering and Information
Sciences - Papers: Part B

Faculty of Engineering and Information
Sciences

2019

Flexible surface electrodes targeting biopotential signals from forearm muscles for control of prosthetic hands: Part 2 - Characterization of substrates for strain sensors

Siobhan O'Brien

University of Wollongong, sob832@uowmail.edu.au

Thomas Searle

University of Wollongong, tas902@uowmail.edu.au

Gursel Alici

University of Wollongong, gursel@uow.edu.au

Follow this and additional works at: <https://ro.uow.edu.au/eispapers1>

Part of the [Engineering Commons](#), and the [Science and Technology Studies Commons](#)

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

Flexible surface electrodes targeting biopotential signals from forearm muscles for control of prosthetic hands: Part 2 - Characterization of substrates for strain sensors

Abstract

This study investigates the use of stretchable strain sensors as an alternative to the gold standard Ag/AgCl surface electromyography (sEMG) electrodes currently utilised to identify movement intention from a user during common hand gestures. Further building on the research in the companion paper, this study documents a series of strain characterisation experiments undertaken on three conductive textiles, two commercial conductive elastomers and one E-skin elastomer produced on site to determine the linearity of each sensor, along with the magnitude of hysteresis in a single stretch and release cycle, and any creep effects present. Gesture identification testing was performed in vivo on two participants, with the three most effective materials across five hand gestures, to assess the functionality of the materials as biopotential electrodes. For this series of experiments, the electrodes were positioned over the site of greatest strain for each gesture. Using a threshold-crossing paradigm, results demonstrated that a commercially sourced conductive fabric can identify 85% of hand gestures performed. The incorporation of flexible strain sensors in hand prosthetic control systems may further increase functionality of such devices, consequently boosting the quality of life of amputees.

Disciplines

Engineering | Science and Technology Studies

Publication Details

O'Brien, S., Searle, T. & Alici, G. (2019). Flexible surface electrodes targeting biopotential signals from forearm muscles for control of prosthetic hands: Part 2 - Characterization of substrates for strain sensors. IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM (pp. 1025-1030). United States: IEEE.

Flexible Surface Electrodes Targeting Biopotential Signals from Forearm Muscles for Control of Prosthetic Hands: Part 2 - Characterization of Substrates for Strain Sensors

Siobhan O'Brien, Thomas Searle and Gursel Alici, IEEE Member

Abstract— This study investigates the use of stretchable strain sensors as an alternative to the gold standard Ag/AgCl surface electromyography (sEMG) electrodes currently utilised to identify movement intention from a user during common hand gestures. Further building on the research in the companion paper, this study documents a series of strain characterisation experiments undertaken on three conductive textiles, two commercial conductive elastomers and one E-skin elastomer produced on site to determine the linearity of each sensor, along with the magnitude of hysteresis in a single stretch and release cycle, and any creep effects present. Gesture identification testing was performed in vivo on two participants, with the three most effective materials across five hand gestures, to assess the functionality of the materials as biopotential electrodes. For this series of experiments, the electrodes were positioned over the site of greatest strain for each gesture. Using a threshold-crossing paradigm, results demonstrated that a commercially sourced conductive fabric can identify 85% of hand gestures performed. The incorporation of flexible strain sensors in hand prosthetic control systems may further increase functionality of such devices, consequently boosting the quality of life of amputees.

I. INTRODUCTION

With rising need for advancements in hand prosthetics, researchers have looked towards alternative control methods [1]. In order to increase the overall operation of, and make myoelectric control of hand prostheses more user friendly, flexible EMG, pressure sensors, strain sensors, or a hybrid sensor control strategy, which are able to record successfully for longer durations, should be trialed [1,2].

Although the majority of myoelectric prostheses employ surface electromyography (sEMG) as the acquisition component of the control system, an alternate way to control prosthetics using movements of the human body is to measure strain changes at the skin level. The human forearm skin undergoes maximum strains between 10% and 20%, mostly during the rotational movements of pronation and supination [3,4]. However, accounting for the fact that these strains will often be in varying directions, due to both the muscle fibre alignment and the skins Langer's lines or lines of greatest tension [5], significantly smaller strains must be detectable and distinguishable for various gestures if strain sensors are to be used in the control of a hand prosthetic. In

order to produce a viable strain based control system for a prosthetic user, the material's sensitivity must be high enough to differentiate small changes in strain.

Wearable strain sensors have been proposed as being either skin-mountable (commonly referred to as e-skins) or incorporated into clothing to monitor human activity [6]. Stretchable strain sensors have, to date, been fabricated with carbon blacks, carbon nanotubes, graphene, nanowires, nanoparticles, silicone elastomers and rubbers. A recent study reported a strain sensor based on single-walled carbon nanotubes and carbon black in a synergistic conductive network [7]. This conductive network was sandwiched between silicone rubber and PDMS layers, in a complex fabrication process. The strain sensors were incorporated into a glove and tested for their ability to measure hand gestures. A similar study introduced a film-like strain sensor which could withstand strain up to 280%, displayed high durability, and exhibited little creep over time [8]. The sensor was incorporated into stockings, bandages and gloves to successfully distinguish different human movements.

Conductive textiles have also been employed as strain sensors, though no known studies have investigated the use of these textiles to measure strain of the skin to identify user intention for a prosthetic device. Guo et al. [9] prepared four different textile strain sensors, two of which were manufactured by coating a textile substrate in a conductive silicone elastomer, whilst the remaining two employed conductive yarns [9]. Another study has looked into the creation of a smart yarn which could be fabricated into a conductive textile for use as a wearable strain sensor to detect human motion [10]. Elastic cotton/polyurethane (PU) core-spun yarn was integrated with single-wall carbon nanotubes through an intricate manufacturing process, with experimentation finding that the composite yarn could withstand up to 400,000 cycles to 40% strain or a maximum 300% strain without obvious damage. The sensitivity of the yarn to changes in strain, called the gauge factor, could be manipulated to be between 0.31 ± 0.06 to 0.65 ± 0.04 by adjusting the number of CNT coats the yarn was subjected to. The yarn was also successful in detecting signals for human movement from the fingers, elbow, leg and eye.

Only one known study has investigated a flexible strain sensor which can measure skin strain caused by muscle activity, rather than the associated movement, and employed the sensor on the forearm to predict opening and closing of the hand [11]. In the study undertaken, 'E-skin' strain

This work has been supported by the funds in Intelligent Nano-Tera Systems Research Laboratory of University of Wollongong.

S. O'Brien (siobhano@uow.edu.au), T. Searle and G. Alici (corresponding author) are with the School of Mechanical, Materials, Mechatronic and Biomedical Engineering, University of Wollongong, New South Wales, 2522, Australia (e-mail: gursel@uow.edu.au).

sensors were manufactured based on ultrathin gold nanowires (AuNWs) as they provide high mechanical flexibility and electrical conductivity to the material in which they are incorporated. The resultant product was highly stretchable and sensitive, withstanding strains up to 300%, whilst also being able to detect strains as small as 0.01%. When applied to the human forearm, the AuNW strain sensor easily detected opening and closing of the hand, with a high signal to noise ratio. These films have successfully recorded muscle movements of the forearm, throat, posterior neck and cheek, and hence could be integrated into a system used to control prosthetic movement based on muscle activation and resultant skin strain.

In this study, six conductive materials were tested for their ability to act as a biometric strain sensor for applications such as use in a hand prosthetic control system. Strain characterisation tests, coupled with a series of gesture tests, in which the strain endured by each material was used to identify common hand gestures, were undertaken to ascertain the most effective material. This work provides a possible alternative for the sEMG control systems currently used in many prosthetics.

II. MATERIALS AND METHODS

A. Materials

Strain sensors made of the six materials described in the companion study (Part 1), five of which were inexpensive and commercially sourced, and one created on site, were characterised throughout this study [12]. Material samples were cut into 40x60mm rectangles for strain characterisation experiments, and 15x15mm squares for gesture identification tests. The three conductive fabrics were tested in both knit directions during strain characterisation experiments to ensure the material was characterised for the wale and course orientations. This was particularly important in both the Knit Jersey and Luxe Silver Knit fabrics, as these materials do not possess the bidirectional elasticity of the purl knit EeonTex.

B. Strain Characterisation of Materials

An Igus Drylin E Screw Driven Rodless Electric Actuator (Igus, Germany), powered by a NEMA17 stepper motor, with a stroke of 250mm, was bolted to a Thorlabs Optical Table (Thorlabs, USA) to implement high quality, programmable strain experiments, as shown in Fig. 1. An Arduino Uno, along with a L298N Dual H-Bridge Motor Controller and a variable power supply were employed to control the actuator speed and displacement. The change in resistance of materials upon strain was recorded using an Arduino Uno and a milliOhm meter board.

Materials which have a higher linearity in their resistance with changes in strain will be more suitable candidates for biometric strain sensors. Similarly, the sensitivity of the material, given by the slope of the strain-resistance response curve is an important characteristic to consider for applications in which strain will be minimal. The linearity and sensitivity of the experimental materials were evaluated

Fig. 1: Strain Characterisation experimental set-up

through the employment of either a high or low strain protocol, depending on material fibre direction and general elasticity. Materials which were tested under the high strain protocol (EeonTex, Luxe Silver Knit (course), Jersey Knit (course) and 3wt% CNT Ecoflex E-skin) experienced strains of 10%, 20%, 30%, 40% and 50% in separate tests, whilst the low strain protocol placed the remaining materials (Luxe Silver Knit (wale), Jersey Knit Direction 1 (wale), Ag/Cu-Silicone, Ni/C-Silicone) under 5%, 10%, 15% and 20% strains. Each test lasted approximately 75 seconds, comprising of 3-5 seconds of baseline readings, movement of the actuator to the strain position at a speed of 120rpm (corresponding to 3mm/s), 60 second hold of final strain position and movement back to the starting position.

The steady state resistance for each strain step was plotted based on an average over three trials. The standard error of the mean was calculated from the mean steady state resistances for all materials at each strain step. From this plot, a regression analysis was undertaken to determine the coefficient of determination, R^2 , for each material, allowing comparison of linearity between samples, with values closer to 1 representing a data fit with greater linearity. The sensitivity of the material was calculated as the absolute value of the slope of the trendline obtained for each dataset, with a greater slope indicating a greater sensitivity.

Materials were analysed for hysteresis effects in a procedure involving increasing strain from 0% to either 20% or 50% depending on the strain protocol (high or low), in increments of 5% or 10%, respectively. The material was held at each strain level for 60 seconds. Upon reaching maximum strain, the actuator reversed direction of movement, and in the same increments as strain increased, stepped back down to 0% strain. Hysteresis loops were plotted based on an average steady state strain for each step during the stretch and release cycles of three separate trials.

The final strain characterisation experiment undertaken measured the creep experienced by each material, in an isochronous creep experiment, over 30-minute time periods for the aforementioned strain steps. The material was held at each strain level for 30 minutes, with a 5-minute recovery interval between each step. Further creep testing, where each step was held for 2.5 hours, was undertaken for the 3% CNT E-Skin due to significant creep throughout initial tests.

C. Gesture Identification by Strain

To establish the viability of the materials in becoming biometric strain sensors, several gestures were performed, and strain data recorded. The three most successful materials from the strain characterisation experiments were utilised – EeonTex Fabric, Ag/Cu-Silicone Industrial Elastomer and the 3wt% CNT Ecoflex E-skin. Five common hand gestures, demonstrated in Fig. 2, chosen based on their prevalence in hand prosthesis literature, were performed in experiments to test the strain sensors. The hand gestures chosen for testing were ‘Hand Open’ (1), ‘Closed Fist’ (2), ‘Index Finger Point’ (3), ‘Thumbs Up’ (4) and ‘Pinch Variation’ (5).

Sensors were placed on the site of the largest observed skin strain based on visual inspection. This corresponded to either the location of belly of the muscle acting to produce the movement in question or the muscle tendon upon entry to the wrist, where the tendon passed through the flexor retinaculum on the anterior of the wrist. The strain sensor placement for each movement was marked on both participants using a permanent marker, with the approximate locations labelled in Fig. 3. The sensors required adhesion to the skin, such that any strain endured by the skin would be reflected in the material. For this testing, double sided tape was applied to the skin in the area of sensor placement.

The raw data obtained from the strain sensors was initially smoothed and plotted for all four trials undertaken using each material in all of the five gestures. A mean RMS value for each gesture was calculated for each material, and overlaid on individual trials. This mean RMS value acted as a ‘threshold’, where, if the change in resistance brought about by the gesture broke through the threshold, the test was deemed a success. The rate of success in each material across all five gestures was determined as a percentage to allow for inter-material comparisons to be undertaken.

Fig. 2: Five gestures tested in gesture identification experiments from left (1) to right (5)

Fig. 3: Placement of strain sensors for five hand gestures

III. RESULTS AND DISCUSSIONS

A. Strain Characterisation of Materials

Analysis of the strain characterisation experiments show that EeonTex Conductive Fabric (Fig. 4) and the Ni/C-Silicone (Fig. 5) are the most linear of the materials tested, with coefficients of determination of 0.96 and 0.97 respectively. Further evident in Table 1, conductive fabric materials are generally more sensitive to changes in strain than elastomers, a result of Holm’s Theory, discussed in detail below. The EeonTex Fabric is the most sensitive of all samples, with a slope of 0.34. This result is echoed in the literature, in which elastic fibre based textiles coated in a conductive formulation have demonstrated significantly higher gauge factors when compared to conductive textile sensors incorporating a stainless steel yarn [9].

Interestingly, the fabrics often experienced a decrease in resistance with increasing strain, as seen in Fig. 4. This result is consistent with the data obtained by Seyedin, Razal et al., who found that knitted conductive textiles had negative gauge factors [13]. This phenomenon is a direct result of Holm’s Theory, which describes that with increased strain, the number of contact points between adjacent loops in a knit will increase. As the conducting fibres of the knit have greater contact area, the contact resistance will reduce

Table 1: Linearity and Sensitivity of Material Samples

Material	Coefficient of Determination	Sensitivity
EeonTex Direction 1	0.95511	0.33531
EeonTex Direction 2	0.87001	0.23462
Jersey Knit Wale	0.81552	0.01203
Jersey Knit Course	0.6266	0.15976
Luxe Silver Knit Wale	0.40528	0.00111
Luxe Silver Knit Course	0.75935	0.04759
Ag/Cu-Silicone	0.7093	0.00528
Ni/C-Silicone	0.96726	0.03396
CNT E-skin	0.50001	0.00977

Fig. 4: Linearity results for EeonTex Fabric

Fig. 5: Linearity results for Ni/C-Silicone

according to Holm's Theory, Eq. 1, where n is the number of contact points, ρ is the resistivity of the fibre, P is the contact pressure and H is the contact hardness.

$$R_c = \frac{\rho}{2} \sqrt{\frac{\pi H}{nP}} \quad (1)$$

In both of the silver based conductive textiles, when significantly strained, an increase in resistance was experienced. In these cases, the maximum strain of the knit has been reached, and in order to strain the sample further, the individual fibres begin to stretch. This phenomenon is again confirmed by the work of Seyedin, Razal et al., who showed that a positive gauge factor was exhibited by individual fibres when strained [13]. Elastomers were seen to increase in resistance with increasing strain. This is a result of the conductive particles in the elastomer being separated when the material is stretched. The elastomers also experienced a longer settling time compared to the materials due to their viscoelastic nature. This viscoelastic effect was most prominent in the 3wt% CNT E-skin material.

The two materials with the best hysteresis characteristics, presenting the narrowest loops as seen in Fig. 6 and Fig. 7, respectively, are the Eeontex Conductive Fabric and the Ag/Cu-Silicone. These fabrics also boast minimal change between initial and final baseline resistances, an important characteristic for a potential strain sensor. Comparatively, the materials which undergo significant hysteresis, and hence have the poorest recovery characteristics, are the two silver knitted textiles, the Jersey Knit and the Luxe Silver Knit. This is evidenced by wide loops and a large difference between the magnitude of resistance at 0% strain before the trial and 0% strain at the end of the trial, corresponding to a maximum of 58% change in baseline readings.

Creep will result in a changing baseline resistance over time, which will have marked ramifications for the prosthetic user if not properly considered. The results of the creep testing are typical of that for an isochronous creep experiment, and therefore experiments were not repeated. From the results in the leftmost column of Fig. 8, it is clear that the conductive textile group of materials responded best

Fig. 6: Hysteresis results for Eeontex Fabric

Fig. 7: Hysteresis results for Ag/Cu-Silicone

to the creep protocol. The Eeontex Fabric undergoes the most significant creep of the textiles, however the creep rate is independent of the strain level, with the same gradient observed for strains from 10% through to 50%. This characteristic indicates that a simple creep model could be established to counteract the material's creep in a biometric strain sensor application such as prosthetic control.

Opposing the textile materials, all three elastomers, shown on the right of Fig. 8, portray obvious signs of viscoelastic creep. Viscoelastic materials such as elastomers exhibit time-dependent resistance creep, in which conductive molecules are able to rearrange themselves to alter the resistance of the material [14]. This is portrayed as a decrease in resistance with time under a constant stress. Much like the Eeontex Conductive fabric, the viscoelastic creep undergone by the Ag/Cu-Silicone, Ni/C-Silicone and 3wt% CNT E-skin is independent of the magnitude of strain. The 3wt% CNT E-skin material exhibited the highest viscoelastic creep. In a secondary test, where the elastomer was held for 2.5 hours at each strain level, shown in Fig. 8f, a constant decline in resistance was observed throughout the duration of the test, up to 43% of the baseline reading throughout each hold phase.

Fig. 8: Creep results for a) Eeontex b) Ag/Cu Silicone c) Jersey Knit Wale d) Ni/Cu Silicone e) Luxe Silver Knit Wale f) 3wt% CNT E-skin

B. Gesture Identification by Strain

The success of each material in each gesture is recorded in Table 2, with the success rate averaged across the 5 gestures. It is evident from this table that the material boasting the greatest success rate in the gesture tests undertaken was the Eeontex Conductive fabric. Fig. 9 shows the changing resistance as the user performs the ‘Hand Open’ gesture. It is evident that, upon opening the hand 5 seconds into the trial, the measured resistance crosses the red threshold value. A similar profile was seen for all gestures. The Eeontex fabric had a success rate of 85%, whilst the Ag/Cu-Silicone could accurately predict the occurrence of the gesture in 80% of the trials. Comparatively, the 3wt% CNT E-skin could only accurately predict 30% of the movements performed.

Overall, the gestures which utilised skin on the anterior side of the forearm: Closed Fist, Pinch Variation, and to some extent, Thumbs Up, had a greater rate of success across all three materials when compared to the gestures which utilised skin on the posterior side of the forearm. This may be attributable to the type of skin covering the anterior forearm, which is a glabrous pre-axial skin, a thinner and more mobile surface than the post-axial skin of the posterior forearm [15]. This is in agreement with the literature that suggests greater strain is experienced by the anterior forearm [15]. 3wt% CNT Ecoflex was unstable and inconsistent, with a baseline resistance significantly different to that which was observed in the strain characterisation tests.

Table 2: Gesture testing success rates

Material	Gesture success rate (%)					
	Hand Open	Closed Fist	Point	Thumbs up	Pinch Variation	Average
Eeontex Fabric	75	100	50	100	100	85
Ag/Cu-Silicone	50	75	75	100	100	80
3wt% CNT E-skin	25	25	25	0	75	30
Average	50	66.67	50	66.67	91.67

Fig. 9: Example gesture identification result for Hand Open gesture

The consistent increase in resistance of Eeontex with skin strain, an example of which is evident in Fig. 9, was not predicted prior to experimentation. The linearity tests undertaken during strain characterisation experiments suggest that materials such as Eeontex undergo decreasing resistance with strain as a result of Holm's theory. The outcome obtained may arise from the significantly smaller strains experienced by the material in these gesture tests. Raw data for the linearity tests show that when fabric materials are strained, a small peak in resistance is demonstrated before the resistance then declines as strain increases further.

IV. CONCLUSION

In order to increase the everyday functionality of myoelectric hand prostheses, flexible EMG or strain sensors, which are able to record successfully for longer durations should be utilised. This study investigated skin strain as a possible prosthetic control system for the identification of user intention for a prosthetic hand device. From the analysis of results from both strain characterisation and gesture experiments undertaken, it is concluded that the material which has the greatest potential to act as a biometric strain sensor in a hand prosthetic control application is the Eeontex conductive textile. Eeontex possesses high linearity over a large range of strains, is highly sensitive, consistent in measurements, and exhibits good recovery characteristics. As outlined in the companion paper to this study, this isotropic fabric is able to be washed, is comfortable and breathable, with good durability and high biocompatibility,

making it suitable for the intended application [12]. Coupled with Part 1, this study points towards dual control systems in which both strain and EMG signal acquisition properties of conductive fabrics may be utilised in the fine control of a hand prosthetic, allowing for greater dexterity and increased consistency over time. Further research is required before 'dry' biometric strain sensors can replace the gold standard Ag/AgCl sEMG electrode currently used in the control of myoelectric prostheses, however, materials including conductive textiles and elastomers show great potential to eventually improve general acceptance of prosthetic devices, reduce rejection rates and increase the quality of life for prosthetic hand users.

REFERENCES

- [1] Geethanjali, P. (2016). "Myoelectric control of prosthetic hands: state-of-the-art review." *Medical Devices : Evidence and Research*, Vol 2016, Iss Issue 1, Pp 247-255 (2016)(Issue 1): 247.
- [2] Nielsen, J. L. G., S. Holmgard, N. Jiang, K. Englehart, D. Farina and P. Parker (2009). "Enhanced EMG signal processing for simultaneous and proportional myoelectric control." *Conference Proceedings: ... Annual International Conference Of The IEEE Engineering In Medicine And Biology Society. IEEE Engineering In Medicine And Biology Society. Annual Conference 2009*: 4335-4338.
- [3] Kim, D.-H., N. Lu, R. Ma, Y.-S. Kim, R.-H. Kim, S. Wang, J. Wu, S. M. Won, H. Tao and A. Islam (2011). "Epidermal electronics." *science* 333(6044): 838-843.
- [4] Russell, C. J., J. A. Bush, G. W. Russell, A. Thorlby, D. A. McGrouther and V. C. Lees (2009). "Dynamic skin tension in the forearm: Effects of pronation and supination." *The Journal of hand surgery* 34(3): 423-431.
- [5] Borges, A. F. (1984). "Relaxed skin tension lines (RSTL) versus other skin lines." *Plastic and reconstructive surgery* 73(1): 144-150.
- [6] Amjadi, M., K. U. Kyung, I. Park and M. Sitti (2016). "Stretchable, Skin-Mountable, and Wearable Strain Sensors and Their Potential Applications: A Review." *Advanced Functional Materials*.
- [7] Guo, X., Y. Huang, Y. Zhao, L. Mao, L. Gao, W. Pan, Y. Zhang and P. Liu (2017). "Highly stretchable strain sensor based on SWCNTs/CB synergistic conductive network for wearable human-activity monitoring and recognition." *Smart Materials and Structures* 26(9): 095017.
- [8] Yamada, T., Y. Hayamizu, Y. Yamamoto, Y. Yomogida, A. Izadi-Najafabadi, D. N. Futaba and K. Hata (2011). "A stretchable carbon nanotube strain sensor for human-motion detection." *Nature nanotechnology* 6(5): 296-301.
- [9] Guo, L., L. Berglin and H. Mattila (2010). "Textile strain sensors characterization-sensitivity, linearity, stability and hysteresis." *Nordic Textile Journal*(2): 51-63.
- [10] Wang, Z., Y. Huang, J. Sun, Y. Huang, H. Hu, R. Jiang, W. Gai, G. Li and C. Zhi (2016). "Polyurethane/Cotton/Carbon nanotubes core-spun yarn as high reliability stretchable strain sensor for human motion detection." *ACS applied materials & interfaces* 8(37): 24837-24843.
- [11] Gong, S., D. T. H. Lai, B. Su, K. J. Si, Z. Ma, L. W. Yap, P. Guo and W. Cheng (2015). "Highly Stretchy Black Gold E-Skin Nanopatches as Highly Sensitive Wearable Biomedical Sensors." *Advanced Electronic Materials* 1(4): 1400063-n/a.
- [12] O'Brien S., T. Searle, and G. Alici, "Flexible Surface Electrodes Targeting Biopotential Signals from Forearm Muscles for Control of Prosthetic Hands: Part 1 – Characterisation of sEMG Electrodes", 2019 *IEEE International Conference on Advanced Intelligent Mechatronics*, Hong Kong, July 2019.
- [13] Seyedin, S., J. M. Razal, P. C. Innis, A. Jeiranikhameneh, S. Beirne and G. G. Wallace (2015). "Knitted strain sensor textiles of highly conductive all-polymeric fibers." *ACS applied materials & interfaces* 7(38): 21150-21158.
- [14] Daver, F., M. Kajatz, M. Brandt and R. A. Shanks (2016). "Creep and recovery behaviour of polyolefin-rubber nanocomposites developed for additive manufacturing." *Polymers* 8(12): 437.
- [15] Standring, S. (2015). *Gray's Anatomy E-Book: The Anatomical Basis of Clinical Practice*, Elsevier Health Sciences.