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Investigation of vibration parameters for needle insertion force reduction

Abstract: Many medical interventions in therapy and diagnostics require needle insertion into tissue. Common complications such as increased pain and formation of haematoma are caused by wrong needle positioning. It has been shown that pain experience and needle positioning can be improved by a reduction of insertion force, which can be achieved by vibrating the needle axially. An experimental setup has been designed to investigate the influences of different combinations of vibration frequencies (10, 100, and 200 Hz) and vibration amplitudes (20, 100, and 500 µm) during needle insertion into thin sheets of polyethylene terephthalate (PET). A customary 20 W loudspeaker was used to generate the vibration. The results indicate a maximum reduction of 73 % in puncture force and up to a 100 % reduction in shaft friction force. However, the additional vibration force generated by the vibration movement has to be high enough to generate positive effects in terms of force reduction.

Keywords: venepuncture, vibratory needle insertion, insertion force, force reduction, pain reduction

https://doi.org/10.1515/cdbme-2020-3155

1 Introduction

Drawing of blood for diagnostic testing is one of the most common invasive procedure performed in healthcare [1]. Despite the frequency and importance of venepuncture, complications such as severe pain and formation of haematoma caused by positioning errors of the needle occur frequently [2]. Different studies correlate an improved pain experience and a more accurate needle positioning with a reduction of insertion force. It has been shown that applying an axial vibration can reduce the required needle insertion forces [3–5].

Begg and Slocum have worked on the concept of an axial oscillating vibration in the range of audible frequencies. They pierced into gelatine phantoms and investigated the reduction of the insertion force in relation to the insertion depth. A vibration with the actuator's resonant frequency at 150 Hz, which resulted in the largest vibration amplitude, showed the lowest insertion forces [6]. Tan et al. also used gelatine phantoms and investigated the additional force generated by a vibration. They claimed that a vibration with 500 Hz creates a 17.9 % higher additional force compared to a vibration with 50 Hz [7]. Barnett investigated the puncture force when piercing into porcine skin. He examined frequencies from 100 Hz to 2000 Hz and amplitudes from 5 µm to 50 µm and achieved a maximum reduction of 35 % in puncture force. This was achieved by applying a vibration with 500 Hz and an amplitude of 25 µm [5]. However, no investigation of the influences of frequency and amplitude on different phases during insertion has been conducted.

This paper, therefore, investigates different combinations of vibration frequencies and vibration amplitudes and the influences on different insertion phases. A sinusoidal vibration movement is used. Combinations of 10, 100, and 200 Hz vibrations and peak-to-peak amplitudes of 20, 100, 500 µm are investigated. For this purpose, a setup is built consisting of a vibration actuator, a force sensor, and a linear motor. This allows the measurement of forces during needle insertion with and without vibration. The force values are analysed in respect to puncture force and friction force.

2 Material and methods

2.1 Experimental setup

A 20 W loudspeaker (FR 10 HMP, VISATON GmbH & Co. KG, Haan, DE) was used to generate sinusoidal vibrations. To transfer the vibrations to the needle, a PMMA plate was glued onto the dust cap of the speaker. A Luer adapter was screwed into the center of the plate to provide an interface for the 21 G hypodermic needle used.

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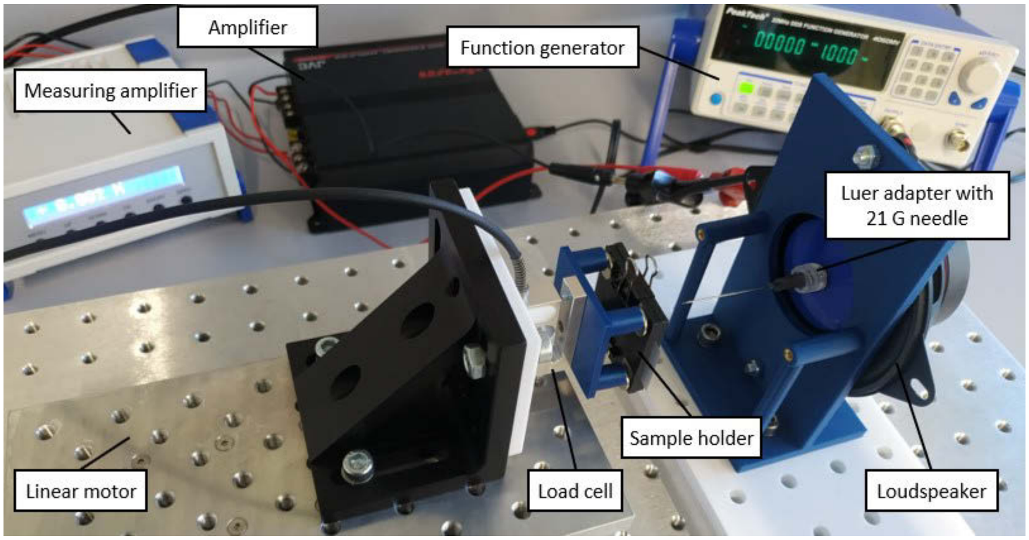

Figure 1: Experimental setup.

The speaker stays stationary during the experiments and is fixated on an optical breadboard. The excitation signal was delivered by a function generator (PeakTech® 4060 MV, PeakTech Prüf- und Messtechnik GmbH, Ahrensburg, DE) in conjunction with an amplifier (KS-DR3002, JVC KENWOOD Corporation, Yokohoma, JP).

A laser Doppler vibrometer (OFV-3001, POLYTEC GmbH, Waldbronn, DE) was used to identify the required excitation voltage to achieve the desired free vibration amplitudes (20, 100, and 500 µm) and frequencies (10, 100, and 200 Hz). Free vibration amplitude describes the peak-to-peak amplitude of the needle if moving freely in space.

The sample was fixed to a 5 N load cell (KD40s, ME-Meßsysteme GmbH, Hennigsdorf, Germany) with an adapter. The load cell itself has an accuracy class of 0.1 % and a resonant frequency of 2 kHz without added mass. It is connected to a measuring amplifier (GSV-2TSD-DI, ME-Meßsysteme GmbH, Hennigsdorf, DE) which forwards the signal to a control PC via USB. The adapter clamped the sample, a 125 µm thin sheet of PET, between two plates, both with a centred 10 mm diameter hole, which allows the needle to pierce the sample completely. PET is commonly used as blood vessel replacement [8]. The connection of load cell and sample holder was mounted to a linear motor (VA LINAX® Lxc 80F40, Jenny Science AG, Rain, CH) that moved the arrangement of load cell and sample towards the stationary speaker vibrating the needle. The experimental setup can be seen in Figure 1.

2.2 Measurements

At the beginning of each measurement, the sample out of PET is loaded into the sample holder. The linear motor moves the sample towards the needle at a constant speed of 1 mm/s [9]. During the whole process, the force data of the load cell was recorded by the measuring amplifier with the maximum sampling rate of 625 Hz. After 15 seconds in which the needle pierced the sample, the forward movement ends and the linear motor returns to the starting position at the same speed after a pause of 1 s. Finally, the recording of the measured force values is ended. Each parameter combination was run five times.

In this setup, the total force comprised of insertion force and vibration force was measured by the sensor during contact. To isolate the insertion force required to advance the needle through the sample, the forces generated by the vibration had to be filtered. A digital 2nd order notch filter was used to suppress the vibration frequency as well as the 2nd and 3rd harmonic. Also, a moving average filter with a window size of 10 was applied to better expose the desired signal. The force curves resulting from the filtering then only provide information about the actual force needed to advance the needle. Exemplary force curves and the power spectra prior and after filtering can be seen in Figure 2.

To determine the puncture force, the maximum force value was determined from the filtered curves. To obtain the value for the shaft friction, the average value over the period of time in which the constant shaft friction was effective was determined. This time period (depicted by E in Figure 2) is set manually. Two-sample t-tests with a significance level of α = 5 % were conducted to compare the identified forces with vibration to the ones for the non-vibrating mode.

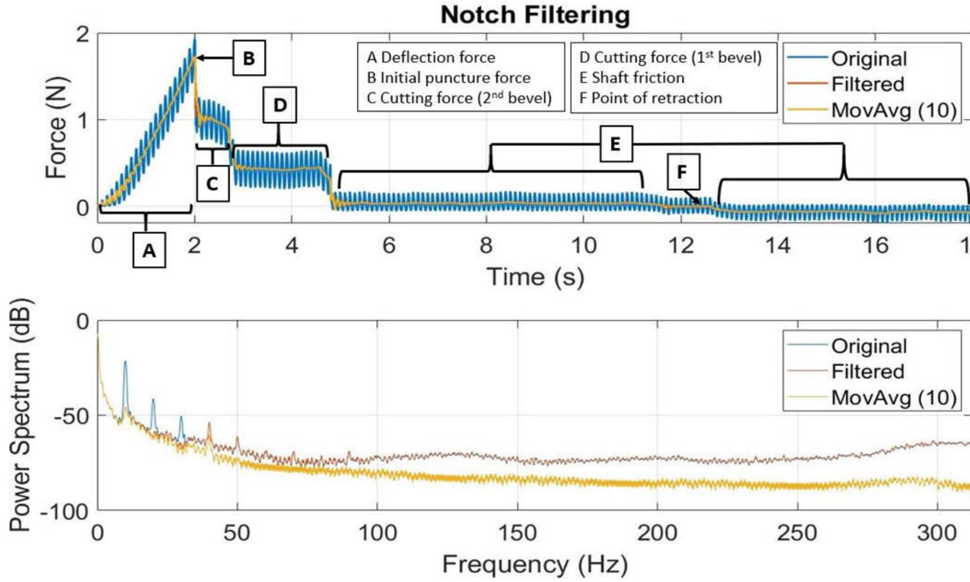

Figure 2: Exemplary force data of a measurement with a 10 Hz – 500 µm vibration mode. The blue line indicates the original data. Force oscillations induced by the vibration can be clearly seen. To remove this force component, a notch filter with the respective vibration frequency is used. The resulting curve after notch filtering and after application of a moving average can be seen in orange and yellow, respectively. In the power spectrum in the lower graph, the increased signal amplitude at 10, 20, and 30 Hz is visible. The orange and the yellow signal show the effectivity of the notch filter and the moving average, respectively.

3 Results

Recorded force curves show characteristic points and phases during puncture. This can be seen in the upper graph of Figure 2. The rising deflection force, the initial puncture force as well as the cutting forces induced by the secondary and primary bevel can be seen. In addition, a phase with a constant very low insertion force can be seen which is characteristic for shaft friction acting only. In the lower graph of Figure 2, the power spectrum of the signal can be seen. The signal amplitude is increased at the respective vibration frequency and from the associated harmonics, as a consequence of the vibratory movement of the needle.

Results for puncture force reduction can be seen in the upper part of Table 1. Puncture force is increased at 100 Hz - 100 µm ($p = 0.033$) and 200 Hz - 20 µm ($p = 0.010$) by about 5 %. At 100 Hz - 500 µm ($p < 0.001$) and 200 Hz - 500 µm ($p < 0.001$), puncture force is significantly reduced by 73 % and 67 %, respectively.

Results for shaft friction force reduction can be seen in the lower part of Table 1. Shaft friction is significantly reduced or increased at all frequencies and amplitudes, except for 200 Hz – 100 µm. An amplitude of 100 µm reduces shaft friction at 100 Hz by more than 40 % ($p < 0.001$). By applying an amplitude of 500 µm, shaft friction is significantly reduced by 74 % at 10 Hz ($p < 0.001$) and up to 100 % at 100 Hz ($p < 0.001$) and 200 Hz ($p < 0.001$).

Table 1: Overview of results for shaft friction force and puncture force: Force values are given in Newton and the deviations from the control insertion are given in percentage (square brackets). Values that are significantly different are marked with an asterisk.

Puncture force				
	0 Hz	**10 Hz**	**100 Hz**	**200 Hz**
0 µm	1.768 ± 0.046 [0.00 %]	-	-	-
20 µm	-	1.821 ± 0.028 [+3.04 %]	1.790 ± 0.033 [+1.26 %]	1.852* ± 0.031 [+4.76 %]
100 µm	-	1.794 ± 0.038 [+1.52 %]	1.852* ± 0.049 [+4.79 %]	1.527* ± 0.016 [-13.62 %]
500 µm	-	1.737 ± 0.035 [-1.71 %]	0.483* ± 0.014 [-72.69 %]	0.582* ± 0.047 [-67.09 %]
Shaft friction force				
0 µm	0.103 ± 0.005 [0.00]	-	-	-
20 µm	-	0.119* ± 0.004 [+14.72 %]	0.122* ± 0.006 [+17.91 %]	0.170* ± 0.002 [+63.83 %]
100 µm	-	0.112* ± 0.004 [+8.09 %]	0.062* ± 0.005 [-40.44 %]	0.108 ± 0.006 [+4.39 %]
500 µm	-	0.027* ± 0.007 [-74.00 %]	-0.018* ± 0.002 [≥ -100.0 %]	-0.026* ± 0.002 [≥ -100.00 %]

4 Discussion

It has been shown that the insertion force required when inserting a needle through a thin sample is reduced by the application of specific vibration parameter combinations. The effect of reduction can be seen in both shaft friction force and puncture force. An amplitude of 500 µm led to shaft friction force reductions by up to 100 %. By applying vibrations of 500 µm and 100 Hz or 200 Hz, the vibration reduces the insertion force needed to puncture the sample by 73 % and 67 %, respectively. However, also negative effects were observed.

A higher friction force during vibration could be due to the partial forward stroke of the needle in direction of the load cell and the inability to complete the forward stroke. At 10 Hz - 100 µm, this effect also occurs but to a lesser extent.

For vibrations at 100 µm and 100 Hz or 200 Hz, the combination of frequency and amplitude is strong enough to generate constant back and forward movements of the needle shaft. As a result, shaft friction forces are significantly lower here.

This also applies to vibrations with an amplitude of 500 µm. Reductions up to 100 % could be observed here. This rather unexpected value could be a measurement artefact resulting from errors of the force sensor since the measured forces are rather small. This is also supported by the fact that the same force values occur when the needle is retracted.

In summary, it must be assumed that the speaker is not able to maintain the vibration in the desired manner when the needle comes into contact with the sample.

The slight increases in the measured puncture force during vibration at 100 Hz - 100 µm and 200 Hz - 20 µm can be explained by the fact that the vibration increases the generated force of the needle tip for a short time. However, the vibration force is still too weak to penetrate the sample.

Filtering took place after sampling at a frequency of 625 Hz. When vibrating at 10 Hz and sampling at 625 Hz, it was found that the harmonics are of too low amplitude to create pronounced aliasing effects and influence the measurement result. It was therefore assumed that this also applies to higher vibration frequencies, which is why these measurements were also sampled at 625 Hz.

In further experiments, more combinations of frequencies and amplitudes have to be tested as well as the force progression in complete tissue phantoms. The here presented results indicate positive effects on insertion forces. However, to further investigate the influence of frequency and the influence of amplitude, it is important and necessary to implement an active control of the vibration mode to maintain the desired vibration. In this setup, the loudspeaker was driven open loop. Future works will, therefore, focus on actively controlling the vibration movement. Also, an additional bearing of the needle is to be integrated to ensure a purely axial vibration movement. Finally, the resonance frequency of the load cell with added mass should be investigated to exclude negative effects on measurements.

Author Statement

Research funding: The author state no funding involved. Conflict of interest: Authors state no conflict of interest.

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