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A Lorentz-Force Actuated Autoloading Needle-free Injector

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Abstract— **The advantages of delivering injections via needle-free methods are numerous. However, conventional methods for needle-free injection lack sufficient control over depth of penetration and shape of injection. Thus, a needle-free injector was designed, constructed, and tested, using a controllable linear Lorentz-force actuator. This actuator allows rapid control of the injection pressure during injections. Using this device, precise control over delivery parameters can be achieved. The injector design was tested for repeatability and evaluated for depth control using acrylamide gel and dye.**

I. INTRODUCTION

DELIVERING injections by needle is a complex and labor-intensive process, especially when multiple injections or multiple recipients are involved. Needle-free injector devices offer several advantages over needles, but have their own inherent drawbacks, namely, a lack of control over injection parameters and an equally low throughput as the needle-free syringes must be loaded by hand.

The concept of needle-free injections dates back to the middle of the last century. Needle-free injection first appears in literature in a paper by R. Hingston, 1947 [1]. In theory, a liquid pressurized to a sufficient degree and ejected through a properly-sized orifice can penetrate skin to depths achievable by injection with needles.

Of primary importance, however, is proper control of the depth and shape of the injection. A needle delivers the entirety of its contents to a predetermined depth, constrained by the length of the needle. This is desirable when the intent is to deliver to a specific depth (i.e. the muscle layer) in the recipient. Many common injections are designed to be injected into specific tissue layers of the human body [2]. A needle-free injector device capable of delivering drugs to different depths based on drug type, skin type, etc., would have significant advantages over injector devices that operated at a single, uncontrollable, depth.

Additionally, certain applications could benefit from a system designed to deliver multiple injections in rapid sequence. Mass vaccinations, or drugs that require multiple deliveries to the same recipient, could be delivered in a significantly smaller amount of time.

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II. BACKGROUND

Operation of a needle-free injector is relatively simple. When fired, a pressure source applies a force to the piston. The piston transmits this force to the drug in the injection cylinder. As most aqueous solutions are essentially incompressible, the pressure of the drug rises. The drug is forced through the orifice and ejected at a speed related (but not strictly proportional, due to turbulence, etc.) to the force on the piston and the diameter and shape of the orifice. If the speed of the ejected drug is sufficient and the nozzle is of the proper diameter, it will breach the skin of the recipient and penetrate to a depth related (but again not proportional) to the speed of the drug and the mechanics of the skin. These relations are poorly understood, although the device presented in this paper is currently being used to study the relationships.

The primary problem with needle-free drug injections is a lack of control over the depth characteristics of the injection. Ideally, the injector would be capable of producing an injection similar to that of a conventional needle, and delivering to a variable depth.

Currently available commercial injectors fire with a fixed pressure verses time profile (a pressure profile), and typically deliver drugs to a bolus beneath the surface of the skin, as indicated by J. Baxter, 2004 [3]. It is hypothesized that controlling the pressure profile of the injector is a means of controlling the depth and shape of the injection. Such techniques could allow for more precise control over delivery.

The key to generating a variable pressure profile injector is generating a variable force to drive the injector's piston. Conventional needle-free injectors, powered by springs or compressed gas, are difficult to control in such a manner. Electrical control is by far the easiest way to control systems in real time, so the ideal device for driving a variable-pressure needle-free injector would be a device whose output force is proportional to an electrical current.

A linear Lorentz-force (voice-coil) motor is this type of device. It is an electromagnetic actuator, commonly utilized today in audio speakers. A commercial voice-coil actuator, a BEI Kimco Magnetics model LA25-42-000A [4], was used in the design of a variable pressure profile injector

device. A cutaway view of this actuator is shown in Figure 1.

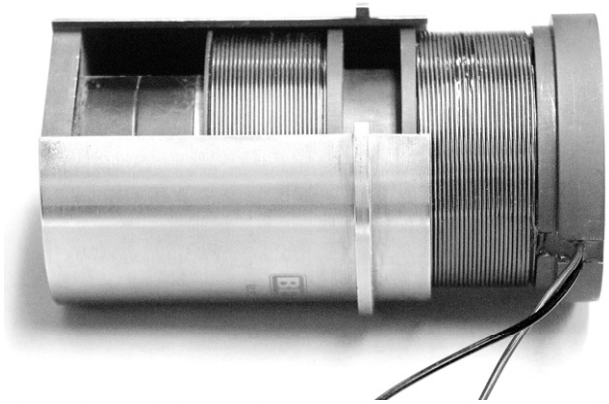

Fig. 1. Photograph of a BEI Kimco Magnetics Lorentz-force actuator, with the side panel machined away, exposing the inner magnetic structure and the coil windings.

III. Injector Device

The injector device is comprised of many components, but can be broken down into three major blocks; the housing and motor structure, the injection cylinder, and the autoloader.

The injector device is designed to deliver 100 µL volume at 60 MPa.

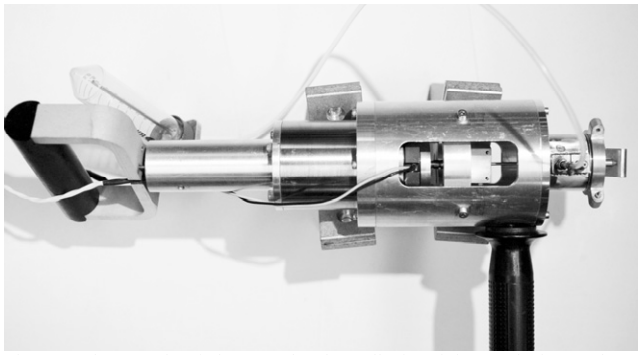

Fig. 2. Photograph of the completed needle-free injector device. The injection cylinder is at the extreme right hand side. The device is supported by a pair of stands in this photograph.

A. Housing / Motor Structure

The housing and motor structure provides a support onto which the rest of the NFI device is attached. It is built around the BEI Kimco Magnetics linear Lorentz-force motor, and provides a constrained, linearly-actuated main shaft to which the piston and cylinder assembly is connected.

A position sensor holder is attached to the bolt pattern on the back end of the motor, and mounts a DC Fastar [5] model DCFS3/4-M inductive position sensor. This sensor allows the control system to determine the position of the piston at all times.

The coil of the motor structure is attached to a 6.35 mm diameter nonmagnetic stainless steel main shaft that runs the length of the motor and protrudes from the front edge of the coil structure. Linear ball bearings inserted into the 12.7 mm diameter race inside the linear motor housing constrain the main shaft.

An axial-misalignment coupling is attached to the front end of the main shaft. This coupling is designed such that the linear force is transmitted between the device's main shaft and the piston (part of the piston and cylinder assembly), but off-axis forces do not cause binding. Thus, the piston and cylinder assembly can be slightly off-axis without appreciably affecting performance.

B. Piston / Cylinder Assembly

Perhaps the most critical piece of the device, the injection cylinder is designed to withstand the pressure of needle-free injection, while providing for a number of other internal passageways that allow for bleeding, autoloading, and pressure sensing.

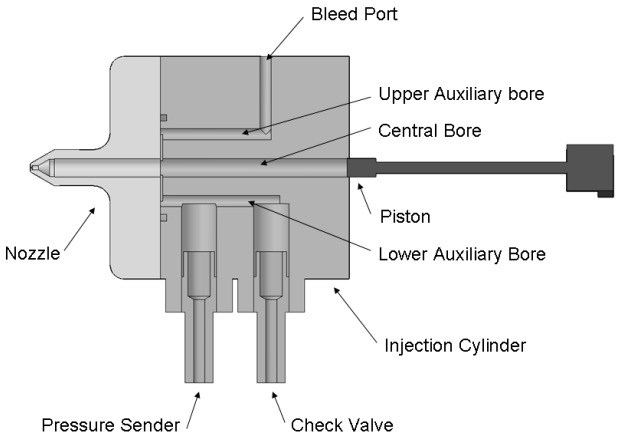

Fig 3. A CAD cutaway diagram of the injection cylinder, with the major functional components labeled.

The cylinder is machined out of a single block of Type 303 stainless steel. A central bore runs the length of the cylinder, and two auxiliary bores, diametrically opposite to each other, are spaced above and below the central bore. The lower bore mounts a check valve and a pressure transducer, while the upper bore is a tap for bleeding air from the system. The central bore is the guide for the piston of the device.

The upper and lower auxiliary bores are connected to the main bore of the cylinder channel milled into the cylinder face between all three passages.

The check valve is a machined automotive-style poppet valve. An O-ring, located beneath the valve head to provides a seal at low back-pressure, while at high back-pressure (such as during an injection), the metal lip of the poppet valve seals against the valve seat.

The piston of the device is a commercially available syringe piston, a Hamilton model #50495-35 [6]. These pistons fit the bore of the cylinder on one end, and the misalignment coupler inside the Housing / Motor Structure on the other.

A ring is milled into the cylinder face to accept an O-ring that seals the nozzle to the cylinder. The O-ring

encompasses all of the high-pressure passageways on the front face of the cylinder.

A six-bolt hole pattern is drilled and tapped into the front cylinder face. These bolts hold the nozzle against the cylinder.

The front of the cylinder is drilled and tapped for a nozzle. Each nozzle is constructed of aluminum, and has a 100 µm nozzle in the end. A nozzle cap clamps over the nozzle and seals it with a silicone rubber seal when the injector is not in use, or during autoloading.

C. Autoloader

The autoloader is a separate system that allows the injector device to be automatically reloaded after each injection. A pressure reservoir (compressed argon) is connected via a solenoid valve to the air space above a drug reservoir. A dip tube that reaches the bottom of the reservoir is connected to the check valve in the injection cylinder on the injector device.

The drug reservoir is a standard 50 mL medical vial. The vial holds enough drug for 500 injections with this device.

During autoloading, the solenoid valve is opened, applying pressure to the drug reservoir. Drug is forced up the dip tube, through the injection cylinder's check valve, and into the cylinder bore. The piston is slowly drawn back to allow the cylinder to fill without creating air bubbles or cavitation.

IV. Injector Control

The injector device is controlled by a linear amplifier, a computer interface, and a laptop. A block diagram of the injector device can be seen in Figure 4.

The peak forces involved in needle-free drug delivery require a significant amount of energy delivered over a very short period of time. It is important that the pressure in the injection cylinder quickly rise to pressures capable of breaching tissue, or much of the drug will be lost before it can penetrate. For an instantaneous pressure rise, an instantaneous force must be applied to the piston, which is impossible to achieve with a voltage-controlled inductive motor. However, the higher the driving voltage, the closer the approximation of instantaneous coil current becomes. Therefore, the source driving the motor should be capable of producing much higher voltages than are needed to produce peak force, so that pressure rise times can be minimized.

The coil is driven by a 4 kW (peak, into 4 Ω) commercial linear audio power amplifier, an AE Techron [7] model LVC5050. The amplifier is driven with a National Instruments [8] DAQPad-6052E data acquisition device, which also controls the autoloader solenoid and monitors the injector device's sensors.

The 6052E's IEEE-1384 interface is connected to a laptop that, in conjunction with the Injector Control software, generates the firing waveforms and controls the autoloading sequence. The injector software is written in the C# language of Microsoft Visual Studio .NET 2003 [9].

The Injector Control software allows the user to purge, autoload, and fire the injector while monitoring its output subsequent to each injection on a laptop. In addition, it provides a static bias current to hold the piston in a retracted position. It also provides a piston stabilization feature designed to prevent piston creep when the injector is not resting horizontally, and a pressure tail-off algorithm designed to brake the piston post-injection and keep the falling pressure from leaking excess drug out the nozzle.

The injector is fired with open-loop computer control. A drive waveform file (a column of output voltages) is read from the laptop's disk. This waveform is checked for validity, and then output via the NI device. The NI device monitors and logs the injector device's sensors during the injection.

The injector autoloads under full real-time feedback control. When the autoload command is given, the solenoid valve in the autoloader is opened, allowing pressurized drug to reach the internals of the injection cylinder. Then, the piston is slowly drawn backwards in small steps, using the position sensor as a reference. The computer monitors movement and modulates the drive power accordingly, as the friction between the injection cylinder and the piston is nonuniform over the travel of the piston. When the piston has fully retracted, both the autoloader pressure and coil drive are shut off.

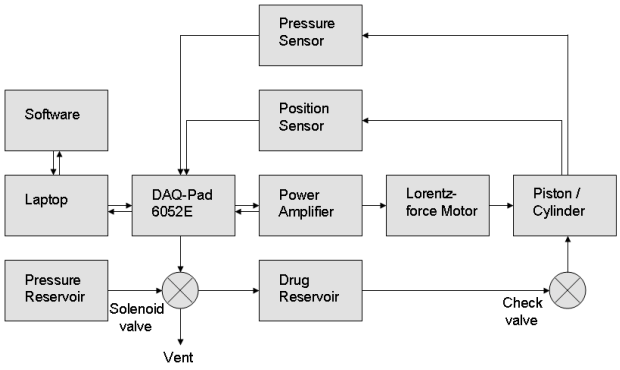

Fig. 4. Block diagram of the injector control system.

The position assist function is a separate thread that runs a real-time feedback control loop on piston position via the position sensor and modulates the bias power of the coil to achieve a steady piston position irrespective of gravitational forces or acceleration of the device as it is moved. Thus, the injector can be held vertically without bleed from the nozzle due to gravity.

V. Advantages of Software Control

Using this system, it is possible to design custom injection pressure profiles for different situations. This needle-free injection system was to be used on live tissue, and as such, was initially tested on acrylamide gels. Profiles were designed to penetrate and deliver drug to specific depths in acrylamide blocks.

The pressure profiles are related, although nonlinearly, to the force provided by the linear motor on the cylinder piston, and therefore to the current running through the motor coil. The pressure and force are not linear due to

second order effects, such as resonances in the complaint components (Teflon piston tip, O-rings, possibly the pressure transducer head). However, the force and coil current are directly proportional to one another.

Thus, pressure profiles are created by modifying the input waveform file, a simple task with the Injector Control software. Primarily, the pressure profiles produced consisted of a 2 to 3 ms pressure "peak" of 40 to 50 MPa, followed by a longer 20 to 30 ms "followthrough" of 10 to 20 MPa. By changing the voltages in the waveform, profiles could be created to damp out resonances. Over time, a library of waveforms was created, each corresponding to a different set of desired parameters.

VI. Injector Verification

The injector device was used extensively, for several thousand firings. Initial design verification was conducted in two ways: repeatability testing and injections into acrylamide gels.

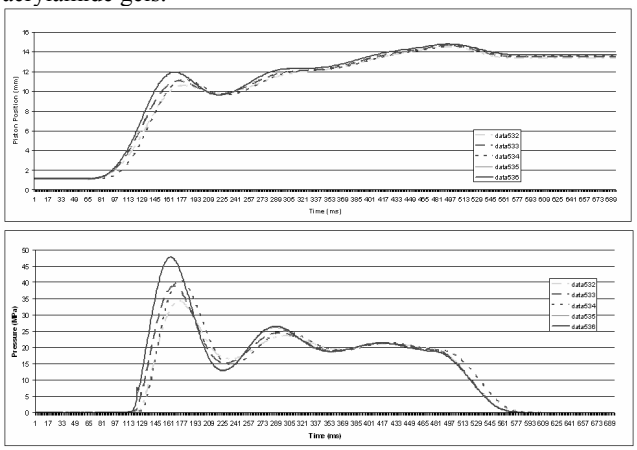

Fig. 5. Graph of traces from the position (top) and pressure (bottom) sensors of the injector device over six injections.

The device was tested extensively for repeatability. Under autoloading computer control, the ejected volumes match to within 3% tolerances. The sensor data from one series of repeatability tests is shown in Figure 5.

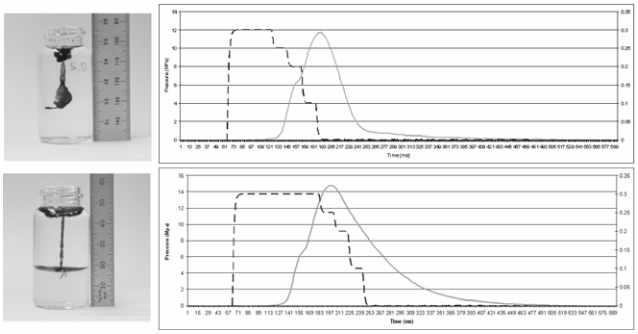

Fig. 6. Photographs and traces from depth testing demonstrating the control available with this injector device. The upper graph shows a waveform designed to inject to a 5 mm depth in 5.0% acrylamide, while the lower graph is a more powerful waveform that can drive dye through the entire block. Switching between waveforms is accomplished rapidly with the graphical user interface of the Injector Control software. Injections are rapid and repeatable using the autoloading system.

Additionally, it was important to demonstrate that the injector is capable of delivering to different depths by modifying the drive parameters using the Injector Control software. Jars of 5.0% acrylamide gel were used as tissue substitute; transparent gels allow for accurate measurement of penetration depth when injected with 0.1% Bromocreasil Green. Multiple injections were performed, and the depth of injection was correlated with the pressure profile, and therefore, the drive waveform. See Figure 6.

VII. Future Directions

Although needle-free drug delivery devices are currently commercially available, much about needle-free injections remains unknown. The field of jet mechanics (how the pressure verses time profile of the injection cylinder, coupled with the shape and diameter of the nozzle influences the depth and shape of the injection) is almost completely unresearched. Before now, the tools required for accurate study did not exist.

The injector device presented in this paper is an optimal platform for jet mechanics studies. It is completely modular, nearly completely automatic, with unparalleled flexibility in control of pressure profiles. Automatic loading and firing allows rapid, repeatable experimentation.

Additionally, with the knowledge of what is achievable using the Lorentz-force actuator in these injectors, it is believed the human market is within reach. The NFI device presented in this paper will be used as a platform for a next-generation, commercially viable device incorporating a custom voice-coil and an integrated power supply and real-time feedback control of the entire device to increase repeatability further. It is expected that such a device will be an excellent tool for fast, mass immunizations.

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