35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Safety System for Moving Coil Pressure Algometer

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***Abstract*— The threat of safety failure during use of potent actuators is a known problem. The use of such actuators in the field of pressure algometry requires adaptation of safety measures since stimulation is applied to human beings. This design provides an additional safety level required in the field of computer-controlled pressure algometry but in principle its usage is not restricted just to this area. The fuse consists of four parts (inner cylinder, outer cylinder lid, outer cylinder guide, and the gauge screw) which are simple and cheap to manufacture, easy to reassemble once the fuse has been triggered, and gaugeable with commercially available tools. The prototype showed acceptable levels of performance given the intended usage of the stimulation setup, namely increasing and repeated musculoskeletal stimulation. Repeatable range of holding force has been attained for the particular application against a rubber mat surface mimicking musculoskeletal tissue (96% for forces $F < 20kg$, and 30% for forces $25kg < F \leq 35kg$).**

I. INTRODUCTION

Moving coil pressure algometer (MCPA) has been previously developed at the center for Sensory-Motor Interaction (SMI), Aalborg University Denmark, and its basic performance described in [1]. The system nominally consists of the pressure application device, controller, user interface, and a pain rating scale. Depending on the intended research aims such as investigations behind peripheral and central pain mechanisms, and depending on the modes of operation of the algometer (position, velocity, force), different levels of safety standards should be considered. The combination of high maximum force (over 50 kg) and seemingly low duty cycle (40 %) would result in average pressure stimulation up to $20kg$. Such level of stimulation could be relevant in above mentioned studies and reasonably sustained by humans. However, unpredictable surge of power or any unexpected disturbance in control could drive the actuator to exert maximum force in a fraction of a second causing harmful injuries. It is therefore of pivotal importance to implement proper precautionary standards which guarantee safe usage and performance of powerful moving coil pressure algometers.

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Safety standards for computer-controlled algometers based on different drive technologies (pneumatic [2, 3], electromechanical [4, 5, 6, 7, 8, 9]) have been previously developed at various research institutions. Under normal circumstances these devices offer to the test subject an option to press the button which stops the actuator from exerting the force, subsequently marking the pressure-pain threshold (PPT) or the pressure pain tolerance limit (PPTo). In addition, the safety system usually includes an emergency stop button that controls supply current powering the electromechanical system or the air solenoid operation in case of the pneumatic system. Emergency stop button is often placed within the reach of the administrator of the experiment. Some systems, including the MCPA algometer, include load-cell triggered power-off relay which can either cut the power to the system or instruct piston retract command once undesired pressure force has been detected (overload protection).

In this study, a mechanical fuse for MCPA algometer has been designed, built, and its performance evaluated in order to ensure operability and usefulness of such device in musculoskeletal pain studies. The mechanical fuse neither relies on electrical signals that monitor performance of the stimulation system nor human reaction time to prevent undesired outcomes; its performance rather depends on physical aspects of the design such as geometry of the fuse and material properties that it is made up of.

The purpose of the present study is to demonstrate how consistent in providing the safety standard the mechanical fuse for potent algometer is, when it comes to single and repeated stimulation paradigms. Mechanical fuse used for both stimulation schemes was tested against the rubber mat and metal surface of the force plate.

II. METHODS

A. The Mechanical Fuse

This mechanical device is meant to serve as a safety precaution in situations where linear force starts to exceed a gauged, maximally allowable value. It acts as a mechanical fuse, thus exclusively relying on principles of friction between two selected materials to trigger the onset of slippage. Fig. 1 shows parts of the pressure algometry mechanical fuse; going from left to right and top to bottom the following can be seen: gauge screw, outer cylinder lid, inner cylinder, and outer cylinder guide. The prototype of the device can be gauged via specifically designed mechanical (physical) method, where torque applied on the gauge screw makes the screw push on the inner cylinder of the fuse until the moment slippage occurs. Once the slippage condition is met, i.e. certain linear force reached, the inner cylinder starts traveling

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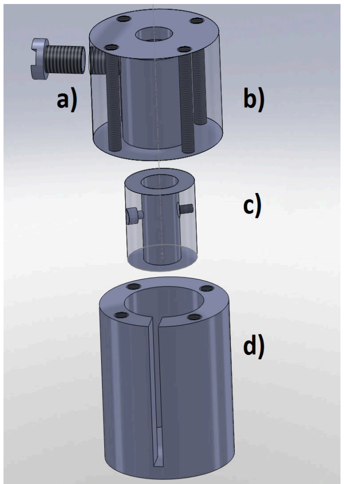

Fig. 1. Mechanical fuse for potent algometer, exploded view, top to bottom: a) gauge screw, b) outer cylinder lid, c) inner cylinder, and d) outer cylinder guide

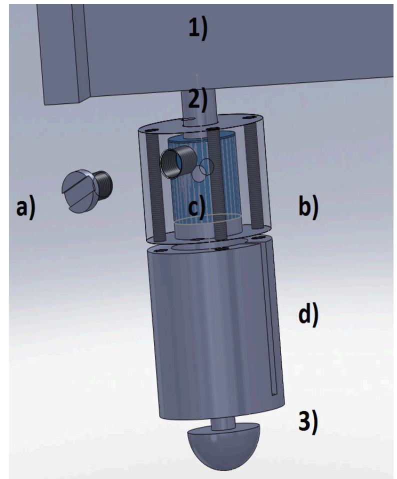

Fig. 2. Assembled view of the mechanical fuse in pressure algometry application. The fuse parts are labeled with letters as in Fig. 1., whereas parts external to it are numbered: 1) actuator, 2) piston, and 3) application probe.

through the outer cylinder guide consequently stopping the transmission of the linear force at the reaction point (probe-tissue contact site).

Fig. 2 shows the assembled design, where the fuse is used in practice (pressure algometry). The inner cylinder is connected to the piston of the actuator with a bolt. The outer cylinder lid covers the inner cylinder (color coded in blue) as in Fig. 2. The outer cylinder lid and the outer cylinder guide are joined via four additional screws. Finally, the gauge screw is tightened with a high precision torque tool to a certain magnitude. The pressure that the flat surface of the gauge screw exerts on the inner cylinder is what holds the fuse in check. Admittedly, the fineness of the gauge screw and the outer cylinder lid threads, size of the screw, as well as the material properties of the all three components (excluding the outer cylinder guide) should influence the behavior of the fuse. Exerted force is directly related to the torque that the gauge screw was previously tightened to and can be estimated as

$$F = \frac{T}{r}\frac{2\pi r - \mu p}{2\pi r \mu + p} \tag{1}$$

where p represents the pitch distance or lead of thread in one turn in m, r is the pitch radius of a screw in m, T is the applied torque at the head of the screw in Nm, and μ is the coefficient of friction (dimensionless quantity). Eq. 1 takes friction into account and assumes that the loading force is applied in the opposite direction relative to the screw jack [10]. Fine calibration instrument is needed to tighten the gauge screw to the specific torque which vouches for the related slippage condition (maximum allowable linear force transfer). Adjustable torque wrench (Syntace Torque Tool $1-20Nm$) was used for the gauging purpose. Torque value of $1Nm$ showed satisfactory performance in this particular application, yielding estimated lateral force of $269.5N$ ($27.5kg$) that is applied to the inner cylinder surface ($r = 0.005m$, $p = 0.001m$, $\mu_{steel} = 0.7$). During operation, the entire structure is translating in space at the same time since it is rigidly connected to the actuator's piston. The stroke length of the piston (distance measuring how far out the piston can get outside of the actuator's housing) determines the length of the outer cylinder guide, which acts a buffer zone when the fuse is triggered. If there is a reaction force at the bottom of the structure, the inner cylinder will be held in place by the gauge screw up to a certain force (approximately $27.5kg$) and moment in time, when the piston all together with the inner cylinder will start traveling past the outer cylinder lid and into the outer cylinder guide. At that moment, linear force of the actuator is no longer transferred at the reaction point (bottom of the fuse), even though the piston may still be exerting large force.

B. Force Assessment

Data was recorded with a 6-axis force and torque sensor (MC3A 250, AMTI Technologies, MA, USA). The rated load cell capacity is $1100N$ in the F_z direction with the output sensitivity of $0.66476\mu V/V_{exc} \times N$. The AMTI MSA-6 instrument is a six channel strain gage amplifier specifically tailored for use with AMTI force/torque equipment. The amplifier was used to filter and enlarge the signal before acquisition. The F_z voltage output was sampled at $1000Hz$ frequency via NI-DAQmx™ data acquisition board connected to the personal computer running Windows 7 operating system.

C. Protocol

The AMTI 250 force sensor was fastened onto a plain surface just below the piston of the actuator, which was mounted vertically on the support frame. The mechanical fuse was attached to the end of the piston and gauged to $1Nm$ of calibration torque. Modular connection interface at the lower end of the mechanical fuse allowed for easy mounting of different probes. Flat probe having a surface area of $1cm^2$ was selected due to its standardized usage in the field of pain studies. The measurements were recorded approximately half way of the actuator's stroke (i.e. piston's position = $250mm$). The force sensor was zeroed prior to each data acquisition procedure.

Paradigms tested during this experiment were chosen due to their relevance to normal usage of the stimulation setup in the pain research studies. Namely increasing stimulation, pulse stimulation, and repeated stimulation are methods often employed to elicit peripheral and central sensitization in the neuromuscular structures.

First portion of the experiment aimed to evaluate consistency of five different pressure force application rates ($0.1kg/s$, $0.2kg/s$, $0.3kg/s$, $0.4kg/s$, and $0.5kg/s$) against a rubber mat ($\rho_{rubber} = 187kg/m^3$) that was placed in between the probe and the sensor, as well as with no medium inserted (i.e. direct probe-to-sensor contact). Even though the muscular density ($\rho_{muscle} = 1059kg/m^3$ [11]) is not the same as for the rubber material used, the stiffness property of the rubber approximately mimics muscular tissue properties under compression. Thirty consecutive measurements were taken for each of the five pressure application rates, where approximately ten seconds break was taken between each data collection sweep. Force gradient was programmed to stop at $25kg$ of pressure force and mechanical fuse was regauged to $1Nm$ every thirtieth time i.e. after each force gradient was finished.

Second part of the experiment aimed to assess holding repeatability of the fuse during pulse stimulation. Algometer was instructed to deliver a burst of force against a force plate. Fifty measurements against the rubber mat previously mentioned as well as no medium inserted were taken for each of the following magnitudes: 15, 20, 25, 30, and $35kg$. Mechanical fuse was regauged to $1Nm$ after each pulse.

Last portion of this study assessed ability of the mechanical fuse to sustain repeated stimulation of a known pulse duration and magnitude. Initially, the MCPA was programmed in force mode to deliver a pulse train of 10 repetitions of the same magnitude where each pulse lasted $500ms$. Time between the ending of the previously delivered pulse and the beginning of the next one was held constant throughout the experiment ($100ms$). Measurements were taken for three different magnitude trains ($5kg$, $10kg$, and $15kg$), where each pulse train was repeated 20 times, and fuse regauged to $1Nm$ after each twentieth time i.e after 200 consecutive pulses at the specific magnitude. Lastly, the procedure was repeated against a rubber mat.

III. RESULTS

Mechanical fuse was able to hold each one of the thirty trials across all five force gradients applied by the actuator without breaking or being regauged, both for rubber mat and no medium inserted. The increasing stimulation paradigm and the transfer of the linear force through the mechanical fuse onto the force plate showed no signs of slippage in the

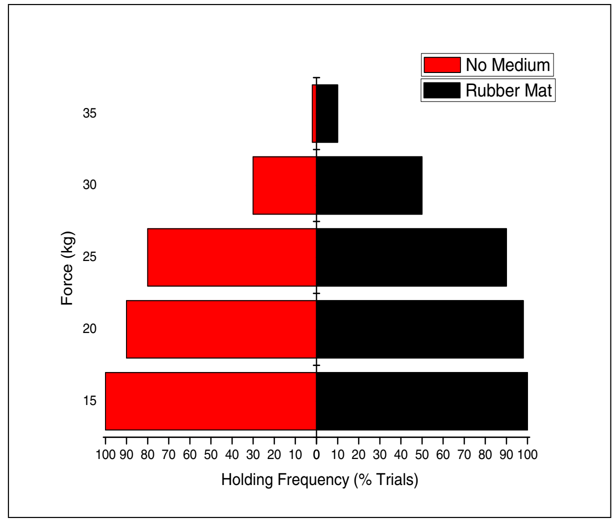

Fig. 3. Mechanical fuse holding frequency distribution for no medium and rubber mat ($\rho_{rubber} = 187kg/m^3$) out of 50 trials for each of the five force pulse amplitudes

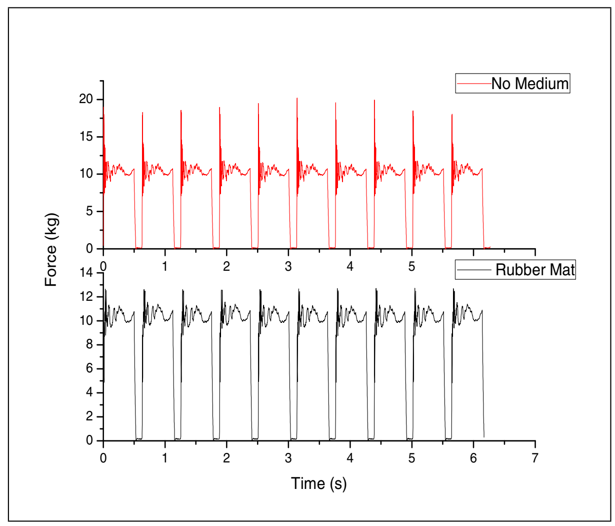

Fig. 4. Transfer of $10kg$ force through the mechanical fuse onto the force plate

intended usage range of the algometer (up to $20kg$). Glitches in performance were observed for forces $F \geq 20kg$.

Fig. 3 shows behavior of the mechanical fuse exhibited against the rubber and no medium inserted during force burst paradigm. The distribution is right skewed for both the rubber mat and no medium inserted between the probe and the sensor.

Pulse train stimulation yielded no breaking of the fuse at the $5kg$, $10kg$, and $15kg$ magnitudes. An example of the repeated stimulation scheme is presented in Fig. 4. As in the single pulse scheme of the study, repeated scheme showed less overshoot for the rubber mat case due to absorbtion of the energy during impact (21% versus 74% for the $10kg$ scheme). The percentage overshoot was defined as the ratio of the first peak minus the mean value of the rest of the pulse divided by the mean value of the rest of the pulse, averaged across ten pulses.

IV. Discussion

Increasing stimulation poses no threat to the subject in the sense that it is a relatively slow and predictable process to which both the subject and administrator of the experiment should be able to react to. The fuse shows consistency in holding the inner cylinder via gauge screw in the stable position across all five force application gradients. However at larger forces, beyond the intended usage range of the algometer ($F \geq 20kg$) mechanical fuse exhibits signs of slight slippage. Nonetheless this glitch does not put in jeopardy the overall performance of the MCPA as the fuse is capable to continue the transfer of the linear force without being regauged.

Second part of the experiment represents an extreme type of mechanical stimulation of the musculoskeletal tissue and therefore is less likely to occur. It however stresses the fuse and offers insights into behavior of such a device in extraordinary situations such as power surge where large forces are likely to occur. Rubber mat case shows more difficulties to activate the fuse as more kinetic energy is absorbed during the shock, thus dampening the force impact. Positive (right) skewness of the data set demonstrates that bulk holding behavior of the fuse is concentrated in the force range $\leq 25kg$ (90% no medium, 96% rubber mat). Forces larger than $25kg$ and less than or equal to $35kg$ are less likely to hold (16% no medium, 30% rubber mat), which was the intention of the design.

Repeated stimulation paradigm showed consistency in fuse operation in the sense that no slippage or breaking occurred. Forces of $5kg$, $10kg$, and $15kg$ present likely scenarios of the repeated stimulation paradigm, during which delivery of the concurrent stimuli is expected. High repeated force application scenarios such as $15kg$ and stronger were not examined since these are less likely to be practiced in the laboratories during human pain studies. Delivering a number of strong repeated stimulations gives both the user and the administrator of the experiment enough time to react in the accidental event.

V. Conclusions

Computer-controlled pressure algometry aims to assess tenderness of musculoskeletal tissue through pressure (force) application. These devices are computer-controlled and seemingly offer good controllability and reliability. However, some of the more potent actuators (used as MCP algometers) can exert high levels of pressure force. In the unexpected event where these devices could go out of control (power surge, bad coding, faulty connections) and produce higher than expected magnitudes, serious damages and/or injuries could result. A mechanical fuse such as described in this study can help to prevent any consequences of such events by absorbing the unpredictable force impact. It does not rely on any electrical signals such as feedback from the load cell or human reaction. It rather relies on the frictional (mechanical) properties of the materials that make up the mechanical fuse, as well as on the geometry (physical aspects) of the device. The mechanical fuse showed acceptable levels of performance given the research goals of the laboratory such as safe and strong musculoskeletal tissue stimulation where increasing and repeated paradigms are used to elicit peripheral and central neuronal response.

VI. Perspective

Different performance may be observed for the future mechanical fuse devices of the same geometry, materials, manufacturing process, as well as gauging equipment. Fine and high quality calibration devices could be used to gauge the system to a particular safety level in terms of maximal allowable pressure force. In addition to performance tests further research is suggested using final element modeling (FEM) to grasp the relation between stresses and geometry for instance, so that performance repeatability can be achieved and operating principle better understood in the future mechanical fuse devices. This should result in understanding how to produce devices that behave consistently within and between themselves.

Finally, the mechanical fuse is generic by nature in the sense that it can stop transferring the linear force once the slippage condition is reached, and this principle of operation could be useful in many applications outside of computer-controlled pressure algometry.

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