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Moving Coil Pressure Algometer Produces Consistent Force Gradient and Repeated Stimulation

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***Abstract*— Computer-controlled pressure stimulation (algometry) offers seemingly good reliability when it comes to pain assessment methods. It is therefore important to ensure through methodological quantification that moving coil pressure algometer (MCPA) exhibits accurate, fast, and precise tissue stimulation techniques. This study 1) demonstrates that MCPA satisfies force gradient capabilities of a conventional computer-controlled algometry, and 2) reports on effectiveness of the MCPA to produce sustained, fast, and repeated stimulation of a known pulse duration ($600ms$) and force magnitude ($10kg$). Solicited force gradients of 500, 1000, and $1800g/s$ showed high correlation values ($R^2 > 0.99$) for both rubber mat and direct probe-to-sensor contact cases. Through fast switching between different modes of operation of the actuator, force overshoot was reduced from as much as 300 to 20% for the same force magnitude, at the expense of a slight delay in repeated pulse delivery scheme.**

I. INTRODUCTION

Different laboratories for experimental pain research as well as clinical institutions have been conducting extensive studies in single point pressure tissue stimulation in order to understand physiological mechanisms, such as peripheral sensitization and central sensitization, responsible for acute and chronic pain disorders respectively [1]. The experimental setup that is used to asses pressure-pain detection (PPT) and pressure-pain tolerance thresholds (PPTo) in algometry nominally consists of an actuating mechanism that applies pressure, computer-controlled monitoring and driving system, and pain rating scale.

Computer-controlled algometers based on various technologies have been developed, tested, and used in the recent past for the purpose of pain assessment: Pneumatic [2], hand-held [3], and tourniquet cuff ones [4]. One such electromechanically driven algometer (Fig. 1) has been previously built at the Center for Sensory-Motor Interaction (SMI), Aalborg University, and practiced in several pressure-pain sensitization studies [5, 6, 7, 8]. It is of critical importance to test and evaluate operability of these medical devices in order to ensure collection of reliable data. This ultimately generates improved pain assessment techniques and allows for cross-correlation of data that are sampled from a number of different point pressure algometers.

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Fig. 1. An example of the pressure stimulation setup: Gearbox of a DC actuator and the pressure application piston with a stimulation probe attached at its tip

The new generation of electromechanically driven pressure algometer that has been developed at SMI, is expected to increase accuracy and usefulness of these devices for research purposes. The main advantage of MCPA over previously mentioned computer-controlled algometers lies in high controllability of this device through instantaneous switching among three different modes of operation namely position mode (PM), velocity mode (VM), and force mode (FM). The outcome of the present study aims to **1)** demonstrate how consistently the MCPA meets the requirements of gradually applying force gradient against different contact surfaces, and **2)** report on MCPA'a ability to produce a consistent pressure stimulation pulse train of a known magnitude and duration. Consistency of feature **1)** is of pivotal importance in obtaining PPT and PPTo thresholds used as a mechanical pain assessment techniques, while repeatability of feature **2)** plays crucial role in understanding mechanisms behind central nervous system sensitization in pain physiology.

II. METHODS

A. Algometer

The basis of the pressure algometer developed at the Center for Sensory-Motor Interaction is the moving coil electromechanical actuator produced by SMAC, California. The device is capable of delivering $20kg$ of sustained pressure force for an extended period of time (hours). The unit contains actuating piston which leaves magnetic housing and

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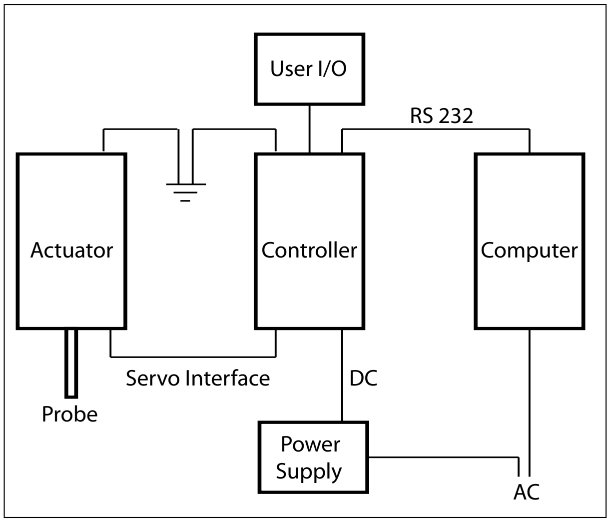

Fig. 2. MCPA's Schematic

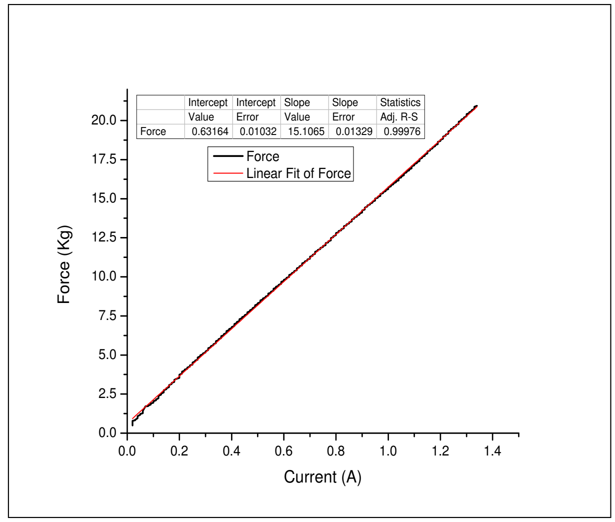

Fig. 3. MCPA's Force vs. Current relation: The force constant of $15.106kg/A$ and a 10 bit A/D converter offer $55g$ of force resolution

retracts into it depending on the direction of the current that is passed through its coils. The novel algometer is controlled by manufacturer's controller unit termed LAC25, which in turn is programmed via assembly type mnemonic code through RS232 serial communication standard (Fig. 2).

User I/O interface includes visual analogue scale (VAS) as a perceived pain sensation rating means, PPT and PPTo buttons, and the emergency shutdown switch. The MCPA is energized via $48V$ power supply and can draw up to $4A$ of current. This current draw amounts to the peak pressure force of $55kg$ controllable within $55g$ increments (0.1% of the maximum force). Return spring prevents the shaft from dropping during vertical operation when power is cut and serves as a mechanical safety precaution. Fig. 3 demonstrates linear relationship between force applied and current drawn, where the slope of the line represents the force constant of the actuator.

Fast switching between three programmable modes of operation (position, velocity, and force) allows the actuator to perform at speeds faster than $1m/s$ or low speeds within five micron accuracy and repeatability. This makes it suitable for a wide range of positioning, measuring, inspection, and pick and place applications, especially where close to perfect verification is required. Such capabilities are of pivotal importance for reliable data collection during pressure-pain sensitization studies.

B. Force Assessment

Collection of force data was taken with a 3-axis force and torque sensor MC3A 250 produced by AMTI Technologies, MA, USA. The rated load cell capacity is $1100N$ ($250lbf$) 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 designed for use with AMTI multi-component force/torque sensors. It was used to filter and amplify the signal before sampling. The F_z voltage output was sampled at $1000Hz$ frequency via NI-DAQmx™ data acquisition board.

C. Protocol

The AMTI 250 force sensor was secured onto a flat surface just underneath the piston of the actuator, which was mounted vertically on the support frame. The measurements were taken approximately at the middle of the actuator's stroke (i.e. piston's distance traveled = $2.5cm$). The force sensor was zeroed prior to each data acquisition procedure. In ordered to ensure better piston-to-sensor adhesion and to reduce impact stress on the sensor, a specially designed square probe ($49cm^2$) was attached to the piston's end.

First portion of the experiment aimed to evaluate consistency of three different pressure application rates ($500g/s$, $1000g/s$, and $1800g/s$) 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). Although the muscle density ($\rho_{muscle} = 1059kg/m^3$ [9]) is different from that of the rubber material used, the stiffness property of the rubber approximately mimics muscular tissue behavior under compression.

Second portion of this study assessed effectiveness of the MCPA to produce sustained repeated stimulation of a known pulse duration and force magnitude in different modes of operation. Initially, the MCPA was programmed in PM and FM modes 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 six different magnitude trains ($3kg$, $5kg$, $8kg$, $10kg$, $13kg$, and $15kg$). Lastly, the novel algometer was programmed using all three modes (PM, VM, and FM, see below) to deliver $10kg$ of repetitive pressure force while soft landing on the sensor. Pulse duration and break between the pulses were as before, $500ms$ and $100ms$ respectively. One repetition cycle with a soft land routine contains the following steps:

1) position move (PM) at high speed and acceleration to a position close to the soft land position

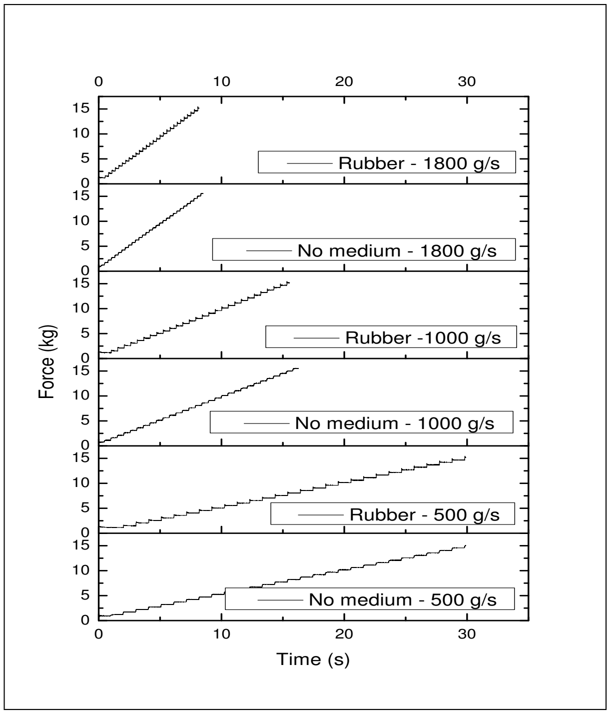

Fig. 4. Force gradients ($500g/s$, $1000g/s$, $1800g/s$) against rubber ($\rho_{rubber} = 187kg/m^3$), and no medium inserted

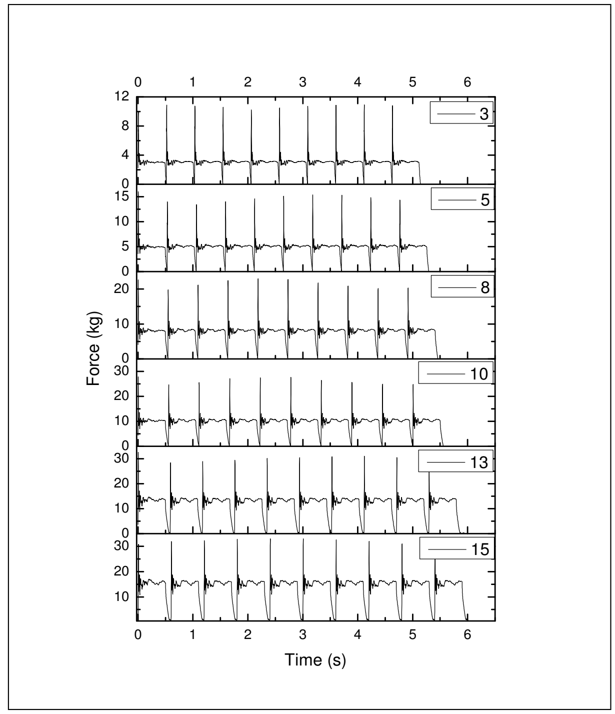

Fig. 5. Repeated stimulation scheme: 10-pulse train with each pulse lasting $500ms$ and inter-pulse time of $100ms$

2) velocity move (VM) at lower speed to land onto the stimulation site
3) check on position error to determine moment of collision
4) apply constant force in force mode (FM)
5) retract to the home position in position mode
6) reiterate process.

During step 2) of the soft land routine the maximum allowable force in the velocity mode was set to two different values in order to examine the overshoot characteristics of the initial impact before switching to the force mode.

III. Results

A. Force Gradient

Fig. 4 shows behavior of the force gradients exhibited against the rubber and no medium inserted. Linear regression on the data was used to quantify the performance of the algometer. Instructed gradient and the regression analysis slope, among other data, are outlined in Table I.

TABLE I
LINEAR REGRESSION OF THE FORCE GRADIENT

Condition	Gradient (g/s)	Slope (g/s)	Offset (g)	R-squared
Rubber	500	485.63	62.55	0.9956
Rubber	1000	966.94	67.56	0.9985
Rubber	1800	1781.62	72.26	0.9954
No medium	500	496.34	65.68	0.9987
No medium	1000	1005.27	70.65	0.9981
No medium	1800	1795.67	80.62	0.9912

B. Repeated Stimulation

Fig. 5 shows behavior of six different ($3kg$, $5kg$, $8kg$, $10kg$, $13kg$, and $15kg$) 10-pulse trains. Each pulse is $500ms$ long with quiescent interval of $100ms$. Note that while the overshoot increases with the increasing magnitude of the applied force, the percentage overshoot decreases. Mean force magnitudes of $13kg$ and $15kg$ not including overshoot were met within 91.4% and 90.6%, respectively. Others were met within $\pm 3\%$ of the solicited value. Table II contains descriptive statistics for each of the six force magnitudes, where the initial overshoot and interstimulus values were not included in the analysis. Finally, note the slight phase shift as intensity increases from $3kg$ to $15kg$ in Fig. 5.

Resulting graphs where soft land routine was engaged are contained in the Fig. 6. No soft land produced 300% overshoot, soft land 1 introduced a 100% overshoot, and soft land 2 resulted in a 20% overshoot with respect to the mean value.

IV. Discussion

Force gradient in a computer-controlled stimulation setup has pivotal importance during pressure-pain sensitivity quantification process. Accurate increasing force induction method offers more standardized collection of data. The three solicited force gradients showed high correlation values with the ones obtained through linear regression analysis ($R^2 > 0.99$) for both rubber mat and direct probe-to-sensor contact cases. The pressure force gets adequately transferred in the direction of applied force since rubber material mimicking musculoskeletal tissue is well capable of absorbing impact

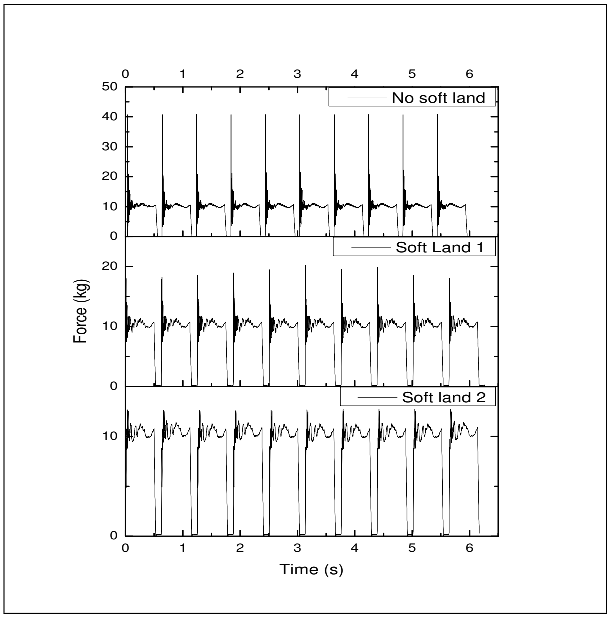

Fig. 6. Repeated Stimulation with soft land feature for $10kg$ pressure force intensity

while nonlinearly deforming only in the initial stage of interaction.

Strong and repetitive stimulation is an important tissue incitement technique when it comes to studying and eliciting central sensitization response in neuromuscular structures. Whilst presented 10-pulse train stimulation demonstrates strength and repeatability during combined position and force modes of operation, it also exposes lack of accuracy. This is manifested in the large initial force overshoot (over 300% in some cases) and in the 91% reached mean force level relative to the projected one for $13kg$ and $15kg$ cases. Percentage overshoot decreases with increasing magnitude of the applied force since for the same set maximum allowable velocity in the PM, the algometer needs to produce higher stimulation force. Therefore it becomes more difficult to move to and away from the stimulation site prior and right after more intense stimulation is applied. Additionally, this phenomenon explains the shift from square to trapezoidal pulse behavior, resulting in slightly longer overall duration of the 10-pulse train as the stimulation increases from $3kg$ to $15kg$.

Force intensity overshoot can be reduced at the expense of pulse duration or the time that elapses between the end of the previous and the beginning of the next pulse i.e. approaching stimulation site at lower velocities. Given that neither of the two methods for surpassing overshoot during repeated stimulation process is desirable in pressure-pain assessment studies, it is suggested to address the issue by engaging all three modes of operation during the soft land routine on the object. The difference between soft land 1 and soft land 2 is in the maximum allowable force parameter that is used in step 2 of the previously described soft land routine. The impact energy is therefore reduced due to the decrease in inertia, which ultimately results in lower overshoot values.

TABLE II

DESCRIPTIVE STATISTICS OF REPEATED STIMULATION IN PM AND FM MODES OF OPERATION

Force (kg)	Mean	STD	Overshoot	% Overshoot
3	3.085	0.211	10.913	253.74
5	4.960	0.223	16.023	223.04
8	7.771	0.251	22.967	195.55
10	9.667	0.282	27.872	188.32
13	11.88	0.788	32.626	174.63
15	13.587	0.809	32.982	142.75

V. CONCLUSIONS

Focal point of the moving coil pressure algometer is an accurate, fast, and strong actuator that can be adequately employed in pressure-pain assessment studies where increasing as well as repetitive stimulation is necessary method to evoke neuronal response. This is owing to the high controllability of the MCPA through flexible switching among different modes of operation namely position, velocity, and force mode. Consistency in force gradient application was showed for rubber and direct contact interface between the novel algometer and the stimulation site. Integration of all three modes of operation is needed to reduce the overshoot of the impact during repeated stimulation process. The force gradient feature of the MCPA is useful in quantifying pressure-pain threshold and tolerance limits whereas fast, accurate, and strong repetitive stimulation is crucial in obtaining deeper understanding of physiological mechanisms underlying central sensitization.

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