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Mechanical Failure Analysis of Needles for Micro-needle Array Dry-electrodes

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ABSTRACT

Dry electrodes, which have an array of vertically aligned conducting micro-needles over a conducting substrate/base are most suitable for long-term continuous monitoring of EEG-signal, and overcomes the disadvantages of conventional wet electrodes. A crucial design requirement for these micro-needle arrays, is the choice of the needle material with suitable mechanical strength to penetrate the skin without mechanical failure. This paper gives, the results of mechanical failure analysis of different needle materials that have been typically used/proposed for invasive use. A conical needle with 150µ width at the base and 10 µ width at the tip, and length in the range 10 µ - 200 µ was taken up for calculation. The Critical load for failure, falls in the following descending order for the selected materials: viz., Carbon nanofibre (CNF), Titanium-alloy (Ti 6-4), single crystal Silicon, Nickel, Tungsten, Platinum-Iridium (Pt 90 % - Ir 10 %), Stainless Steel (SS304), Poly Methyl Methacrylate, Polyimide, Polycarbonate, Gold, Silver, Photoresist-SU8, Polyurethane and Poly Dimethyl Siloxane. Taking the most accepted value of 0.1N as the penetration force required for needle penetration into skin, it is seen that for a needle length of 100 µ, the following materials, CNF, Ti 6-4, Single Crystal Silicon, Nickel, Tungsten, Platinum -Iridium (Pt 90 % - Ir 10 %) and SS304, can penetrate the skin without mechanical failure.

Keywords: Needle, Vertically-aligned, Critical Load for Failure, Dry-electrode, EEG

1. INTRODUCTION

Electroencephalogram (EEG) is a record of the electrical signals generated by the brain's activity[1]. It is useful in monitoring the sleep quality and alertness; in clinical applications for diagnosis and treatment of patients suffering from epilepsy, Parkinson's disease and; other neurological disorders and for continuous monitoring of fatigue/alertness of personnel/soldiers deployed in field or working under strain.

Conventional wet-electrodes use electrolytic gel to diffuse into skin and establish a conducting path with the body fluid[1]. A major disadvantage of the wet electrodes is that, the electrolytic gel dries within few hours, making long-term continuous monitoring difficult, in addition to producing motion artefacts in the recorded signal due to the relative motion between the electrode surface and skin. These disadvantages can be overcome, by the use of Dry-electrodes, which have an array of vertically aligned conducting micro-needles over a conducting substrate/base.

Two important design requirements for the needle used for EEG signal acquisition are (i) the length of the needle should be higher than 20 µ, so that it penetrates the stratum corneum of the skin at the scalp and touch the interstitial fluidic layer below, and should be less than 200 µ length so that the needle does not enter into the dermis and touch the blood vessels and nerves, (ii) the choice of needle material with suitable mechanical strength and shape, so that it penetrates the skin without mechanical failure. This paper describes, the results of mechanical failure analysis of different needle materials that have been typically used/proposed for invasive use. Other design requirements of the needle for EEG acquisition include a good electrical conductivity and biocompatibility of the needle material, and a conducting biocompatible surface coating in the case of insulating or non-biocompatible material.

2. MECHANICAL FAILURE OF NEEDLES-THEORY

The mechanical failure analysis of needles used for biomedical use is analogous to the theoretical approaches used for straight/tapered columns[2].

When a micro-needle penetrates the skin it can undergo mechanical failure through two modes, buckling and yield failure. Longer structures/columns are more elastic than shorter ones, and tend undergo failure by buckling, whereas for shorter structures, compression failure is more dominant. If the critical load for these failures is less than the penetration force required for the needle to penetrate into skin, the needle will undergo mechanical failure before entering into skin. These values are determined by the geometry and the mechanical properties of the needle.

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A column is termed short or long based on its slenderness ratio. If the slenderness ratio (SR) of the column is less than its column constant (C_c), then it is called short column.

The slenderness ratio is given by

$$SR = L_e/r_g = (K.L)/r_g \tag{1}$$

where L and L_e are the actual and the effective length of the needle. The effective length of a column is given by,

$$L_e = K.L \tag{2}$$

where K is the end-fixity factor for the column, which is normally is taken as 1 for pinned-pinned, 0.7 for pinned-free and 0.5 for free-free configurations of the column.

r_g is the radius of gyration of the column and is given by

$$r_g = D_e/4 \tag{3}$$

where D_e is the equivalent diameter, which in case of tapered solid columns is given by

$$D_e = D_{tip} + (D_{base} - D_{tip})/3 \tag{4}$$

The column constant C_c is given by,

$$C_c = \sqrt{(2\pi^2 E/S_y)} \tag{5}$$

where E and S_y are the Young's modulus and Yield strength of the material used for the needle.

Longer elastic columns undergo mechanical failure by buckling above a critical applied axial load, which is governed by Euler's formula,

$$P_{cr} = \pi^2 EA/(L_e/r_g)^2 \tag{6}$$

where $A = \pi r_g^{\,2}$ is the area of cross section of the column.

Shorter short columns undergo mechanical failure by compression, which is governed by Johnson's Formula

$$P_{cr} = AS_y\,(1 - S_y(L_e/r_g)^2/4\pi^2 E) \tag{7}$$

3. RESULTS AND DISCUSSION

For the present calculations, a conical shaped needle with pointed tip was assumed, as it facilitates easier penetration into skin. Looking into the literature available on silicon, polymer and metal microstructures used for bio-potential measurement[3-5], a nominal 150 μ width for the needle base, 10 μ width for the needle tip and length in the range 10 μ - 200 μ, as shown in Fig. 1 was taken up for the calculations. Since the needles are tapered, an equivalent diameter calculated (using Eqn. (4)) from the tip-diameter and base-diameter of the needle, was used. Since these needles when used for penetrating the skin, are fixed at one end and pinned at the other end, an end fixity factor K=0.7 was used, to calculate the effective length (L_e) of the needle (using Eqn. (2)). The software, Microsoft Origin was used for the calculation of critical load for failure and generation of plots.

The slenderness ratio (SR) calculated for the needle of geometry shown in Fig.1, is given in Table 1, for few different needle lengths. These slenderness ratio (SR) values, are smaller than the column constant (C_C) values, as shown in Table 2 for all the materials taken up in this analysis. Hence these needles fall into the category of short–needles and hence Johnson's formula (Eqn. (7)) was used for calculation of critical load for failure.

The critical load for failure was calculated for the needle lengths in the range 10 μ - 200 μ, in steps of 10 μ, and plotted for some of the needle materials that have been commonly used/proposed for invasive use. The materials taken up for calculation are, stainless steel (SS304), Tungsten, Platinum-Iridium (Pt 90 % - Ir 10 %), Silver, Titanium Alloy (Ti 6-4), Nickel, Gold, Single Crystal Silicon, Carbon Nano Fibre (CNF), Plolymeric Photoresist-SU8, Poly Methyl Metha

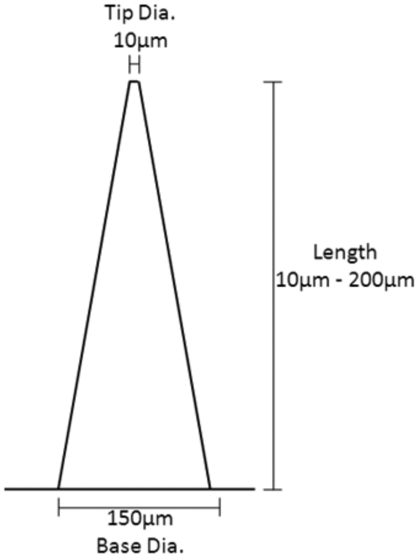

Figure 1. Geometry of the needle used in the present calculations.

Table 1. Slenderness ratio (SR) for the needle of geometry given in Fig. 1 for few different needle lengths

Length of the needle –L (μ)	Radius of gyration -r_g (μ)	Slenderness ratio -SR
50	15	2.33
100	15	4.66
150	15	7.00
200	15	9.33

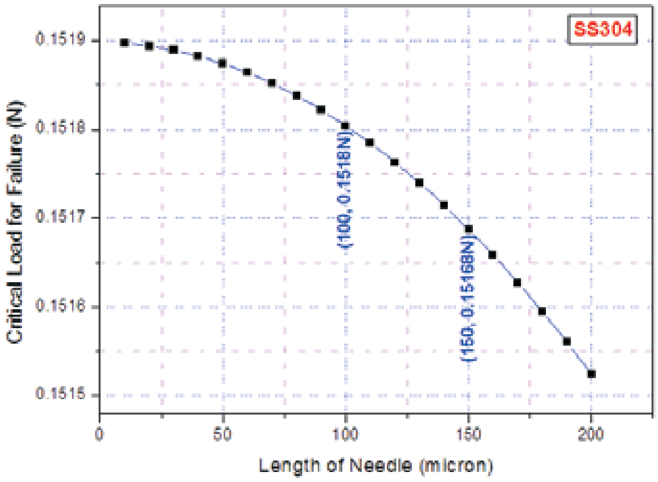

Figure 2. Critical load for failure versus the length, for SS304 needle, for the geometry shown in Fig. 1.

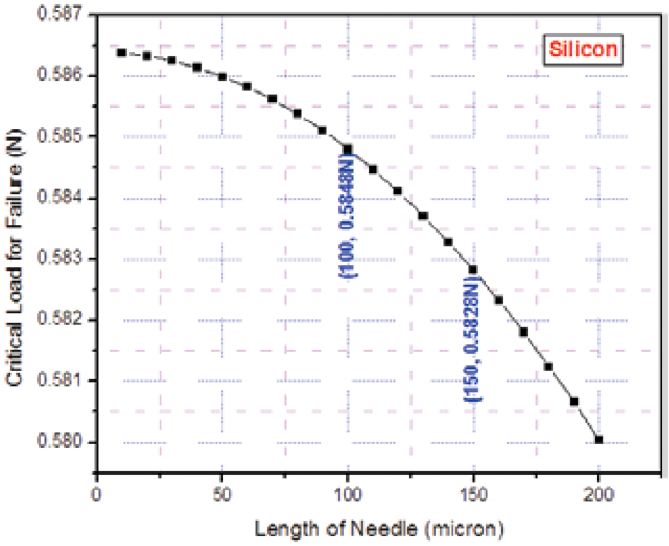

Figure 3. Critical load for failure versus the length, for single crystal silicon needle, for the geometry shown in Fig. 1

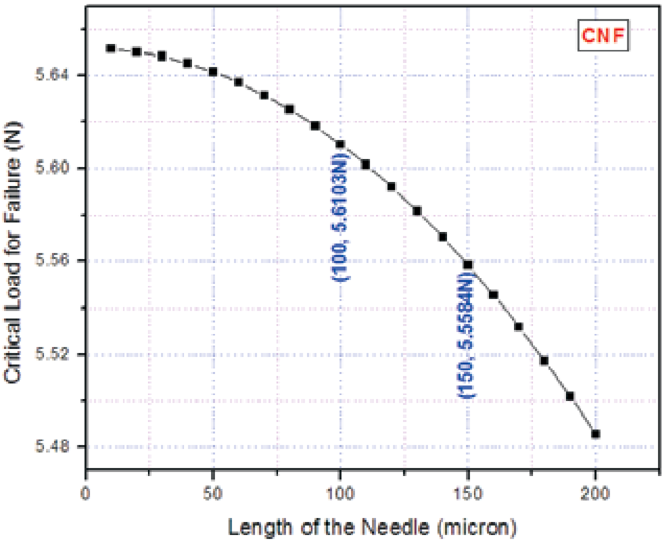

Figure 4 . Critical load for failure versus the length, for carbon nanofibre for the geometry shown in Figure.1

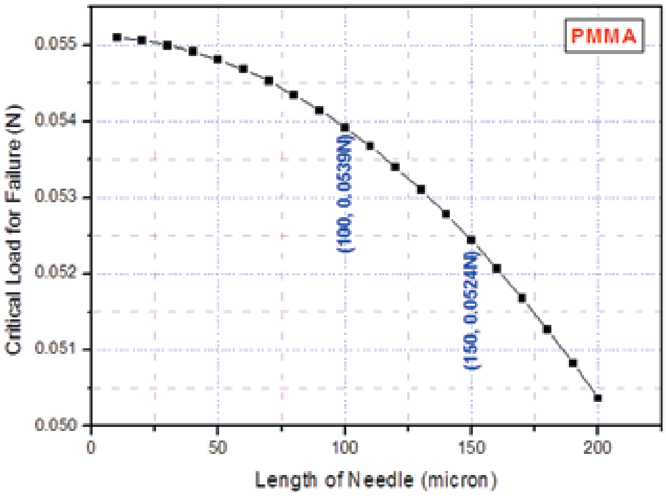

Figure 5. Critical load for failure versus the length, for PMMA needle for the geometry shown in Figure.1

Acrylate (PMMA), Poly DiMethyl Siloxane (PDMS), Polyimide, Poly-carbonate and Poly-urethane. These typical plots are shown below for four different materials viz, stainless steel (SS304) in Fig. 2, single crystal silicon in Fig. 3, Carbon nano fibre (CNF) in Fig. 4 and PMMA in Fig. 5 were shown. It can be seen that, as the length of the needle increases, the critical load for failure decreases, and while this decrease is steep in the 100 μ - 200 μ length range, it is shallower in the 10 μ - 100 μ length range.

A comparison of the critical load for mechanical failure for a 100 μ length needle, for the different materials is shown in Table 2. It can be seen that, while the geometry of the needle plays a role in determining whether the needle is short or long, it is primarily the needle material's intrinsic properties viz. the

Table 2. The Critical Load for failure for 100μ length needle, of the geometry given in Figure 1

Material	Young's Modulus[1]and Yield Strength[2]	Slenderness Ratio (SR) and Column const (C_c)	Critical Load for Failure, for 100 μ length (N)
SS304	193 GPa, 215 MPa	4.6, 133	0.1518
Tungsten	411 GPa, 550 MPa	4.6, 121	0.3883
Platinum (90 per cent)-Iridium (10 per cent)	168 GPa, 250 MPa	4.6, 115	0.1765
Silver	83 GPa, 54 MPa	4.6, 174	0.0381
Titanium (Ti 6-4)	114 GPa, 970 MPa	4.6, 48	0.6821
Nickel	23 GPa, 830 MPa	4.6, 23	0.5747
Gold	72 GPa, 54 MPa	4.6, 162	0.0381
Silicon	169 GPa, 830 MPa	4.6, 63	0.5848
CNF	600 GPa, 8 GPa	4.6, 38	5.6103
SU8	4.02 GPa, 35 MPa	4.6, 47	0.0246
PMMA	2 GPa, 78 MPa	4.6, 27	0.0539
PDMS	2 MPa, 130 KPa	4.6, 17	$8.85x10^{-5}$
Polyimide	3.1 GPa, 73 MPa	4.6, 28	0.0509
Polyurethane	100 MPa, 30 MPa	4.6, 8	0.0176
Polycarbonate	2 GPa, 55 MPa	4.6, 26	0.0382

[1,2]-There is considerable variation in the Young's modulus and Yield strength values in the literature. The most common values have been taken. The sources for these values include, http:/ /www.mit.edu/6.777/matprops/, http://www.engineering tool box.com/and http://www. designer data.nl/

combination of Young's modulus and Yield strength, which determines the critical load for failure, and hence its suitability to penetrate the skin.

The results show that, for the needle of geometry shown in Fig. 1 and for a length of 100 μ, the Critical load for failure, falls in the following descending order for the selected materials: viz., Carbon Nanofibre (CNF), Titanium-alloy (Ti 6-4), Single Crystal Silicon, Nickel, Tungsten, Platinum-Iridium (Pt 90 % - Ir 10 %), Stainless Steel (SS304), Poly Methyl Methacrylate (PMMA), Polyimide, Polycarbonate, Gold, Silver, Photoresist-SU8, Polyurethane and Poly DiMethyl Siloxane (PDMS).

The published data available on the insertion force for needle to penetrate into skin, is predominantly on hallow hypodermic needles used for drug delivery[6,7]. The main factor which governs the insertion force, is the interfacial area between the skin and the needle tip, and is determined by the sharpness of the tip. The value of the insertion force arrived from simulation and experimental measurements for a needle to penetrate upto a depth 200 μ**,** is approximately 0.1N[8]. Taking this value as the reference value, it can be seen that, for the needle geometry given in Fig.1 and 100 μ length, the following materials, Carbon Nanofibre (CNF), Titanium-alloy (Ti 6-4), Single Crystal Silicon, Nickel, Tungsten, Platinum Iridium (Pt 90 % - Ir 10 %), Stainless Steel (SS304), penetrate the skin without mechanical failure. For other materials with poorer mechanical strength, a modification of the needle shape into, cone with broader base, tubular shape, + and H cross sections, etc., can improve the critical load for failure, but with a more painful skin insertion.

4. CONCLUSIONS

A crucial design requirement for a microneedle array dry electrode, is the choice of the needle material with suitable mechanical strength to penetrate the skin without mechanical failure. For a conical needle with 150 μ width at base, 10 μ width at tip and 100 μ length, the Critical load for failure, falls in the following descending order for the selected materials: viz., Carbon Nanofibre (CNF), Titanium-alloy (Ti 6-4), Single Crystal Silicon, Nickel, Tungsten, Platinum-Iridium (Pt 90 % - Ir 10 %), Stainless Steel (SS304), Poly Methyl Methacrylate (PMMA), Polyimide, Polycarbonate, Gold, Silver, Photoresist-SU8, Polyurethane and Poly DiMethyl Siloxane (PDMS). Taking the most accepted value of 0.1N as the penetration force required for needle penetration into skin, it is seen that, the following materials, Carbon Nanofibre (CNF), Titanium alloy (Ti 6-4), Single Crystal Silicon, Nickel, Tungsten, Platinum -Iridium (Pt 90 % - Ir 10 %) and Stainless Steel (SS304), can penetrate the skin without mechanical failure.

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