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The role of impulse, tissue stretching and tip geometry for tissue penetration of polymer needles

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Abstract

Polymer needles for medical injections offer a range of opportunities like compatibility with magnetic resonance scanning and simultaneous delivery of more than one drug. However, the lower stiffness property of polymers compared to steel is a challenge for penetration. This paper explores strategies for higher penetration success, which include impulse insertion, tissue stretching and different tip geometries. The strategies are experimentally examined using 3 layers of nitrile rubber gloves and sticking glue to create an artificial skin model. It is demonstrated that polymer needles have higher penetration rates when the strategies are applied. Penetration rates were only 10-20% when using slow speed insertion (0.2mm/s) but 100% penetration rates was achieved using impulse insertion. Penetration forces are similar for slow insertion speed and high speed (impulse insertion) and for needles made out of different material (polymer or steel). Conical and pyramidal tips were studied for polymer needles and a commercial bevel steel needle tip. The result was lower penetration forces and 100% penetration success was possible using the pyramidal polymer needles. For the model in study was observed a similar behaviour (penetration force and rate of penetration success) for steel and polymer pyramidal needles. An Anova statistical analysis show significance when using springs and strain, as well for the combination of both.

Keywords: Medical needles, biomimetics, skin penetration, polymer needles, impulse, skin tension

1. Introduction

Every year around 16 billion of injections are administrated worldwide, according to data from World Health Organization [1]. In 2010, due to unsafe injection, 33,800 people were infected with HIV, 315,000 with hepatitis C virus and 1.7 million were infected with hepatitis B virus. The most used needles are hypodermic steel needles. Such needles are well suited for

transdermal drug delivery due to their characteristics such as high strength, low cost and ease of manufacture. However, beyond the problem of needles being re-used, steel needles show problems such as safe disposal. In order to combat these contrarities new materials were proposed to produce hypodermic needles. One of the most viable solutions is the polymer needle.

Polymer needles will promote new and innovative types of medical treatments and can also increase the quality of existing treatments. The polymer needles offer a range of highly interesting functionalities allowing new biomedical and biotechnological solutions. These can be used within MRI-scanners to permit the use of very short lived and non-toxic tracers such as hyperpolarized metabolic contrast agents [2]. The tracers allow small cancer metastases to be detected within MRI-scanning. Furthermore, the needles can be made of transparent materials, enabling direct photonic analyses of chemical indicators in the body in combination with the medical injection.

However, there is a challenge for the polymer needles. The penetration process is affected due to the lower stiffness of polymers, promoting buckling failures and, consequently, no penetration.

The buckling phenomenon happens due to an unstable equilibrium that relieves an axial load by changing it into a bending moment.

For the use of a needle, the first part of the penetration into skin is crucial. When a needle encounters the skin's surface an axial load is applied to the needle. This situation is predicted in the Euler's buckling theory also named as Euler's column theory as described by formula (1) [3].

$$F_c = \frac{\pi^2 EI_p}{(\beta L)^2} \quad (1)$$

E is the modulus of elasticity, I_p is the area moment of inertia or second moment of inertia, L is the length of the column and β is the column effective length factor (depends on the end conditions: fixed or pivoted end).

The Euler's column theory holds that a slender column will collapse if a critical load is applied [3].

To prevent buckling two different strategies can be used. The critical load force of the penetration tool can be increased, or the penetration force of the substrate can be decreased. These conditions can be obtained by static or dynamic loading. In the present paper the main focus will be on the dynamic loading since it combines an increase in the critical force and a decrease in the penetration force.

If the step size of a load becomes short enough, the load can be considered as an impulse load. According to [4] a material, onto which an impulse load is applied, can sustain higher loads compared to a static load. This means that if a dynamic load is applied to a column it will have a higher critical load force than in the static load case and in this way the critical force is increased.

Additionally, the phenomenon of penetration with a dynamic load, can be compared to an inelastic collision [5]. An inelastic collision is a collision where all the penetration energy comes from the kinetic energy. In our case, this collision happens between a needle (moving body) and a model (non-moving body). A lower penetration load, results from the damping and inertia of the model (reaction force to the penetration load) which prevents the movement and the deformation of the model. In this way the penetration force can be decreased.

Nature presents us with a lot of examples where an impulse load is applied to penetrate a substrate. The cnidarians and the woodpecker are just two animals that use this biological strategy.

One of the fastest movements known in the animal kingdom is the discharge of nematocytes in the cnidarians. The nematocytes can be used as different mechanisms, depending on their morphology, such as prey capture or defensive and locomotory functions [6].

Derived from high-speed studies was found that the discharges happen with accelerations of 5 400 000g in 700ns, an average velocity of 18.6ms^{-1} and a peak velocity of 37.1ms^{-1} . A force of 13.2-53.1 μN is applied in the prey. However, if the cnidarians applied a static load their critical force would be approximately $0.48 \times 10^{-3}\mu\text{N}$ [7].

When the woodpecker chisels wood from a tree, its beak strikes the tree with a velocity between $3\text{--}6\text{ ms}^{-1}$, promoting an acceleration of over 1200g on each impact. The woodpecker can beat into wood around 20 times/s [8].

To achieve these velocities the woodpecker uses its own natural frequency. For that, according with Vincent et al., the woodpecker starts by contracting the muscles connected to the legs and tail then, in the swing-back phase, to achieve a backward acceleration, the woodpecker contracts the thigh muscles and extend the legs. Finally, their body starts to move in direction to the tree due to the force provided by the legs [9].

To penetrate wood a critical force between 250-3150N is needed. However, according with the conditions of the woodpecker, if it applies a static load, their critical force will be around 1.5N, which is insufficient to penetrate the wood [5].

Another biological strategy used to reduce the penetration force is skin tension. This strategy is applied by the mosquito. The mosquito proboscis is formed by 7 elements, the labium, the labrum, the hypopharynx, two maxillae and two mandibles. The labium is the central element. In their tip are presented two flaps that are pushed to each side when the proboscis is pushed towards the skin, promoting this way skin tension [10].

The impact of the presented biological strategies on penetration forces will be experimentally analysed in this work. Furthermore, we will examine the effect of the application of a combination of strategies on the penetration force for polymer and steel needles.

1.1. Previous work on impulse, skin stretching and needle tips

As described previously animals have a range of strategies to penetrate substrates using lower applied forces. With the main focus of reducing the penetration force and increase the rate of penetration, different strategies were introduced and tested experimentally to evaluate their impact.

Several experiments were run to study the influence of the velocity in the penetration force. In earlier work conducted by Crouch et al., needles were injected in a silicone gel with velocities between 3 and 21 mm/s [11]. The results show that higher velocities lead to higher penetration forces. Similar results were found by Webster et al. who also found that the penetration force increase with higher insertion velocities using a rubberlike skin model and velocities between 5 and 25 mm/s [12]. On the other hand, when biological tissues are used the values of penetration force decrease with the increase of velocity [13], [14].

The influence of the needle tip has earlier been analysed. Previous works on the role of tip shape studied the angle of the tip, the number of cutting edges and the diameter. The most common needle tip shapes are blunt, bevelled, conical, sprouted, diamond and tuohy. A study conducted by Okamura et al. concluded that the friction force decreases when the number of cutting edges increases [15]. Another study, developed by Hirsch et al. showed a reduction of 23% in the penetration force for a 5-facet bevel needle tip when compared with a 3-facet bevel needle tip [16]. Aoyagi et al. realized a FEM simulation to study the influence of the needle tip angle. Needles with 10 deg, 20 deg, 30 deg and 40 deg were simulated and was found that lower the tip angle(that means sharper the needle tip) easier the penetration [17].

To study the influence of skin tension, Aoyagi et al, performed an experiment were a silicone rubber was stretched. The results show a 25% reduction in penetration force when the tension was applied, reducing the penetration force from 0.4N to 0.3N [17]. In another study diverse strains (0.03, 0.06 and 0.12) were applied to a polyurethane strap, resulting in a reduction of 14.4% in the values of penetration force for 25G steel needles [18].

However, more strategies can be used to improve skin penetration of polymeric needles. In a work developed by Busillo and Colton, the influence of lubricant in the penetration success and penetration force was tested. Busillo and Colton tested the effect of Dow Corning MDX4-4159 50% silicone medical grade in plastic needles. The lubricant was chosen since it is the one commonly used on steel hypodermic needles. The influence of the lubricant was obtained based

on penetration tests. Two different skin models were used, a polyurethane film and pig skin. The used needles were the Ticona LCP needles with 38,1 or 25,4mm length. The former needles were not able to penetrate the pig skin, but demonstrated a rate of penetration between 14% and 40% for the polyurethane film. For the 25,4mm long cannula needles the penetration success was 75% for both skin models [19].

2. Testing penetration strategies

When considering buckling, one of the most important parameters is the Young Modulus (E) of the material. In our case, the polymer needles were made of TOPAS 5013S-04 with a $E=3.2\text{GPa}$, having a length of 7mm, a diameter of $480\mu\text{m}$ and 3 inner channels each with a $80\mu\text{m}$ diameter. Considering these conditions, the critical force calculated was 3.42N. For a 25G steel needle, with a length of 7mm the critical force calculated is 264.12N. The critical force for a steel needle is almost 80 times higher than the critical force for a polymer needle. While steel needles don't show any difficulty in penetrating a substrate the opposite is the case with polymer needles. In fact, the used polymer needles could not penetrate any of the used substrates. Inspired by the impulse strategies used by the cnidarians and the woodpecker a spring-based mechanism was created and experimented with. The impulse mechanism was used to study the rate of penetration success and the penetration forces. The experiment conducted can be compared to a high-speed insertion. To compare the obtained results for the impulse experiments a low speed experiment was additionally performed.

The influence of the needle tip was also analysed. For that purpose different tip shapes were made in the polymer needles (conical and pyramidal) and their penetration behaviour (penetration force and rate of penetration success) was compared with the penetration behaviour of 25G steel needles.

Lastly, an experiment was conducted where strain and impulse were conjugated. For that, a strain (0.06) was applied to the skin model while executing the impulse experiment.

The presented experiments were used to study two hypotheses. First, it was studied if, with the aid of an impulse, the polymer needles can penetrate a substrate and secondly, it was studied if the polymer and the steel needles have similar penetration behaviour.

2.1. *Experimental equipment and condition*

Two experiments were made in order to study the penetration and the respective values for polymer and steel needles in a model.

The realized experiment to study the penetration in a model with low velocities was done using a Single Column Instron 3345 testing machine, a 3-jaw chuck and a skin model (3 layers of nitrile rubber gloves (Nitrile carbamate free, Papyrus Sverige AB). The needles were placed in the 3-jaw chuck that was connected to the Instron machine. The insertion velocity was set to the lowest possible value 0.2mm/s, which in previous work was found to give the lowest penetration forces [18]. All the values were recorded with the Bluehill software. A schematic illustration of the experiment can be found in Figure 1.

Fig.1. The experimental setup for low velocity tests

The general set up to evaluate and record the values of penetration force when an impulse and strain were applied was composed by a Lloyd Instruments materials testing machine and a load cell, a data acquisition system by National Instruments, a personal computer (LabView software) and an impulse device. The data acquisition system was connected with the load cell of the Lloyd Instruments machine and with the computer. The impulse device was also connected with the load cell and all the tested needles were attached to the impulse device. In this way, the penetration forces could be detected by a computerized system as shown in Figure 2. The impulse device was a 3D printing housing, with lateral openings (in order to compress and release the spring), where a spring can be attached in one end. In the other end of the spring was placed a needle holder that supported the needles and guaranteed that the needles were centred in the impulse device.

Fig. 2. The experimental setup for impulse tests

In order to study the influence of different impulses, two different springs were used in the impulse device. Their characteristics can be found in Table 1.

Table 1 – Characteristics of spring 1 and spring 2.

	Spring 1	Spring 2
Length (mm)	24	24
Weight (g)	0.1702	0.1440
Constant k (N/m)	134.58	336.46
Type	Compression spring	Compression spring

A skin model used to perform the tests was formed by 3 layers of nitrile rubber gloves (Nitrile carbamate free, Papyrus Sverige AB) mimicking the skin's upper layer stratum corneum and sticking glue for wall mounting to mimic the hypodermic fatty layer of skin. The fixture for the model was a polymer box with a cylindrical hole. The nitrile rubber was attached in both sides of the polymer box making it possible to control the amount of strain applied. The chosen model should allow needle penetration when impulse was applied but not in the low velocity experiments using polymer needles. Due to the higher stiffness of traditional skin models made from polyurethane straps such models were not applicable. Earlier work found that a strain of 0.06 promotes the greatest reduction in the penetration force values [17], [18]. Accordingly, a strain of 0.06 and no strain were the 2 chosen conditions.

Fig. 3. Schematic representation of the needle tips used

To study the influence of the tip in the penetration process 3 different types of needles were used, two made of polymer and one made of steel. The polymer needles had either grinded conical or cleaved pyramidal tips, while the steel needles were commercial 25G needle (BD Microlance, 25G x 5/8", coated with silicone) with bevel tips, as presented in Figure 3. To be able to attach the needles in the impulse device the luer connector of the steel needles was removed by heating the attachment glue, cleaning the needles with ethanol, which also removed the silicone coating, and cut to obtain a free length of 7 mm after mounting it in the impulse device.

The sharp conical tips on the polymer samples were fabricated by using a DP-U2 grinding drum and Silicon Carbide 1200/4000 grinding paper holding a grinding angle of 55 degrees and a radius of 0.166.

3-sided pyramidal type was chosen since this shape will ensure an equal distribution of forces and at the same time the sharp edges will ease the penetration process. The pyramidal was achieved using a razor blade and a tip angle of 43 degrees and a radius of 0.025.

Each experiment was repeated 5 - 10 times. 3 different parameters were analysed, the spring (spring 1 and spring 2), the tip (conical tip, pyramidal tip and bevel tip) and strain (0 and 0.06). All the needles were tested with a free length of 7mm after being attached to the impulse model and the needles were only used once to prevent errors due to tip damages. In total 90 experiments were performed (30 experiments for low speed tests, 10 for each type of needle, and 60 experiments for the impulse tests, 5 for each type of needle with the different conditions).

2.2. Results

Table 2 presents the values of penetration force, standard deviation and the rate of penetration success for the low velocity experiments ($v=0.2$ mm/s). For a conical tip needle was found a penetration success of 10% with a penetration force of 3.848N, while for a pyramidal tip needle was obtained a penetration force of 0.426N with 20% penetration success. The penetration force for a bevel tip was 0.438N and the penetration success was 100%.

Table 2 – Penetration force, standard deviation and rate of penetration success for low velocity experiments.

Material	Type of tip	Low speed tests (v=0.02mm/s)		
		Force (N)	Stand. dev.	Penetration success (%)
Polymer	Conical	3.848	0	10
	Pyramidal	0.426	0	20
Steel	Bevel	0.438	0.015	100

Table 3 – Penetration force, standard deviation and rate of penetration success for all impulse experiments performed with spring 1.

Material	Type of tip	Impulse			Impulse + strain (0.06)		
		Force	Stand.	Penetration	Force	Stand.	Penetration
		(N)	Dev.	success (%)	(N)	Dev.	success (%)
Polymer	Conical	1.408	0.065	40	1.352	0.041	60
	Pyramidal	1.366	0.014	100	1.359	0.056	100
Steel	Bevel	1.383	0.029	100	1.378	0.019	100

Results from impulse experiments are found in Table 3. As seen does impulse and strain leads to lower penetration forces. Impulse alone increases the penetration success to 40% for the conical tip needles. When the strain is conjugated to the impulse it was possible to obtain a further reduction of 0.06N for the penetration force and an increase to 60% penetration success. For needles with pyramidal tip and bevel tip only trivial penetration force reductions were observed (0.007N and 0.005N). For both type of needles the penetration success was 100%.

Table 4 – Penetration force, standard deviation and rate of penetration success for all impulse experiments performed with spring 2.

Material	Type of tip	Impulse			Impulse + strain (0.06)		
		Force	Stand.	Penetration	Force	Stand.	Penetration
		(N)	Dev.	success (%)	(N)	Dev.	success (%)
Polymer	Conical	1.470	0.021	100	1.462	0.024	100
	Pyramidal	1.517	0.062	100	1.411	0.071	100
Steel	Bevel	1.494	0.038	100	1.375	0.030	100

Table 4 shows the results from the same experiment as seen in Table 3 but using the stronger spring 2. The experiments shows higher penetration success than the one's performed with the spring 1. In fact, all the experiments realized with the spring 2 exhibit 100% of penetration success. The lowest values for penetration force were found for the bevel tip needles when impulse and strain were applied together. However, when adding strain, the force reductions achieved were small (0.008N, 0.106N and 0.119N) for needles with conical tip, pyramidal tip and for bevel tip.

Tables 3 and 4 illustrate that pyramidal tip needles and bevel needles performs in a similar way. The behaviour of both type of needles were further analysed using an Anova statistical analysis and a Pareto effect analysis.

The Anova analysis showed results that were significant ($p < 0,05$) for type of spring ($p < 0,030$), for the strain ($p < 0,039$) and for the interaction between the spring and the strain ($p < 0,043$). Graphs from the Anova analysis for all possible interactions can be found in Figures 4, 5 and 6 [20].

Fig. 4. Plot of spring versus tip needle interaction

Fig. 5. Plot of spring versus strain interaction

Fig. 6. Plot needle tip versus strain interaction

A pareto analysis can be used to investigate which effects that influence the results and whether the influence is positive (will increase the values of penetration force) or negative (will decrease the values of penetration force) [21]. The Pareto effect analysis for the needles with pyramidal tip and bevel tip can be found in Figure 7.

Fig. 7. Pareto analysis for needles with pyramidal and bevel tips

The pareto analysis confirms that the behaviour of needles with pyramidal tips and bevel tips is similar since the tip only contributes with 0.006. The most significant effects come from the spring (0.078), and from the strain (-0.054). The third most influential parameter is the combination of strain and spring (-0.054). Other indications of the small influence of the tip is the

fact that all the interactions that involves the role of the tip has very low values (-0.003 and -0.004).

3. Discussion

The results show that it was possible for a polymer needle to penetrate a tissue model when an impulse is added using similar penetration forces as for a steel needle.

In the low velocity experiments the penetration success was as low as 10% (i.e. 1 out of 10 tested needles) for a conical tip needle using the very high penetration force of 3.848N. This is about 8 times higher than for the other needles. The reason is probably that it is almost impossible for the conical tip needle to penetrate the tissue model and a very large force is therefore required. For the needles with pyramidal tip and bevel tip the penetration force values were similar (0.426N and 0.438N) but there were large differences in the rate of penetration success (20% and 100%). This is understandable considering the large differences in stiffness between polymer and steel. It is therefore interesting that the application of impulse insertion has such a drastic positive effect on the penetration success for the polymer needles while maintaining penetration forces that are comparable to steel needles.

The impulse experiments showed that the weaker spring 1 resulted in smaller penetration forces than the stronger spring 2. This fact is correlated with the higher velocities promoted by spring 2 when compared with spring 1. This complies with previous work which also found that higher insertion velocities promote higher penetration forces in artificial skin models [11], [12]. However, other authors found the opposite that higher velocities lead to lower penetration forces [13], [14]. These works were based on animal (porcine) tissues. The different tests models can justify the obtained differences.

However, another important parameter is the rate of penetration success. We found the best results for the stronger spring 2 that for all the three types of needles showed 100% of penetration success while the weaker spring 1 reduced the penetration rate to as little as 40% for the conical tip needle. In fact, the failed conical tip needles bended plastically close to the superior

end of the needle (not on the tip end). These results showed a fixed-pinned condition. To prevent the needles of bend a similar strategy to the one used by the mosquito's labium can be used. Once the labium only provides support to the fascicle penetration preventing this way the bending of the fascicle. The impulse mechanism, independent of the used spring, showed to very effective in making possible to inject polymer needles when comparing with low velocity experiments.

Penetration behaviour (penetration force and rate of penetration success) was found similar for needles with pyramidal tip and the bevel tip. The conical tip needle performed worse showing low penetration success in most cases and higher penetration forces. These results can be explained with the lack of cutting edges in the conical tips, which complies with previous findings that a higher number of cutting edges result in lower penetration force values [15], [16]. Another possible explanation for these results is the tip angle. In fact, the tip angle of the conical needles was higher than the tip angle of the pyramidal needles. These results comply with the obtained results in a work conducted by Aoyagi et al. where was found that higher tip angles leads to higher penetration forces [17].

The needles with pyramidal and bevel tips behaved similarly in a number of ways. When a stronger spring was used in the impulse experiments the penetration force increased. When a strain was applied to the tissue model both tips showed lower values for penetration forces. This was further confirmed by the Anova statistical analysis that found significance ($p < 0.05$) for the role of the spring ($p = 0.03$), the use of strain ($p = 0.039$) and the combination of impulse and strain ($P = 0.043$). The Pareto analysis showed the same tendency. Both tips exhibited similar penetration forces and the Pareto analysis confirmed that the tip do not influence the size of the penetration force (for pyramidal and bevel tips).

4. Conclusion

The present paper combines two different strategies to penetrate skin, namely impulse and strain. These strategies were biologically inspired from the defence mechanism of cnidarians, the peck of the woodpecker and skin tension of the mosquito. When applied to polymer needles the ability to penetrate a skin model was demonstrated, while the opposite happened under static

conditions. Rates of 100% of penetration success were found for pyramidal and conical polymer needles tip when impulse and strain were applied together. In opposition, when static conditions were applied, rates of 20% and 10% of penetration success were found for the pyramidal and the conical polymer needles tip respectively. It was also shown that a pyramidal polymer needle tip can have a similar penetration behaviour as a bevel tip needle (penetration force and rate of penetration success) when an impulse load was applied to the needles in the artificial skin model.

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