DISSERTATION

INTERACTIVE VARIABLE RESISTANCE EXERCISE APPROACH TO MAXIMIZING FORCE OUTPUT BASED ON LIFTING VELOCITY

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY DAVID PAULUS, ENTITLED "INTERACTIVE VARIABLE RESISTANCE EXERCISE APPROACH TO MAXIMIZING FORCE OUTPUT BASED ON LIFTING VELOCITY", BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

INTERACTIVE VARIABLE RESISTANCE EXERCISE APPROACH TO MAXIMIZING FORCE OUTPUT BASED ON LIFTING VELOCITY

The purpose of the research was to extend the fundamental contributions by Troxell (1982) on the Interactive Variable Resistance Exercise (IVRE) approach to maximizing force output. The testing apparatus was a Smith machine modified for pneumatic resistance and equipped with pressure, position, and velocity transducers. The resistance level varied interactively with the user based on velocity to accommodate for changing biomechanics.

The squat exercise is a multijoint lift that does not have a universal force profile. Mechanical means such as a cam may not be used to match the changing strength capacity throughout the range of motion (ROM). Therefore, this exercise requires another method such as the IVRE approach to vary the resistance for maximizing the force output through the ROM.

A study was conducted in which the isometric strength profile was experimentally determined. The lowest force on the strength curve illustrated the Isometric Sticking Region Force (ISRF). Also, the linear Force-Velocity (F-V) curve for each subject was determined experimentally. The intercept of the force axis at zero velocity is the theoretical maximum force, F_0. The F-V curve was used to set the desired velocity, V_D, by which the resistance level varied on the IVRE lifts. During IVRE if the participant's instantaneous resultant velocity, V_R, exceeded V_D, then the resistance was increased. Thus at maximal exertion a higher velocity indicates more strength capacity, and the resistance level increased accordingly.

Contributions are delineated into machine development and human subject testing results. The research accomplished its objective of developing and verifying an IVRE apparatus capable of providing isometric, constant, and variable resistances as well as collecting data for select parameters. Human testing results revealed that the ISRF occurs at the 90° knee angle, and the ISRF corresponds to approximately 50% of F_0. Thus the ISRF may be used to predict F_0 permitting dynamic strength to be assessed with a single isometric exertion, and future IVRE research can utilize the F-V curve used to select an initial resistance level and the V_D.

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CHAPTER 1

INTRODUCTION

The Ancient Greeks had a phrase that carries timeless virtue: *Mens sana in corpore sano* – A sound mind in a sound body. In light of this ideal, the research effort herein applies knowledge of the biomechanics involved in strength training to further the development of a superior resistance exercise method. The method interactively varies the resistance level such that it is capable of maximizing the user's force production dynamically throughout the Range Of Motion (ROM). The interaction between the human and the machine is based on experimentally proven biomechanical parameters that are explained and implemented in an original manner.

For economy of design in a strength and conditioning program, whether it is to increase strength or prevent losses in strength (from both bone and muscle) as might be experienced by persons in microgravity (Schneider et al, 2003), an exercise that stresses as many critical muscles as possible in one safe movement is desired. The squat exercise is just such an exercise. While it predominantly stresses musculature of the knee complex, loads are transferred from the shoulders, through the spine and torso, and down through the legs.

1.1 Parameters of Resistance Exercise Training

Important aspects of a resistance exercise program include loading the muscles throughout the ROM, concentric and eccentric loading, intensity, and volume of exercise including the number of repetitions and sets (Fleck and Kraemer, 2004). Resistance exercise acts as a stimulus from which the body responds with an increase in strength and/or muscle size (muscular hypertrophy). Strength has been defined as the maximal amount of force a muscle or muscle group can generate for a specified movement pattern at a specified velocity of movement (Knuttgen and Kraemer, 1987). A repetition is one complete movement of an exercise consisting of the concentric and eccentric phases, and a set is a group of repetitions performed continuously without stopping or resting. The concentric portion of the lift is traditionally considered a load being lifted and the muscles involved normally shortening. The eccentric phase is thought of as lowering a weight with the muscles involved normally lengthening in a controlled manner. A Repetition Maximum (RM) is the maximum number of repetitions per set that can be performed with proper lifting technique using a given resistance (Fleck and Kraemer, 2004).

Maximal Voluntary Muscular Actions (MVMAs), often referred to as overloading the muscle, are an effective way to increase muscular strength (Fleck and Kraemer, 2004). This means that the muscle must move with as much resistance as its present fatigue level will allow. It does not mean that one must lift with the maximal resistance possible for one complete repetition. Maximal increases in strength can occur in some populations, such as seniors, without performance of MVMAs during each training session per week (Hunter et al, 2001). However, according to Fleck and Kraemer (2003) all competitive Olympic weightlifters, power lifters, and bodybuilders use voluntary maximal muscular actions at some point in their training programs, revealing that competitors at this level realize the need for overload to bring about optimal gains in strength and muscular hypertrophy. Moreover, Berger and Hardage (1967) found that heavy resistances resulting in MVMAs need to be lifted multiple times per session to bring about optimal strength improvement.

Intensity of an exercise is similar to an MVMA, and it can be estimated as a percentage of the 1 repetition max (1RM). Approximately 80% of 1RM results in maximal strength gains in weight trained individuals (Rhea et al, 2003), and the minimum intensity level that results in strength gains that can be used to perform a set to momentary voluntary fatigue is 60 to 65% of the 1RM for young healthy participants (McDonagh and Davies, 1984; Reah et al, 2003).

1.2 Introduction to Resistance Exercise Machines

One benefit of using an exercise machine over traditional free weights for resistance training is reduced risk of injury because the movement pattern is constrained. Resistance exercise machines have evolved over the past fifty years, and some specific changes are noted to illustrate this evolution. In 1957 Harold Zinkin of Universal Gym Company introduced the first selectorized resistance exercise machine in the United States (Pearl and Moran, 1986). It was a multi-station piece with several weight stacks offering the ease and convenience of adjusting the weightload using a selectorized pin, hence the title "selectorized." Around the same time Bob Clarke developed one of the first off-centered, cam-operated, variable resistance machines (Pearl and Moran, 1986). It focused on matching the changing biomechanics of the arm curl.

In 1970, Arthur Jones introduced the Nautilus brand exercise machines that used a cam that acted as a transmission to vary the resistance level throughout the ROM based on average strength curves (Pearl and Moran, 1986). Nautilus aggressively promoted variable resistance as a feature on selectorized machines and began the trend toward selectorized machines with variable resistance provided by a cam. Jones also began a training philosophy of the twenty minute workout, three days per week, with one set of eight to twelve repetitions to muscular failure at "two counts up, four counts down" accounting for momentum by minimizing forces due to accelerating the mass. Other companies followed suit by producing single station selectorized machines such as Polaris, Paramount, Dynacam, and Eagle. In 1984 Cybex acquired Eagle and further promoted selectorized equipment by introducing a user-accessible weight stack, a cable drive, and a smaller footprint for each machine.

As the popularity of selectorized equipment increased, manufacturers sought ways to modify the resistance mechanism to make their products unique (Brzycki, 2000). In 1978 Dennis Keiser developed a pneumatic training machine that used pressurized air as the form of resistance. Other companies such as Hydrafitness and Minigym introduced hydraulic systems that used oil filled cylinders for resistance. In 1988 Life Fitness introduced the Life Fitness Circuit which was the first single-station line of equipment to use computer or electrical resistance (Pearl and Moran, 1986). Life Fitness Circuit also included a strength profile much like a cam. Similarly, electrical resistance has been used for isokinetic machines made by Cybex, Biodex, and Iso Technologies primarily for rehabilitation exercise. Isokinetic training involves working against an accommodating resistance with an upper limit set on velocity that the user cannot exceed (Brzycki, 2000). Elastic bands have also been used historically as a form of resistance, but they have an increasing resistance profile that may not match the user's strength profile and thus limit the ability to increase strength (Pearl and Moran, 1986).

Several attempts have been made to offer variable resistance; however, none have been able to match each user's individual strength capacity throughout the ROM, which is discussed in greater detail in chapter two. Historically, variable resistance and strength curve data have been limited to single joint motions with one rotational degree of freedom.

1.3 Microgravity Application of IVRE

After only five to eleven days of spaceflight, the body adapts to microgravity with decreased muscle volume (LeBlanc et al, 1995), reduction in myofibril cross-sectional area of both Type I and Type II fibers, altered enzymatic properties, and decreased muscle capillarity (Edgerton et al, 1995). Fourteen cosmonauts and astronauts on the Russian Mir Space Station underwent a significant decrease in lean body mass (LBM) and bone mineral density (BMD) after 4 – 14 month missions in spite of vigorous exercise for one to two hours per day including treadmill, cycle ergometer, and a variety of resistive exercises with elastic expanders (LeBlanc et al, 2000). In the earth's 1-g environment, skeletal muscle strength is increased and myofiber hypertrophy is induced from high-intensity resistive exercise (Kraemer et al, 2002). Bamman et al (1997) attempted to simulate the microgravity environment with subjects undergoing 14 days of bed rest which consisted of one group performing resistive exercise and a control group that did not perform any exercise. The control group showed reduced leg muscle mass and strength. However, the group that performed high-intensity leg press and plantar flexion exercises every other day did not experience the previously mentioned deconditioning effects. This leads to the theory that muscle atrophy associated with microgravity exposure simulated by bed rest may be overcome with high-intensity resistance exercise.

BMD has been shown to increase in the 1-g environment from recurring resistive exercise (Menkes et al, 1993). Baldwin et al (1996) proposed that high intensity resistive exercise targeting the susceptible back and lower-body regions may prevent bone demineralization which occurs during bed rest or exposure to microgravity. Therefore, high-intensity (i.e. > 80% of 1RM) resistive exercise is recommended as a countermeasure to the adverse physiological effects (decreased bone density, muscle mass, and strength) associated with exposure to microgravity (Baldwin et al, 1996).

In microgravity the removal of gravitational forces result in not only muscle atrophy, but also an early increase in bone resorption (Smith et al, 1998) and either no change or a slightly decreased bone formation (Zerwekh et al, 1998; and Smith et al, 1999). In order to maintain bone and muscle mass and strength, high-intensity resistive exercise such as the squat is needed to target the susceptible back and lower-body regions (Schneider et al, 2003 and Baldwin, 1996).

Presently, an elastomer-based resistance exercise device termed the interim Resistance Exercise Device (iRED) is being used as a countermeause in the International Space Station (ISS) (Schneider et al, 2003). The iRED consists of two canisters containing elastomer wheels that stretch for resistance (Fig. 1.1). The canisters are connected to cables that attach to a shoulder harness similar to football shoulder pads that transmit the resistance to the user's shoulders for a squat exercise.

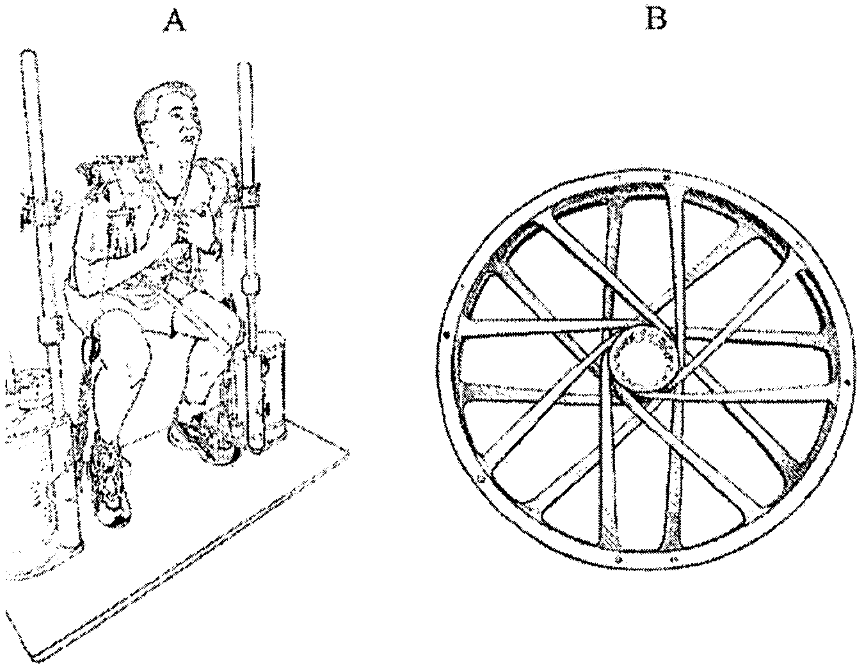


Figure 1.1: A) Sketch of the interim Resistive Exercise Device (iRED) B) FlexPack elastomer from one of the canisters (Schneider et al, 2003)

The device is practical for the ISS because it is small, lightweight, and requires no external power. However, the strength curve produced by an elastomer device is not ideal for intensive weight training (Schneider et al, 2003), and the strength and muscle volume responses after training with an elastic exercise device are “less than those generally reported for short-term resistance-training programs using free weights” (Hostler et al, 2001). Another limitation of the iRED is the inability to select and quantify the resistance level. A dial is turned until the resistance level feels high enough at the top of the ROM at full extension. The exact force profile of the iRED is unknown, and the resistance level reduces throughout the eccentric portion of the lift and increases throughout the concentric portion. The lack of knowledge of the force profile and ability to precisely select the resistance level limits the development of prescribing an appropriate resistance exercise program to counter the effects of microgravity. Pneumatic Interactive Variable Resistance Exercise (IVRE) would be applicable in microgravity as a countermeasure to atrophy because mass is no longer a feasible form of resistance and exercise time is a serious constraint.

1.4 Purpose and Objectives

The purpose of the research is to appropriately vary the resistance level during a squat exercise to meet the participants’ strength capacity based on their lifting velocity. The strength capacity of the multi-joint squat exercise varies throughout the ROM differently for each individual (Fleck and Kraemer, 2004). As a result there is not a cam or other universal force profile that can adequately change the resistance based on the relationship between force and displacement; however, research has shown that for the squat exercise lifting velocity linearly decreases as the resistance level increases (Rahmani et al, 2001). For this reason the research herein proposes to accommodate for the individual biomechanical differences in the multi-joint squat by varying the resistance level, or force, based on the subject's instantaneous velocity.

The research shows that the technology has been developed to provide accommodating resistance for maximizing muscle hypertrophy and intensity throughout the ROM. The goal is met by developing a variable resistive exercise system that interacts with the user to create real-time maximal resistance (Kulig et al, 1984). This, in turn, reduces exercise time and number of exercises required by increasing the efficiency of each exertion. Thus, the objective of the study is to experimentally determine the validity of variable resistance exercise that elicits the user's maximum force output by way of monitoring the lifting velocity.

The relationship between force and velocity could be used to create interactive variable resistance. Lifting velocity is a parameter that could replace the force – displacement or cam approach to variable resistance because the subject's lifting velocity capacity linearly decreases with increasing resistance, and it instantaneously changes uniquely for each individual. An appropriate velocity in which to monitor strength capacity is selected based on this force-velocity relationship such that it corresponds to 80% 1RM, as further discussed in chapter two. If force is varied based on instantaneous lifting velocity, muscles could be maximally loaded with a single multijoint exercise that will minimize exercise time and maximize hypertrophy at each joint position. The concept of interactive variable resistance exercise has application anywhere muscle hypertrophy is desired. Besides the obvious use in traditional strength training and athletics, the concept could be used as a countermeasure to the adverse effects of exposure to microgravity, which acts as a model for atrophy associated with aging, as both are attributed to disuse (Drinkwater, 1995).

1.5 Dissertation Statement

The interactive variable resistance exercise approach is capable of maximizing force based on lifting velocity. Biomechanics dictate that the force capacity changes throughout the ROM such that the force production capability decreases as shortening velocity increases (Fleck and Kreamer, 2004). Therefore, the resistance level is appropriately varied to accommodate for the changing biomechanics based on velocity.

1.6. Research Scope and Limitations

The prototype has been tested for the squat exercise alone. The application of the interactive variable resistance exercise system could be applied to several resistance exercises; however, only the squat exercise was studied because it is one of the most widely used exercises for increasing physical power and strength (Abelbeck, 2002). The squat exercise is also appropriate for microgravity applications that would be interested in spine and lower extremity loading. A commercially available Nautilus Smith machine (Fig. 1.2) will be used as the research platform. Due to the vastness of such a research endeavor, limitations must be placed on what is studied and what will be left for future work. Thus, only the concentric portion of the squat exercise is to be explored in this research effort.

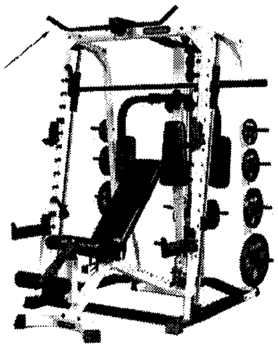


Figure 1.2. Nautilus Smith machine with optional attachments and bench.

1.7 Primary Research Aims

The initial research aim was to engineer, i.e. design, build, and verify, an IVRE apparatus. Data collection with human subjects was used to further the understanding of the biomechanics of the squat exercise. An assumption is made that the exercise is performed with maximal exertion. The contributions of the research aims are separated into two categories: equipment engineering and human subject testing. They are listed separately below.

Equipment Engineering

- Modify an existing Smith machine such that it is capable of providing isometric and dynamic resistance with pneumatics. Also, make the device able to record instantaneous position, velocity, and pressure and provide controllability to the resistance such that it is capable of interactively varying the resistance.

- Validate the static force, dynamic pressure, and velocity to ensure that the machine does what it is designed to do.
- Perform system response testing to show that the pneumatic system is capable of changing the resistance level with sufficient response.

Human Subject Testing

- Experimentally determine the user's individual maximal isometric strength curve. From this the lowest force exerted over the ROM is determined to be the maximum Isometric Sticking Region Force (ISRF).
- Experimentally quantify the force-velocity (F-V) relationship of the squat with constant pneumatic resistance. This reveals the average force intercept, F_0, and slope of the F-V curve.
- Vary the resistance level interactively to maximize force output based on the input velocity, V_D, which is based on the ISRF and the F-V curve.

1.8 Research Justification

Further research is needed for an interactive variable resistance exercise approach because current applications of Dynamic Constant External

Resistance, single and multiple sets of isometrics, mechanical cams, and pneumatic and hydraulic equipment do not vary the resistance to match the instantaneous strength capacity of the user throughout the entire range of motion. While isokinetics are necessary for rehabilitation, such variable resistance would only accentuate weak points in the exercise cycle and not preload muscles for optimal resistance over the entire ROM for healthy participants. The background of these forms of resistance exercise are explored further in chapter two.

All of the previously mentioned resistance exercise approaches will elicit strength and hypertrophy gains if used with proven strength and conditioning programs. However, the research herein is attempting to take the next logical step in creating a more efficient method of resistance exercise. While strength gains are possible without overload, optimal gains are achieved under such conditions. There is room for improvement in variable resistance exercise that promotes MVMA's by dynamically varying the resistance level throughout the ROM to meet the individual's instantaneous strength capacity while preloading the beginning of the lift and minimizing inertial effects.

1.9 Outline of Dissertation

Chapter two gives a background for the development of variable resistance exercise. It begins with the types of resistance exercise and then gives an overview of the relationship between force and displacement for single-joint and multijoint lifts. Next, it describes the relationship between force and muscle length as well as the relationship between force and lifting velocity. Chapter two also provides a background of variable resistance exercise and the biomechanics of the squat exercise including the linear squat. Chapter three covers the methods of the design of the apparatus and pneumatics and an overview of the human subject testing. The system validation and response are also detailed. Chapter four gives the results for each set of the human subject tests, and chapter five provides discussion of the results. Finally, chapter six summarizes the entire research effort and provides contributions, recommendations, and future work to be done.

CHAPTER II

BACKGROUND

This chapter gives a background and explanation of types of strength training used as a foundation for the development of the IVRE approach. The relationship between force and displacement, lifting velocity, and muscle length are explained in the context of applying them to resistance exercise such that they match the biomechanical changes of the human body. A history of the interactive variable resistance exercise approach along with the biomechanics of the squat are presented as well.

2.1. Background on Types of Strength Training

Lifting free weights or training with weight-stack machines has traditionally been termed isotonic exercise, defined as a muscular action in which the muscle exerts a constant tension. However, because the force exerted by a muscle varies with the mechanical advantage of the joint(s) involved in the exercise, a better term for such training is Dynamic Constant External Resistance (DCER). DCER is a more descriptive term because it implies that the weight being lifted is held constant and not that the force developed by a muscle(s) during the exercise remains constant. Limitations of the traditional DCER squat are that effort is not maximized through the complete range of motion because there is a need to slow the ascent and come to a stop at the top of the lift accounting for the inertial effects of accelerating a mass. Furthermore, the load is only overloading the muscles at the sticking region, which will be discussed in further detail below. Thus, each repetition is not maximized.

Strength gains are achieved by taxing the muscle to its limit, or immediately beyond, according to the overload principle (Kulig et al, 1984). This theory of strength development provides the basis for variable resistance. The work output is greater with variable resistance exercise than that of constant resistance (Troxell, 1982). Constant resistance only taxes the muscle to its limit at the "sticking point" or a critical joint configuration of the exercise cycle (Kulig et al, 1984). The sticking region is thought to result from muscles being in positions that produce poor mechanical force. The position of the muscles also contributes to decreased utilization of stored elastic strain energy in myosin cross-bridges and tendons (Escamilla, 2000).

Maximal force exertion could be attained through a single position isometric muscle action in which the muscle is activated and develops force, but no visible movement at the joint occurs. However, this is not optimal for maintaining or increasing strength because muscle strength is increased only at the position used for the exertion. Joint angle specificity is the term used to describe the phenomena of strength gains occurring predominantly at or near the joint angle at which the isometric training is performed. Much research indicates that isometric training results in static strength gains that are joint-angle specific (Bender and Kaplan, 1963; Gardner 1963; Kitai and Sale 1989). Neural adaptations such as the inhibition of the antagonistic muscles at the trained angle and increased muscle fiber recruitment at the trained angle result in joint-angle specificity (Fleck and Kraemer, 2004). Thus, isometric training at a single joint angle is an inefficient means of training for dynamic strength (Schott, McCully, and Rutherford 1995).

A logical next step would be to consider multiple locations with isometric muscle actions to load the muscles over the full range of motion. For increasing strength throughout the entire ROM using a series of isometric muscle actions, two guidelines should be met. First, the training should be performed at joint-angle increments of approximately 10 to 30° (Weir, Housh, and Weir 1994; Weir et al 1995). Second, the total duration of isometric training quantified as the duration of each muscle action multiplied by the number of muscle actions per session should be long (3 – 5 second actions, 15 to 20 actions per session) (Meyers, 1967). However, isometric muscle actions are less metabolically demanding and may be less conducive to hypertrophy increases than dynamic muscle actions (Ikai and Fukunaga, 1970; and Ryschon et al, 1997). Therefore, although a series of isometric muscle actions is an improvement to single joint/position isometrics, such a method would require many repetitions and still not fully address the need for dynamic exercise.

The squat exercise has an ascending strength curve. That means that more weight could be lifted if only the last half or quarter of a repetition is performed than if the complete range of motion of the repetition is performed (Fleck and Kraemer, 2004). In an attempt to match the increase or decrease in strength (strength curve) throughout the range of motion, exercise equipment manufacturers have created variable resistance with lever arms, cams, or pulley arrangements in an attempt to force the muscle to contract near maximally throughout the ROM to yield maximal strength gains. However, because of variations in limb length, the point of attachment of the muscle's tendons to the bones, and torso size, none of the mechanical arrangements successfully match all individuals' strength curves for a particular exercise (Fleck and Kraemer, 2004). Hence, mechanical cam-type variable resistance equipment does not appear to successfully match the strength curve of all individuals. Furthermore, applying a cam or fixed proportion of change in the resistance is not ideal due to the complex nature of a multi-link body segment as well as individual differences that should be taken into account. Thus, the resistance level would need to vary according to a parameter other than a fixed cam-like proportion that is based on the force–displacement relationship to match each individual's strength capacity.

Isokinetic training is another method of variable resistance exercise that refers to a muscular action performed at constant angular limb velocity. It is different from other types of resistance training because the velocity of movement is controlled, and there is no specified resistance to meet (Fleck and Kraemer, 2004). The exercise begins with movement from an acceleration of zero degrees per second and accelerates virtually un-resisted until the set velocity is achieved. After reaching the set velocity, further acceleration is not possible and any force applied against the equipment results in an equal reaction force until deceleration begins (Fleck and Kraemer, 2004). Isokinetic equipment is especially practical in a rehabilitation setting when a specific locus in a range of motion is painful. The subject can reduce the effort at this point while still exercising the joint system in the other non-painful regions (Shirakura, Kato, & Udagawa, 1992). The person could also simply stop in the middle of an exercise without being concerned about controlling the load. When lifting free weights, high tension is developed in a muscle even before movement occurs from supporting the load isometrically, called preloading. Because there is no load at the beginning of the exercise cycle for isokinetic exercises, high-tension is not developed in the muscle in the early part of the range of motion. Research shows that this lack of load prior to muscle action retards strength development (Hunter and Culpepper, 1995; Hunter and Culpepper, 1988; Kovaleski et al, 1995). Thus, a disadvantage of current isokintetic machines for strength development in healthy participants is the lack of preloading and an accentuation of weaker regions in the range of motion.

Unlike isokinetic devices, current applications of hydraulic and pneumatic resistance devices provide an accommodating resistance without controlling the movement speed. Hydraulic systems provide concentric resistance by transferring fluid between chambers with adjustable orifice size to control the resistance level (Fothergill, Grieve, & Pinder, 1996; Pinder and Grieve, 1997). The greater the force exerted by the user, the greater the resistance provided by the device. But as the applied force increases, the movement speed increases as well. Like isokinetic machines, hydraulic machines do not preload the contracting muscle.

Pneumatic systems also provide a variable resistance by a compressor that changes the resistance in the form of pressure. Pneumatic systems offer the benefit of having the ability to change the pressure rapidly which enables the performance of eccentric muscle actions (Enoka, 2002). However, the benefits of fluid power have not been used to vary the resistance level to match the user's instantaneous strength capacity, so a pneumatic system with proper control holds promise of creating a variable resistance with minimal mass/inertial effects that could sufficiently preload the muscles at the beginning of the ROM and quickly change the resistance level over the ROM. Pneumatics are attractive for a microgravity application because they do not use mass for resistance, and a leak of air in the space station is relatively benign compared to a hydraulic leak.

2.2 Single Joint Force-Displacement Relationship

Throughout a lifting motion the biomechanical advantage of the body's leverage system changes. The net force about a joint changes with the changing displacement. As a demonstration of this concept, consider the *biceps brachii* muscle insertion on the ulnar/radial bones of the forearm during an arm-curl lift. The contracted muscle generates a force along the line of the muscle. This force is broken into its rotational and stabilizer components. The stabilizer acts toward (or away from) the joint in an adhering (or dislocating) fashion. The rotational component is responsible for the limb movement. The magnitude of the rotational component varies throughout the arc of joint movement with its greatest value occurring when at a right angle or 90° (Troxell, 1982). The variable force available for work (Fig. 2.1) is illustrated by showing the torque, or effective resistance, on the bicep while lifting a thirty-pound barbell. (Wolf, 1984).

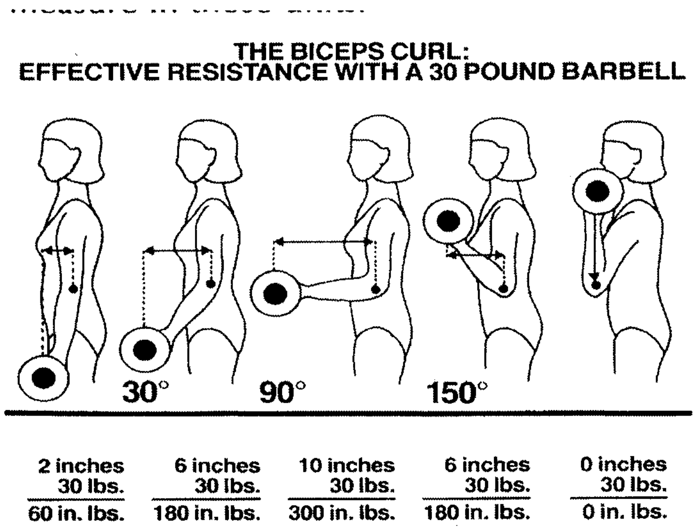


Figure 2.1 Biomechanical leverage changing the effective resistance as demonstrated with the biceps curl with 30-pound barbell (Wolf, 1984).

The moment arm is the perpendicular distance away from the thirty-pound force acting downward. The length of the moment arm changes as the elbow changes angle. When the moment arm is two and six inches long, the effective resistance is 60 and 180 inch-pounds respectively. Note that the largest effective resistance of 300 inch-pounds occurs at the right angle. The arm curl, like many other single-joint exercises, has a bell shaped force–displacement profile meaning that it is possible to lift more resistance if only the middle portion of the range of motion is performed (Fleck and Kraemer, 2004). This illustrates the concept of biomechanical leverage. The barbell does not change weight; however, the bicep muscle does not receive the same amount of resistance throughout the ROM. The simplified example does not take into account the fact that one could argue that the moment arm created by the biceps brachii muscle itself similarly changes with the changing moment arm of the weight, which allows for higher forces from the muscle over the ROM than those indicated in the example. It should also be noted that in order to move the barbell from zero velocity, some acceleration must take place. During such acceleration the force increases by the same measure causing some variation in the load placed on the muscle. Moreover, only one muscle is discussed, most joints have more than one muscle crossing the joint that contributes to the movement of the limb. Each muscle has different properties that sum to create the total force-displacement profile for a joint action.

2.3 Multijoint Force-Displacement Relationship

Multijoint exercises are those that involve more than one joint for the movement of a barbell. For instance, the bench press involves the shoulder girdle, shoulder joint, elbow, and wrist joints to move the barbell. Troxell (1982) developed a force-displacement curve for the multi-joint bench press action using Rogers' Strength Index (Larson, 1970). Twenty Colorado State University varsity football players were tested using a cable/tensiometer apparatus set up to simulate the bench press action. The maximum static strength output was measured at 4-inch incremental steps from chest level to full arm extension. The twenty unique force curves were averaged and plotted versus the intervals of the arm (Fig. 2.2).

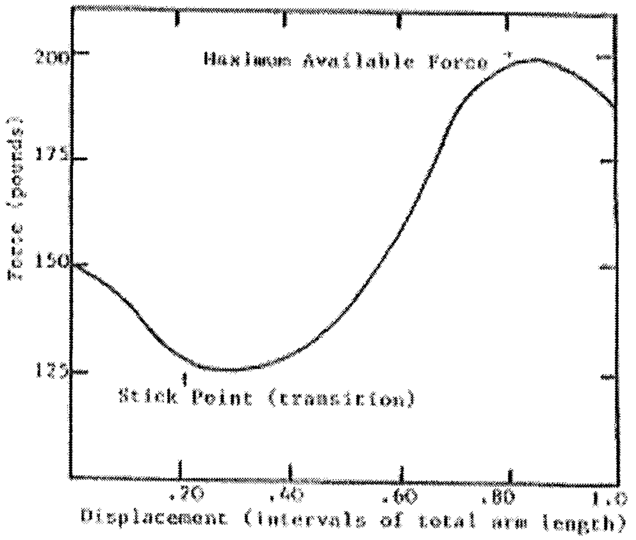


Figure 2.2: Force-Displacement curve for the bench press exercise (Troxell, 1982).

The curve presents a valid indication of how the available force varies isometrically during one repetition of a multijoint closed kinetic chain exercise. In closed kinetic chain exercises, the hand or foot is "fixed", and a force is transmitted directly through the hand or foot to the device creating the resistance (barbell or ground). Examples of closed kinetic chain exercises are the bench press and the squat. Conversely, during open kinetic chain exercise, the foot or hand is not "fixed" and the peripheral segment can move much more freely, such as the leg extension exercise (Steindler, 1955).

At chest level the *pectoralis M.* are the prime movers when the arm is being adducted. A transition occurs at a 30% increment of full extension. This represents the weakest point in the bench press exercise commonly known as the "sticking region" (Troxell, 1982). The force generated by the *pectoralis M.* muscle action is being minimized while the *triceps M.* of the arm are just beginning to take over. The available force increases to a maximum of 80-85% of the interval. From this interval to full extension the maximum available force decreases. The conclusions drawn from Troxell's curve, which apply directly to the present research, are (Troxell, 1982):

a) Biomechanical advantage of the muscles involved varies throughout the full range of a multijoint closed kinetic chain exercise.

b) In lifting a constant load, the sticking region represents the maximum load that can be lifted.

c) When lifting a maximum constant load, the intervals above and below the sticking region are not being loaded to their maximum capabilities.

d) There is a theoretical need for an exercise system that can vary the loading at various intervals in the repetition of the exercise to apply a maximum load depending on each person's unique biomechanical capabilities.

2.4 Force-Muscle Length Relationship

The Tension-Sarcomere Length (Force-Length) curve (Fig. 2.3) illustrates that there is an optimal length at which muscle fibers generate maximal force (Gordon, Huxley, Julian, 1966). At lengths less than or greater than optimal, less tension is developed. (Gordon et al, 1966).

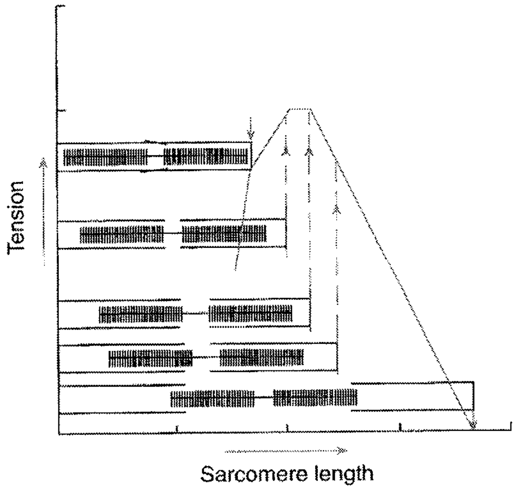


Figure 2.3: There is an optimal length at which a sarcomere develops maximal tension (Gordon, Huxley, Julian, 1966).

According to the sliding filament theory, within each muscle fiber element called a myofibril (each about 1μm in diameter) the myosin and actin myofilaments slide past each other causing a change in muscle length to occur. (Kravitz, 2004). Actin consists of two thin filaments shaped in a double helix, and myosin is a thicker filament with globular heads called cross-bridges. Upon activation the myosin cross-bridges bind to sites on the actin and rotate, which causes the sliding of the filament. The myofilaments do not change in length. It is the sarcomere, or smallest contractile unit of skeletal muscle, that shortens or lengthens with a resultant production of force (Hunter, 2000). The organization of skeletal muscle is shown below (Fig. 2.4).

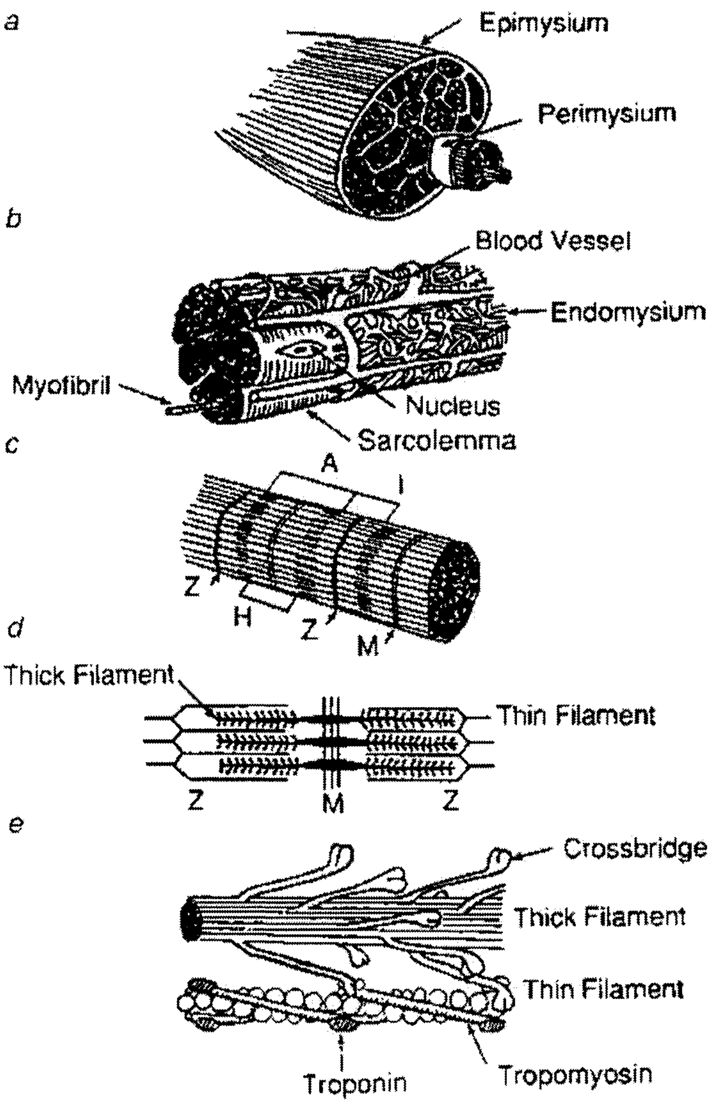


Figure 2.4: Organization of skeletal muscle from the gross to the molecular level. a) entire muscle b) group of muscle fibers c) one myofibril with bands and zones d) a sarcomere including the bands and zones e) one thin filament (actin) and one thick filament (myosin) (Pitman and Peterson, 1989).

The resultant force developed depends on the total number of myosin cross-bridges interacting with active sites on the actin. There is a potential for maximal force when the cross-bridge interaction is maximal, which occurs at the optimal length. When the sarcomere length is greater than the optimum length, there is progressively less overlap between the actin and myosin resulting in reduced potential for cross-bridge contact and less force development. Similarly, when the sarcomere length is less than the optimum length, the actin filaments overlap and interfere with each other's ability to contact the myosin cross-bridges, which also results in reduced force development (Gordon et al, 1966).

2.5 Force-Velocity Relationship

Traditional resistance training with the squat exercise involves lifting a resistance level that is some percentage of 1RM. However, the resistance involved is not the only parameter that must be considered for strength gains because programs using different speeds of movement have shown a velocity-specific increase in strength (Behm and Sale, 1993). Thus, in order to achieve specific performance goals, it is important to perform training exercises at a specific load and velocity that elicit the desired outcome (Wilson et al, 1993). For instance, training with light loads improves power production, but training with heavy loads enhances strength (Caiozzo et al, 1981).

Hill (1938) determined that there was a hyperbolic relationship between *in vitro* (outside living body) force and shortening velocity of an isolated frog muscle (Fig. 2.5).

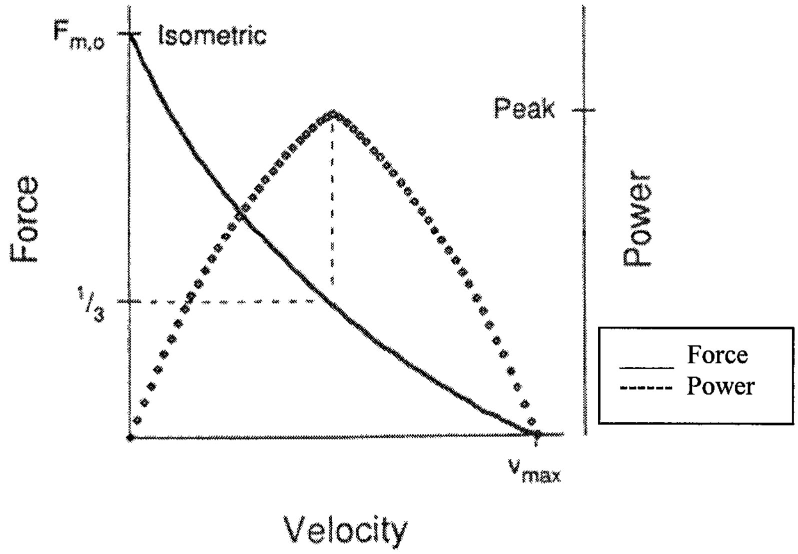


Figure 2.5. In vitro relationship between muscle shortening velocity and force (Hill, 1938).

Some conditions must be met in order to apply Hill's F-V relationship for a single muscle to a system of muscles and bones about a joint. One criterion is that it is applied to a simple joint geometry. An example of a simple joint geometry would be the elbow if studying the forces produced by the elbow flexor muscles. Another criterion is that it involves few muscles. The few muscles involved must have small origins and insertions. Again, the elbow flexor muscles fit these criteria. The squat exercise is not an acceptable exercise for the application of Hill's equation because it is a multijoint lift incorporating several major muscle groups with large origins and insertions. Moreover, studies have shown that the F-V relationship of the squat exercise is linear and does not fit the hyperbolic trend of Hill's equation (Rahmani, 2001; Bosco et al, 1995).

The maximal force a muscle can produce concentrically decreases as the velocity of movement increases (Fleck and Kraemer, 2003). Empirically, the relationship between force and velocity may be considered if an athlete lifted his 1RM and the velocity was recorded. The velocity at 1RM would be expected to be lower than if the same athlete lifted only 20% of the 1RM. The maximum velocity occurs when no external resistance is applied. This peak velocity is limited by the maximal rate at which the sum of individual cross-bridges can be formed and broken with the actin active sites (Fleck and Kraemer, 2003).

Bosco et al (1995) showed that the F-V relationship for the half squat follows a trend of relative linearity. There is an inverse and linear relationship of average force and corresponding average velocity developed during a half-squat exercise performed with various loads from 35% to 210% of the subject's body mass. That means that as the average force was increased, the average velocity decreased. Another finding is that male and female F-V relationships are statistically different (Bosco et al, 1995). The linearity of the F-V curve as well as the difference in slope between men and women is seen below (Fig. 2.6). The power is also shown, but that is not of primary concern in this research.

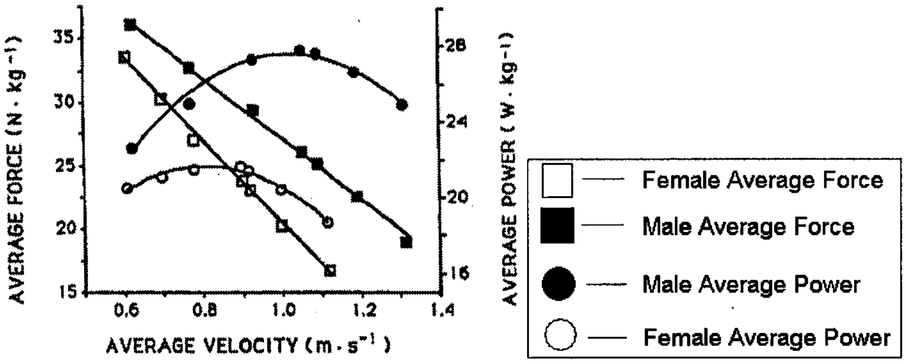


Figure 2.6. Relative F-V linearity of squat exercise (Bosco et al, 1995).

Because of the difference in the male and female force-velocity relationship, both male and female subjects should be studied.

Rahmani et al (2001) also describes the F-V relationship during the squat exercise. The mean ground reaction forces developed during squat exercises with loads from 60kg to 180kg were recorded. The maximal force, F_o, corresponding to zero velocity was extrapolated from the F-V curve and compared to a maximum isometric force produced at a 90° knee angle. The linear relationship between force and velocity was experimentally quantified and is in agreement with the findings of Bosco et al (1995). F_0 was 23% higher than the maximum isometric force. However, the maximum isometric force was only recorded at the knee angle of 90°; whereas, the dynamic forces were measured throughout the ROM from 90° to 180°. Peak dynamic force was generated at a knee angle of approximately 110°. The linear F-V relationship as well as the isometric force produced at a 90° knee angle is seen below (Fig. 2.7).

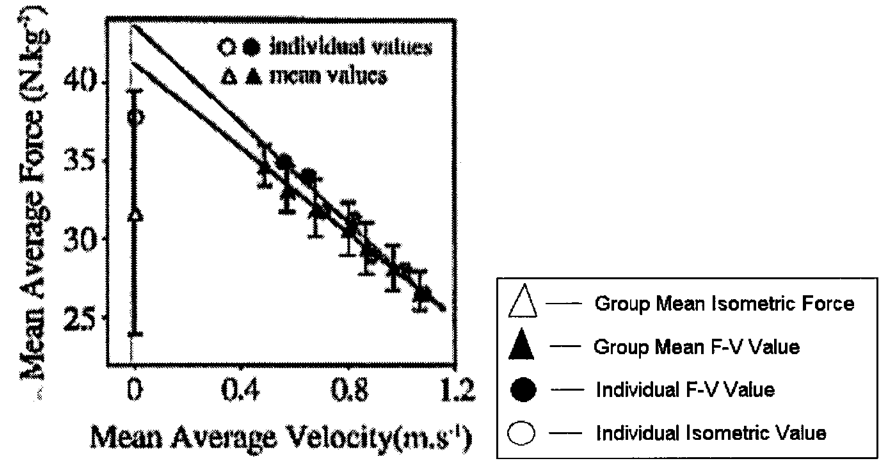


Figure 2.7. Mean forces developed during squat exercises performed with loads from 60kg to 180kg with maximum isometric force at 90° displayed on the vertical axis at 0 m/s (Rahmani et al, 2001).

Cycling and squatting both involve a leg extension motion. In cycling the relationship between force (F) and peak velocity (V) is linear and expressed by $V=V_0(1-F/F_0)$, where F_0 and V_0 correspond to the intercepts with the force and velocity axes, respectively (Driss et al, 2002). The linear F-V relationship is shown for cycling (Fig. 2.8), which is similar to that of the squat exercise.

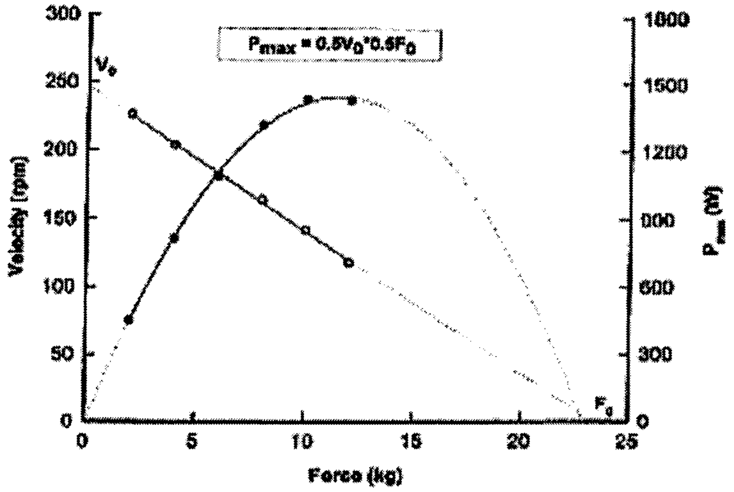


Figure 2.8. The force-velocity relationship (empty circles) obtained on a friction loaded cycle ergometer (Driss et al, 2002).
Note that axes are inverted relative to previous plots.

This linear F-V relationship is of interest because Driss et al (2002) used the F-V curve to extrapolate the curve to zero velocity to obtain the theoretical maximal force, F_0. They attempted to test the hypothesis that parameter F_0 expresses strength ability. There was a significant correlation between F_0 and Maximal Voluntary Isometric Force (MVIF) during isometric knee extension. The results confirm the hypothesis that the parameter F_0 of the force-velocity relationship on a cycle ergometer is an index of maximal strength. This means that there is a relationship between the measured isometric force and a predicted value of maximal force, F_0, taken from extrapolating the F-V curve to zero velocity. This is an important finding because it is contrary to results of previous studies by Baker et al (1994) and Murphy and Wilson (1996) in which isometric tests were poorly correlated with dynamic performances. Several studies (Murphy and Wilson, 1996; Murphy et al, 1995) have demonstrated that significant correlation between isometric and dynamic strength performances are mainly observed when force is measured at similar angles during isometric and dynamic exercises.

Driss et al (2002) discusses the possibility that F_0 is an index of explosive and dynamic strength rather than maximal isometric strength. Hence, although the difference between cycling and squatting is acknowledged, Driss et al show that an isometric force may be used to predict a dynamic strength. This is important because a peripheral goal of the present research is to illuminate the relationship between maximal isometric and dynamic strength in order to predict dynamic strength by a single isometric exertion. This is useful in any application where strength assessment is desired; however, it is of primary importance to the development of the IVRE approach to maximizing force by knowing maximal strength, F_0, once assessed. It can to be used in assigning an appropriate initial resistance level as a percentage of the maximum.

Escamilla (2000) states that the relationship between acceleration and force is the same for the squat and bench press exercise. It was determined that the sticking region for the bench press occurs when the bar is between 30% and 50% of its vertical ascent displacement. This is shown by a reduction in upward bar velocity at the sticking region (Escamilla, 2000). The velocity will go to zero if the load is too great creating an isometric (F_o) situation. Hence, velocity is an appropriate measure for adjusting the load to accommodate for the sticking region.

Optimal velocity for resistance training is a subjective parameter because one has the ability to exercise the entire ROM with a controlled magnitude of velocity when lifting a sub maximal load. However, if lifting under the assumption of maximal exertion, the lifting velocity depends more heavily on the level of external resistance to overcome. As shown by the inverse linear relationship of the F-V curves for the squat exercise (Fig. 2.7), the peak force occurs during the isometric condition in which velocity is zero. As force decreases, the lifting velocity increases until an unloaded maximal velocity is reached showing that lower velocities would be expected with correspondingly greater maximal exertion forces. As discussed in chapter one, an intensity level of 80% of the 1RM results in maximal strength gains (Rhea et al, 2003); in traditional DCER weight training, 80% of the 1RM corresponds to the six repetition maximum (6RM), which is considered heavy, but not maximal (Baker, 1995). Tan (1999) also found that strength is best developed with 1–6 repetition maximum loads. One could infer that the "optimal" velocity for strength gains would be that which corresponds to 80% of the 1RM on the F-V curve. Therefore, in order to elicit maximal force for strength gains from high resistance levels (80% 1RM), a correspondingly low velocity range from an F-V curve would be appropriate.

2.6 Variable Resistance Exercise Background

Ideal strength gain is achieved during an overloaded muscular action (Kulig et al, 1984). Variable resistance exercise changes the resistance profile over the ROM. This is different than traditional approaches of setting a sub-optimal constant force resistance, although the force is subject to changes caused by accelerating the mass governed by Newton's second law of motion (F=ma, where "F" is force, "m" is mass, and "a" is acceleration). The biomechanical advantage of the body's leverage system changes throughout a lifting motion due to the inherent biomechanics and structure of the human body described later in this chapter. Constant resistance exercise machines simulate a dead load lift and do not accommodate for changing biomechanics. Previous attempts at creating variable resistance did not change the resistance in a way that met the user's individual strength capacity (Ciccarelli, 2002).

The most common methods of incorporating variable resistance have used a mechanical or programmable cam profile to change the resistance by a set proportion (Fig. 2.9).

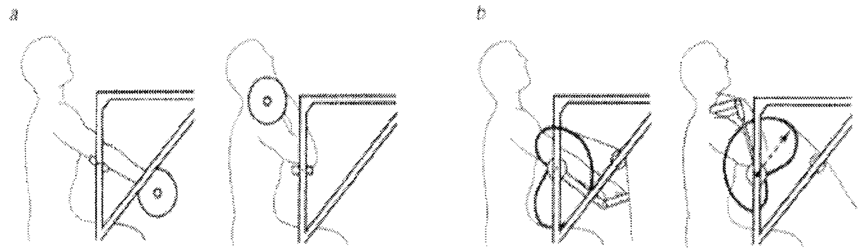
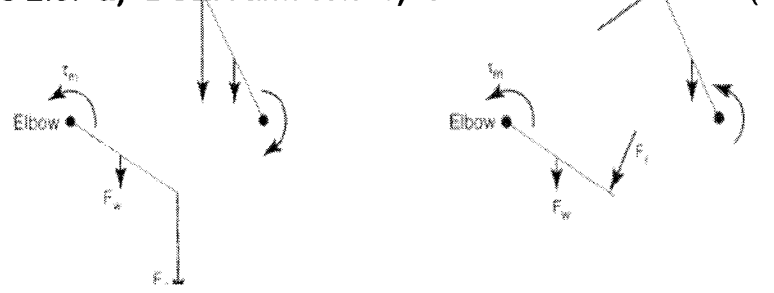


Figure 2.9: **a)** DCER arm curl **b)** cam machine arm curl (Enoka, 2002)



The Nautilus cam machines are an example. Other machines have attempted to quantify the volume of exercise by adding electronic readouts. Some machines, such as the Keiser machines, use the benefits of pneumatics, but they do not exploit the benefits of fluid power technology to optimize the overloading of muscles for maximum results. Ciccarelli (2002) studied the shape of the resistive torque patterns provided by Nautilus, Cybex, and Icarian variable resistance leg extension machines using cam technology for similarities to the shape of the strength curve of the human knee extensors. A result of the study shows that the force provided by each of the machines did not match the human force capability (Ciccarelli, 2002). As a result, there is a need to develop a method of employing interactive variable resistance that matches the instantaneous strength capacity.

Conventional methods of resistance such as free weights or weight stack machines apply a constant external load to a muscle group. If the load does not vary, it does not complement the changing biomechanical advantage of the individual. According to Tihanyi, et al (1985) there is much variance in the strength curve for the squat exercise because the study shows that peak force output occurs between 102° and 164° knee flexion. There is a wide range of knee angles in which the peak force occurs, illustrating that variance in the squat strength curve.

Work is defined as a scalar quantity that describes the extent to which a force can move an object in a specified direction (Enoka, 2002). In the case of exercise, more force exerted over the same distance improves the efficiency of the exercise. Calculation of work with each exercise cycle provides feedback as to the level of exertion, which is assumed to be maximal. There is an intrinsic source of motivation to exert maximally because the quantification of work allows one to compare one lift to the next. Such motivation is important for the development of maximal strength according to Hollmann and Hettinger (Astrand, 1977) because maximal muscular strength occurs through the maximal exertion of the subject's willpower. Intrinsic motivation greatly influences an athlete's desire to train, and it is defined by Deci (1978) as a desire to be competent and self-determining. Such self determinacy is important in resistance exercise to create an inward drive to exert maximally in order to achieve ones potential maximal velocity throughout the ROM. During IVRE an increase in velocity would signal the machine that there was an increase in strength capacity which would call for a proportional increase in resistance level. Thus, the intrinsic motivation to exert maximally elicits one's potential maximum velocity with the current resistance level which brings about an increase in the force exerted over the specified distance during IVRE.

Previous attempts at variable resistance exercise improved the efficiency compared to constant resistance but fell short of interactively maximizing the force exerted. Thus, the level of resistance should be capable of changing to the upper limit of force capacity of the user at the point it is needed. Troxell (1982) developed the concept for an interactive variable force exercise system applied to the bench press exercise. The theory of interactive variable resistance exercise approach is described as having the capability of varying the level of resistance in order to exert a variable, maximal load to accommodate the changing biomechanical advantage. Muscular strength, defined as the maximal force that a muscle or muscle group can generate at a specified velocity (Knuttgen and Kraemer, 1987), can be achieved under this exercise approach (Troxell, 1982). The objective was to elicit maximal power by varying the resistance level such that constant barbell velocity was maintained. The desired velocity was determined based on Hill's (1938) classical hyperbolic inverse relationship between force and shortening velocity of an isolated in-vitro muscle in which maximum power occurs at one-third maximum force and velocity (Fig. 2.10) (Astrand, 1977).

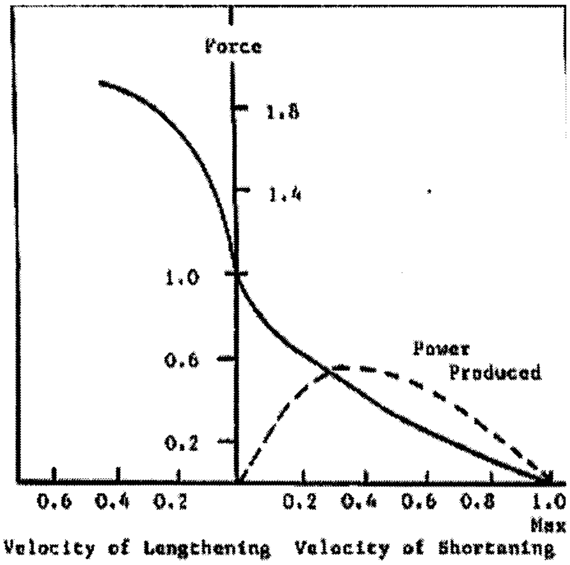


Figure 2.10: Hill's (1938) hyperbolic F-V relationship and maximum power occurring at one-third maximum force and velocity used by Troxell (1982).

The research previously performed by Troxell (1982) introduced the concept for creating interactive variable resistance exercise; however, the next step is to expand the theory in terms of experimentally determining the lifting velocity to use as the parameter for controlling the resistance level. Instead of basing the desired lifting velocity on the force-velocity curve of a single in-vitro frog muscle (Hill, 1938), the desired velocity is to be determined experimentally from each individual's F-V curve associated with the complex, multijoint linear squat with pneumatic resistance.

2.7. Biomechanics of the Squat Exercise

The squat exercise is considered a multijoint exercise because it requires movement at more than one joint (i.e. the knee and hip) and uses more than one muscle group. Such a multiijoint exercise requires neural coordination among several muscle groups (Fleck and Kraemer, 2004). Fleck and Kraemer (2004) also state that whole-body multijoint exercises like the squat are particularly advantageous when training time is limited and it is necessary to train more than one muscle group with each exercise.

During the squat exercise the knee extensor muscles are primarily responsible for the motion. Thus, the moment about the knee (T_m) is responsible for limb motion (Fig. 2.11) (Enoka, 1994).

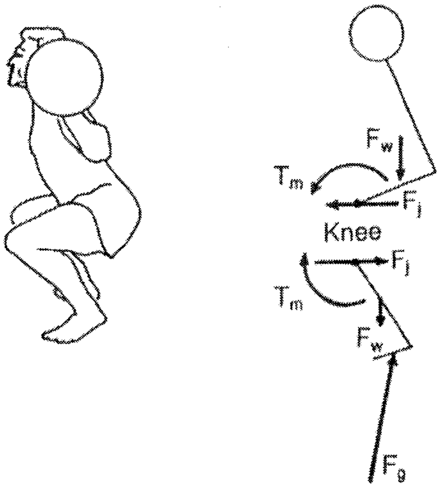


Figure 2.11: Free body diagram of knee joint for the squat exercise (Enoka, 1994).

The relationship between the anatomical, link-segment, and free-body diagram models respectively is presented (Fig. 2.12) (Winter, 1990).

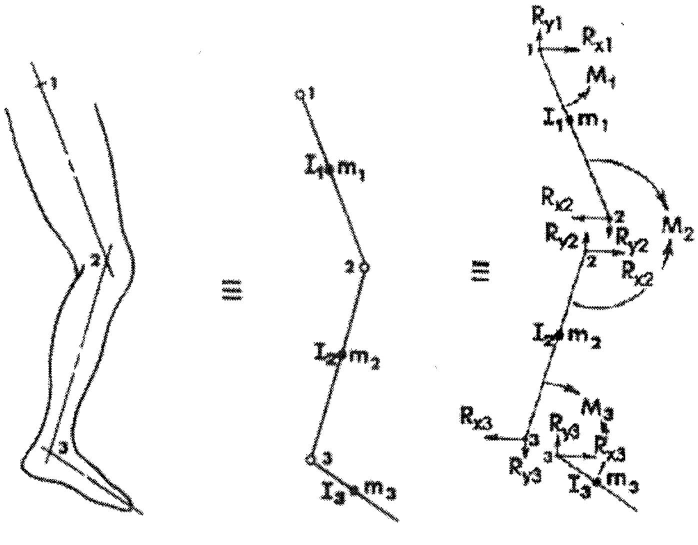


Figure 2.12: Relationship between anatomical, link-segment, and free-body diagram models (Winter, 1990).

Hinge, or pin, joints in the link-segment model replace the joints from the anatomical model. The segments are replaced by masses and moments of inertia located at each segment's center of mass. For the free-body diagram model, each segment is separated at the joints, and the reaction forces and moments of force acting at each joint are included.

Lowering the weight during the countermovement phase of the squat consists of the knee extensor muscles lengthening to assist in lowering the body. This is called the eccentric portion of the lift, and negative work is being done; more specifically, work is being done on the muscles by the weight of the barbell and lifter. When the lifter raises the weight, or when the knee extensor muscles are active concentrically, he/she performs positive work (Enoka, 1994). Different knee extensor muscles are activated during flexion and extension of the knee. The knee joint flexors are the three hamstring muscles (biceps femoris, semimembranosus, and semitendinosus), the sartorius, and the gracilis. The sartorius and the gracilis are mostly important at the early stage of flexion. The extensors are the quadriceps femoris group consisting of the rectus femoris, vastus intermedius, vastus lateralis, and vastus medialis (Wells and Luttgens, 1976). A schematic shows these muscles with a posterior (back) and two anterior (frontal) views from left to right (Fig. 2.13) (Wells and Luttgens, 1976).

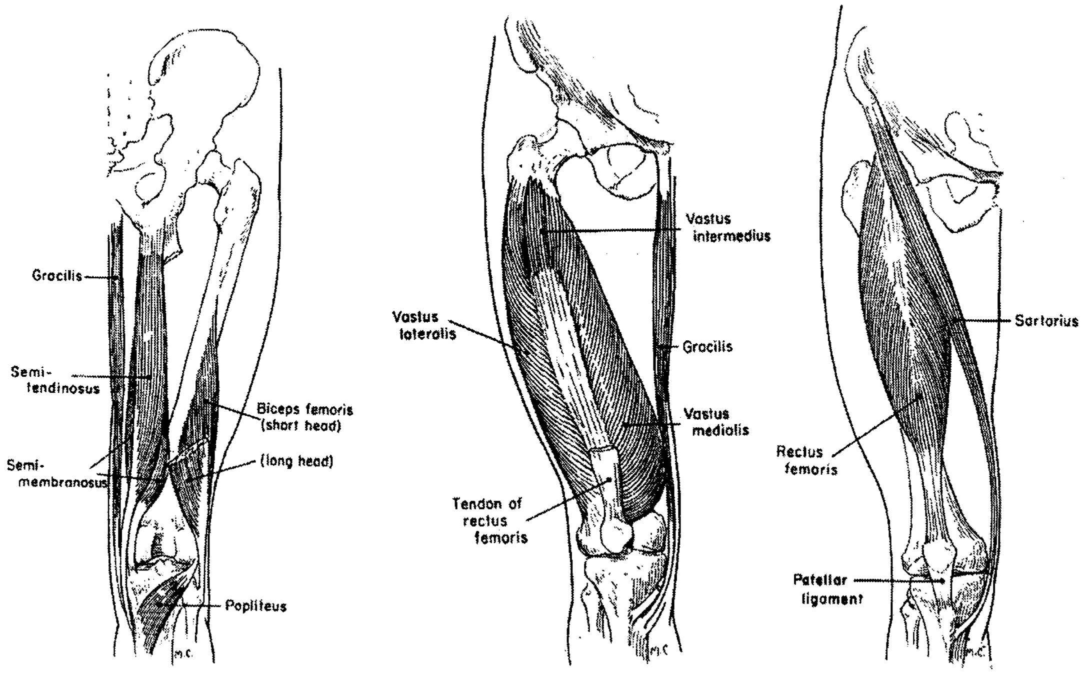


Figure 2.13: Posterior and two anterior views of the thigh from left to right, respectively (Wells and Luttgens, 1976).

A muscle must cross a joint in order to cause limb movement upon muscle action. Notice that some of the muscles such as the rectus femoris and semimembranosus cross two body joints and are called two-joint muscles (Williams and Stutzman, 1959). The length of such muscles is affected by both joint angles. For example, if an individual bends forward at the waist, the hamstring muscles will tighten, allowing them to generate more torque than when standing upright, as demonstrated with the Force-Length curve. The shape of the range of motion as well as torque curves change also (Williams and Stutzman, 1959).

Two-joint muscles provide advantages in the control of the musculoskeletal system. First, two-joint muscles couple the motion at the two joints they cross (Enoka, 2002). According to Zajac (1993), one-joint muscles provide propulsive energy for vertical jump as the two-joint muscles refine the coordination. Second, the shortening velocity of a two-joint muscle is less than that of its one-joint synergist (Enoka, 2002). For example, during concurrent hip and knee extension of the concentric phase of the squat, the shortening velocity of the two-joint rectus femoris is less than the shortening velocity of the single-joint vasti (Ingen Schenau, Bobbert, & Soest, 1990). The two-joint muscles are then higher on the F-V curve compared to the single-joint muscles.

More than one muscle acts together to cause movement about a given body joint, and the different muscles are at different points in their force-length curve at each joint angle (Hunter, 2000). A model of the hip and knee joint musculature (Fig 2.13) shows muscles 1 through 4 cross only one joint while muscles 5 and 6 cross both the knee and hip joints (Ingen Schenau, Bobbert, & Soest, 1990).

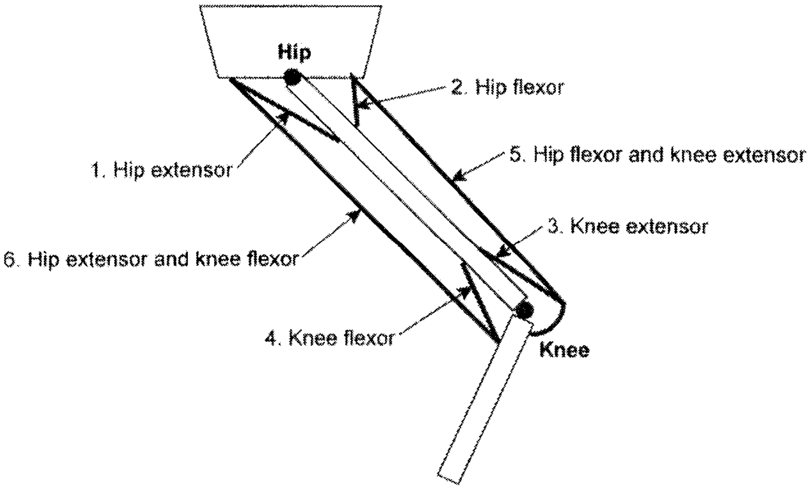


Figure 2.13. Model of hip and knee joint musculature. Muscles 1 through 4 cross only one joint while muscles 5 and 6 cross both the knee and hip joints (Ingen Schenau, Bobbert, & Soest, 1990).

During the concentric phase of the squat exercise, both the knee and hip joint concurrently extend. Such extension could be carried out by the gluteus maximus and the vasti (1 and 3) single joint muscles alone. However, the rectus femorus (5) and the hamstrings (6) are two-joint muscles that are also active. The rectus femoris is active at the beginning of the lift because the moment arm at the knee is longer than at the hip, so it requires greater muscle torque about the knee. The hamstrings are active toward the end of the exercise cycle when the moment arm about the knee is reduced. A greatly simplified model of the changing biomechanics during the concentric squat exercise would be using the free-body diagram (Fig. 2.14) with F_w representing the load on the barbell and upper body equal to 1000 N.

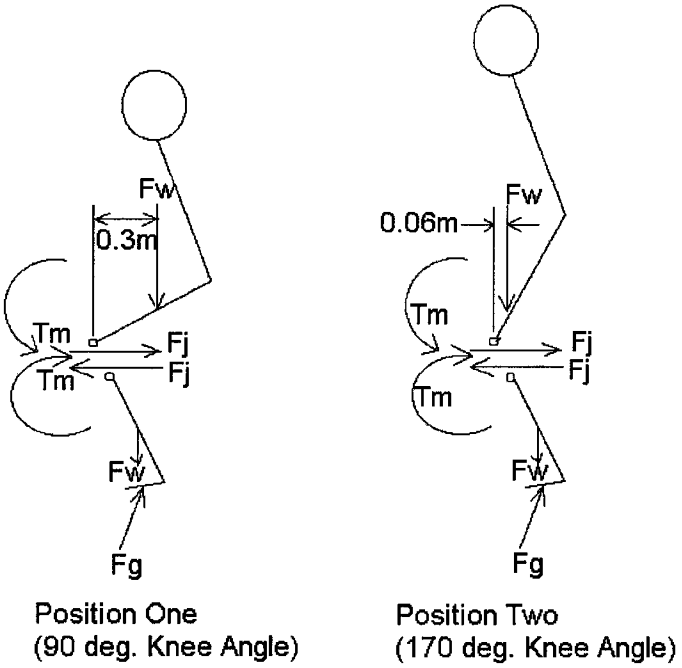


Figure 2.14: Simplified biomechanical model of free-body diagram of squat exercise for positions one and two.

Consider the knee angle to be 90° for position one and 170° for position two. Assume that the moment arm lengths, or perpendicular distance from the center of mass of the body segment to the knee joint, are equal to 0.3 m and 0.06 m for positions one and two, respectively. Thus, moments about the knee, T_m, are 300 Nm and 60 Nm, respectively. At position one the knee extensor muscles would have five times greater resistance than at position two although the external load remained constant.

Using a linear machine for squats allows for the possibility of freedom of foot position. For example, in a traditional squat, the combined center of gravity of the weights and the user must remain directly over the user's feet. Otherwise, the user will fall over. Using a linear machine allows for variation in the foot placement because the center of gravity no longer has to remain directly over the feet. The resulting horizontal forces that would otherwise tip the user may now be applied to the machine and consequently the floor. This allows for variation in anterior-posterior foot placement, which significantly changes the loads on the body (Abelbeck, 2002). During a squat exercise there is a nearly inverse and linear relationship between moments about the knee and hip. With the feet positioned farther anterior to (in front of) the body, the knee moment decreases, but the hip moment increases. A higher moment about the hip results in more stress on, and thereby work done by, the hip extensor/flexor muscles. With the feet positioned closer under the body, there is a higher moment about the knee, resulting in greater stresses on, and work done by, the knee extensor/flexor muscles.

CHAPTER III

METHODS

The following chapter gives an overview of the testing apparatus design, validation and experimental procedure, the form of the results, and an overview of the human subject testing protocol. The engineering and pneumatic designs were performed with the English unit system, so all specifications from manufacturers are relayed as such. The English units are in parenthesis next to the SI units, and for ease of reference, the following conversion factors may be used: 1 in = 25.4 mm, 1 lb = 4.4482 N, and 1 psi = 6.8948 kPa (Jong and Rogers, 1991).

3.1 Testing Apparatus Design

A Nautilus Cage and Smith Attachment (NT1600/1610, Nautilus, Inc., Louisville, CO) designed for performing linear motion squats with Olympic weights has been modified with pneumatic resistance. Because this apparatus is to be used exclusively for research, functionality is of primary concern. The structure was over-built to ensure rigidity and minimize flexion. A single pneumatic cylinder (TA-MS2-3.25x24, TRD Manufacturing, Inc., Loves Park, IL) mounted above the Nautilus cage provides resistance to the barbell. The piston in the cylinder is equipped with a magnet that is read by the linear position transducer (Micropulse BTL-5-PI-MO610-R-SU145-KA05, Balluff Inc., Florence, KY). A velocity processor (Micropulse BTM-A1-002-VU024, Balluff Inc., Florence, KY) differentiates the position signal with time to give the instantaneous velocity. The processor's velocity range is 50.8 – 10160 mm/s (2 – 400 in/sec) with an update rate of 0.5 ms. A National Instruments data acquisition card (NI PCI-6036E, National Instruments, Austin, TX) transfers the data to and from the LabVIEW (Version 6.1, National Instruments, Austin, TX) code. A detailed overview of the apparatus design may be found in Appendix A, and specifications for the devices may be found in Appendix B, both in the English unit system in which they were designed. A digital image (Fig. 3.1) shows the entire apparatus.

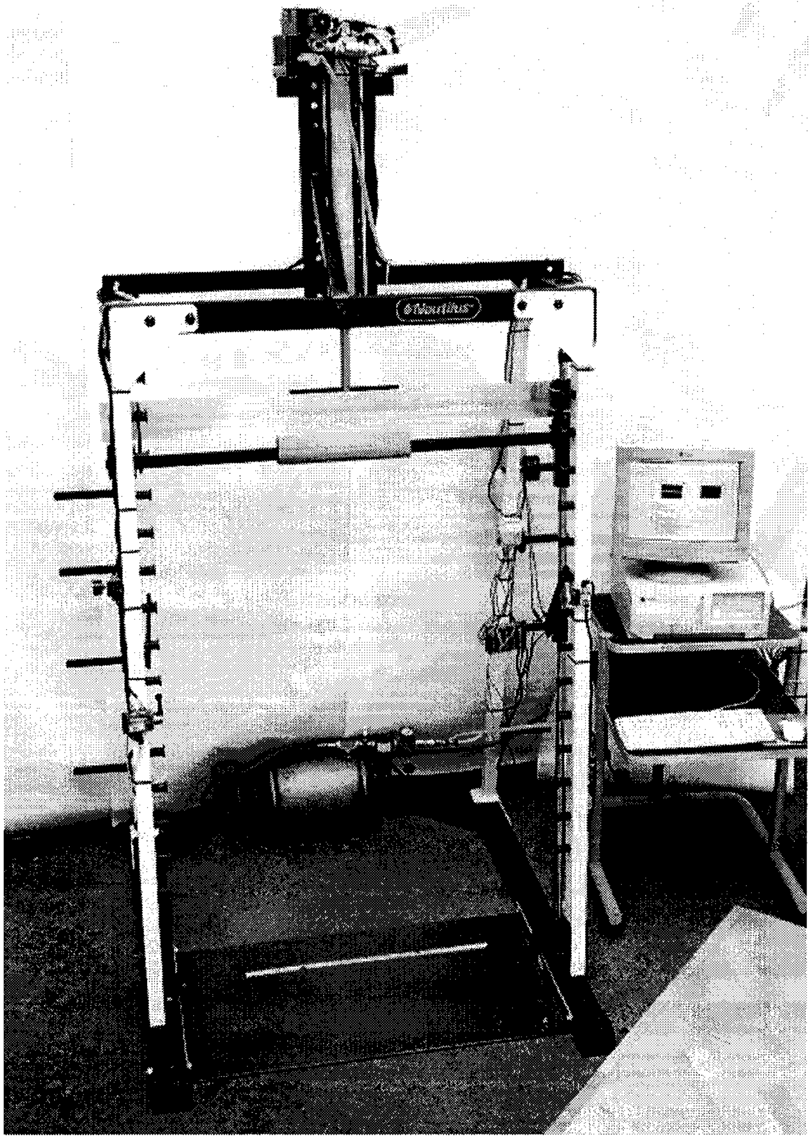


Figure 3.1: Front view of the entire apparatus. The pneumatic cylinder and valves are mounted above the Smith cage with the data collection computer to the right.

3.2. Pneumatics Design

The pneumatic system is described with an American National Standards Institute (ANSI) schematic diagram (Fig. 3.2).

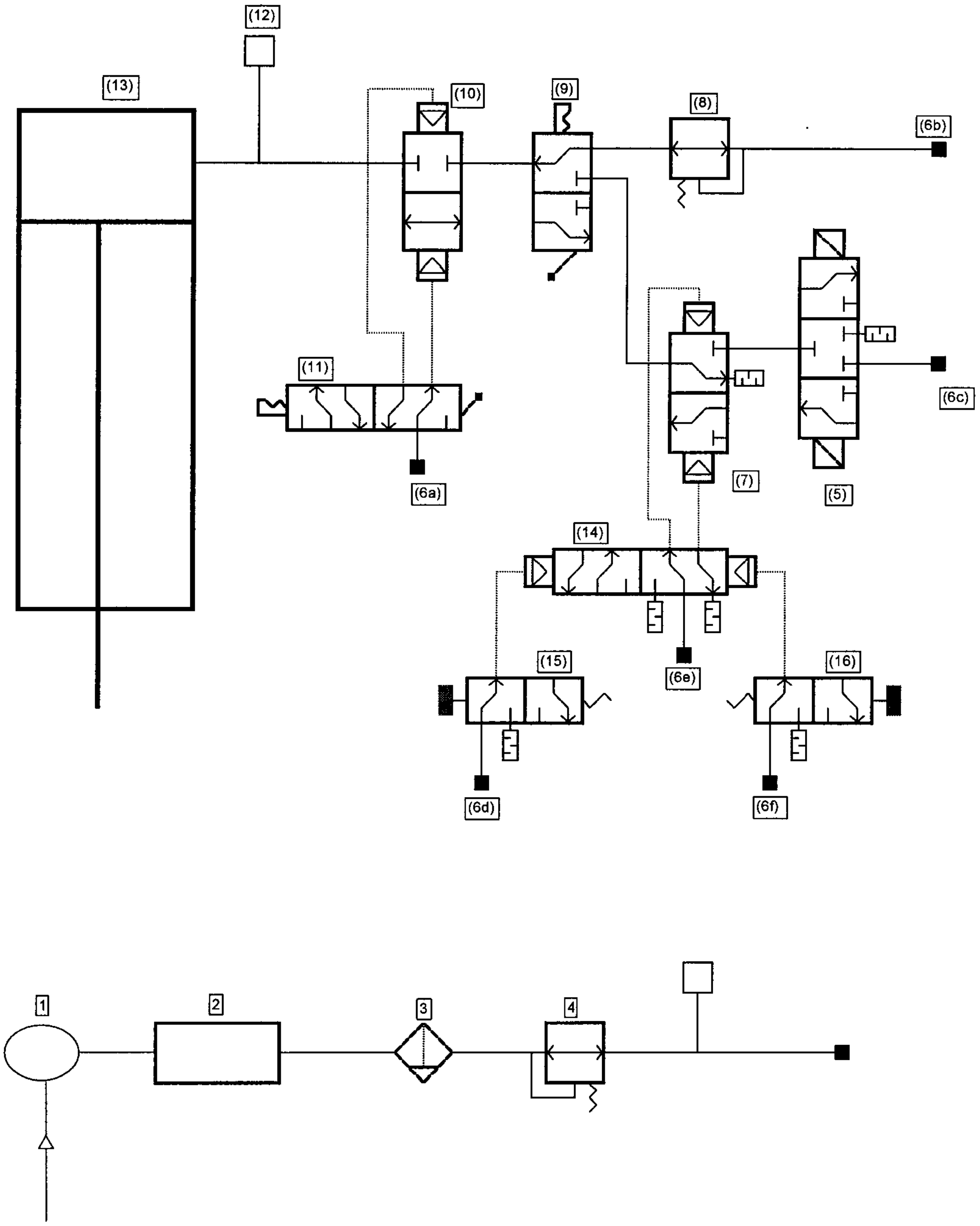
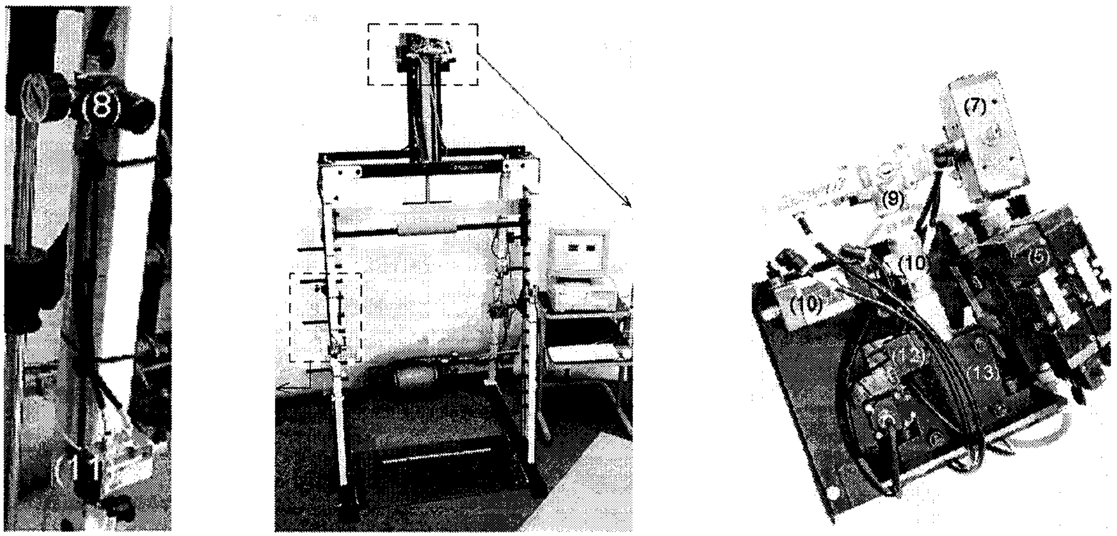


Figure 3.2: American National Standards Institute (ANSI) schematic diagram of pneumatic system. Numbering corresponds to text and Figure 3.1 descriptions.

A compressor (1) supplies 551.6 kPa (80 psi) compressed air to a 1.89×10^{-2} m^3 (5 gal) accumulator (2). The air is then passed through a filter (3) that condenses water vapor and removes particles greater than 5 microns. A pressure regulator (4) maintains a constant inlet pressure of approximately 517.1 kPa (75 psi). Next, the inlet pressure is split between the Proportional Pressure Controller (PPC, model 93A, MAC Valves Inc., Wixom, WI) (5) and a manifold that provides pressure (6) for several pneumatically operated valves. One destination of the manifold supply pressure (6b) is a regulator (8) used to directly control the pressure in the cylinder (13) for the isometric series when a manual valve (9) lever is turned 90° such that the regulator (8) is the source of pressure for the cylinder. When the manual isometric conversion valve (9) lever is turned 90° in the other direction, the PPC is the source for cylinder pressure. The manifold pressure (6c) also supplies inlet pressure to the PPC. Another pressure destination (6a) is the manual shutoff valve (11) that controls the shutoff valve (10) to close the cylinder when the desired pressure is reached for the isometric series. Supply pressure is sent to each of the three valves used in the emergency pressure relief system (6d, 6e, 6f), which consists of two punch button operated valves (15, 16) and an air operated four-way valve (14) that actuates the safety valve (7) closing the line between the cylinder and the PPC and exhausting any air in the cylinder. Lastly, a pressure transmitter (12) is located at the entrance to the cylinder and measures the cylinder pressure.

The actual hardware of the system is shown (Fig. 3.3), and it is numbered the same as in Fig. 3.2.



(a) (b) (c)

Figure 3.3: Front view of the testing apparatus in the center with enlarged views on left and right for detail: **(a)** the isometric regulator (8), and cylinder shut-off valve actuator (11), **(b)** front view with the pneumatic cylinder and valves mounted above the Smith cage and computer on the side, and **(c)** plan view of proportional pressure controller (5), safety valve (7), manual ISO valve (9), cylinder shut-off valve (10), pressure transmitter (12), and the cylinder (13).

The design specifications of the pneumatic system and the PPC are listed (Table 3.1 and Table 3.2, respectively) as published by the manufacturers.

Table 3.1. Design specifications of pneumatic system (TRD Manufacturing, Inc. Catalog TRD1-300).

Flow Media	Compressed Air
Pressure Range	0-80 psi
Maximum Force Required	500 lbsf
Cylinder bore diameter	3.25 in
Bore Area (Push)	8.296 in^2
Bore Area (Pull)	7.511 in^2
Road Diameter	1 in
Volumetric Displacement	199.2 in^3
Cubic Feet Displacement Per Inch Stroke	0.00480 ft^3/in
Pipe Size Diameter (Dynamic Resistance)	0.5 in
Pipe Size Diameter (Isometric Resistance and Supply Pressure)	0.25 in

Table 3.2. Design specifications of PPC (MAC Valves, Inc. Catalog: Proportional Pressure Controller, www.macvalves.com).

Fluid	Compressed Air
Accuracy	± 2.5% F.S. (±1.5psi)
Analog Command Signal	0 - 10 Vdc differential
Port Size	0.5 in NPTF
Pressure Range (Gage)	100 psi
Minimum Closed End Volume	100 in^3
Max Flow, Cv	6.2
Max Inlet Pressure (for 10-100 psi output pressure)	120 psi max for 100 psi
Max Inlet Pressure (for 10 psi outlet pressure)	20 psi
Calibration Gain	1V = 6psi

The PPC is sized for the flow factor, C_v, with equations and tables taken from the National Fluid Power Association (NFPA) standard T3.21.3. With a traditional orifice valve, it is considered good engineering practice to limit the pressure drop (ΔP) to approximately 10% of the primary pressure, and the secondary pressure should be at least 53% of the primary pressure so the flow does not become sonic (NFPA T3.21.3). The smaller the allowable pressure drop, the larger the required valve will become. The MAC proportional pressure controller has the technology to control the outgoing pressure from the onboard pressure transducer and control system, so it is not required to limit the pressure drop to 10% of the primary pressure or the secondary pressure to 53% primary pressure. The proportional pressure transducer rule of thumb for calculating C_v is to allot for a pressure drop of (15-20 psid). Because the valve C_v is specified in English units, the calculation is presented in the same unit system. The equation for calculating C_v is shown below in eqn. (3.1):

$$C_v = \frac{F \times L \times C}{B \times t \times 29} \tag{3.1}$$

where:

C_v = Flow factor (unitless)

F = Cylinder push bore area (in^2) = 8.30 in^2

L = Cylinder Stroke (in) = 24.00 in

C = Compression factor (at $P_{inlet.}$ = 80psi) = 6.4

B = Pressure drop factor (at $P_{inlet.}$ = 80psi, ΔP= 15psid) = 33.5

t = Time to complete one cylinder stroke (sec) = 1/3 sec

C_v is calculated using the most extreme condition (someone lifting approximately 2.23 kN (500 lb) the entire stoke of 609.6 mm (24 in) in a time of 0.333 seconds). The system has been limited to 2.23 kN (500 lb) resistance by calibrating the 0 - 10 V command signal to 10 V = 413.7 kPa (60 psi). The calculation of C_v is shown in eqn (3.2) as:

$$C_v = \frac{8.30 \times 24.00 \times 6.4}{33.5 \times 0.333 \times 29} = 3.94 \approx 4.0 \tag{3.2}$$

Therefore, a valve must be selected that has a C_v factor of 4.0 or higher. As seen on Table 3.2, the C_v of the PPC is 6.2; thus, it is sized appropriately.

3.3 Interactive Variable Resistance Control System Theory

The method of creating interactive variable resistance depends on the control logic. LabVIEW was used to program the logic subsystem that controls the pneumatic resistive system. The components of the closed loop feedback system contain a PPC with an on-board pressure transducer, a linear position transducer, and a velocity processor. The PPC compares the desired input pressure signal to the actual pressure in the cylinder and then rapidly supplies and exhausts air to reconcile the difference. The pressure in the cylinder determines the force on the cylinder rod (Pressure x Area of cylinder = Force). This provides the basis for the modulating system (Fig. 3.4).

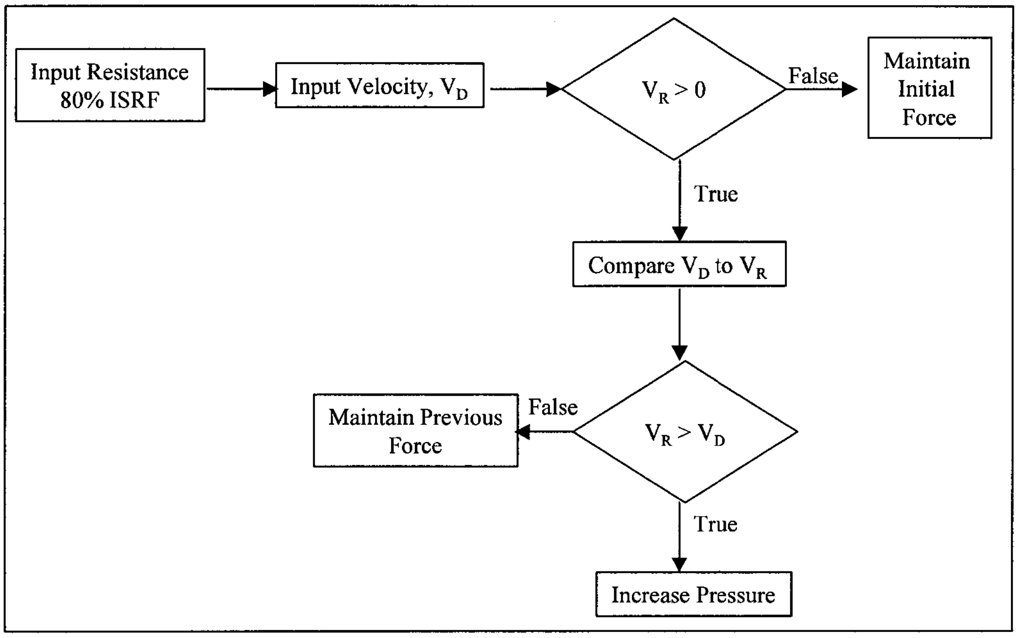


Figure 3.4: Flow chart of IVRE control logic with example input of 80% ISRF as utilized in study. V_R is the resultant velocity, and V_D is the desired velocity.

The input resistance level and desired velocity (V_D) are set to be the force and velocity that correspond to 80% of the ISRF on the F-V curve. The resistance then varies based on the participant's instantaneous resultant velocity

(V_R), such that if the V_R falls below V_D, the resistance level remains constant, but if V_R exceeds V_T, the resistance is increased. At maximal exertion a higher velocity indicates more strength capacity and the resistance level increases accordingly. Appendix D contains a printout of the actual code.

Multi-joint isokinetic squat studies of strength development consequent to repetition manipulation over a velocity spectrum show significant force improvements were significantly greater only at the slowest velocity (Weiss et al, 2001). Therefore, the desired velocity that is input for each individual is the velocity that corresponds to the force of 80% of the ISRF on the F-V curve. Eighty-percent of the ISRF was chosen because in traditional weight training, 80% of the one repetition maximum (1RM) corresponds to the six repetition maximum (6RM), which is considered heavy, but not maximal (Baker, 1995). Furthermore, Tan (1999) found that strength is best developed with 1 – 6 repetition maximum loads. Setting the initial resistance level to 80% ISRF assumes that the ISRF is approximately equal to the dynamic 1RM; however, regardless of the initial set point, the program quickly interacts with the participant and responds with a resistance level that is appropriate for the velocity that a participant is able to attain.

The exercise apparatus was tested for internal validity in order to ensure that the machine actually provides the resistance level that is desired and that the velocity data collection device measures what it was designed to measure. Three validation studies were performed to ensure validity: static force validation, dynamic pressure validation, and velocity validation.

3.4 Static Force Validation

The static force has been validated with the use of a digital scale (Healthometer, Inc., Bridgeview, IL, Model 4040) with a 1.78 kN (400 lb) capacity. The set up consisted of the digital scale placed on the steel footplate that rests directly on the floor. A steel support bar was placed on the scale and was used to transmit the force from the barbell to the scale (Fig. 3.5).

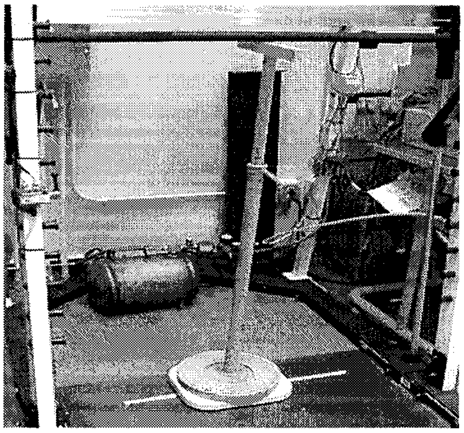


Figure 3.5: Support bar transmitting the force of the barbell to a scale.

The desired force to be output was entered into the LabVIEW control program, and the corresponding pressure was set by the PPC (1 V = 41.4 kPa or 6 psi). Once the system came to steady state, the force measured by the scale was recorded. The force was measured at a spectrum of positions, but the difference was negligible. Therefore, all measurements were taken at the middle of the twenty-four inch stroke.

The Nautilus "Smith" attachment constrains the motion at an angle of 5° off vertical; however, the scale only reads the vertical component of the force.

The vertical component is calculated by multiplying the resultant vector by the sine of 85°, or 0.9962. This could also be interpreted that 99.62% of the resultant force from the barbell is directed vertically, so the horizontal component of the force is virtually negligible and need not be included.

The test procedure consisted of placing the unloaded barbell on the support bar and setting the scale to zero. The weight of the barbell and support bar 184.6 N (41.5 lb) was considered tare weight and was not included in the forces that were recorded. The input force was applied to the barbell, and the measured force was recorded. After a measurement was taken, the input force was set to zero, the scale was returned to zero, and the process was repeated five times per input force. The average of the five measurements was taken and then used to calculate the percent difference between the input and measured force. The accuracy of the proportional pressure controller is ±2.5% full scale. That means that a measured force of ± 55.6 N (12.5 lb) of the input force is within the expected accuracy. The range of forces was from 111.2 N (25 lb) to 1.89 kN (425 lb) in 111.2 N (25 lb) increments. The input and measured forces are plotted against each other with high linearity ($R^2 = 1$) (Fig. 3.6).

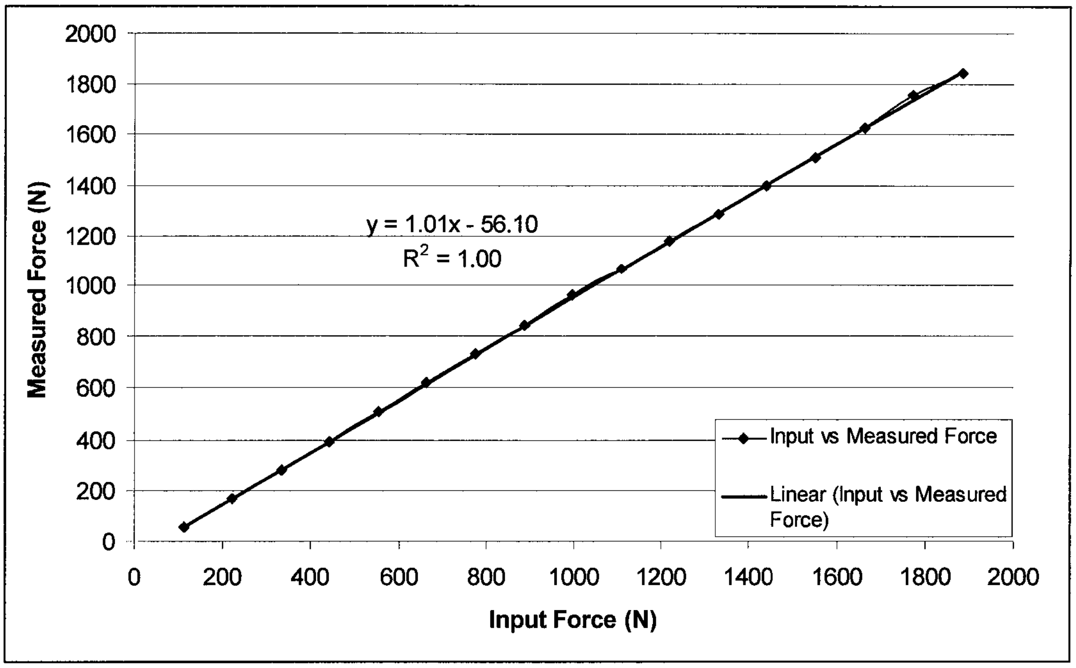


Figure 3.6: Input and measured forces tabulated to the left and plotted to the right.

The only point that is out of the specified accuracy is at the lowest expected force. This may be explained by the specification that for an outlet pressure below 68.9 kpa (10 psi) (equivalent to a force of 369 N or 83 lbs), the inlet pressure must be below 137.9 kPa (20 psi). During the testing the inlet pressure remained set above 482.6 kPa (70 psi) and may be attributed to the loss of accuracy only at the lowest expected force. A future recommendation would be to reduce the inlet pressure if such a low resistance level is expected.

3.5 Dynamic Pressure Validation

The dynamic pressure validation testing compared the desired or input pressure signal to the actual or output pressure signal recorded in the cylinder. This was achieved by inserting an independent pressure transmitter in the line between the cylinder and the proportional valve that controls the cylinder pressure. The pressure transmitter was a SUNX DP2-Series (Aichi, Japan) digital pressure sensor with LED display. The PPC was sent a constant voltage signal to maintain a constant pressure in the cylinder. Then the pressure transmitter linked to a data acquisition card logged the actual pressure throughout the lifting. A single subject performed four lifts in a row at maximal exertion at each input voltage. Then the input pressure was compared to the actual pressure with a t-test to reveal statistical significance. Figure 3.7 shows all the position, velocity, and pressure (actual and desired) data recorded for an input voltage of 4 V with the subject performing four repetitions in a row. English units are used (Fig. 3.7) in order to show the position and velocity on the same scale as pressure (i.e. 24 psi corresponds to full stroke of 24 inches for position and maximum velocity of 24 in/sec).

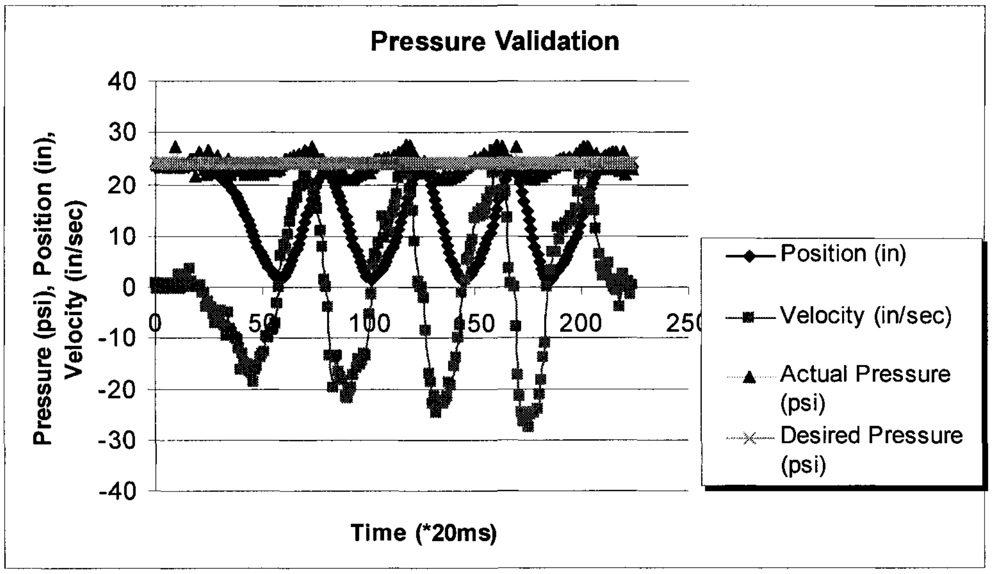


Figure 3.7: Dynamic pressure compared to desired pressure (165.5 kPa or 24 psi). The position and velocity are also given to show that it was recorded during four full repetitions.

The position starts near the top of the stroke (55.9 cm or 22 in) and decreases as the barbell is lowered to the bottom of the stroke (7.62 cm or 3 in) and increases back to the top of the stroke representing one repetition. This is repeated four times on Fig 3.7 representing the four repetitions. The velocity starts at zero and increases to the peak velocity (61.0 cm/s or 24 in/sec) for each repetition. The following three repetitions show a slightly greater magnitude of negative velocity for each progressive eccentric portions of the lift. The desired pressure remains constant (165.5 kPa or 24 psi) and the actual pressure closely oscillates above and below the desired pressure (Fig.3.7). The pressure increase that corresponds to the maximum velocity in Fig 3.7 can be explained by the frequency response testing that will be discussed later in this chapter, but it is sufficient to state that these pressure increases occur because the valve has a finite response capacity. For example, if the concentric portion of the lift takes 500 ms and the valve is only able to update its pressure ten times per second (10Hz), there is a 100 ms window for the pressure to exceed the set accuracy of the valve.

Statistical analysis using a t-test tells if there is a significant difference between the desired pressure and the actual pressure. The probability level for statistically significant difference was set at 0.05. The statistical analysis was performed in the same manner as a similar study that determined the validity and reliability of a kinematic device for measuring force developed during squatting with constant external resistance (Rahmani et al, 2000). The probability level for statistical significant difference (0.05) is exceeded in all cases (Table 3.3).

Table 3.3: No significant differences between desired and actual pressure.

Input Voltage (volts)	Desired Force (lbf)	Desired Force (N)	Probability Desired and Actual Pressure are Not Signif. Diff. (p=0.05)
1	50	222.4	0.93
2	100	444.8	0.12
3	150	667.2	0.11
4	200	889.6	0.49
5	250	1112.1	0.5

If the probability that the actual and desired pressures are equal is less than 0.05, the data sets are significantly different. Because the probabilities are all much greater than 0.05, there is no statistical difference between the desired and actual pressures at all force levels. The magnitude of the difference is great enough to rule out statistical significance that could result from collecting data with more trials. The reason for stopping at an input voltage of 5 V is that the subject was unable to lift loads exceeding that corresponding force value.

3.6 Velocity Validation

The velocity measurement taken from the velocity processor is tested for validity by comparing the recorded instantaneous velocity from the processor to the velocity recorded with a Peak Motus 8.0 (Peak Performance Technologies, Inc., Englewood, CO) camera system used to measure motion. The full range of velocities of a previously trained male subject at maximal exertion is covered. The extreme fastest velocity is recorded by lifting the unloaded barbell at a maximum velocity. Next, the extreme slowest velocity is recorded by lifting near the subject's 1RM resistance level. After that, three increments between maximum and minimum velocities are recorded. Four full ROM squats were performed at each resistance and consequently velocity range. The data are compiled and the mean of the four peak values are taken from each set and plotted against each other (Fig. 3.8).

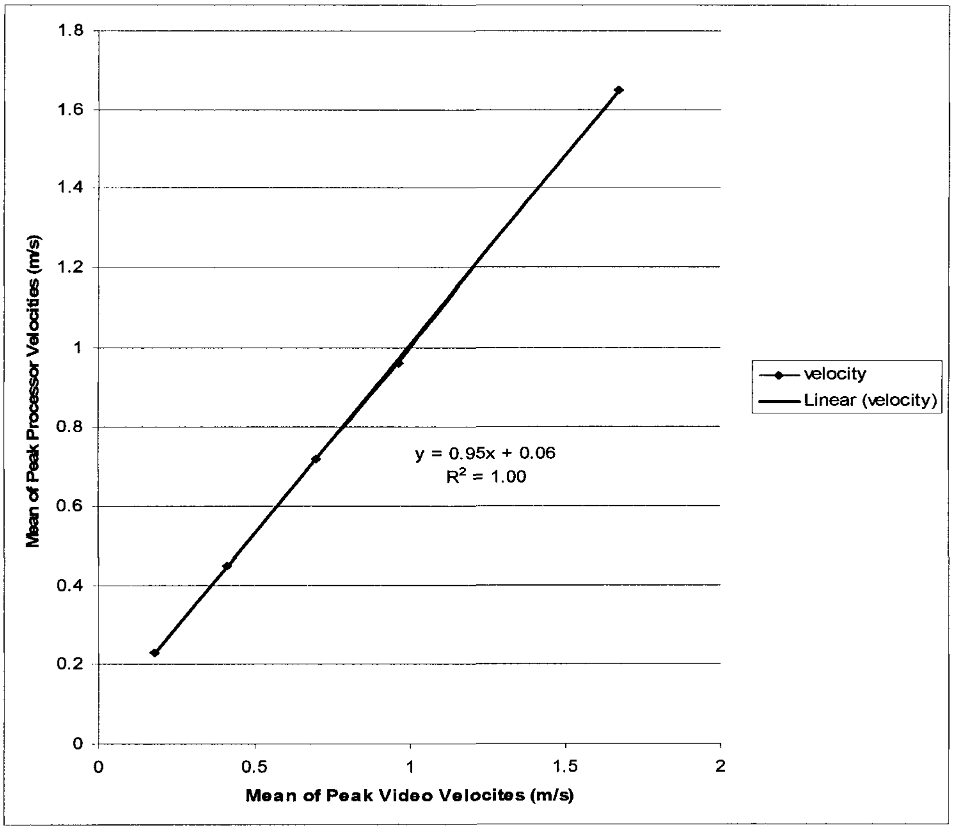


Figure 3.8: Plot of mean of peak video and processor velocities. Linearity shows agreement from the two systems.

The two systems have a high linearity showing agreement, thus the velocity processor is deemed valid.

3.7 System Response

System response analysis is based on the relationship between the desired output and the actual output (Histand and Alciatore, 1999). In theory, a system should respond in such a way that it replicates all frequency components of the input signal exactly. In reality, systems are limited in their ability to replicate all frequencies. The bandwidth of a system is the range of frequencies that it can adequately reproduce. The cutoff frequency, or high corner, is where the amplitude ratio (A_{out}/ A_{in}) is approximately equal to 0.707, or -3dB. Some factors that affect the bandwidth of a system are mass, stiffness, and damping in mechanical systems (Histand and Alciatore, 1999). The frequency response curve plots the amplitude ratio versus the input frequency. An ideal system would have a frequency response value of one at all frequencies from zero to infinity without amplification or attenuation.

The system response of interest is the PPC's ability to change the pressure in the pneumatic cylinder such that it matches the input signal. A sine wave generator was used to drive the PPC at a spectrum of frequencies. A pressure transducer located between the PPC and the cylinder is used to measure the output value. Before testing could begin, acceptable values for amplitude and direct current (dc) offset of the input sine wave had to be selected.

An appropriate amplitude for the input signal was determined to be 0.5 V (13.8 kPa or 2 psi). The reason for selecting this amplitude is the PPC is accurate to pressure changes greater than ±2.5% full scale or 10.3 kPa (1.5 psi). In other words, if there is not a difference greater than 10.3 kPa (1.5 psi) within the valve, then it will not supply or exhaust air to match the signal. Furthermore, because the application of the system is to provide resistance to a human subject, it is still reasonable to change the loading in increments of ±13.8 kPa (±2 psi), which is the equivalent to ±73.8 N (±16.6 lb).

The dc offset of the input sine signal was set at 5 V (206.8 kPa or 30 psi), which is the median of the entire range. DC offsets from 0.25 V through 9 V were used, and they showed no difference in frequency response among each other. Because frequency response is the variable of interest in this experiment, the fact that dc offset had little effect on the primary variable led to the decision to only use the median value as the dc offset.

The volume of the cylinder, as determined by the position of the barbell, affected the frequency response. Therefore, testing was performed over the entire range of the cylinder stroke.

The test set up included a function generator used to provide an input sine wave signal. The signal was delivered into a LabVIEW program used to drive the PPC. An oscilloscope and voltmeter were used as visual feedback to verify that the function generator was providing the desired signal (Fig. 3.9).

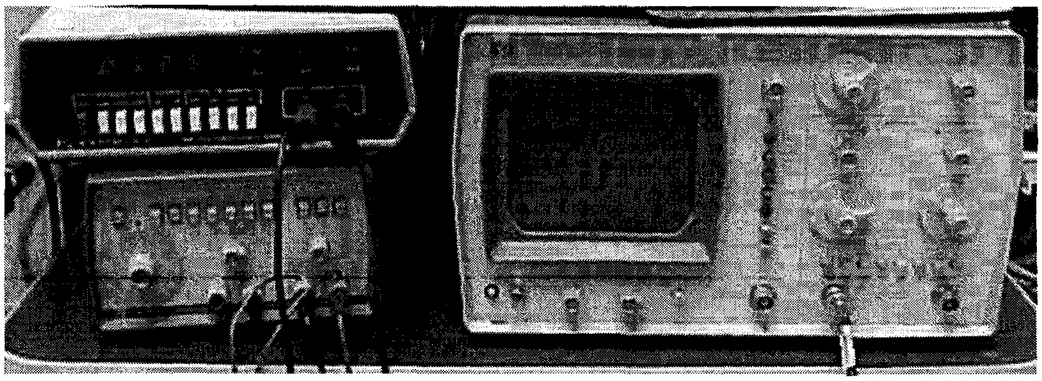


Figure 3.9. Voltmeter resting on the function generator with an oscilloscope to the right.

A digital pressure sensor with LED display was located at the entrance of the cylinder to measure the actual output pressure value over time. This string of values was also sent to the LabVIEW program for data logging and graphed as a visual aid. The pressure sensor location in the system is presented (Fig. 3.10).

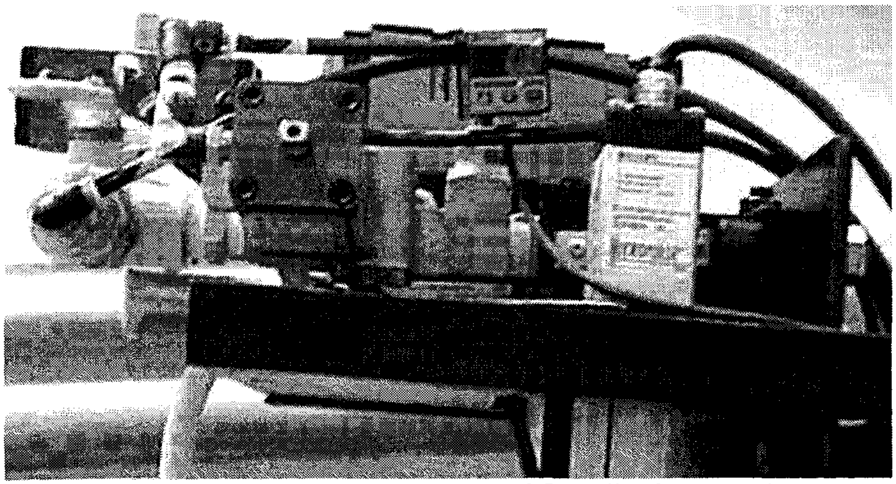


Figure 3.10. The pressure sensor with LED display used to record actual pressure.

The position of the rod is measured as zero with the piston in the lowest position (closest to the ground) and as 61.0 cm (24 in) with the piston in the highest position. The results of the experiment show that the frequency response is the greatest (best) between the positions of 35.6 cm and 53.3 cm (14 and 21 in) with a bandwidth of approximately 0 to 10 Hz. At the positions from 0 to 30.5 cm (12 in), the bandwidth was approximately 0 to 6.5 Hz. However, at the very top of the stroke at a position of 61.0 cm (24 in), the bandwidth was only 0 to 1 Hz. It is likely that this is caused by the valve overshooting because it has such a small volume of air, which would allow it to respond too strongly. The frequency response high corner (3 dB) at the positions that showed a transition in frequency response is shown (Table 3.4).

Table 3.4: The frequency response high corner at different positions.

Position (cm)	Frequency Response High Corner (Hz)
0 to 30.5	6.5
35.6 to 53.3	10
61	1

These values have practical meaning. For instance, responding with 10 Hz means that the system is able to respond with ±13.8 kPa (±2 psi) pressure ten times per second. Therefore, if a person required one-half of a second to complete the lift, the system would be able to respond five times with ±13.8 kPa (±2 psi) pressure, making a total change in force of ±572.3 N (±83 lbs). In most cases, the lifter demands a response of only adding pressure, so instead of ±13.8 kpa (±2 psi), it would respond with only +27.6 kpa (+4 psi) or 37.3N (166 lb). Notice that the faster response occurs on the high end of the lift when a person is capable of lifting more weight and would require more response from the IVRE control program. The very end position has a low response of 1 Hz.

This is acceptable because it is the end of the lift where little IVRE response is needed, and few people use the entire stroke. Later testing revealed that this end position was never reached while collecting data.

The design specifications of the PPC claim a minimum closed end volume of $1.64*10^{-3}$ m^3 (100 in^3), but due to the large volume of the cylinder of approximately $3.28*10^{-3}$ m^3 (200 in^3), it was undesirable to allow for $1.64*10^{-3}$ m^3 (100 in^3) of volume before entering the cylinder. This is the case because the bottom of the stroke would have a volume of $4.92*10^{-3}$ m^3 (300 in^3), and the system response is reduced greatly at such a large volume because that much more air must be delivered. The entire stroke splits the difference of the design operating point because the majority of the users will not be operating the cylinder at the extreme end points. This would explain the poor system response at the very top of the stroke because there was not enough volume in the cylinder for the valve to modulate the pressure with as much accuracy.

An interesting anomaly was realized while analyzing the amplitude ratio data. For positions from 0 to 35.6 cm (14 in), the amplitude ratio showed amplification ($A_{out}/A_{in} > 1$) as the system response diminished. However, from positions of 45.7 cm (18 in) to (61.0 cm (24 in), the amplitude ratio showed attenuation ($A_{out}/A_{in} < 1$) upon diminishing response. The author speculates that this is the result of a slower response with the larger volume at the bottom of the stroke. At the top of the stroke there is less volume and a faster response causing the PPC to overshoot causing a higher A_{out} than A_{in}, or amplification of the amplitude ratio.

3.8 Overview of Human Subjects Testing Procedure

Participants are healthy male and female adults between the ages of 18 and 24 years with no history of back pain or illness. The sample size is twelve males and twelve females. In order to address the research questions, data were collected from resistance exercise throughout the full ROM. The subjects were familiar with the squat exercise and apparently healthy with no history of knee or back pain. Prior to any lifting, a health questionnaire (Appendix D) was completed and reviewed with the investigator. All subjects were screened with medical examination consisting of a medical history report and an informed consent form (Appendix E). Height, in bare feet, along with mass was taken. Both men and women are studied due to the subtle difference in musculoskeletal characteristics between genders (Arendt, 1996).

The research herein does not allow for a change in foot position in order that the Smith squat motion mimics the biomechanics of free weights. Each subject performs the lift with his or her feet positioned such that the center of gravity of the system is directly over his or her feet. A schematic shows the Smith squat and knee flexion angle measurement (Fig. 3.11) (Tihanyi et al, 1985).

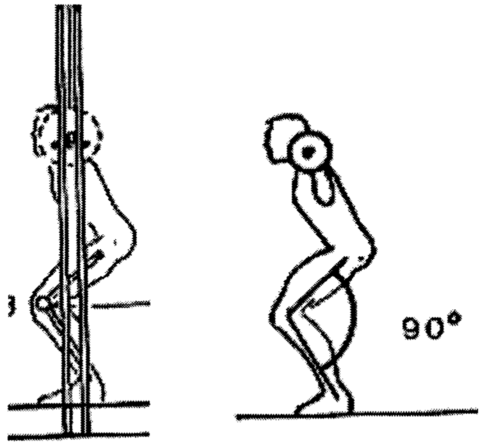


Figure 3.11. Schematic of Smith squat and knee flexion angle measurement (Tihanyi et al, 1985).

The testing protocol makes an assumption that the user is maximally exerting on each lift. The level of statistical significance was set at $p<0.05$ for all statistical procedures for all statistical analysis and result presentation. A difference from previously discussed research practices is that this research uses a mass-less (or mass-minimized) resistance which removes some of the inertial effects. However, the force values are normalized by body weight plus the weight of the barbell (9.32 N).

The subjects perform a total of twenty-two exertions. The first series of testing is a series of five maximal isometric muscle actions with negligible joint movement at knee angles of 90, 110, 130, 150, and 170° flexion (180° defines full extension) in random order. After a single five-second exertion for data collection with a sampling frequency of 50 Hz, the computer calculates Maximal Voluntary Isometric Force (MVIF) corresponding to the highest force at that knee angle every 20 ms. This 20 ms interval was digitally filtered with a LABView Mean filter to eliminate the effect of a very small voltage superimposed to the output of the pressure transducer (Driss et al, 2002). The maximum force produced over five seconds at each knee angle was recorded. This procedure was then repeated for each knee angle chosen at random, and a second set was repeated in reverse order to account for fatigue and learning curve. The two sets of data were averaged for further analysis. The ISRF is the lowest force produced during the isometric series. The form of results is shown in Appendix F (Table F.1).

A manual goniometer (Lafayette Instrument Co, Inc., Lafayette, IN) was used to measure each participant's knee angle, and the barbell height was adjusted accordingly such that the participant maintained the knee angle with their body configured in the proper form used during the squat exercise (Baechle et al, 1994). The mechanical stops of the Smith machine were moved to support the barbell at the desired location. This way, the barbell would not force the participant downward should the subject lose his or her balance or need to stop for any reason. Next, the cylinder was pressurized to the desired pressure such that the barbell could be moved upward slightly to accommodate for the compressibility of air, but less than two centimeters. Then the cylinder was closed off, the subject exerted maximally, using a safe building of effort to maximum and then slowly backing off of maximum effort over the five second interval, and the peak force was recorded. After the data point was taken, the cylinder pressure was relieved and the barbell was moved to the next corresponding knee angle. The mechanical stops were set in place, and the procedure was repeated.

The next five repetitions are full ROM squats at the constant resistance levels of 40, 50, 60, 70, and 80% of ISRF in order to create the force-velocity relationship. According to Tihanyi et al (1985), four data points are enough to generate the F-V curve. The mechanical stops were placed such that the barbell would not go down past 90° knee flexion as discussed for the isometric series. The subjects were instructed to stand beneath the barbell and support it with their shoulders as they released the barbell hooks from the rack. Then they were told to slowly lower the barbell to the mechanical stops. Each subject was instructed to exert maximally such that they moved the barbell as fast as possible and to rack the barbell at the end of the lift. The maximum positive velocity during the concentric phase of the lift is recorded during each of these lifts with the same digital filtering previously discussed. The force linearly extrapolated to zero velocity, F_0, is recorded from the F-V curve. The velocity that corresponds to 80% ISRF, or V_D, is also recorded. This procedure is also repeated in reverse order and the maximum velocities per resistance level are averaged. The form of results is seen in Appendix F (Table F.2).

The last two repetitions involve maximally exerting as the machine interactively varies the resistance level based on the user's instantaneous lifting velocity. The desired velocity is input, and the corresponding resistance level is set from the force–velocity curve generated from the previous sets. The subjects were instructed to slowly lower the barbell set at a constant resistance level to the mechanical stops and then to exert maximally to move the barbell as fast as possible on the concentric phase. They were informed that the resistance level would only increase during the concentric phase if the input desired velocity was exceeded. Thus, during the concentric phase if the resistance is too low and the subject exceeded V_D, the machine will increase the load in order to match the user's instantaneous strength capacity throughout the entire ROM. The changing resistance level is then recorded. The code was set such that once the peak IVRE resistance was reached, it would remain constant for the negative acceleration portion of the lift or until V_D was exceeded again. A lift must start and end with zero velocity. That means if the program continued to interact with the subject after the peak resistance was reached, the resistance would essentially go to zero as the velocity approaches zero. A programming tradeoff was made to maintain a constant resistance for the very end of the lift instead of allowing the resistance to return to zero.

CHAPTER IV

RESULTS

The purpose of this chapter is to give an overview of the human subjects testing results from the experimental testing. Although the engineering was performed and presented in English units, the results of the human subject testing are presented in SI units. After receiving university-approved informed consent, twelve men and twelve women between the ages of 18 and 24 years old (men: age = 20.3±2.1 yrs, height = 181.8±8.3 cm, mass = 80.4±16.0 kg; women: age = 21.0±2.2 yrs, height = 174.3±5.6 cm, mass = 71.4±16.4 kg) completed the exercise protocol. The Body Mass Index (BMI) is a metric used to describe relative weight for height, and it is significantly correlated with total body fat content (Vega and Jimenez, 2004). BMI is calculated as weight (kg) divided by height (m^2) and the average and standard deviation of all the subjects is tabulated (Table 4.1).

Table 4.1: BMI of human subjects who participated in the research.

Variable	Men (n=12)		Women (n=12)		Combined (n=24)	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
BMI (kg/m^2)	24.3	3.3	25.6	5.2	25.0	4.3

4.1 Isometric Series Results

The pneumatic design successfully supplied the desired cylinder pressure for isometric strength assessment and recorded peak pressure which was converted to peak force by multiplying by the effective push area of the cylinder. The structural design of the strength assessment device was a success in that it allowed for full ROM isometric testing for the entire sample of human subjects.

The average MVIF at each knee angle normalized by body weight and barbell weight of all the subjects is tabulated (Table 4.2) with a t-test between the sexes.

Table 4.2. Values of Normalized MVIF at each knee angle and t-test of means between the sexes.

Variables	Men (n=12)		Women (n=12)		
	Mean	Standard Deviation	Mean	Standard Deviation	t-test of means between sexes (p)
Normalized Force (N/N)					
$MVIF_{90}$°	1.05	0.29	0.70	0.27	
$MVIF_{110}$°	1.46	0.37	1.08	0.35	
$MVIF_{130}$°	1.86	0.51	1.42	0.41	
$MVIF_{150}$°	1.92	0.44	1.50	0.38	
$MVIF_{170}$°	1.80	0.41	1.37	0.35	
					p<0.001

The t-test reveals that the sexes are significantly different ($p<0.001$) in MVIF. The peak MVIF occurred most frequently at 150° knee flexion (Fig. 4.1).

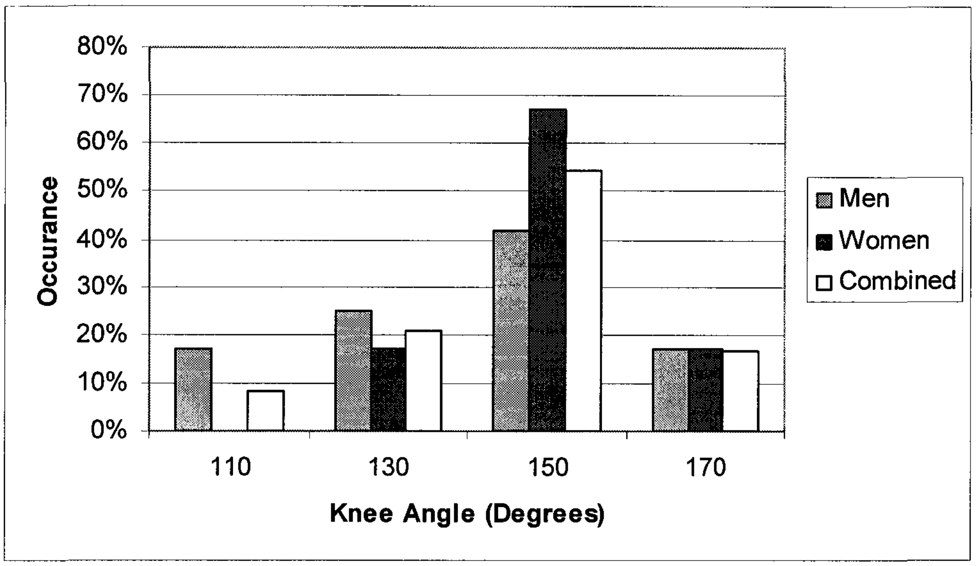


Figure 4.1: Histogram of peak MVIF at corresponding knee angle.

The data are plotted (Fig 4.2) and separated as men only, women only, and combined.

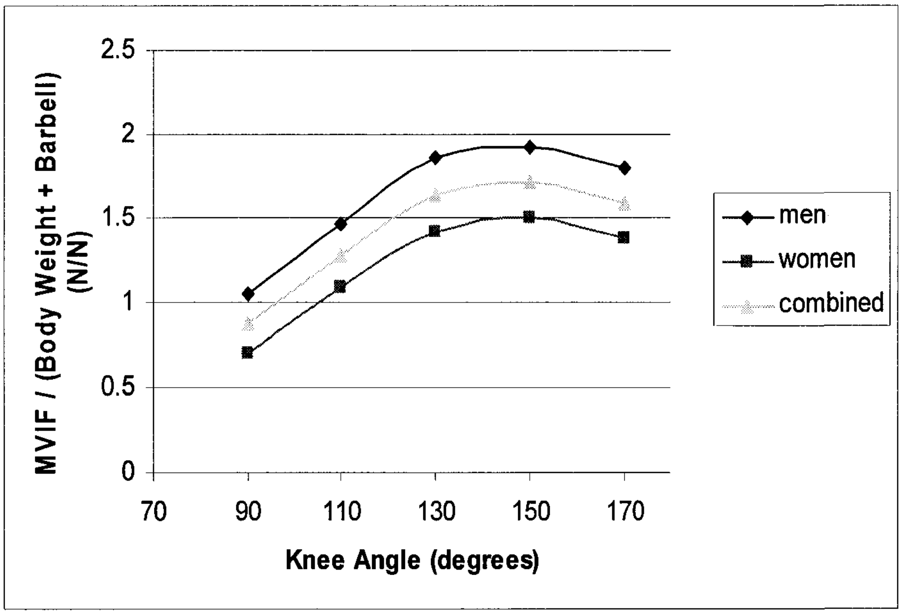


Figure 4.2: Average MVIF / (Body Weight + Barbell) at each knee angle for men, women, and combined men and women.

The mean percent difference between the peak MVIF value and the Isometric Sticking Region Force (ISRF) is 46% (±13%) for men and 57% (±10%) for women. The combined data shows that the peak MVIF is an average of 51% (±13%) higher than the ISRF.

A typical trend of an isometric strength curve is represented by the single person exemplar data (Fig. 4.3).

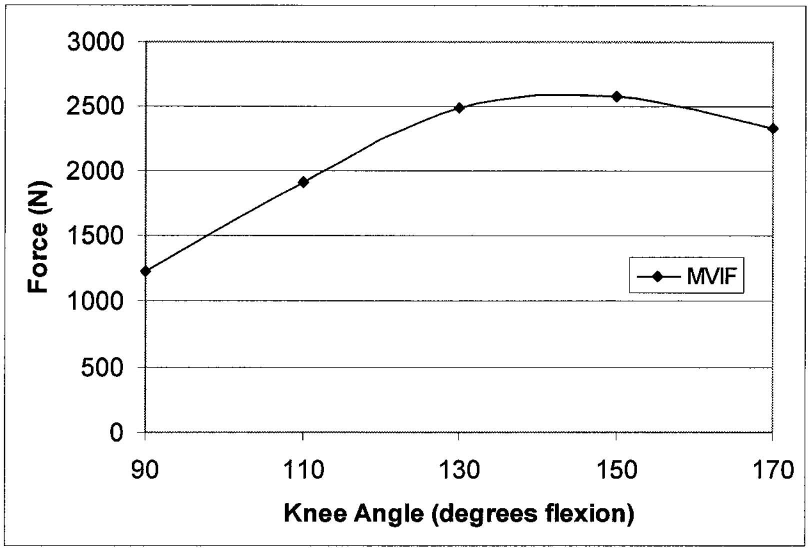


Figure 4.3. Exemplar isometric strength curve for one participant.

A point to be noted about the exemplar isometric curve (Fig. 4.3) is that the range of strength is captured with the 90° and 150° knee flexion forces for this person. Another key piece of information gleaned from the isometric series is that the ISRF occurred at a 90° knee flexion angle.

The effects of gender and condition (knee angle) were examined with a 2x5 repeated-measures Analysis of Variance (ANOVA). If the interaction between the gender and condition was found to be significant, then simple main effects (SME) were analyzed to determine the differences between genders and conditions. If differences were found across condition for each gender, then a post-hoc, one-way repeated measures ANOVA with Bonferroni confidence interval adjustments were conducted to determine where the differences existed.

If the interaction between gender and condition was not found to be significant, but the main effect for condition was significant, then a post-hoc one-way repeated measures ANOVA with Bonferroni confidence level adjustment was conducted to investigate the location of the differences in the whole group. Regardless of the significance of the interaction between gender and condition, if the main effect for gender was found to be significant, simple main effects were conducted to determine the condition(s) where differences occurred.

Due to the exploratory nature of this study, $p< 0.05$ was used to determine statistical significance. The condition for the isometric testing is knee angle. The results of the ANOVA reveal that men produced significantly greater force than women at every knee angle ($p=0.001$). The interaction between gender and condition was not found to be significant (0.536), but the main effect for condition was significant (0.001). The location of the differences in the whole group reveal that the forces at 90° and 110° are significantly different from each other as well as with those at 130°, 150°, and 170° for both men and women ($p<0.02$). However, the forces at 130°, 150°, and 170° ($p>0.05$ each) were not significantly different from each other for both sexes ($p=0.536$). The lowest MVIF over the ROM, or the ISRF, occurred at 90° knee flexion angle without variation.

4.2 Force Velocity Results

The maximum velocity of the concentric lift was recorded at five increments with resistance levels ranging from 40% to 80% of the ISRF. A single person exemplar data set shows a typical velocity profile at a relatively fast rate (Fig. 4.4).

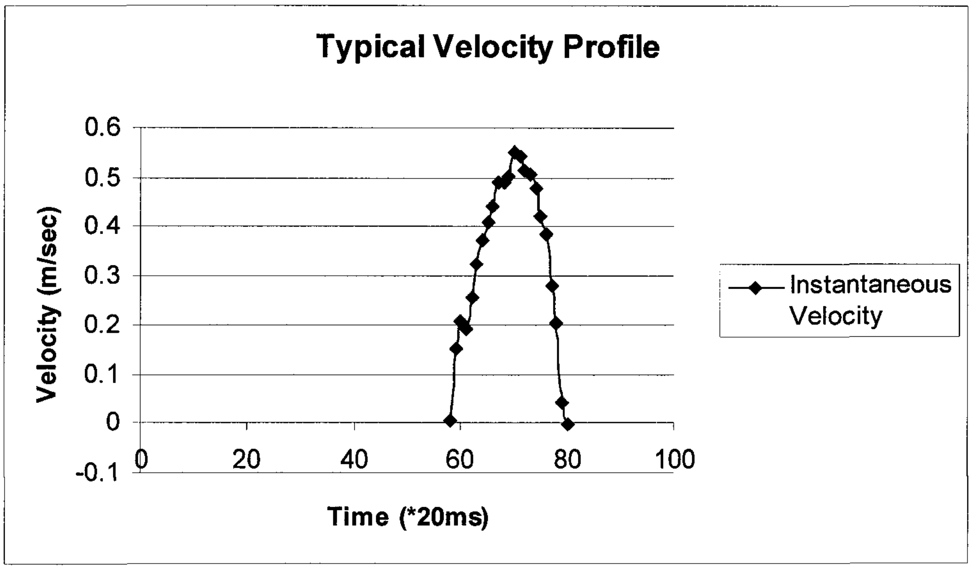


Figure 4.4: Exemplar Velocity – Time curve for one participant.

The velocity plotted over time in Fig. 4.4 was taken from only the concentric (raising) portion of the lift because the eccentric (lowering) portion of the lift was not of primary concern in this particular study. Only the peak value of instantaneous velocity was taken to plot the individual Force-Velocity curve. The average peak velocity from the two lifts per force was plotted against its corresponding force normalized by body weight and the weight of the barbell (184.6 N or 41.5 lb). The average compiled data are tabulated (Table 4.3) separated by men only, women only, and combined and plotted (Fig. 4.5)

Table 4.3: Average normalized force and velocity values with a t-test of the means between the sexes.

Variables	Men (n=12)		Women (n=12)		
	Mean	Standard Deviation	Mean	Standard Deviation	t-test of means between sexes (p)
Average Velocity (m/s)					
$V_{40\%ISRF}$	1.12	0.18	0.85	0.12	
$V_{50\%ISRF}$	1.04	0.17	0.80	0.14	
$V_{60\%ISRF}$	0.98	0.14	0.75	0.13	
$V_{70\%ISRF}$	0.88	0.16	0.71	0.09	
$V_{80\%ISRF}$	0.82	0.16	0.63	0.09	
					0.0003
Average Force (N/N)					
$F_{40\%ISRF}$	0.42	0.12	0.28	0.11	
$F_{50\%ISRF}$	0.53	0.14	0.35	0.14	
$F_{60\%ISRF}$	0.63	0.17	0.42	0.16	
$F_{70\%ISRF}$	0.74	0.20	0.49	0.19	
$F_{80\%ISRF}$	0.84	0.23	0.56	0.22	
					0.0011

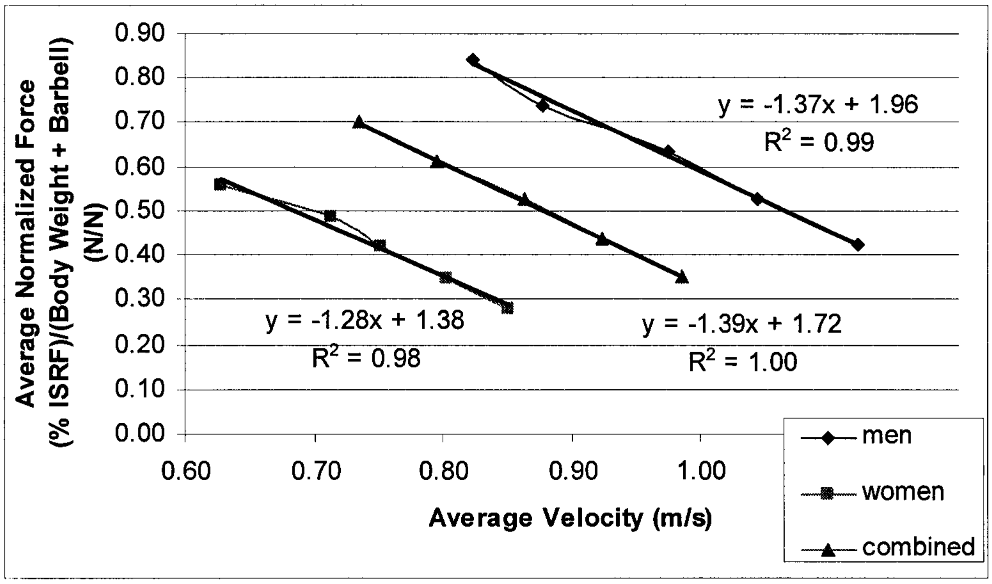


Figure 4.5: Results of average F-V curves for men, women, and combined.

The dark black trend line of Fig. 4.5 shows the linear trend line of the data, and would reveal F_0 if extrapolated to the y-intercept. The compiled average data shows the slope-intercept equations with the R^2 value. In order to determine if an isometric value could be used to predict dynamic F_0, the men and women's average intercepts are compared with the individual values of peak MVIF and ISRF (Table 4.4).

Table 4.4: Average F_0 compared to isometric values of peak MVIF and ISRF to determine a relationship between isometric and dynamic values.

Variables	Men (n=12)			Women (n=12)		
	Mean	Standard Deviation	t-test of each individual's value with average F_0 (p)	Mean	Standard Deviation	t-test of each individual's value with average F_0 (p)
Average F_0 (N/N)	1.96			1.38		
Average Peak MVIF (N/N)	2.00	0.45	0.72	1.58	0.40	0.12
Average ISRF (N/N)	1.05	0.29	$3.31*10^{-7}$	0.70	0.27	$3.13*10^{-6}$

The men and women's individual values of peak MVIF are not significantly different from the average F_0 (p = 0.72 and p = 0.12, respectively). However, ISRF is significantly different than F_0 for both men and women ($p = 3.31*10^{-7}$ and $p = 3.13*10^{-6}$, respectively). The percent difference between peak MVIF and F_0 is 2% for the men and 13% for the women. The average percent difference between ISRF and F_0 is 46% for the men and 49% for the women. Although the men's peak MVIF is close to F_0, there is variation as to the knee angle in which the peak MVIF will occur. However, the ISRF consistently occurs at 90° knee flexion, so it would be feasible to predict F_0 with the ISRF value because the percent difference of approximately 50% is known.

An ANOVA was also performed on the force-velocity data. The results of interest show that there was an interaction between gender and condition ($p=0.001$). The velocity for men was higher than that of women in all cases ($p=0.021$). The SME showed that men were faster in every condition ($0.01<p<0.015$). The 1x5 across conditions showed a significant difference between points for men and women ($p<0.001$ each). This is because the slope for the women was less steep, but there was still a trend on inverse linearity.

4.3 Interactive Variable Resistance Results

A typical IVRE force profile for a man during the concentric portion of the lift is shown (Fig. 4.6). Although the data presented was recorded for a man, the general trend is similar between the sexes. Notice that the resistance level remains constant when the maximum resistance is reached. This is due to a control system trade-off discussed in chapter three. The variable of interest is the peak force reached as the peak velocity was reached (around time = 88 * 20 ms).

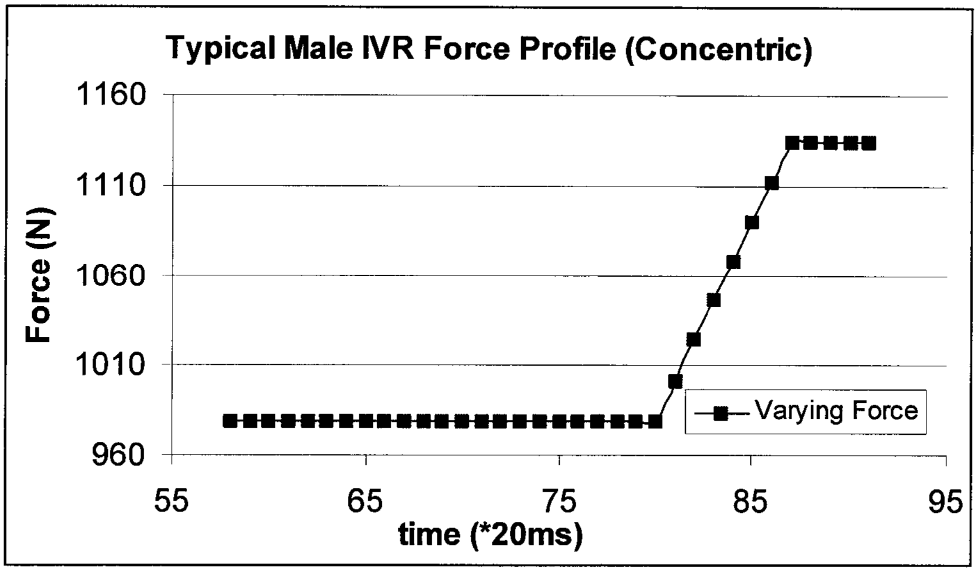


Figure 4.6: Typical male IVRE force profile during concentric lift.

A single person exemplar data set for instantaneous velocity during the IVRE lift is plotted (Fig. 4.7). The positive slope of the velocity-time curve is speeding up, and the negative slope is slowing down.

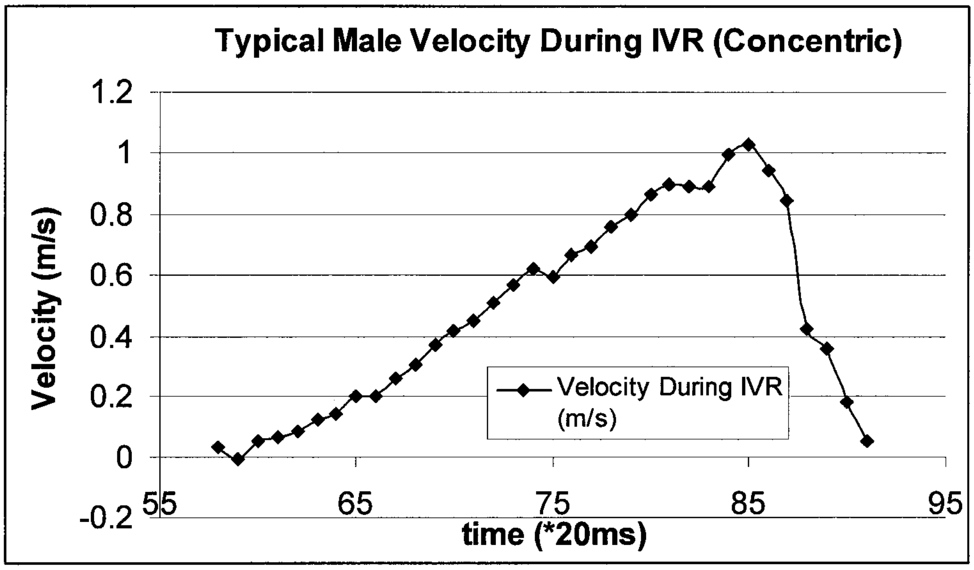


Figure 4.7: Typical velocity profile for a male during IVRE concentric lift.

The mean and standard deviation percent increase in force delivered during the IVRE was calculated for men only, women only, and combined (Table 4.5). The average percent increase in resistance during the IVRE lift was approximately 14% for men and 29% for women. A t-test between the men and women on the percent increase in force from the IVRE revealed that there was a significant difference (p = 0.005) in the percent increase with the women having a higher percent increase.

Table 4.5: IVREE percent increase significantly different between sexes.

Variable	Men (n=12)		Women (n=12)		Combined (n=24)		
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	t-test of means between the sexes (p)
Average IVRE % Increase	14%	5%	29%	14%	22%	13%	0.005

Another relationship that was explored (Table 4.6) is between the peak value attained during the IVRE lifts and the ISRF. There is no significant difference between the IVRE maximum and ISRF for men or women (p=0.06 and 0.111, respectively). The average percent difference between peak IVRE value and ISRF was approximately -6% for men and 11% for women. That means that the men peaked at an average of 6% below the ISRF value during the IVRE lift, but the women exceeded it by an average of 11%.

Table 4.6: Average percent difference between IVRE Max and ISRF.

Variable	Men (n=12)			Women (n=12)			Combined (n=24)		
	Mean	Standard Deviation	t-test between IVRE Max & ISRF (p)	Mean	Standard Deviation	t-test between IVRE Max & ISRF (p)	Mean	Standard Deviation	t-test between IVRE Max & ISRF (p)
Average Percent Difference between IVRE Max & ISRF	-6%	9%	0.06	11%	17%	0.111	3%	16%	0.727

The average percent difference between the peak force value during the IVRE lift and the ISRF tells how the machine responds with an initial loading of 80% ISRF. A t-test was performed between the peak IVRE value and 80% ISRF immediately after the subject performed the lift to verify that the control program was working properly. It showed whether each individual's changing force profile was significantly different from the initial force had it remained constant throughout the ROM. The individual data is presented in Appendix G, and the aggregate data shows the difference in peak IVRE value and the initial resistance level of 80% ISRF.

The change in resistance level is from the initial resistance of 80% ISRF to the IVRE maximum (Fig. 4.8). The percent increase from initial resistance level to the maximum was an average of 14% (±5%) for men and 29% (±14%) for women with 22% (±3%) average combined increase. The men's maximum normalized resistance level was significantly higher than the women's (p=0.04), but the women had a significantly greater percent increase (p=0.005).

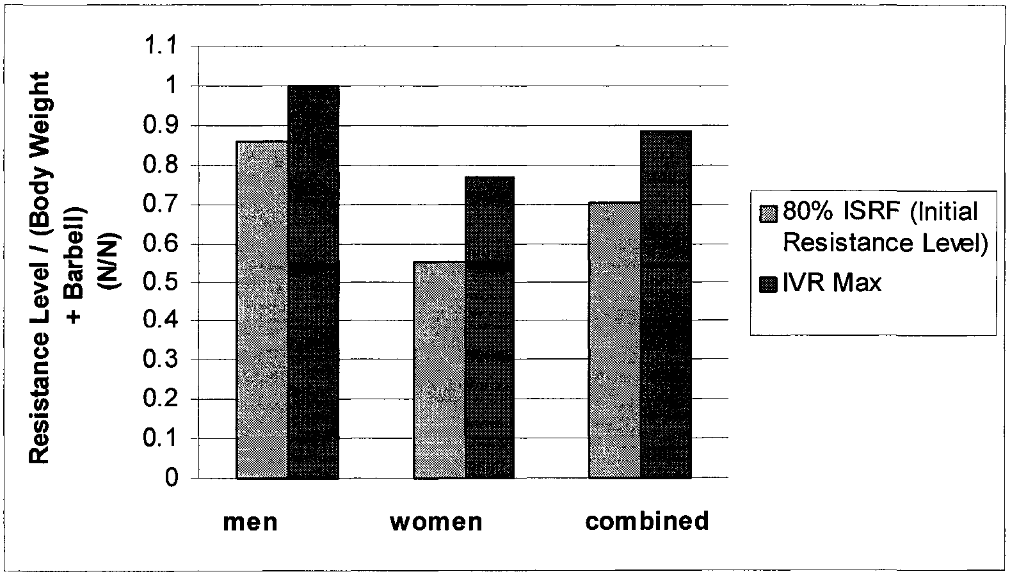


Figure 4.8: Change in normalized resistance level from initial (80% ISRF) to maximum during IVRE.

CHAPTER V

DISCUSSION

The following chapter discusses the results of the research and how they correspond to the findings of other studies. A brief discussion is given on the human subjects and the results of the isometric, force–velocity, and IVRE results to bring to light any new biomechanical knowledge gleaned from the research. The human subject testing data consists of the average of two exertions per condition. The average of only two performances is not sufficient to completely rule out the possibility of variability of performance. Factors such as daily diet, sleep, fatigue, or even motivation could play an important role in changing someone's results from one day to the next. While extreme care was taken to ensure accurate data collection, multiple tests and more participants would be needed to make a more absolute statement as to the overall trend of these results.

5.1 Human Subject Comparison to National Average

Some limitations of using BMI include overestimating body fat in very muscular people or underestimating body fat in those of advanced age who have lost muscle mass. Overweight is defined as a BMI of 25 to 29.9 kg/m^2 and obesity as BMI ≥ 30 kg/m^2 (Vega and Jimenez, 2004). According to a recent

U.S. National Health and Nutrition Examination Survey (NHANES 1999-2000), 64.5% of the adult population is overweight, including 30.5% of U.S. adults that are obese (Flegal et al, 2002). The human subjects that participated in this research were on average overweight but right at the cutoff with normal (Table 4.1).

Nine out of the twenty-four participants (five men and four women) had a BMI > 25, categorizing 38% of the sample size overweight including the two subjects (one man and one woman), or 8%, categorized as obese. The remainder were within the normal range. In order to eliminate the effects of body weight, the results were normalized by body weight plus the weight of the barbell, since in general a heavier person is expected to be stronger (Vega and Jimenez, 2004).

5.2 Isometric Discussion

The histogram of peak MVIF per knee angle (Fig 4.1) shows an interesting trend. Although there is a high frequency of peak MVIF at 150° knee flexion, there is still variance as to the knee angle at which the peak occurs. This further proves the variability of the strength curve for the squat exercise from person to person and trial to trial as found by Tihanyi et al (1985). The variance could also be related to the limited number of trials per person. Motivational factors that were discussed in chapter two could also introduce variability.

The consistency of the ISRF occurrence at 90° leads to the conclusion that the ISRF may be determined from a single isometric exertion at a 90° knee angle. Further information gleaned from the data is that the majority of the isometric strength curve range is captured with the isometric force at 90° knee angle and one other isometric force as the lower and upper extremes, respectively. Because the ANOVA revealed no significant difference between the forces produced from 130° to 170° knee-flexion, it could be possible to determine the entire range of isometric strength capacity with only two exertions such as 90° and 150° as seen with the averaged data (Fig. 4.2).

Each person's individual maximum ROM for the traditional free-weight squat exercise depends on the lowest or "bottom" position of the lift according to Earle and Baechle (2004). It is determined by allowing the hips and knees to flex until one of the following events first occurs: the thighs are parallel to the floor, the trunk begins to round or flex forward, or the heels rise off the floor. Testing was not performed below 90° knee-flexion partly because it is generally that there is an increased risk of knee injury associated with deep knee bend squats as performed in competitive weight lifting. The greater stress about the knee at the lower portion of the ROM was explained in the biomechanics of the squat exercise in chapter two in which there is a greater moment arm at the knee placing most of the torque on the knee complex. The range of motion studied in this research effort was also limited to the portion of the lift from 90° to 180° knee-flexion also to eliminate the variance of each individual's maximum range of motion. Bosco et al (1996) also limited their subjects to this ROM sometimes referred to as a "half-squat" even though more than half of the ROM is encompassed in this range. Hence, the results of ISRF occurring at 90° knee-flexion should be qualified that 90° knee-flexion was set as the lower limit on the ROM. Without this qualification there is the possibility that an individual's ISRF could occur below 90° knee-flexion.

The force production capability at the ISRF, or 90° knee-flexion, is an average of 51% lower than that at the force possible at the strongest point of the exercise cycle for men and women combined. This delta further enforces the need for an exercise system that can provide variable resistance that meets the user's strength capacity throughout the ROM. The greater percent difference in isometric force for women than men could show a biomechanical difference between the sexes in terms of variation of strength capacity throughout the ROM. It is possible that this variation is a result of the difference between the genders in muscle length and pennation angle, which is the angle of the muscle fiber's direction of pull relative to the direction of pull of the entire muscle or the direction of pull needed to produce movement at a joint (Fleck and Kraemer, 2004). It is determined by the angle at which muscle fibers attach to their tendons. Muscle fiber pennation angle and length are associated with muscle fiber force and velocity shortening capabilities (Fleck and Kraemer, 2004). A larger pennation angle may allow a greater amount of muscle packing, which creates a greater force exerted on a tendon for the same muscle volume. Although only a few studies have examined the effect of gender on muscle fiber characteristics (Fleck and Kraemer, 2004), Chow, et al. (2000) found that the gastrocnemius and soleus muscles of females have greater average muscle fiber length and greater variation in fiber length. Males had greater pennation angles in these same muscles. Longer muscle fibers have more sarcomeres arranged in series, which allows greater muscle contraction velocity and excursion. However, no firm conclusions concerning gender differences in muscle fiber length and pennation angles can be made with absolute certainty because relatively few studies have examined these characteristics (Fleck and Kraemer, 2004). It is possible that men have greater pennation angles and women have longer muscle fibers in general, but this could also be an isolated case in the calf muscles. However, if men did have steeper pennation angles in general, it would contribute to men producing higher forces, and if women have longer muscle fibers in general, it could theoretically create a greater delta in force production capability.

The average trend of the experimental isometric strength curve results agree with the simplified theoretical model (Fig. 2.14) in that the force production capability increases with knee extension angle, except that the force production is reduced at 170°. The reduced force at 170° could result from muscle lengths having reduced cross-bridge attachments as well as a limited muscle moment arm reducing the force output capabilities of the contracted muscles.

Rahmani et al (2001) found the extrapolated F_0 to occur 23% higher than MVIF at a 90° knee angle, unlike the current research that found F_0 to be approximately 50% higher than the MVIF 90° knee angle. However, the forces that were measured were ground reaction forces taken from a force plate underfoot while lifting a mass for resistance. Newton's second law states that the force would need to be higher when accelerating the mass from rest. The present research used pneumatics, which is a reduced mass form of resistance, although the subjects still had to accelerate their body mass and that of the barbell assembly. Also, the velocity used by Rahmani (2001) was an average velocity instead of the peak velocity used in the present research. Peak velocity was used because it reveals the human performance parameter of instantaneous maximum velocity capacity without being filtered out in an average over the time spent accelerating and decelerating the barbell at the beginning and end of the lift. Moreover, this instantaneous maximum velocity is the parameter of interest in IVRE because it is the variable by which the control system varies the resistance level.

Murphy et al (1995) recommend performing isometric tests at the joint angle at which the peak force is developed during the performance of interest. Rahmani et al (2001) found peak dynamic ground reaction force developed during the squat exercise to occur at a knee angle of 110°. The results of this static research indicate that the MVIF at 110° did not correspond to the theoretical peak dynamic force, F_0. While several subjects in this study did produce their peak MVIF at 110°, the majority were at 150°. 150° is more reasonable because the hamstrings would be active and the moment about the knee would be reduced.

5.3 Force–Velocity Relationship

The squat exercise exhibited an inverse linear relationship between average force and velocity with a combined $R^2 = 1$. Such a linear relationship agrees with those obtained during cycling, another multi-articular movement

(Vandewalle et al, 1987; and Driss et al, 2002). This linearity between force and velocity was also found in studies involving the squat exercise with DCER (Rahmani et al, 2001, Bosco et al, 1995).

Figure 4.5 shows the slope of the averaged data. Men recorded higher average forces and velocities with every lift. This is in agreement with results from Bosco et al (1995). This difference between the sexes could be attributed to the biological effects associated with heavy resistance training. Weiss et al (1983) found that during this type of training an increase of serum testosterone was shown in men but not in women. Therefore, since all the participants were previously trained, it is likely that adaptive changes associated with sex hormones were more pronounced in the men than the women. This is also evident in the isometric series results which showed men consistently producing forces greater than in the women.

Other gender related differences exist that could account for men producing higher forces and lifting velocities. For example, although muscle fibers in men and women are similar in fiber-type distribution and histochemical characteristics (Faigenbaum, 2000), men tend to have larger muscle fiber cross-sectional area than women. Women are generally weaker than men in terms of absolute strength because of their lower overall quantity of muscle. However, there is no difference between the sexes when comparing strength relative to cross-sectional area, indicating muscle quality is not specific to sex (Faigenbaum, 2000).

Women's maximal power (force*velocity) output in absolute terms as well as relative to muscle size is lower than men's in some physical tasks (Fleck and Kraemer, 2004). The reason for this is not known for sure, but it could be attributed to differences in type I (slow-twitch) and type II (fast twitch) muscle fiber cross sectional area and differences in rate of force development between the sexes. There is no consistent evidence that percent muscle fiber type varies by gender within a particular muscle (Drinkwater, 1984), but there is a difference in women having a smaller type II relative to type I muscle fiber area that results in women producing lower power output per cross sectional area than men (Fleck and Kraemer, 2004).

Figure 4.5 shows that women's average linear fit slope is less steep than men's which disagrees with Bosco et al (1995) whose findings show women having a steeper slope than the men. The difference could be attributed to the difference in sample populations used. Bosco et al (1995) used seven female and fourteen male track and field athletes, which is a more specific population of seasoned athletes than the criteria used in the present research of familiarity with the squat exercise. It is possible that the highly trained female subjects used by Bosco et al (1995) exhibited physiological adaptations from training that would alter their performance such that the females performance was more similar to males than the general population of females. This theory is supported by Taylor et al (2000) who found that women with at least one year of weight training experience exhibit longer time periods of growth hormone elevation above resting values. This elevation results in a greater magnitude of growth hormone response compared to women with no regular weight training experience. When comparing the slopes from previous studies to the present research, it is important again to delineate between them such that "apples" are compared with "apples." A primary difference to keep in mind is the velocities used by Bosco et al (1995) and Rahmani (2001) are average not peak values, and the forces are average ground reaction forces produced while lifting a mass, not forces produced from constant pressure in a cylinder for resistance. Although there are many similarities in the general trend of the relationships between both methods of calculating force and velocity, the differences must be maintained for proper comparison. Thus the magnitude of slopes should not be numerically compared; rather only the general trend should be compared.

The force-velocity plots of Fig. 4.5 show that there is a subtle difference in slope between the men and the women; however, the intercepts are very different. The difference in intercept exists because the men's force-velocity curve is higher in both force and velocity making the intercept subsequently higher as well. Bosco et al (1995) also found a higher intercept for men than women.

Empirically, the greatest velocity would occur at the lowest resistance level. For example, if an athlete was asked to perform an unloaded squat at maximal exertion, her peak velocity would probably by greater than if she performed another repetition with a load close to her 1RM (Fleck and Kraemer, 2004). However, two data points in the women's force–velocity data set did not follow this trend. An unusually high velocity was recorded at the greatest resistance level. It is likely that this is a result of the subjects showing much greater motivation for maximal exertion when knowing the greatest resistance level was to be lifted. Out of all twenty-four subjects, these two data points were the only ones in which this phenomenon occurred. Thus a decision as to what to do about these outliers was to be made. In order for the data to not be skewed from two outliers, the outlying velocity for the highest resistance level was omitted with the justification that only four data points are sufficient to create an F-V curve (Tihanyi, 1985). After manipulating the data as such, these two data sets were no longer outliers.

5.4 IVRE Discussion

The positive acceleration phase of Fig. 4.7 (positive slope of velocity-time curve) is approximately five times larger in duration than the negative acceleration phase (negative slope of velocity-time curve). In other words, most of the time in the concentric phase is spent accelerating the barbell from zero velocity and then interacting with the machine after the desired velocity is exceeded. It is when the subject is increasing his or her velocity (positive acceleration) that the machine is interacting with the person with an increase in resistance level. Once the peak acceleration is reached, only a short time remains for negative acceleration of the barbell back to zero velocity. Thus, the majority of the lift takes place with positive acceleration, and that is when it is critical to vary the load to meet the instantaneous strength capacity. The negative acceleration phase occurs when the subject slows the ascent toward the "top" of the lift. This happens very quickly and confirms that the programming trade-off to maintain a constant resistance level after the peak has occurred is acceptable because the barbell must undergo negative acceleration anyway in order for it to return to zero velocity at the end of the lift.

During the IVRE lifts the women showed a greater percent increase in resistance level. It is possible that the women had more time during the lift to interact with the machine and receive more loading which resulted in a larger percent increase (Fig. 4.8) as women showed slower velocities than men for every resistance level. Another possible explanation of why women tended to have a greater percent increase during the IVRE lift could be due to the inherent biomechanical difference between men and women which seems to appear in women having a greater percent increase on the isometric strength curve. These gender differences have been discussed in the previous two sections of this chapter.

Another relationship that was explored (Table 4.6) is between the peak value attained during the IVRE lifts and the ISRF because there is no significant difference between the IVRE maximum and ISRF for men or women ($p = 0.06$ and 0.111, respectively). It is possible that this is a result of the initial resistance level being set at 80% of the ISRF and the resistance level could only change 20% after exceeding the desired velocity. This relationship could simply be an artifact of the percentage of ISRF that was initially set. Conversely, it could reveal that that once the ISRF was reached, the subject's velocity fell below the desired velocity to plateau the resistance level because maximum strength capacity was reached, which could show that the IVRE approach varies the resistance such that the 1RM is achieved. Future work will have to explore this relationship.

The linear relationship between force and lifting velocity proved to be a suitable relationship by which to interactively vary the resistance level because as the subjects moved out of the sticking region of the ROM they where able to accelerate, which signaled the resistance level to increase in order to maximize each individual's force output at the points in the ROM, with greater strength capacity.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

The research makes several advances in the general understanding of the squat exercise as well as improvements in the method of providing appropriate resistance throughout the ROM. Equipment was designed and built to be used as a platform for this specific research as well as for subsequent studies. The equipment was validated and used for data collection with human subjects. The research revealed previously unknown aspects of the biomechanics of the squat exercise and revealed benefits of applying the IVRE approach for strength and conditioning or as a countermeasure to the effects of exposure to microgravity.

6.2 Contributions

The contributions of the research are divided into the two categories of equipment engineering and human subjects testing. The equipment engineering research contributions are as follows:

- A Smith machine was modified with pneumatic resistance that is capable of recording instantaneous position, velocity, and pressure that provides isometric, constant, and interactive variable resistance.

- The machine was proven valid in the areas of static force, dynamic pressure, and velocity.
- The pneumatic system response was proven to be fully capable of changing the resistance as required.

The human subject testing revealed the following contributions:

- The ISRF was experimentally determined to occur at 90° knee-flexion without variation.
- The percent difference from ISRF to peak MVIF was determined to be significantly higher for women than for men.
- Taking MVIF at 90° and one other knee angle reveals the range of isometric strength.
- The isometric value of ISRF is approximately 50% of the dynamic F_0 for both men and women. Thus, the ISRF could be used to predict F_0 to estimate the F–V curve using the average slopes of Fig. 4.5. This curve could be used to set a reasonable pre-load resistance level and desired velocity for IVRE with one isometric exertion at a 90° knee angle.
- There was a statistically significant percent increase in resistance during the concentric phase of the IVRE lift.

- The peak IVRE resistance level was not significantly different from the ISRF for both men and women.

6.3 Recommendations

The first recommendation would be to experiment with the IVRE code. The code that was used for the testing compensated for the unavoidable end velocity of zero by maintaining a constant resistance level during the negative acceleration portion on the velocity-time curve. There are other programming alternatives that could be incorporated such as forecasting for the negative acceleration condition and thus limiting the amount of decrease in resistance level to a set amount. Using various algorithms to vary the resistance level also could be researched.

There is much left to be studied in applying the IVRE approach to the eccentric portion of the lift. A starting point could be to program in a lag that would maintain the end constant resistance level until a negative velocity was sensed. Alternatively, the resistance level could be consistently reset to a pre-set value at the end of every lift so that the eccentric portion begins with a known resistance level. As for varying the load on the eccentric portion, one must be careful not to vary the resistance in the same manner used for the concentric segment. The reason for this is to ensure safety. For instance, if the user lost control of the lift and exhibited negative acceleration, he would receive greater resistance when the opposite was needed.

The proportional pressure controller that was used performed exceptionally well for this particular study. However, if greater accuracy is required and cost is not prohibitive, such as for microgravity applications, higher accuracy valves could be substituted. If higher accuracy valves do not currently exist "off-the-shelf," a valve could be designed to the meet the specifications required.

6.4 Future Work

Now there is a validated test platform that can answer the questions specific to this research that can also be used for future studies. One in particular would be to use a force plate under-foot while lifting to obtain the ground reaction forces exerted by the user. This would show the biomechanics involved by calculating the net torque at each joint revealing which muscle groups are primarily activated. The muscle activation also could be verified with electromyography (EMG) data. The force plate analysis would also incorporate the human into the lift for the comparison between actual reaction force generated and the input desired force. The result would show the lifting efficiency.

It would be of great interest to perform additional IVRE testing using a spectrum of percentages of ISRF with the corresponding velocity and not just 80% as the initial resistance. This would reveal the relationship between peak IVRE force and the ISRF. This study would show if a lower desired velocity but higher initial force would allow for a greater percent increase in resistance during

IVRE because there was more time to interact with the machine. An opposing conclusion could be that the peak IVRE values achieved remained the same because the peak resistance level reveals their 1RM.

A final study for the future would be to determine the efficacy of the IVRE approach by quantifying the strength gains achieved using IVRE compared to other resistance exercise approaches. It is important to find out if the IVRE approach can produce hypertrophy similar to free weights or at least better than that of the IRED system currently used as a countermeasure in microgravity.

In conclusion, the IVRE approach appreciably increased the force exerted over the range of motion at the instant that an increase in lifting velocity revealed greater strength capacity. The validation and frequency response testing showed that the device is capable of doing what it was designed to do, and the results of the study contribute new and useful information to the overall biomechanics body of knowledge. The knowledge that has been gained from this study serves as a basis from which seemingly unlimited research questions may be explored.

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APPENDIX A

Apparatus Design

The apparatus was designed in English units and is presented as such. A single pneumatic cylinder made by TRD Manufacturing, Inc. (TA-MS2-3.25x24) mounted above the Nautilus cage provides resistance to the barbell. The cylinder is mounted to a quarter-inch thick steel plate with four half-inch diameter bolts. A series of holes are drilled in the plate for adjustability of the cylinder as well as the shelf used to hold the proportional valve. The steel plate holding the cylinder, or cylinder plate, is supported by two pieces of 2" x 2" quarter-inch thick angle iron positioned horizontally above and below the top of the Nautilus cage. For added stability, an eighth-inch thick angle iron bracket supports the front of the cylinder plate. Figure A.1 is a picture of the pneumatics support structure.

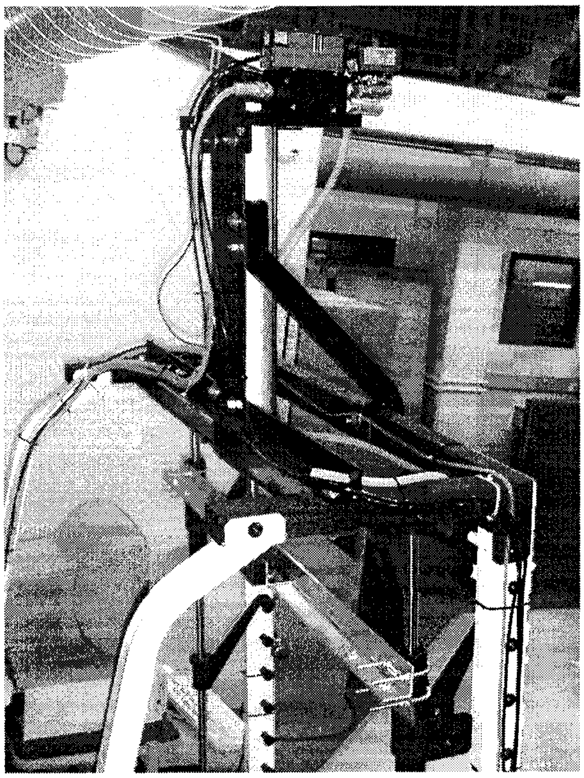


Figure A.1: Pneumatics modification structure holding cylinder to Smith cage and connecting to barbell.

The force exerted by the cylinder rod is transferred to the barbell through two pieces of 2"x2" eighth-inch thick angle aluminum that are secured to the linear bearing assembly on the Smith attachment with two U-bolts per side. The angle aluminum is bolted together such that it forms a "T" beam for added rigidity. Figure A.2 shows a digital image of the aluminum beam.

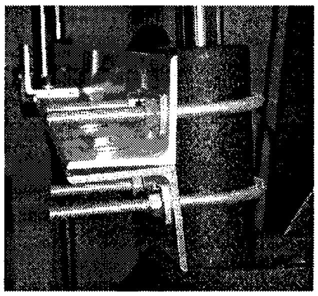


Figure A.2: Aluminum beam and U-bolts connecting cylinder rod to barbell.

Aluminum (6061-T6) was selected because of its high tensile strength (45,000 lb/in^2) and low weight in order to minimize the additional mass to be lifted. A hole was drilled in the aluminum "T" through which the cylinder rod could pass. The rod also goes through a six-inch long piece of 1.5"x1.5" eighth-inch thick angle iron in order to spread out the load of the rod over the aluminum beam. This reduces the pressure and stress on the hole. Figure A.3 shows the angle iron used to distribute the load of the rod.

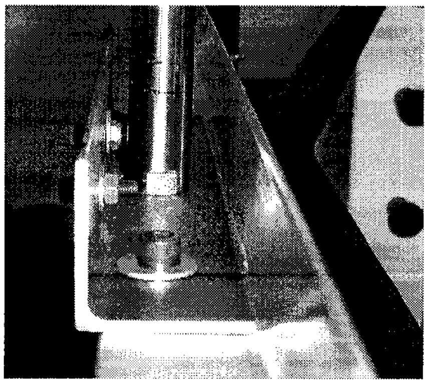


Figure A.3: Angle iron for load distribution from rod to beam.

A jam nut secures the rod to the aluminum beam. For additional safety, another piece of angle iron is bolted to the back of the angle iron used to disribute the load. It acts as a "catch" in case the rod somehow breaks through the aluminum beam and angle iron. It would keep the rod from coming in contact with the lifter. Figure A.4 shows the safety catch.

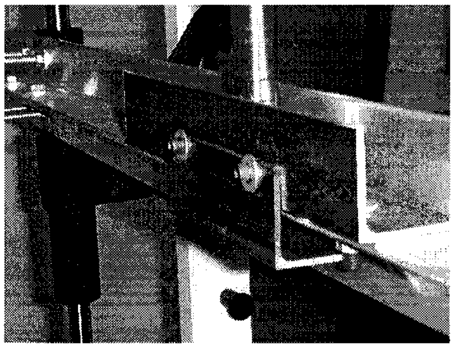


Figure A.4: Rod safety catch in case rod broke through beam.

A two-foot by four-foot piece of quarter-inch thick steel was used to replace the existing footplate for added rigidity of the system. Figure A.5 shows the steel foot plate.

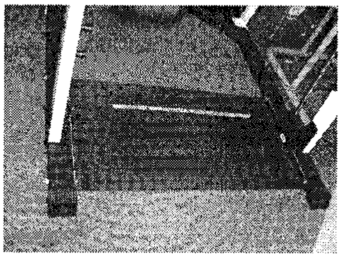


Figure A.5: Steel foot plate.

The valve that controls the pressure in the cylinder is a MAC Proportional Pressure Controller (P-PC 093). Figure A.6 is a photo of the actual valve as a part of the system.

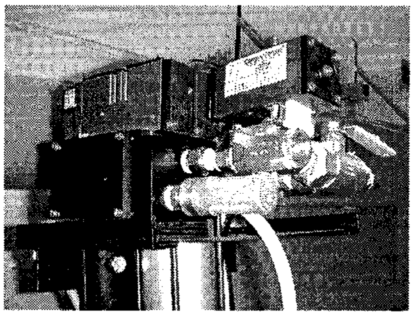


Figure A.6: Proportional Pressure Controller from MAC.

The linear position transducer is a Balluf Micropulse (BTL-5-PI-M0R610) is shown in Fig.

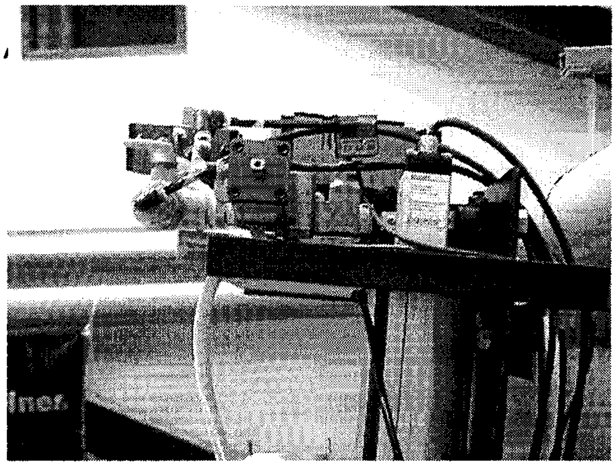


Figure A.7: Linear position transducer traces the magnet on the piston in the cylinder.

The velocity processor is a Balluf (BTM-A1-002 VU024), shown in Fig. A.8.

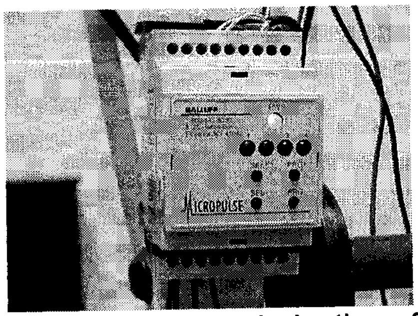
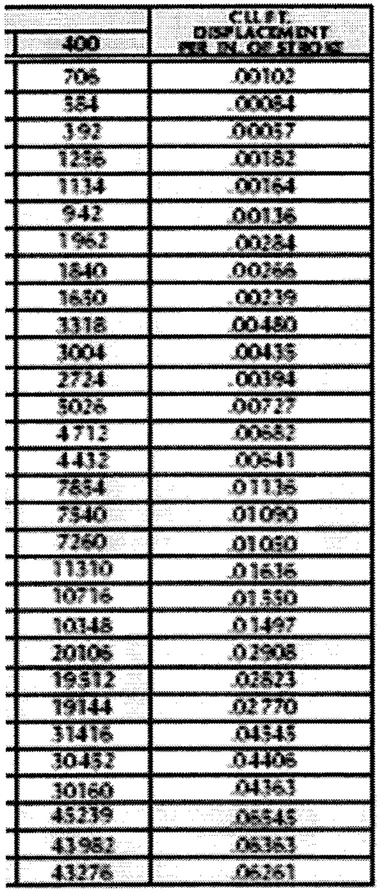


Figure A.8: Velocity processor takes derivative of position with time for instantaneous velocity.

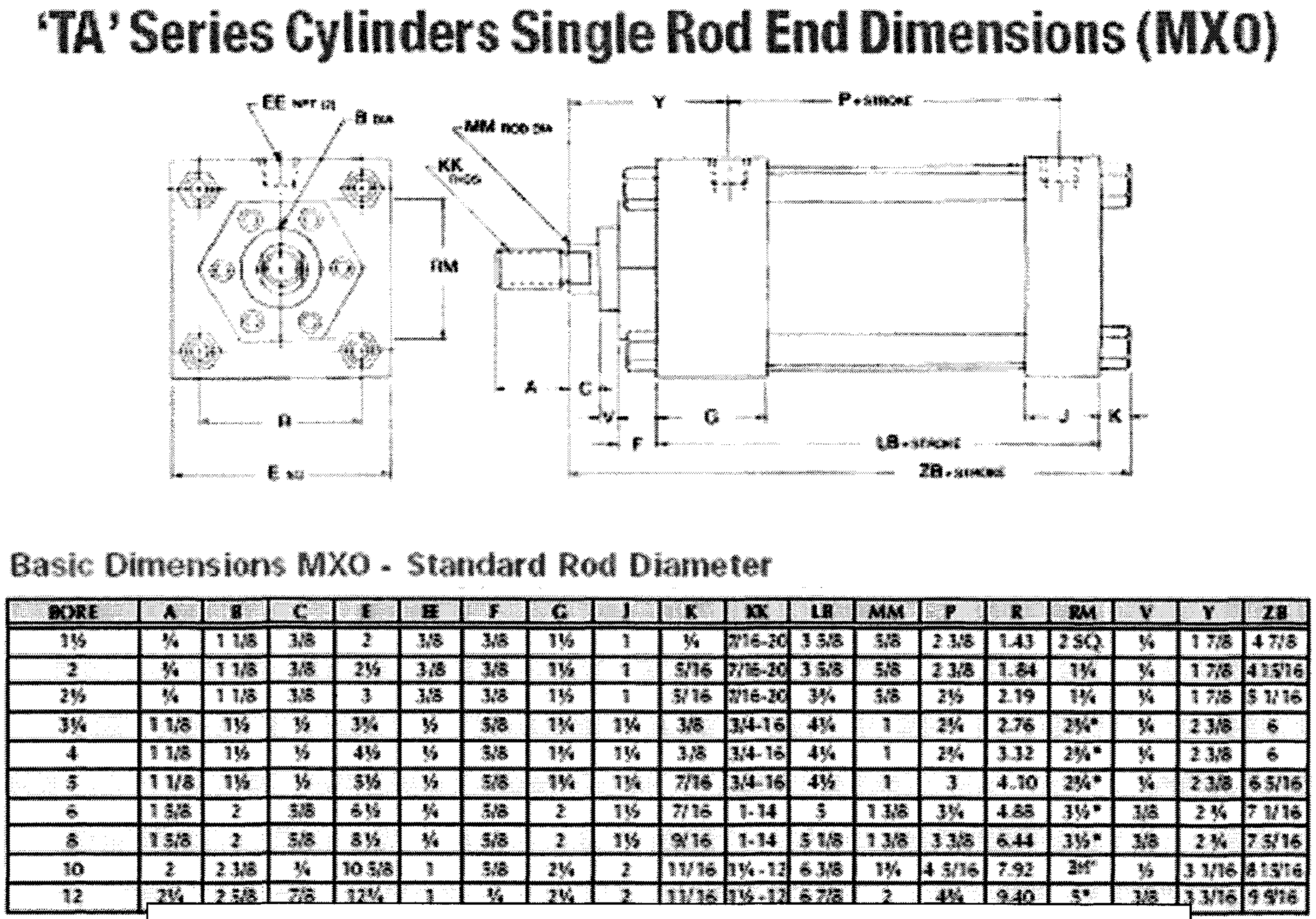
APPENDIX B

Component Specifications



400	CU. FT. DISPLACEMENT PER IN. OF STROKE
706	.00102
554	.00084
392	.00057
1256	.00182
1134	.00164
942	.00136
1962	.00284
1840	.00266
1650	.00239
3318	.00480
3004	.00435
2724	.00394
5026	.00727
4712	.00682
4412	.00641
7854	.01136
7540	.01090
7260	.01050
11310	.01636
10716	.01550
10348	.01497
20106	.02908
19512	.02823
19144	.02770
31416	.04545
30452	.04406
30160	.04363
45239	.06545
43982	.06363
43276	.06261

Figure B.1: Force/volume chart specifications provided by TRD Manufacturing, Inc.

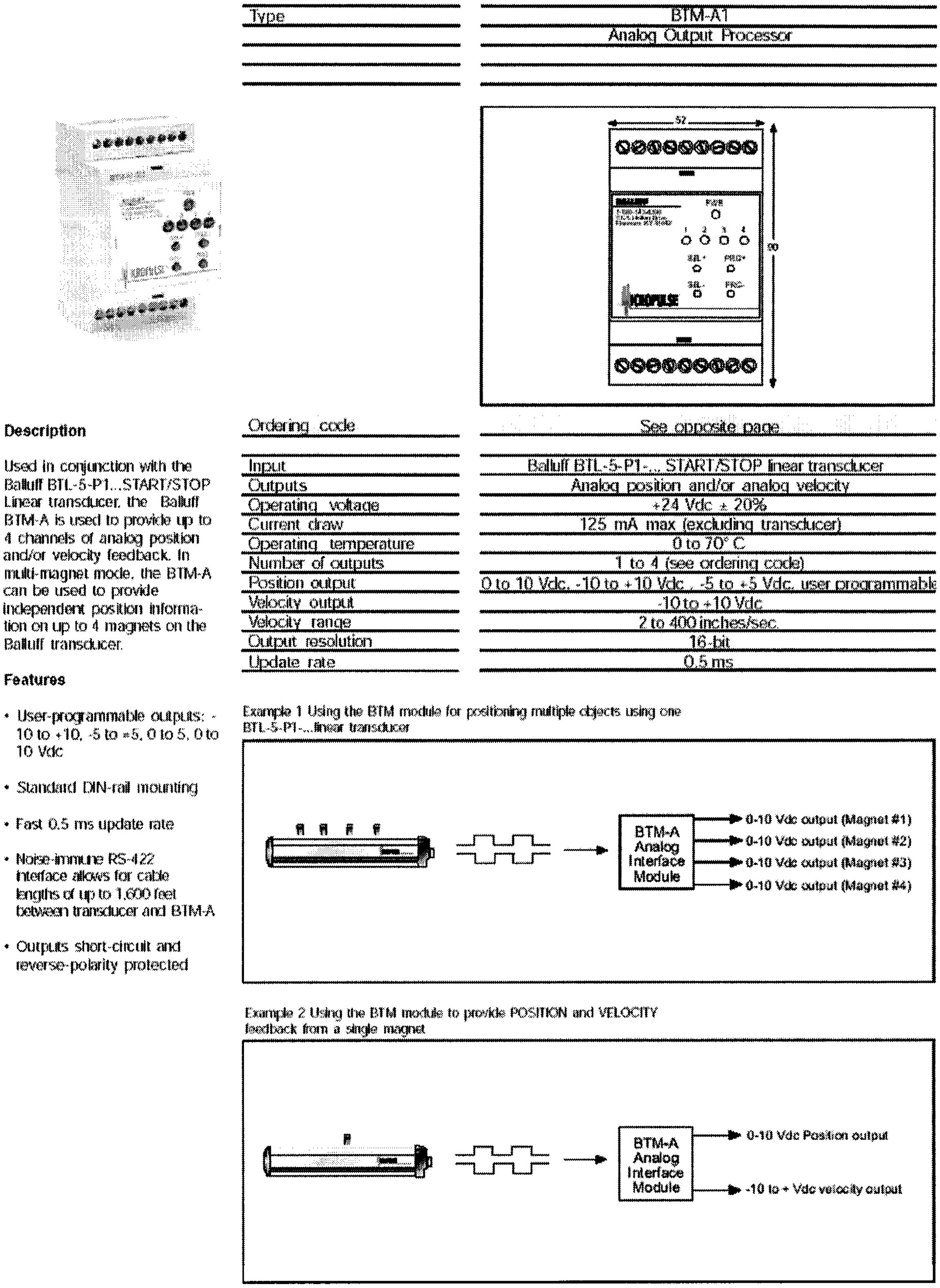


'TA' Series Cylinders Single Rod End Dimensions (MXO)

Basic Dimensions MXO - Standard Rod Diameter

BORE	A	B	C	E	EE	F	G	J	K	KK	LB	MM	P	R	RM	V	Y	ZB
1½	¾	1 1/8	3/8	2	3/8	3/8	1½	1	¼	7/16-20	3 5/8	5/8	2 3/8	1.43	2 SQ.	¼	1 7/8	4 7/8
2	¾	1 1/8	3/8	2½	3/8	3/8	1½	1	5/16	7/16-20	3 5/8	5/8	2 3/8	1.84	1¾	¼	1 7/8	4 15/16
2½	¾	1 1/8	3/8	3	3/8	3/8	1½	1	5/16	7/16-20	3¾	5/8	2½	2.19	1¾	¼	1 7/8	5 1/16
3¼	1 1/8	1½	½	3¾	½	5/8	1¾	1¼	3/8	3/4-16	4¼	1	2⅝	2.76	2⅝*	¼	2 3/8	6
4	1 1/8	1½	½	4½	½	5/8	1¾	1¼	3/8	3/4-16	4¼	1	2⅝	3.32	2⅝*	¼	2 3/8	6
5	1 1/8	1½	½	5½	½	5/8	1¾	1¼	7/16	3/4-16	4½	1	3	4.10	2⅝*	¼	2 3/8	6 5/16
6	1 5/8	2	3/8	6½	¾	5/8	2	1½	7/16	1-14	5	1 3/8	3⅛	4.88	3½*	3/8	2 ⅝	7 1/16
8	1 5/8	2	5/8	8½	¾	5/8	2	1½	9/16	1-14	5 1/8	1 3/8	3 3/8	6.44	3½*	3/8	2 ⅝	7 5/16
10	2	2 3/8	¾	10 5/8	1	5/8	2¼	2	11/16	1¼-12	6 3/8	1¾	4 5/16	7.92	3⅝*	½	3 1/16	8 13/16
12	2¼	2 5/8	7/8	12¾	1	¾	2¼	2	11/16	1½-12	6 7/8	2	4¾	9.40	5*	3/8	3 3/16	9 9/16

Figure B.2: Pneumatic cylinder dimension specifications provided by TRD Manufacturing, Inc.



Type	BTM-A1
	Analog Output Processor

Description

Used in conjunction with the Balluff BTL-5-P1...START/STOP Linear transducer, the Balluff BTM-A is used to provide up to 4 channels of analog position and/or velocity feedback. In multi-magnet mode, the BTM-A can be used to provide independent position information on up to 4 magnets on the Balluff transducer.

Features

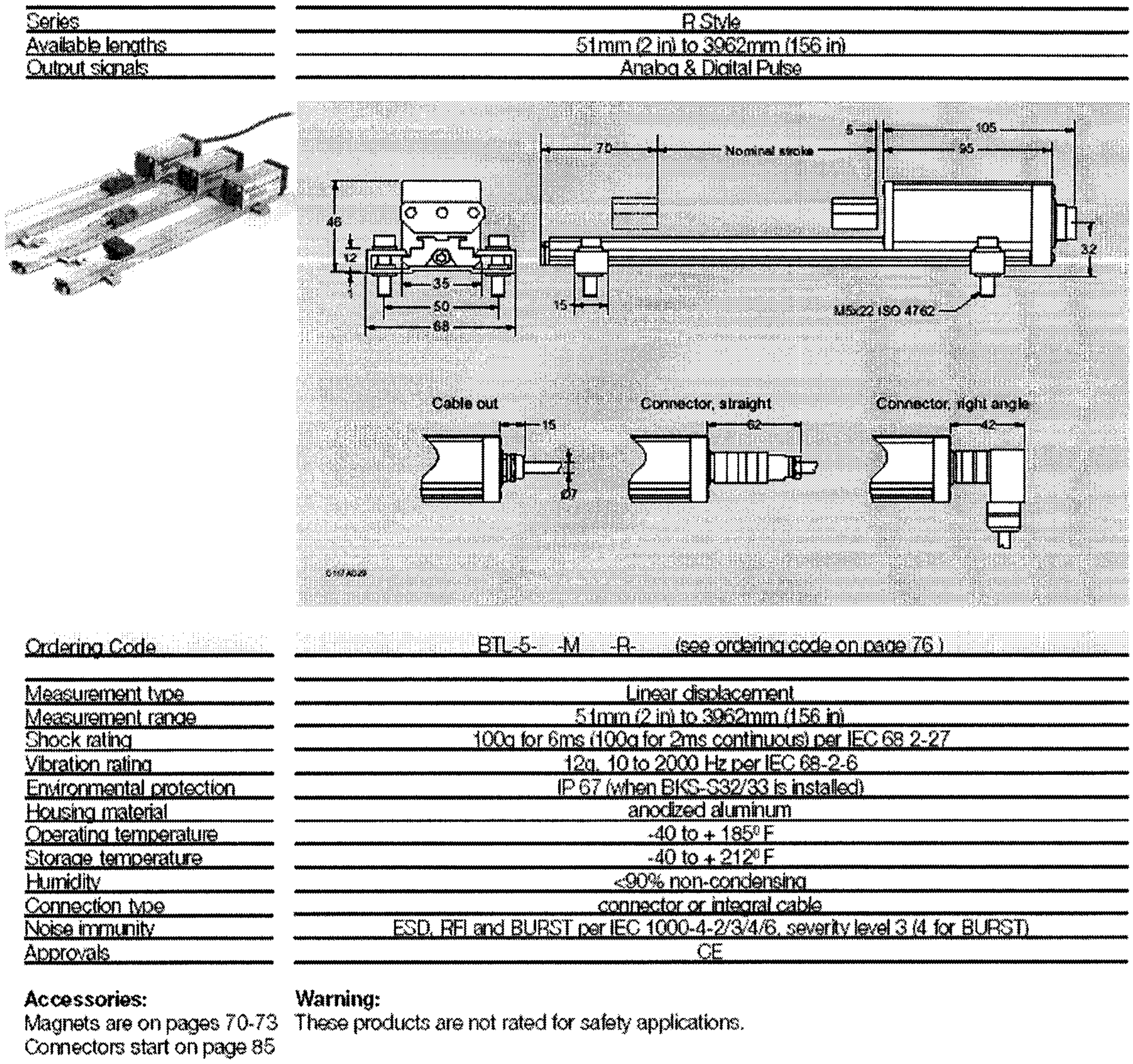
- User-programmable outputs: -10 to +10, -5 to +5, 0 to 5, 0 to 10 Vdc
- Standard DIN-rail mounting
- Fast 0.5 ms update rate
- Noise-immune RS-422 interface allows for cable lengths of up to 1,600 feet between transducer and BTM-A
- Outputs short-circuit and reverse-polarity protected

Ordering code	See opposite page
Input	Balluff BTL-5-P1-... START/STOP linear transducer
Outputs	Analog position and/or analog velocity
Operating voltage	+24 Vdc ± 20%
Current draw	125 mA max (excluding transducer)
Operating temperature	0 to 70° C
Number of outputs	1 to 4 (see ordering code)
Position output	0 to 10 Vdc, -10 to +10 Vdc , -5 to +5 Vdc, user programmable
Velocity output	-10 to +10 Vdc
Velocity range	2 to 400 inches/sec.
Output resolution	16-bit
Update rate	0.5 ms

Example 1 Using the BTM module for positioning multiple objects using one BTL-5-P1-...linear transducer

Example 2 Using the BTM module to provide POSITION and VELOCITY feedback from a single magnet

Figure B.3: Balluff Micropulse multi-channel analog output processor specifications.



Series	R Style
Available lengths	51mm (2 in) to 3962mm (156 in)
Output signals	Analog & Digital Pulse

Ordering Code	BTL-5- -M -R- (see ordering code on page 76)

Measurement type	Linear displacement
Measurement range	51mm (2 in) to 3962mm (156 in)
Shock rating	100g for 6ms (100g for 2ms continuous) per IEC 68 2-27
Vibration rating	12g, 10 to 2000 Hz per IEC 68-2-6
Environmental protection	IP 67 (when BKS-S32/33 is installed)
Housing material	anodized aluminum
Operating temperature	-40 to + 185° F
Storage temperature	-40 to + 212° F
Humidity	<90% non-condensing
Connection type	connector or integral cable
Noise immunity	ESD, RFI and BURST per IEC 1000-4-2/3/4/6, severity level 3 (4 for BURST)
Approvals	CE

Accessories:
Magnets are on pages 70-73
Connectors start on page 85

Warning:
These products are not rated for safety applications.

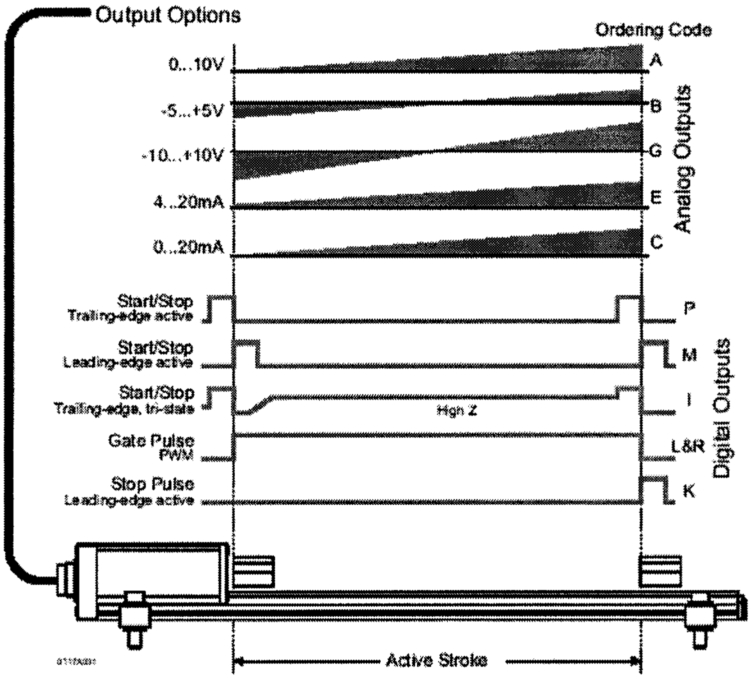
Figure B.4: Balluff Micropulse linear position transducer electrical specifications.

Electrical interface	Analog	Analog	Digital
Electrical type	Voltage	Current	Start/Stop & PWM
Part No. Code	**A, B, G**	**E,C**	**P, M, I, L, K**
Output	0...+10V,-5...+5V,-10...+10V	0...20 mA, 4...20 mA	Start/Stop or Pulse-width-modulated (RS422/RS485
Output load	>2KΩ (5 mA max)	≤500Ω	per spec
Resolution	≤0.1mV	≤0.2µA	Controller dependent
Non-linearity	±100mm to 500mm stroke, ±0.02 % over 500mm stroke	±100mm to 500mm stroke, ±0.02 % over 500mm stroke	±100mm to 500mm stroke ±0.02 % over 500mm strok
Repeatability	Resolution/ min 2µm	Resolution/ min 2µm	Resolution/ min 2µm
Hysteresis	5µm	5µm	5µm
Sampling rate	1KHz	1KHz	1KHz
Temperature coefficient*	[150µ V/° C + (5ppm/°C*P*V/NL)] * ΔT	[0.6µA/°C + (10 ppm/°C*P*V/NL)] * ΔT	[0.6µA/°C + (10 ppm/°C*P*V/NL)] * ΔT
Operating voltage	24 Vdc ±20%	24 Vdc ±20%	24 Vdc ±20%
Operating current	≤150mA	≤150mA	≤150mA

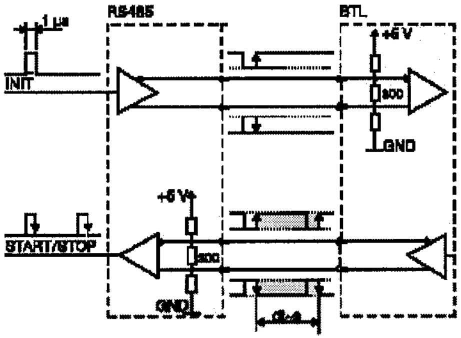
Notes:
Analog voltage output versions incorporate both rising and falling outputs. Analog current version must be ordered as rising or falling ouputs.

***Temperature coefficient variables:**

V = output range in V
I = output range in [mA]
ΔT = temperature change
P = magnet position

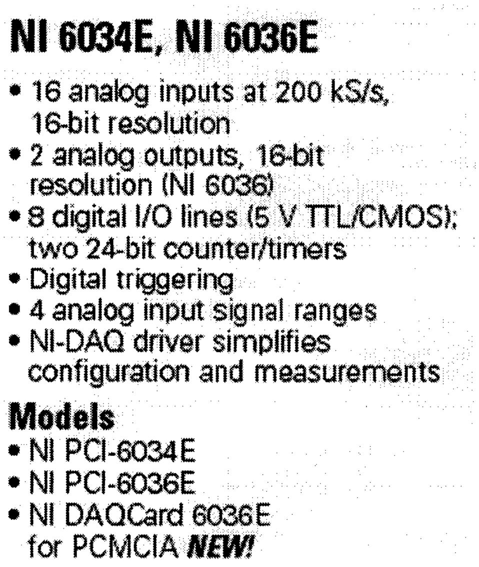


Analog and Digital Output Options for the Micropulse R Style



RS485 Transmission of digital signals

Figure B.5: Balluff Micropulse linear position transducer electrical specifications.



NI 6034E, NI 6036E

- 16 analog inputs at 200 kS/s, 16-bit resolution
- 2 analog outputs, 16-bit resolution (NI 6036)
- 8 digital I/O lines (5 V TTL/CMOS); two 24-bit counter/timers
- Digital triggering
- 4 analog input signal ranges
- NI-DAQ driver simplifies configuration and measurements

Models

- NI PCI-6034E
- NI PCI-6036E
- NI DAQCard 6036E for PCMCIA ***NEW!***

Figure B.6: National Instruments data acquisition card specifications.

APPENDIX C

LABView IVRE Control Program

IVRE Code Explanation

The initial resistance level (Input Force) and Desired Velocity are input variables. The resistance level remains constant until the velocity exceeds positive 3 in/sec. This tells the program that the subject has transitioned from eccentric to the concentric phase of the lift. Then the resultant velocity (Velocity) is compared to the Desired Velocity. If the Velocity is greater than the Desired Velocity the resistance level is incremented by the (Increment to vary force) variable which was also input. Once the Velocity has exceeded the Desired Velocity and the resistance level has increased at least once, the resistance level will plateau at the last reached level when the velocity falls below the Desired Velocity. Next, the instantaneous values of position, velocity, pressure, and time are stored as strings of data.

Page 1

IVRtest_final.vi
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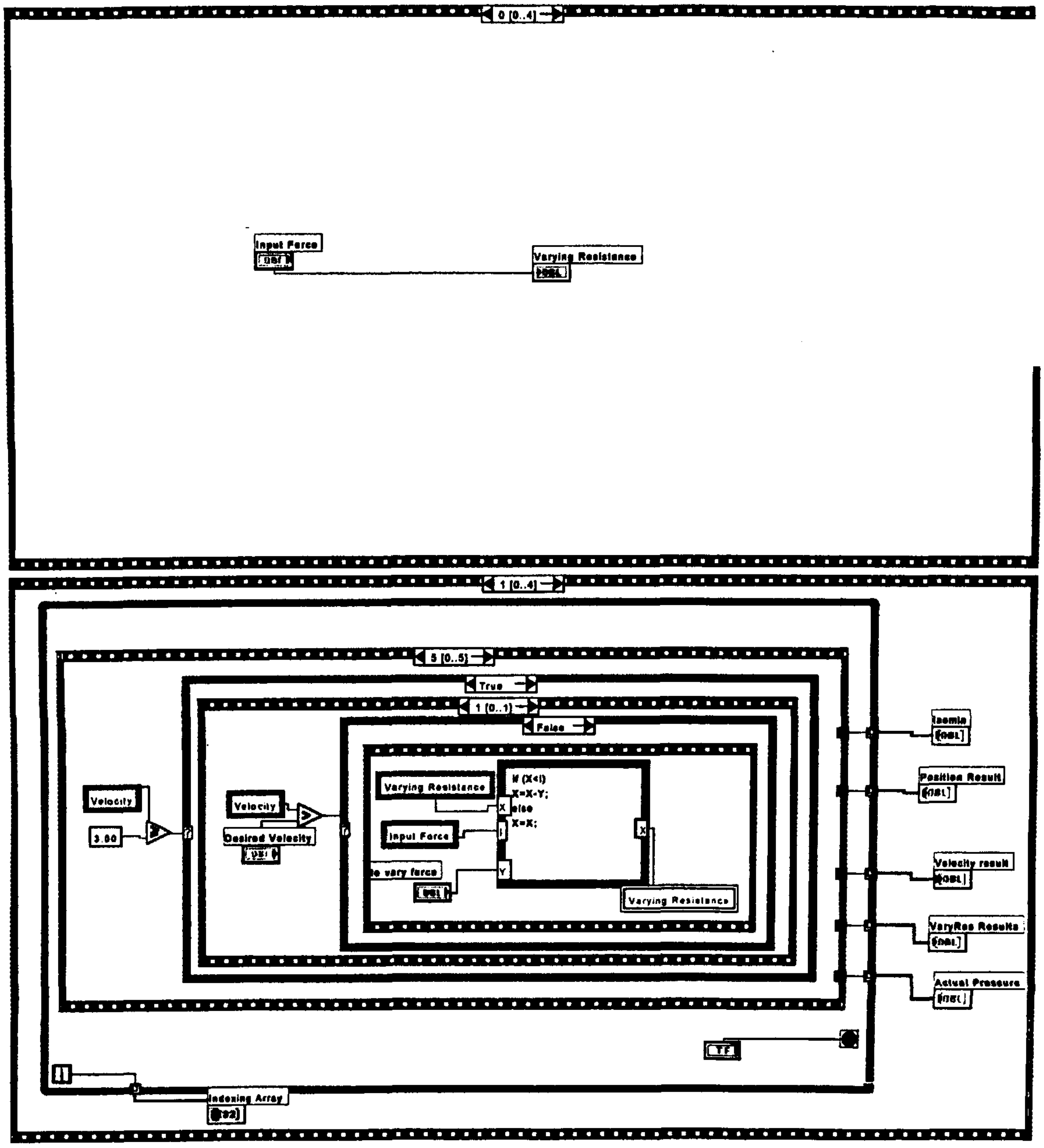

Figure C.1: IVRE code comparing resultant velocity to desired velocity.

Page 2

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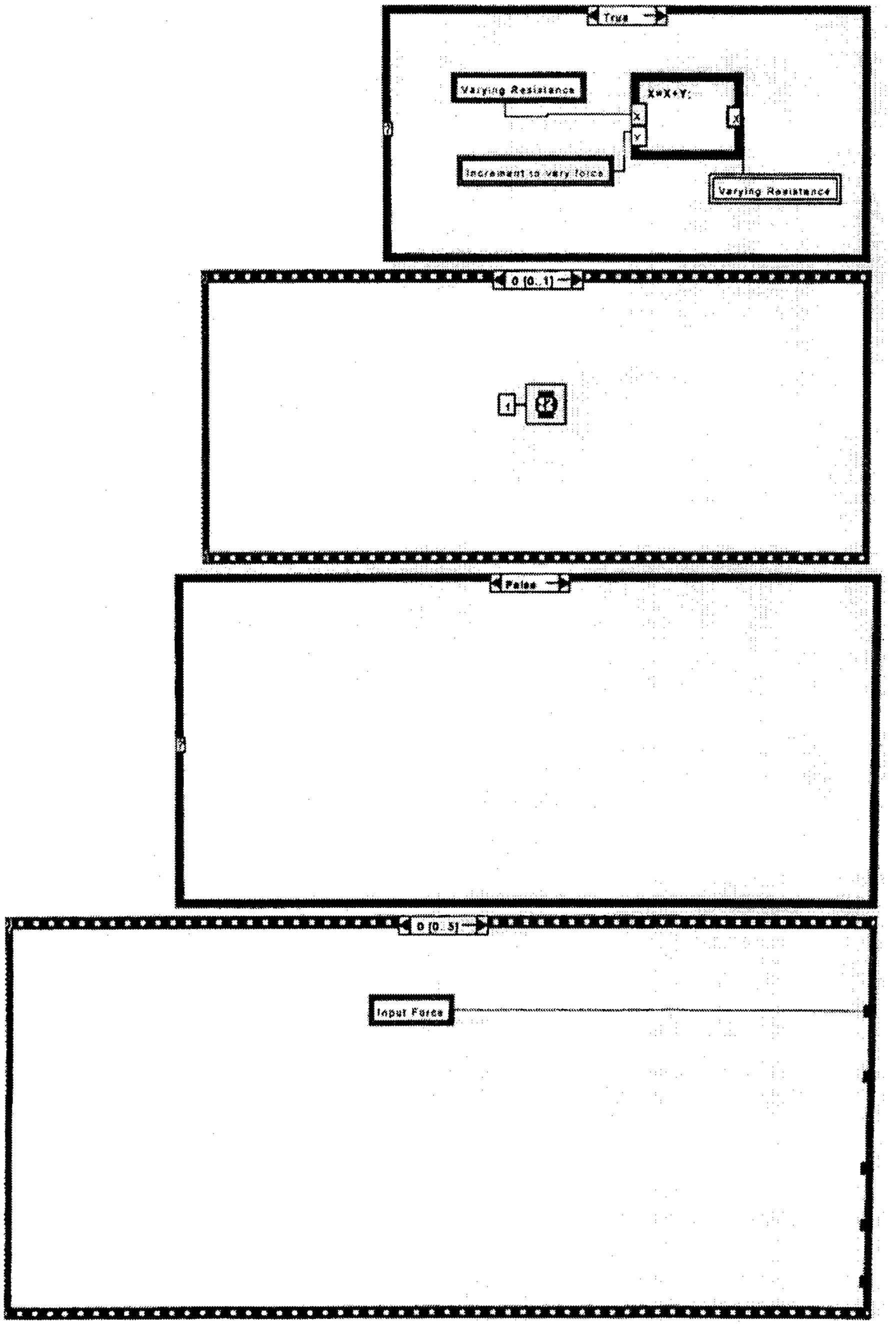

Figure C.2: IVRE code incrementing resistance when desired velocity was exceeded.

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Page 3

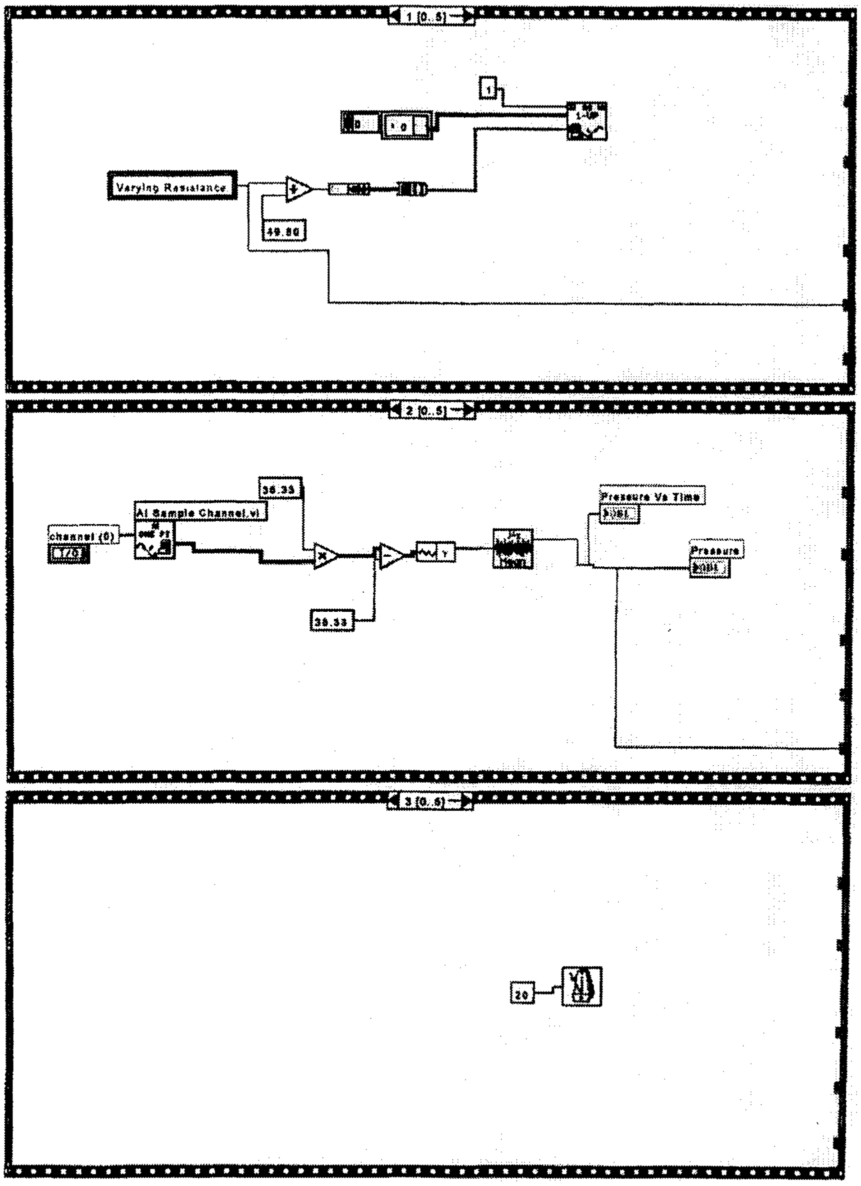

Figure C.3: IVRE code unit conversion, filtering and sampling rate of 20 ms incrementing resistance when desired velocity was exceeded.

Page 4

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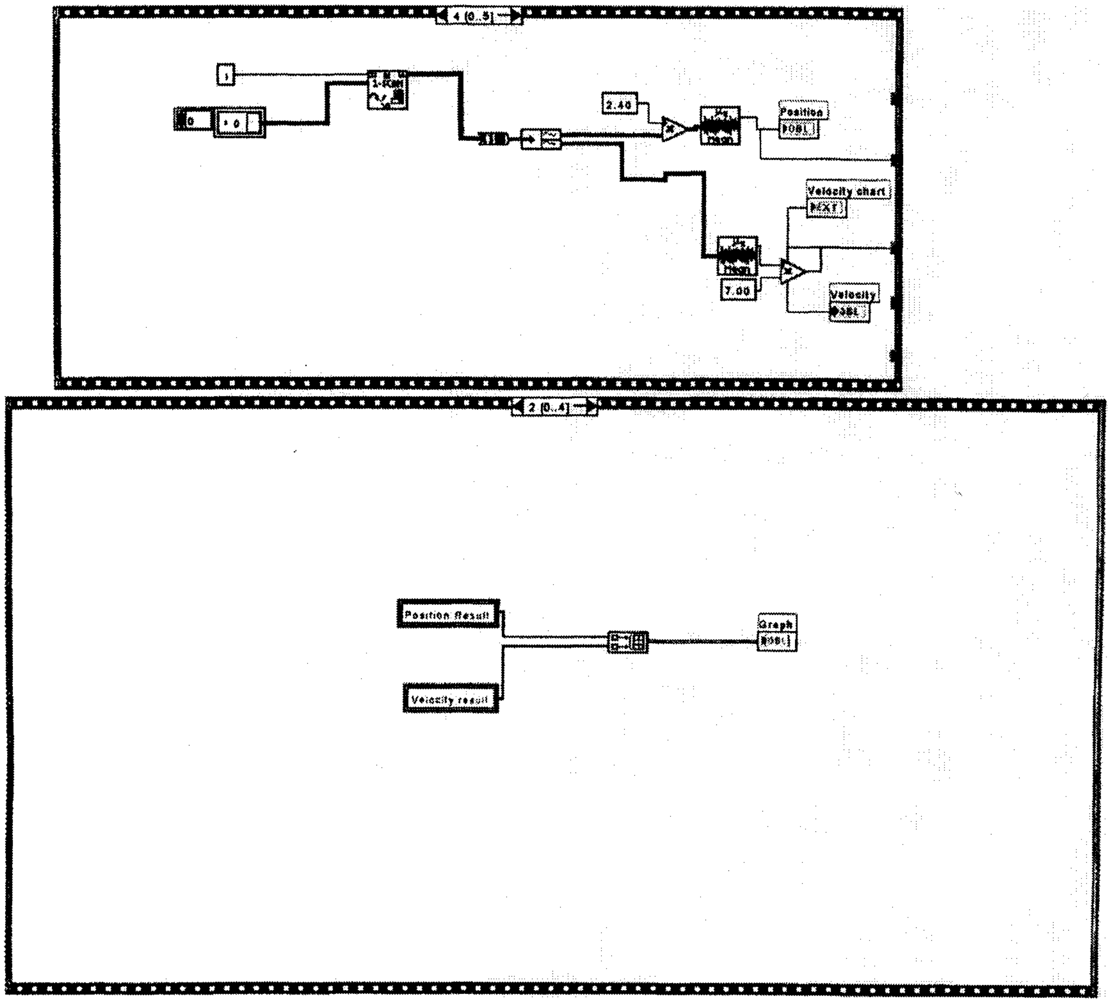
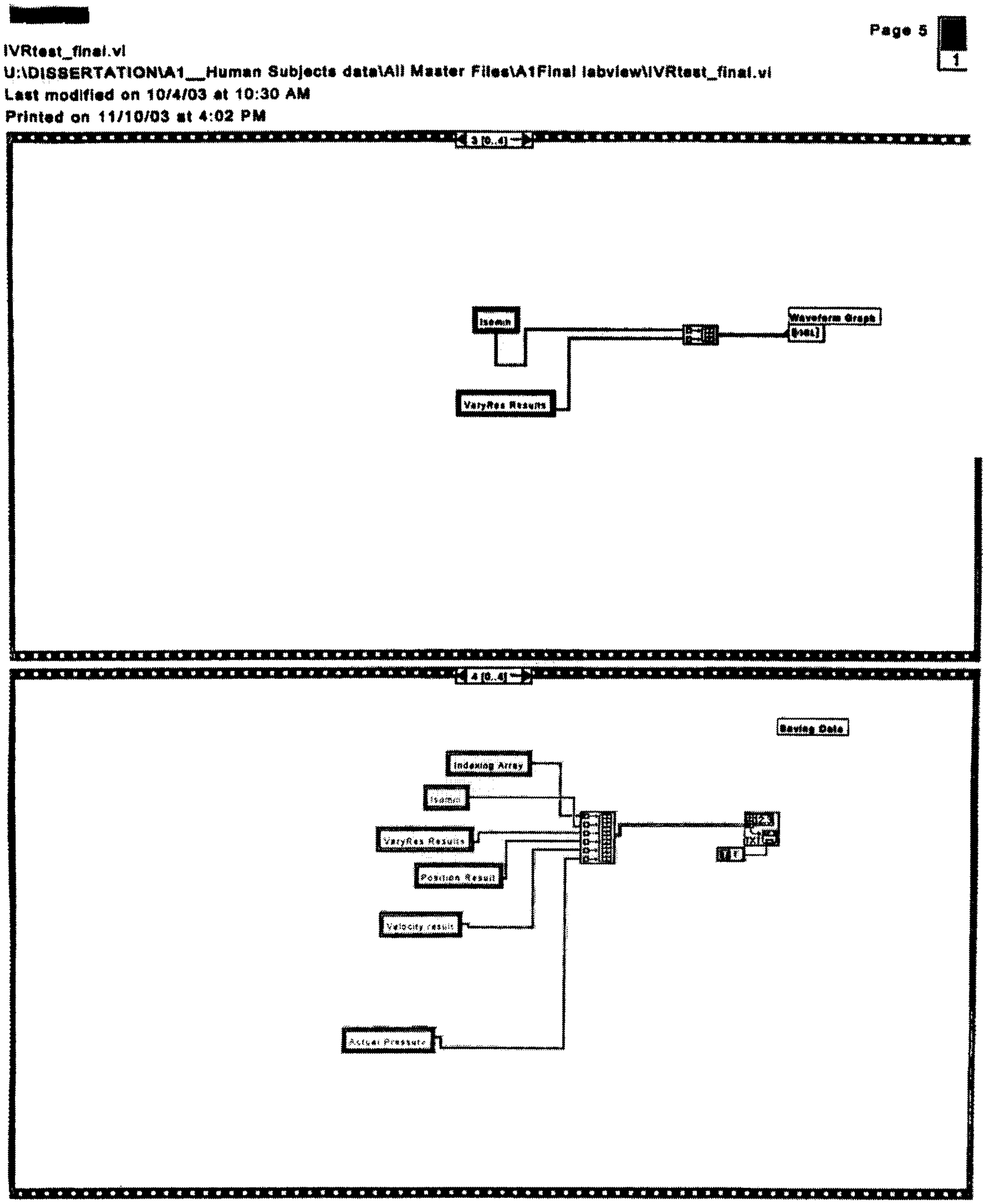


Figure C.4: IVRE code output of variables.



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Page 5

Figure C.5: IVRE code saving strings of data.

APPENDIX D

Health Questionnaire

HUMAN PERFORMANCE CLINICAL/RESEARCH LABORATORY
COLORADO STATE UNIVERSITY
CONFIDENTIAL HEALTH HISTORY QUESTIONNAIRE

STUDY____________________ **DATE**_ **SUBJECT ID #**____________________

Reviewed by (must be PI):____________________________________

PLEASE PRINT

GENERAL MEDICAL HISTORY

Do you have any current medical conditions?	YES ☐	NO ☐	If Yes, please explain:
Have you had any major illnesses in the past?	YES ☐	NO ☐	If Yes, please explain:
Have you ever been hospitalized or had surgery? (include date and type of surgery, if possible)	YES ☐	NO ☐	If Yes, please explain:
Have you ever had an EKG?	YES ☐	NO ☐	If Yes, please explain:
Have you been diagnosed with diabetes?	YES ☐	NO ☐	If Yes, please explain:

Age at diagnosis_

Are you currently taking any medications, including aspirin, hormone replacement therapy, or other over-the-counter medications?

YES ☐ NO ☐ If Yes, please explain:

Medication	Reason	Times taken per Day	Taken for how long?

PI Initials____________________________

SPECIFIC MEDICATIONS

	YES	NO
Aspirin (chronically)	☐	☐
Ibuprofen	☐	☐
Acetominophen	☐	☐
Steroids (costisone, etc.)	☐	☐
Other anti-inflammatories	☐	☐

FAMILY HISTORY

	Age (if alive)	Age of Death	Cause of Death
Father			
Mother			
Brothers/Sisters			
	______	______	______
	______	______	______
	______	______	______

Do you have a family history of any of the following: (Blood relatives only, please give age at diagnosis if possible)

	YES	NO	Relation	Age at Diagnosis
a. High blood pressure	☐	☐	______	______
b. Heart Attack	☐	☐	______	______
c. Coronary bypass surgery	☐	☐	______	______
d. Stroke	☐	☐	______	______
e. Diabetes	☐	☐	______	______
f. Obesity	☐	☐	______	______

TOBACCO HISTORY (check one)

None ☐
Quit ☐ (when)______
Cigarette ☐
Cigar ☐
Pipe ☐
Chew Tobacco ☐
Snuff ☐
Total years of tobacco use______

CURRENT TOBACCO USE
(if applicable)

	# per day
Cigarette	
Cigar	______
Pipe	______
Chew Tobacco	______
Snuff	

PI Initials______

CARDIORESPIRATORY HISTORY	**YES**	**NO**
Are you presently diagnosed with heart disease?	☐	☐
Do you have any history of heart disease?	☐	☐
Do you have a heart murmur?	☐	☐
Occasional chest pain or pressure?	☐	☐
Chest pain or pressure on exertion?	☐	☐
Episodes of fainting?	☐	☐
Daily coughing?	☐	☐
High blood pressure?	☐	☐
Shortness of breath?		
At rest?	☐	☐
lying down?	☐	☐
After 2 flights of stairs?	☐	☐
Do you have asthma?	☐	☐
Do you have a history of bleeding disorders?	☐	☐
Do you have a history of problems with blood clotting?	☐	☐

If you checked YES to any of the above, you will be asked to clarify your response by an investigator so we can be sure to safely determine your ability to participate.

MUSCULOSKELETAL HISTORY	**YES**	**NO**
Any current muscle injury or illness?	☐	☐
Any muscle injuries in the past?	☐	☐
Do you experience muscle pain at rest?	☐	☐
Do you experience muscle pain on exertion?	☐	☐
Any current bone or joint (including spinal) injuries?	☐	☐
Any previous bone or joint (including spinal) injuries?	☐	☐
Do you ever experience painful joints?	☐	☐
Do you ever experience swollen joints?	☐	☐
Do you ever experience edema (fluid build up)?	☐	☐
Do you have pain in your legs when you walk?	☐	☐

If you checked YES to any of the above, you will be asked to clarify your response by an investigator so we can be sure to safely determine your ability to participate.

PI Initials ______________________________

NUTRITIONAL SURVEY

How many times do you usually eat per day? ____________

What time of day do you eat your largest meal? ____________

How many times per week do you eat out ? ____________

Are you taking any diet supplements? **YES** ☐ **NO** ☐. **IF YES, PLEASE PROVIDE DETAILS:**

How many times per week do you normally eat the following:

Ground beef____ Sausage________ Bacon________ Beef__________

Pork__________ Cheese________ Fish__________ Poultry________

Shellfish Fried Foods_____ Breads________ Cereals________

Fruits_________ Vegetables_____ Eggs__________ Desserts_______

Other_________ (describe)

How many servings per week of the following do normally consume:

Whole milk_____ 2% Milk________ Skim milk______ Buttermilk______

Coffee_________ Tea___________ Soft-Drinks_____ Beer__________

Wine__________ Liquor________ Water__________

Have you ever dieted? YES ☐ NO ☐

If YES, have you dieted within the past 12 months or are you currently on a diet?

YES ☐ NO ☐

If YES, please describe the diet:

a). Name (if applicable):______________________________________

b). Prescribed by a Physician/nutritionist? YES ☐ NO ☐

c). Have you lost weight? YES ☐ NO ☐

d). Duration of diet___________

PI Initials______________________________

What was your weight 12 months ago?

What is your current weight?

Have you dieted other than in the past 12 months? YES ☐ NO ☐

If YES, please answer the following:

a). How many times have you dieted?

b). How old were you?

c). Weight loss (amount)?

You may be asked to complete a more detailed diet survey if you are volunteering for a research study.

PHYSICAL ACTIVITY SURVEY

Compared to a year ago, how much regular physical activity do you get? (Check one)

- Much less ☐
- Somewhat less ☐
- about the same ☐
- somewhat more ☐
- much more ☐

Have you been exercising regularly for the past three months? YES ☐ NO ☐

If YES, what type of exercise do you regularly participate in? (check those that apply)

	Days per week	Minutes per session	Intensity (1=easy, 10=very hard)
Walking ☐			
Running ☐			
Cycling ☐			
Swimming ☐			
Aerobics ☐			
Weight Training ☐			
Martial Arts ☐			
Other (describe)			

EDUCATION: Please check the highest degree obtained:

- Grade School ☐
- Junior High ☐
- High School ☐
- College Degree ☐
- Master's Degree ☐
- Doctorate ☐

PI Initials____________________

APPENDIX E

Consent Form

COLORADO STATE UNIVERSITY
INFORMED CONSENT TO PARTICIPATE IN A RESEARCH PROJECT

TITLE OF PROJECT: Interactive Variable Resistance Exercise Approach to Maximal Force Output Based on Optimal Lifting Velocity

NAME OF PRINCIPAL INVESTIGATOR: Wade O. Troxell, PhD

CONTACT NAME AND INFORMATION FOR QUESTIONS/PROBLEMS: David C. Paulus
970-491-8155 (dpaulus@engr.colostate.edu)

PURPOSE OF THE RESEARCH: The purpose of the study is to see the effects of changing the resistance level during a squat exercise to match how strong you are at all points of the lift. But, in order to know how to match your strength, two other sets of data must be recorded first. More specifically, the maximal isometric (muscle contraction with no motion) force that you can produce at several points of the lift must be determined as well as the how your lifting velocity changes at as the resistance is increased.

PROCEDURES/METHODS TO BE USED: You are asked to volunteer for this study. You have been selected to participate in this study because you are a healthy adult with no history of back pain or illness. Your health status will be determined by a health questionnaire. You are also a good candidate for this research if you are accustomed to resistance exercise, though this is not necessary. However, if you have any conditions that prevent you from performing resistance exercise you should not participate in this research. Additionally, you should not participate if you have any conditions that affect lifting such as joint pain from arthritis or tendonitis.

In order to address the above questions, data will be collected from resistance exercise throughout the full range of motion. Prior to any lifting, a health questionnaire must be completed and reviewed with the investigator. All subjects will be screened with medical examination consisting of a medical history. Your height in bare feet will be taken along with the following body segments: torso (shoulder to hip), thigh (hip to knee), and shin (knee to ankle). Following this, your weight will be taken on a digital bathroom scale. We will then use the remainder of your time during this visit to the laboratory to familiarize you with the exercise conditions, apparatus, and correct exercise form. Your time commitment for this first visit to the laboratory will be approximately 45 minutes.

If you are comfortable with the procedures necessary to collect the required data, a second visit to the laboratory will be scheduled. This second visit will require approximately 1.5 hours of your time. Upon arriving at the laboratory you will need to change into appropriate clothing consisting of shorts, t-shirt, and athletic shoes. The second visit is to record the data from the exercise protocol. You will perform ten maximal effort squat exercises on a squat machine. The squat machine is a Nautilus 1600 "Smith" machine. The barbell glides on a vertical track, and the track has mechanical stops to keep the barbell above your waist height at all times. A pneumatic (air) cylinder resists the movement of the barbell instead of traditional free weights. If you feel that you need to stop the exercise at any point during the lift, there is an emergency stop button that will exhaust any air pressure and unload the barbell. The first repetition is divided into a series of five maximal isometric contractions in which you will push against the barbell, but it will not move. At least a five-minute rest will be given between isometric contractions. The next five repetitions are full range of motion squats at different constant resistance levels. Again, a minimum of a five-minute rest will be taken between repetitions. Finally, the last two repetitions involve maximally exerting as the machine interactively changes the resistance level based on your lifting velocity. In the unlikely event that your data is collected erroneously, you may be re-contacted in the future and asked to perform some, or all, of the procedures a second time.

RISKS INHERENT IN THE PROCEDURES: Risks associated with the study are those associated with maximal resistance exercise including fatigue and muscle soreness and strains. It is not possible to identify all potential risks in research procedures, but the researcher(s) have taken reasonable safeguards to minimize any known and potential, but unknown, risks. For example, an emergency relief valve is included in order to allow the subject to exhaust the air in the cylinder causing the resistance to immediately go to zero. Other attempts to minimize risks have been made by instituting the familiarization session, screening of participants, warm-up procedures prior to lifting the designated load, and constant visual and auditory monitoring of participants well being. Because participants will be monitored at all times, they are encouraged to report any discomforts caused by the activity. Additionally, participants are permitted to withdraw at any time without prejudice. There is no known risk involving the following: psychological trauma or stress, social/economic harm, legal risk, loss of confidentiality.

Please be aware that for this study the University has made special arrangements to provide initial medical coverage for any injuries that are **directly related** to your participation in this research project. The research project will provide for the coverage of reasonable expenses for emergency medical care related to the treatment of research-related injuries, if necessary.

Page 1 of 2 Participant's initials _______ Date _______

BENEFITS: The benefits of the study are that you will receive a complete strength assessment on the squat exercise. You will be provided with your unique isometric strength curve showing your strong and weak areas throughout the entire range of motion. This also shows what is typically referred to as the one-repetition max (1RM). You will also graphically see the relationship between your force output and lifting velocity. This information may be applied to your personal resistance exercise routine after the study is completed. Lastly, you will be introduced to an innovative approach to resistance exercise in which each repetition maximizes force output by varying the resistance based on instantaneous strength capacity.

CONFIDENTIALITY: You will be assigned a non-personal ID number. All subject information and data will be expressed/published anonymously. The method of connecting your name to your ID number will be kept with the other forms will be held secure in the PI's office. Upon completion of the study, method of identifying you with your ID number will be destroyed.

LIABILITY: The Colorado Governmental Immunity Act determines and may limit Colorado State University's legal responsibility if an injury happens because of this study. Claims against the University must be filed within 180 days of the injury.

Because Colorado State University is a publicly-funded, state institution, it may have only limited legal responsibility for injuries incurred as a result of participation in this study under a Colorado law known as the Colorado Governmental Immunity Act (Colorado Revised Statutes, Section 24-10-101, et seq.). In addition, under Colorado law, you must file any claims against the University within 180 days after the date of the injury.

In light of these laws, you are encouraged to evaluate your own health and disability insurance to determine whether you are covered for any physical injuries or emotional distresses you might sustain by participating in this research, since it may be necessary for you to rely on your individual coverage for any such injuries. Some health care coverage will not cover research-related expenses. If you sustain injuries, which you believe were caused by Colorado State University or its employees, we advise you to consult an attorney.

Questions concerning treatment of subjects' rights may be directed to Celia S. Walker at (970) 491-1563.

PARTICIPATION: Your participation in this research is voluntary. If you decide to participate in the study, you may withdraw your consent and stop participating at any time without penalty or loss of benefits to which you are otherwise entitled.

Your signature acknowledges that you have read the information stated and willingly sign this consent form. Your signature also acknowledges that you have received, on the date signed, a copy of this document containing 2 pages.

____
Participant name (printed)

______________________________ ________________
Participant signature Date

______________________________ ________________
Witness to signature (project staff) Date

Page 2 of 2 Participant's initials Date

APPENDIX F

Data Collection Forms

Table F.1. Maximum isometric force output at various knee angle degrees flexion.

Knee Angle (degrees)	Set #1 Max Force Produced (pounds)	Set #2 Max Force Produced (pounds)	Avg. Max Force Produced (pounds)
90			
110			
130			
150			
170			

Table F.2. Form of results from the constant resistance testing.

Percent 1RM (%)	Max Velocity (in/sec)	Max Velocity (in/sec)	Avg. Max Velocity (in/sec)
40			
50			
60			
70			
80			

F_o = ____________ lb

V_D at 80% ISRF= ____________ in/sec

APPENDIX G

Compiled Data From Human Subjects Testing

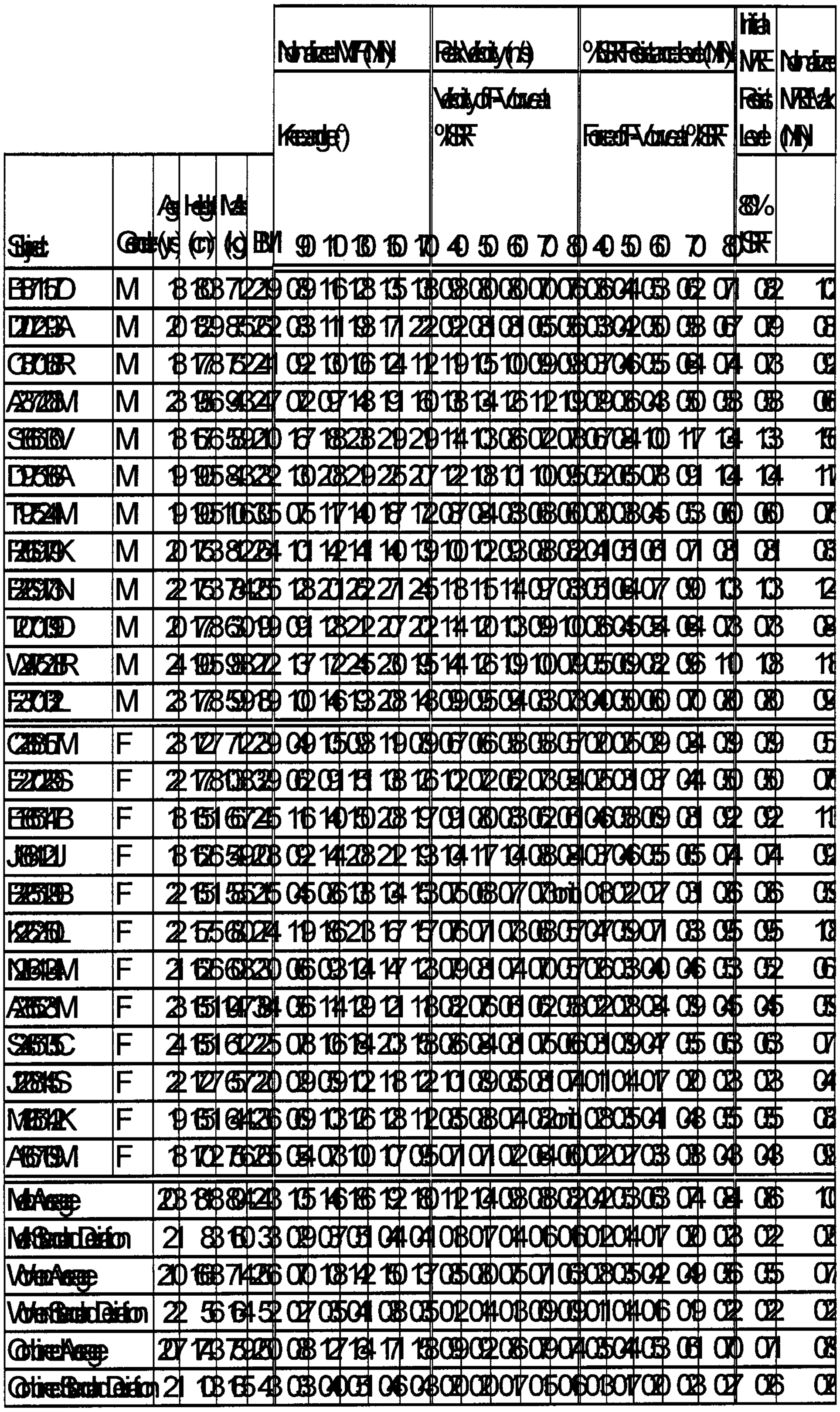

Figure G.1: Compiled data from human subjects testing.