MICROPROCESSOR CONTROLLED ROBOTIC EXERCISE MACHINE FOR ATHLETICS AND REHABILITATION

Wayne Book and David Ruis
School of Mechanical Engineering
Georgia Institute of Technology, Atlanta, GA
and
Russell Polhemus, President
Optimal Athletics, Inc., Atlanta, GA

Abstract

The need for an improved resistance training exercise machine is documented and the microcomputer controlled Robotic Exercise Machine is proposed as the answer to that need. A description of the mechanical and electrical hardware and the control software is given. The control algorithms which provide for path and force teaching and velocity command generation are discussed. The safety features of the machine are explained.

INTRODUCTION

Current technology is finding increasing application in leisure and medical endeavors. Popular concern with physical conditioning has led to new products and services on the market. Microprocessor controlled devices have not yet capitalized on this market, although other consumer oriented applications indicate ready public acceptance. The Robotic Exercise Machine (patent pending) is a computerized resistance training machine which uses microprocessor technology to overcome a number of shortcomings of conventional resistance exercise machines. Rehabilitation, unlike other areas of medicine, is technologically underdeveloped. Here too, the Robotic Exercise Machine makes important contributions to the needs described below.

THE NEED FOR AN IMPROVED EXERCISE MACHINE

Muscular strength is most rapidly developed by using various types of devices and machines which provide forces to resist movement by the user. In order to attain a rate of increase of strength and a level of strength greater than those attainable through participation in most sports and other athletic activities, relatively high resisting forces must be used. The most common available means for obtaining high-resistance exercise are the pulley-weight machine, the barbell, spring-action devices, and frictional devices, of both mechanical and fluid type.

The highest levels of muscular size and strength are attained through high-resistance exercise of short duration, involving only a few muscle groups at any one time. Complete isolation of individual muscles or muscle groups during exercise tends to produce the highest rate of increase in muscular strength [1,2,3]. Exercise in which the user-exerted force is in a direction opposite to the direction of movement, called "negative exercise," is especially effective in development of strength. It is most effective when used in combination with "positive exercise," in which the user-exerted force and the movement are in the same direction [4,5,6]. Exercise against light resistance has relatively little effect on muscular strength, but, if sustained for sufficiently long periods of time, it is most effective in increasing muscular endurance.

The amount of force that can be exerted by the arms or legs is highly dependent on their position and angular orientation. It depends both on the direction in which force is being exerted and on the angles of the joints. In order to obtain maximum muscular strength throughout the full range of movement, the resisting forces of an exercise must vary according to the individual's strength potential at any given position along the path of motion [7,8]. Only a few very expensive machines provide for this kind of variable resistance, and these machines do not provide for variation of the fundamental relationship between resistance and position. Thus, they do not conform to the individual user's strength-potential curve but only to that of some "average" user. Exercise in which the resisting force does not conform to the user's particular strength-potential curve results in lower development of strength over certain segments of a path of motion as compared to that over other segments. Exercising a muscle in one position only is not effective in increasing strength at other positions [9,10].

In order to achieve maximum rates of strength increase, muscles must be exercised independently, and with high intensity [11,12]. In order to maximize strength increases throughout a movement required in some athletic event, or, to be more specific, to maximize the integral of strength with respect to displacement along this path of motion, a high-resistance exercise must be used, and the path of motion must be very similar to that of the movement required in the event [13]. The above facts suggest that there is a need for a machine which provides for variation of paths of exercise motion as well as resisting force. This unique capability is among the most important objectives of the invention described in this paper.

There is a definite need for greatly improved exercise machines in the medical field of physical rehabilitation [8,14]. The same principles of muscular strength development apply to victims of accident or disease as to athletes. But rehabilitation patients are in even greater need for highly individualized and carefully regulated exercise. In rehabilitation, the objectives are to achieve the greatest possible increases in muscular strength, in specific muscles and movements, in the shortest possible time. In cases involving nerve damage or paralysis a further objective of exercise therapy is the development of nerve pathways to the affected muscles. Recent studies have shown that exercise machines which are capable of actively moving a paralysis patient's arms or legs in a cyclic motion can be of great benefit in partially restoring nerve function [15,16].

Exercise equipment for rehabilitation is at about the same state of advancement as athletic equipment. In fact, standard athletics-oriented machines are often used in rehabilitation clinics. In the cases where specialized machines have been built, their effectiveness is highly limited, largely due to the fact that they are suitable for only one very specific exercise.

The complaints about present exercise machines from hospitals and clinics with rehabilitation facilities and from doctors who specialize in this field are numerous and significant. One common problem is that most machines use weights to provide the resisting force. The inertia of the weights allows the patient to throw or jerk the device in order to avoid exercising through regions of extreme weakness, precisely the regions where exercise is most needed. Other problems mentioned are lack of fine enough variation of resisting force, lack of adaptation to the patient's size, no allowance for the adjustment of the variation of resisting force with position, and general lack of adaptability of the individual patient's specific needs.

The Robotic Exercise Machine under development is designed to overcome the limitations of conventional exercise machines with new resistance laws and exercise modes.

ROBOTIC EXERCISE MACHINE - CONCEPT

The Robotic Exercise Machine was designed to satisfy needs discussed above. The machine objectives are to:

1) Provide for constrained paths of motion which are variable and readily programmed to the individual's needs.
2) Provide new resistance laws for resistance training which are noninertial and also provide for positive and negative exercise.
3) Provide for varying resistance characteristics over the path of an exercise motion and between repetitions of the motions, the variation being adaptable to each user's strength potential at the various points on the path.
4) Provide for measurement of user performance for instantaneous feedback to the user and for later analysis of his progress.

In order to achieve these objectives a radical departure from the passive, fixed motion conventional exercise machine was necessary. The Robotic Exercise Machine is hydraulically powered and servo controlled in two degrees of freedom and is shown in Fig. 1. The measurements of force, position, and velocity are used by the microcomputer to command the two electro-hydraulic servo valves. Thus, an arbitrary path of motion of the bar can be "taught" to the machine along with the user's strength potential along that path. This data can then be used to control the bar's response to forces in an exercise session.

An exercise session with this machine might follow this scenario: A new user with specific exercise needs for rehabilitation, strength or endurance gains logs on to the computer. The machine calibrates its own force transducers and gives the user the go ahead. The user leads the end attachment of the machine--say a conventional bar--to the beginning of the exercise path. The bar behaves in a weightless manner during the motion. The user requests the teaching of a new exercise path, arm curls for example. The path of motion then followed is stored by the computer. After completing the path the user signals the machine which returns the bar to the beginning of the path. The path is now retraced at a slow constant speed with the user applying maximum force. The force component tangent to the path indicates the user's strength potential and is stored in a form to allow variation of the resistance parameters in the exercise session which follows. The path and force data are saved for use in later exercise sessions and to allow evaluation of progress.

The same user returns two days later. The exercise file is recalled. He may repeat the exercise, measure his strength increase, or evaluate the severity of an injury sustained in the intervening period.

THE ROBOTIC EXERCISE MACHINE - HARDWARE DESCRIPTION

Mechanical Description. A large portion of the skeletal muscle exercises require motions in a plane. Popular names of these exercises include: Bench Press, Squat, Power Clean, Dead Lifts, Military Press, Snatches, Clean and Jerks, Arm Curls, Leg Curls and Leg Extensions. The prototype Robotic Exercise Machine was designed to move the "bar" grasped by the user in a plane in response to user applied forces in that plane.

To obtain the motion, two identical hydraulic motors power the bar in a rectilinear motion as shown in Fig. 1. The horizontal range of motion is about 1.2 m (4 ft) while the vertical range of motion is about 1.7 m (5½ ft) for the prototype machine. The hydraulic motors move the carriages by means of a redundant chain drive at velocities up to 1.2 m/sec (4 ft/sec) and with forces up to 3000 N (700 lb_f). The hydraulic fluid flow is controlled by two stage electrohydraulic servo values. Hydraulic fluid is provided by an electrically driven power supply supplemented with a large 15 ℓ (4 gal.) hydraulic accumulator and gas bottle 15 ℓ (4 gal.) for peak demands. System pressure will normally vary between the accumulator precharge of 5171 kPa (750 psi) and the maximum pressure of 10,340 kPa (1500 psi).

Hydraulic power was chosen because of the high forces and rapid response (high bandwidth) needed. The rectilinear motion provides essentially independent motion state variables in the two directions which simplifies control computation and coordinate transformations. The rectilinear motion also resulted in a smaller hydraulic power supply than alternative revolute joints for the range of forces and velocities that were envisioned. The linear motion is guided by tracked rollers.

Electronic and Electrical Description. A Texas Instruments 990/4 16 bit word Microcomputer with 12 K words of RAM is used to monitor general operation in two modes and to servo the bar in response to its position and velocity and user exerted forces. (See Software Description.)

Position measurement is provided by conductive plastic potentiometers and velocity measurement is provided by d.c. tachometer-generators. Force transducers are provided at the bar attachment to measure two components of the user applied force. These transducers are integrated circuit pressure transducers which measure the pressure inside a metal bellows created by the user applied force. The range of the force measurements can be varied by changing support springs in the bar mounts. This somewhat unconventional measurement technique is used to provide high level output (2-12 V) directly from the transducer in order to minimize electrical noise problems and eliminate amplifiers.

All measurements are converted to two's complement binary by a multiplexed 12 bit analog to digital converter at a rate of 55 μs per point. Thus, all six measured variables can be read in a time of 0.33 ms. Samples are repeated every 2.5 ms (400 Hz). The resulting digitization of the exercise space gives a correspondence of 1 bit = 0.397 mm (1/64 in). The velocity discretization is 0.595 mm/sec (.00195 ft/sec). The force correspondence depends on the spring constants in the transducer mount.

Since motivation is most important in training and rehabilitation, the user's force is displayed to him via two, three digit 1.27 cm (1/2 in) high displays. These displays are situated to provide the user feedback on his force component tangent to the path of motion at all times.

The digitized data is read by the Texas Instruments 990/4 Microcomputer for processing, as described in a later section. The results of the computation is a direct command to the hydraulic servo valves. The valve command is converted to an analog voltage by 12 bit digital to analog converters and integral sample hold, then amplified to the appropriate power levels. The force display value is also calculated by the microcomputer. The Texas Instruments computer facilitates interfacing by using a Communications Register Unit (CPU) which is used in this application.

User safety is given highest priority in the Robotic Exercise Machine. Solenoid operated shutoff valves (normally closed) will stop the exercise bar upon malfunction. Malfunctions may be detected in several ways. Computer software can constantly cross check the incoming data for consistency, for example between velocity and rate of change of position. These checks are detailed in the software description. A "watchdog" timer independent of the computer must be reset by the computer every 10 ms or it will close the shutoff valves. Finally, a hand held switch is provided for spotter use should he observe any user difficulty.

THE ROBOTIC EXERCISE MACHINE - SOFTWARE DESCRIPTION

System Overview.

In order to carry out the objectives of the Robotic Exercise Machine, the system software must not only provide for the exercise session itself, but it must provide for collecting data on the user's physiology (exercise trajectory and strength potential curve) and must allow for selection of the exercise parameters. As an additional convenience the system provides for storage and retrieval of files containing the exercise data and parameters.

The machine operates in two basic modes: the Command Mode, and the Servo Mode. In the Servo Mode a proportional plus integral (PI) direct digital control (DDC) algorithm receives its set point from one of the six supervisors enclosed in broken lines in Fig. 2. In the Command Mode the bar has been safely stopped and the clock interrupts have been disabled. In this mode exercise parameters can be changed, files can be saved or retrieved and the teach functions and exercise functions can be initiated. Transition from the Command Mode to the Servo Mode is achieved by a command to begin the teaching process (Teach command) in preparation for exercise, or to begin exercise using data retrieved from an exercise file (Exercise command). Other commands for file management, parameter printout and modification, force plotting and others do not effect a change in modes. These features are important but are not the topic of this paper. To leave the Servo Mode one must issue a Quit command which generates a keyboard interrupt which is serviced only under appropriate safe conditions.

After entering the Servo Mode via the Teach command one would normally progress through five supervisors. MMSPV allows the bar to be led with minimal resistance to the path starting point. After the bar is stopped PTSPV then commands minimal resistance motion and sampling of position to save the exercise path (path teaching). On completion of path teaching RTSPV returns the bar to the path beginning by reversing the motion just completed. FTSPV then moves the bar at a constant speed along the path and stores the force data. Here the user applies maximum force to determine his strength potential curve. RTSPV again returns the bar to the path starting point but this time branches to EXSPV for the exercise session. During the exercise session the bar is servoed to move only along the exercise path with a velocity determined from the tangential force, the resistance law, the exercise parameters, and the position along the path.

If instead path and force data has been recalled from stored files the Exercise command is used. IPSPV initializes bar position and other parameters according to that file and branches to EXSPV for the exercise session.

Much of the calculation is not carried out in the supervisor routines proper, but in various subroutines and service routines for efficiency. Only a few of these are illustrated in Fig. 2. SERVO and KBINT are interrupt service routines as previously mentioned. INIT provides machine initialization including transducer calibration via OFFSET. TRPFT provides much of the arithmetic calculation including location of the desired point on the path, calculation of a position error correction, and resolution of the user applied force into the component tangent to the path. NPNS is a subroutine which provides one of the resistance laws to be implemented.

Path and Force Teaching Methods. A number of methods of storing paths for computer controlled machines such as machine tools and robots are found in the literature [17,18]. The method programmed for the Robotic Exercise Machine is efficient with respect to computation and programming time with some penalty in terms of memory and accuracy. It seems to serve this particular application well.

The path is stored as a series of integer coordinate pairs (x_i,y_i) where the distance between successive points is ideally fixed at 1.27 cm (1/2 in). This distance is equivalent to 32 position units or 2^5. Depending on the integer values of (x_i,y_i) and (x_{i+1},y_{i+1}) a considerable error may arise due to finite word size if points actually read are used. This is critical as a fixed distance is assumed in later sine and cosine calculations. This problem is greatly alleviated by allowing the coordinates to vary up or down by one least significant bit from that point actually measured. The pair (x_i,y_i) which minimizes the deviation from the assumed fixed distance from the preceding point is stored. The resulting position variation of the point of .04 cm (1/64 in) is insignificant.

During force teaching a tangential force value is associated with each (x_i,y_i) pair. This value is obtained by averaging with double precision the tangential force measured over the preceding 1.27 cm segment. The force is sampled at 400 Hz.

Desired Position Location and Position Error Correction. Because of disturbances normal to the exercise path and the curvature of the path itself, it is necessary to correct the position of the end point to return it to the path. It is desired that these corrections be perpendicular to the path. Motion tangent to the path is regulated by the resistance law of the exercise, the parameters of which vary along the path. To correct the position the desired point on the path must be located.

First the appropriate path segment must be determined. (See Fig. 3.)

1. The path has been divided into segments S_i of constant length L from (x_i,y_i) to (x_{i+1},y_{i+1}) by path teaching.
2. Define neighborhood N_i as the area between perpendiculars to S_i constructed at each end of S_i. Overlaps and interstices between neighborhoods will exist as shown. Define (x_i,y_i) as the basepoint of N_i.
3. Assume that at sample t the bar is at (x_t,y_t) in N_i.
4. The desired position preserves the distance a_t parallel to S_i, where a_t is calculated from measured (x_t,y_t) and stored path coordinates

$$a_t = (x_t - x_i)\cos\theta + (y_t - y_i)\sin\theta$$

$$\cos\theta = \frac{x_{i+1} - x_i}{L}, \quad \sin\theta = \frac{y_{i+1} - y_i}{L}$$

5. If $a_t > L$ increment the basepoint. If $a_t < 0$ decrement the basepoint.
6. Repeat 4. and 5. until $0 < a_t < L$, but prohibit the immediate return to an old basepoint. Thus the interstice is treated as an extension of the next neighborhood.

The appropriate segment is thus determined. The desired position along the segment (or its extension should (x_t,y_t) be in an interstice) is the intersection of S_i and a perpendicular line through (x_t,y_t) as shown in Fig. 4. The resulting x and y components of position error E_x and E_y are used to generate x and y components of a position correction velocity command V_{ex} and V_{ey}, respectively:

$$V_{ex} = G_E E_x$$

$$V_{ex} = G_E[a_t \cos\theta + x_i - x_t]$$

$$V_{ey} = G_E E_y$$

$$V_{ey} = G_E[a_t \sin\theta + y_i - y_t]$$

where G_E is a constant. These velocity commands are added to the tangential velocity commands and issued to the PI controller.

Desired Tangential Velocity and the Resistance Law. The velocity of the bar tangent to the path V_a is related to the force applied through a resistance law. For a pure inertial resistance the velocity would be proportional to the integral of tangential force F_a over time:

$$V_a = \frac{1}{m}\int_{t_o}^{t} F_a d\tau$$

where $F_a = F_x \cos\theta + F_y \sin\theta$. A gravity force would add a constant to F_a. The disadvantages of inertial resistance laws were discussed early in this paper.

The Robotic Exercise Machine can simulate inertial or frictional resistance laws as well as other laws never previously used. One such resistance law with promise is the Noninertial, Positive-Negative Speed Limited (NPNS) law depicted in Fig. 5. It is basically a frictional law with the equilibrium force F_E shifted from zero to provide for negative exercise. During force teaching the average tangential user force F_{pi} over segment S_{i-1} is stored along with the basepoint (x_i,y_i). During exercise with NPNS, F_E at basepoint i is established at some fraction of F_{pi}. Between basepoints a linear interpolation establishes F_E. The other resistance law parameters, F_L, F_H and V_{max} are input via keyboard.

Having by some resistance law determined V_a it is resolved into x and y coordinates

$$V_{ax} = V_a \cos\theta \; ; \qquad V_{ay} = V_a \sin\theta$$

and added to the position error correction velocity commands then issued to the standard discrete PI velocity control algorithm.

Safety Considerations. With potentially large forces and velocities generated by the Robotic Exercise Machine extensive safety precautions are imperative.

With these precautions installed, the machine can be safer than conventional free weight exercise. Certainly with a spotter which can stop the machine by pushing a button the machine is safer. Even without a spotter, software checks for malfunctions and user difficulty and a fail safe design produce a machine which should prove to be safer than conventional free weights.

A total of twenty-six malfunction checks are provided in the software. Some of the more significant checks are listed in Table 1 with the type of malfunction they can detect. Parity error and power failure checks are implemented on the TI 990/4. The watchdog timer protects against computer software and hardware failures. Other checks listed protect against transducer and/or servo valve failure.

Table I. Malfunction Checks

Method of Detection	Malfunction Detected
1. Excessive velocity error	Tach, servovalve, converters
2. Excessive velocity	Tach, servovalve, converters
3. Velocity x time ≠ distance	Pot, tach, converters
4. Failure to stop in time limits	Servovalve
5. Excessive force	Force transducer, servovalve, and others
6. Incorrect spacing of basepoints	Converter
7. Excessive position error	Pot, tach, servovalve, converters, motors
8. Failure to stop within trajectory limits	Servovalves
9. Failure to reset timer	Computer
10. Parity error	Computer

CONCLUSION

The Robotic Exercise Machine creates new possibilities for resistance training in athletics and rehabilitation. These possibilities are now being evaluated with a prototype machine, all features of which cannot be described in the space allowed. The microcomputer forms the basis for many of these features. The digital hardware itself has contributed significantly to the cost of the prototype, but interfacing, actuators, transducers, fabrication, and power supplies will overwhelm this cost on production models. Software development (assembly language) is a large fraction of development cost and indicates the need for higher level languages. This is especially true where an almost unlimited number of software features beg for evaluation.

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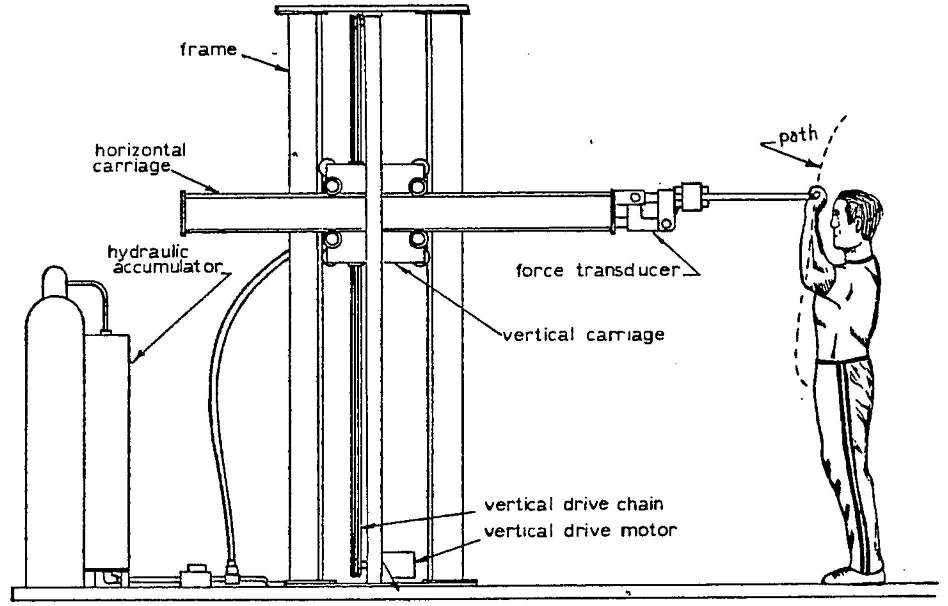

Figure 1. The Robotic Exercise Machine Prototype Shown in the Plane of Motion.

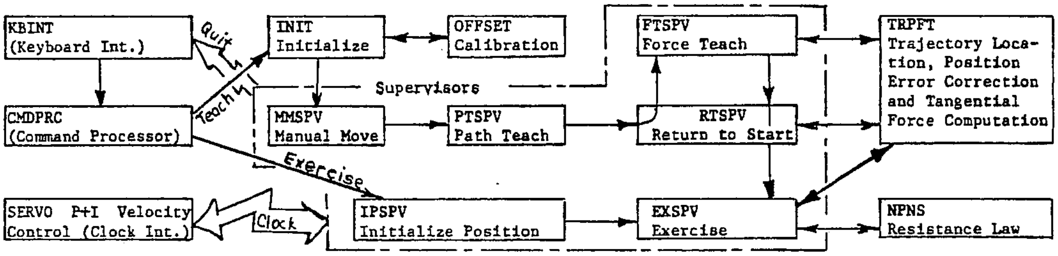

Figure 2. Software Module Relationships for Teach and Exercise Commands.

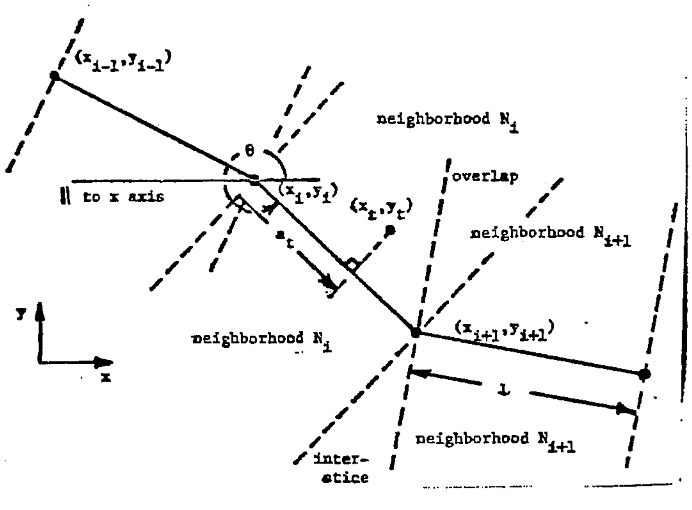

Figure 3. Path Segment Location Scheme.

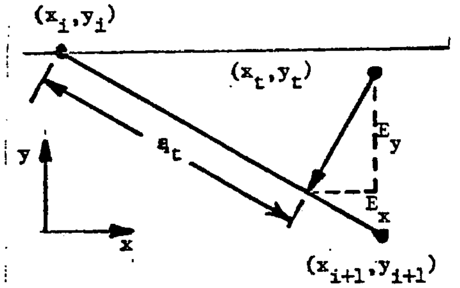

Figure 4. Position Error Correction.

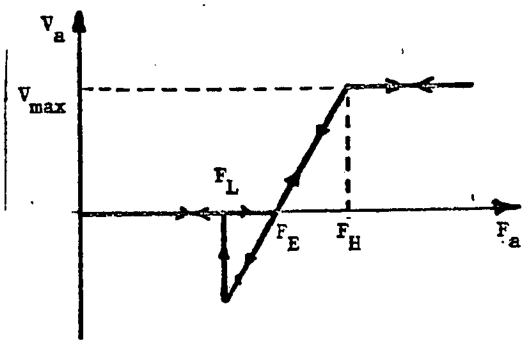

Figure 5. NPNS Resistance Law.