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A BIOMECHANICAL ANALYSIS OF THE BENCH PRESS

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by

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ABSTRACT

Weight training is a popular activity offering many physical and psychological benefits and the bench press is one of the most popular weight training exercises among both competitive and recreational lifters. The purpose of this study was to increase the body of knowledge concerning the biomechanics of the bench press as performed by novice lifters. Muscular activity and the kinematics of the lifter, as well as the kinematics and kinetics of the bar, were assessed during different variations of the exercise.

While most training regimens incorporate multiple repetition sets, there is little data describing how the kinematics of a lift change during a set to failure. The purpose of the first study was to examine these changes in novice lifters. Subjects were recruited and asked to perform a maximal single lift (1-RM) and then as many repetitions as possible at 75% of the 1-RM load; three-dimensional kinematic data were recorded and analyzed for all lifts. Statistical analysis revealed differences between the maximal and submaximal lifts, and also that the kinematics of a submaximal lift change as a subject approaches failure in a set. Within the set, the time to lift the bar more than doubled from the first to the last repetition, causing a decrease in both mean and peak upward velocity. Furthermore, the peak upward velocity occurred much earlier in the lift phase in these later repetitions. The path the bar followed also changed, with subjects keeping the bar more directly over the shoulder during the lift. In general, most of the kinematic variables analyzed became more similar to those of the maximal lift as the subjects progressed through a set, but there was considerable variation between subjects as to which repetition was most like the maximal lift.

The purpose of the second study was to determine the vertical and lateral forces applied along the bar during a maximal and a submaximal effort bench press lift. Novice lifters were asked to perform a maximal and submaximal (80% of maximal lift) bench press. These lifts were performed using a bar instrumented to record forces applied to it in the vertical direction as well as along the long axis of the bar (lateral force). Statistical analysis revealed the average lateral force was between 22 and 29% of the applied

vertical force. The profile of the lateral force tended to be similar to the profile of the vertical force in both lifts. The absolute vertical and lateral forces were greater for the maximal lift than for the submaximal lift, but these forces were not different when compared as a percentage of the load lifted. Thus, it is clear that a substantial portion of the force generated by the lifter is applied along the long axis of the bar.

The purpose of the third study was to determine how electromyographic (EMG) activity, lift kinematics, and vertical and lateral forces applied to the bar were affected when performing the bench press at different grip widths. Again, novice lifters were recruited and asked to perform a maximal bench press at self-selected grip width, and then five submaximal (75% of maximal lift) lifts at predetermined grip widths. EMG data were recorded for the pectoralis, the triceps, the biceps, and the anterior deltoid. Statistical analysis revealed that peak vertical and lateral forces decreased as grip width increased, with the magnitude of the lateral forces remaining about one quarter of the vertical forces. Higher peak forces and EMG recordings were observed in the descent rather than the lift phase; neither peak nor mean EMG levels were systematically affected by grip width. Given that the same load was lifted with smaller vertical and lateral forces, it appears that a wider grip appears to be a more efficient position for performing the bench press.

The general findings of this research project show that novice lifters displayed different kinematic and muscle activation patterns than those reported in experienced recreational and competitive lifters. These novice lifters moved the bar differently when performing sets of repetitions for training than they do when performing maximal lifts. They displayed very little change in muscle activation pattern when lifting maximal versus submaximal loads. Kinetic analysis revealed that a substantial portion of the force generated by novice lifters is applied outward along the bar. The magnitude of this lateral force was about one quarter that of the vertical force. Lifting with narrower grip widths resulted in greater vertical and lateral forces, but contrary to published literature, did not alter muscle activation levels.

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CHAPTER 1

Introduction

1.1 Background

Weight training is a popular activity offering many physical and psychological benefits. It is recommended for improving muscular strength and endurance for the purpose of increasing both physical function and performance. Its history spans at least 3,000 years, with evidence of exercises being performed in the ancient Greek, Egyptian, and Chinese societies. Often, early depictions, for example on vases, include soldiers lifting stones or bags of sand as physical preparation for the rigors of battle. According to Greek legend, the undefeated wrestler Milo carried a calf every day as part of a conditioning program. As the calf grew, Milo grew stronger, making this perhaps the earliest example of a progressive resistance training program. Training programs and equipment have certainly evolved over time, as exemplified by machines designed for weight training dating back to the early 1600s.

Competitions in weight lifting have been held formally for well over 100 years, with the first world championship competition held in England in 1891, and have been included in almost every modern Olympics. The weight lifting competition in the 1896 Olympics consisted of the one-handed lift and the two-handed lift. The two-handed lift, similar to a clean and jerk, was won by Viggo Jensen of Denmark. His lift of 110kg was the same as that of the second place finisher, Launceston Elliott of Great Britain, but Jensen was awarded the victory when his lift was declared to have been a cleaner lift. The one-handed lift was a snatch-type event and followed immediately. In this event, Elliott’s lift of 71kg far outpaced Jensen’s second place effort of 57kg. Apparently Jensen had injured his shoulder during the two-handed competition. Weight lifting events were included again in the 1904 games and, following a temporary suspension, have been included in every Summer Olympics since 1920, though the events have changed.

Current weight lifting competitions are separated into two categories. "Weightlifting" competitions, including those performed in the Summer Olympics, consist of the snatch and the clean and jerk. "Powerlifting" competitions involve three exercises: the squat, the dead lift and the bench press. Because of their powerful influence on total muscular strength, competitions in both Powerlifting and Weightlifting are conducted in categories based on both sex and body mass.

As a result of its inclusion in Powerlifting, as well as its overwhelming popularity in general weight training, the bench press is probably the most popular weight training exercise. Perusal of almost any introductory or higher level text on weight training will include the bench press. It is a multi-joint, upper body exercise that involves muscles of the torso, the shoulders and the upper extremity.

1.2 Definition of Movement in the Bench Press

The bench press is a simple, classic exercise. It is typically performed with the lifter in a supine position on a flat bench. A straight bar is held with the arms extended upward and the palms turned toward the lifter's feet. Typical grip width is shoulder width or slightly wider apart, although different grip widths may be used to alter the muscles emphasized. The bar is lowered to the chest and then lifted back up until the arms are fully extended once again. For the purposes of this research, the bench press is divided into two phases, the descent phase and the lift phase, which are defined as follows:

> ***The descent phase***: Starting with both arms extended upward, the time from the onset of downward movement to the point at which the bar touches the chest and reaches zero vertical velocity.
>
> ***The lift phase***: The time from the beginning of upward movement of the bar from the chest until the bar reaches its highest point and vertical velocity returns to zero.

A more thorough description of the movement and these time point definitions appears in Chapter 3.

1.3 Purpose of the Study

The purpose of this study was to increase the body of knowledge concerning the biomechanics of the bench press. Muscular activity, as well as the kinematics and kinetics of the bar, were assessed during different variations of the exercise.

1.3.1 Specific Aims of the Study

There were three specific aims of the study.

Aim 1 was to compare the kinematics of the bar of a single, maximal effort lift with those of a multiple repetition set performed at 75% of the maximum load. The vast majority of the data available on single, maximal lift mechanics was collected on highly competitive power lifters. There is little data on non-elite and recreational lifters, which by definition, make up the majority of the population of people who weight train. Since most weight training programs involve multiple repetition sets, it is important to know the differences in mechanics that may exist between single and multiple repetition efforts.

Aim 2 was to examine the forces exerted by the lifter on the bar, specifically vertical and along the bar, in the bench press. The vertical forces applied by the lifter have been reported, but there is no report of any horizontal forces. Understanding the magnitude and direction of the forces applied may shed light on methods for better performance of the exercise. It may prove that a different force pattern would be beneficial when performing a maximal and a submaximal lift. To achieve this aim, an instrumented bar was designed to record vertical and horizontal forces applied to the bar during a flat bench press.

Aim 3 was to examine the effects of varying the grip width in the bench press. More specifically, the goal was to determine the how an increase in grip width alters the relative muscular activity and the forces, both vertical and along the bar, during the bench press.

1.4 Overview of the Study

To achieve the general purpose of this study, kinetic, kinematic, and electromyography (EMG) data were collected on a group of subjects performing different variations of the bench press. Those variations included: a single lift with maximal load; a single lift at various grip widths; and multiple repetitions performed in a set to failure. These different tasks were chosen based on the specific aims of the study.

1.5 Dissertation Structure

Following this introduction, this document will be divided into five chapters.

1.5.1 Chapter 2: Review of Literature

This chapter contains a review of the literature as it pertains to the biomechanical analysis of the bench press. Primary topics of interest and discussion include: 1) Patterns of the bar kinematics in both maximal and submaximal effort, as well as patterns observed in highly skilled and less skilled lifters; 2) Vertical forces applied to the bar; and 3) Muscular activation in the bench press. Additional attention is paid to modification of the lift, including varying grip widths and how these changes affect relative activity of the muscles involved during the lift, as well as lifting performance. Finally, the application of the research techniques involved in this study will be discussed in other resistance training applications, including the squat.

1.5.2 Chapter 3: Fatigue effects on bar kinematics during the bench press

The goal of this study was to examine the differences in the kinematics of the bar when performing a single, maximal lift and when performing set to failure at 75% of maximal lift load. Little change was seen in the descent phase of each repetition, so specific attention was paid to a) the velocity of the bar, and b) the path the bar followed during the lift phase. Clear differences were seen in both velocity and path when comparing the lifts. The first and last repetitions were significantly different from each other in a set to failure. Furthermore, as a subject progressed through the set to failure, the lifting pattern tended to become more similar to the maximal lift, but still maintaining observable differences. The impact of this on training program development is discussed. This chapter consists of an article that has been published in the Journal of Strength and Conditioning Research.

1.5.3 Chapter 4: Forces applied to the bar during the bench press

This purpose of this study was to determine the vertical and lateral forces applied to the bar during the bench press. Three dimensional kinematic analysis of the bar was combined with a unique, instrumented bar designed for this study that made assessment of vertical and lateral kinetics possible. Lateral forces are indeed applied to the bar, and they average approximately one quarter the magnitude of the vertical forces. The vertical force profile of the novice subjects in this study was similar to descriptions of the vertical force profile of more experienced lifters. This chapter consists of an article that has been accepted for publication in the Journal of Strength and Conditioning Research.

1.5.4 Chapter 5: Kinetic and electromyographic changes when grip width is varied in the bench press

The purpose of this study was to determine changes in muscle activation patterns, estimated via electromyography (EMG) and the vertical and lateral forces applied to the bar during a single repetition bench press performed at several different grip widths. Three dimensional kinematic data were again combined with data collected using the instrumented bar as well as superficial EMG data. Statistical analysis revealed that muscle activity patterns are different between the descent and lift phases but few changes are seen between the maximal and submaximal lifts, or across grip width positions. Forces applied to the bar, both vertically and laterally, tended to decrease as grip width increased.

1.5.5 Chapter 6: Summary and Conclusions

This chapter summarizes the main work and findings from the three studies. It discusses the limitations of this work and makes recommendations for further work.

CHAPTER 2

Review of literature

2.1 Introduction

The following subsections will discuss the body of literature that covers the topic of biomechanics as it relates to the bench press. Specific topics to be covered include: kinematics and kinetics of both the lifter and the bar during the bench press; electromyography (EMG), especially its use in assessing force output and muscle fatigue during weight lifting tasks; a description of the literature on other weight training tasks that may provide insight on studying the bench press; and finally, some of the training aspects that affect lifting performance.

2.2 Kinematics of the Bench Press

The following sections will outline the available literature describing the kinematics of the both the bar and the lifter during the bench press.

2.2.1 Arm Kinematics

The kinematics of the upper extremity during the bench press, while relatively simple, have not been closely examined. The relationship between grip width and bench press performance has been examined and will be discussed later in this chapter. Madsen and McLaughlin (1984) and others have discussed changes in bar path, but have not mentioned corresponding changes in lifter kinematics. The only direct discussion of upper extremity orientation found in the literature is in McLaughlin's article in Power-Research (1985). In this coaching and performance oriented but non-peer reviewed journal, he briefly discusses the position of the elbow relative to the trunk ("elbows in" versus "elbows out"), but does not offer any definite conclusions. This lack of data is likely the result of the two dimensional analyses performed in most of the literature on bench press. For accurate kinematic data on the upper extremity to be produced, data would have to be collected in three dimensions.

2.2.2 Bar Path

Competitive lifting rules and general safety guidelines state that the bar should be kept horizontal at all times during the bench press. As a result, the path of the long axis of the bar has typically been described as a para-sagittal plane movement. Madsen and McLaughlin (1984) describe typical sagittal plane bar paths for both recreational and competitive lifters. For both groups, the path during the descent phase is nearly linear with a slight inferior deviation as the bar travels from the top to the bottom of the lift. During the lift phase, recreational lifters display a bar path that remains inferior (caudal) to the downward path while competitive and elite lifters move the bar closer to the head. In fact, elite lifters display a noticeable, early superior excursion of the bar as compared with the competitive lifters. The authors theorize that this pattern leads to greater lifting success by decreasing the moment created by the bar weight about the shoulder joint during the lift phase.

The skilled lifter group also started and finished the exercise with the bar at a lower height than the unskilled lifters. The authors analyzed high-speed video of the skilled lifters performing during national and world competitions and did not have direct access to the skilled lifters, therefore, they were not able to measure upper limb length. They were able to estimate upper body length from the video however, and found no significant difference between the skilled and novice groups. With this evidence, the authors suggested that the difference in bar height at the start of the lift was likely due to a wider grip rather than shorter arms for the skilled lifters (Madsen and McLaughlin, 1984).

2.2.3 Bar Velocity and Acceleration

Of all of the mechanical aspects of the exercise, the vertical kinematic profile of the bar during the bench press has received the most attention in the literature. Several articles have addressed the topic (e.g. Lander, Bates, Sawhill, and Hammill, 1985; Elliott, Wilson, and Kerr, 1989; Wilson, Elliott, and Wood, 1991) with Madsen and McLaughlin (1984) giving the most thorough description. They described six points on a time plot of bar velocity (Figure 2.1). In order, they are: Start (initiation of downward movement) (Point 1 in Figure 2.1), Maximum Downward Velocity (Point 2), Chest (when the bar is in contact with the chest) (Point 4), Maximum Upward Velocity (Point 6), First Local Minimum Upward Velocity (minimum upward velocity between the two peaks) (Point 8) and End (Point 9). The authors describe three points in the acceleration profile, all during the lift phase. They are: First Local Maximum Upward Aceleration (Point 3), Maximum Upward Acceleration (Point 5), and First Local Minimum Acceleration (Point 7).

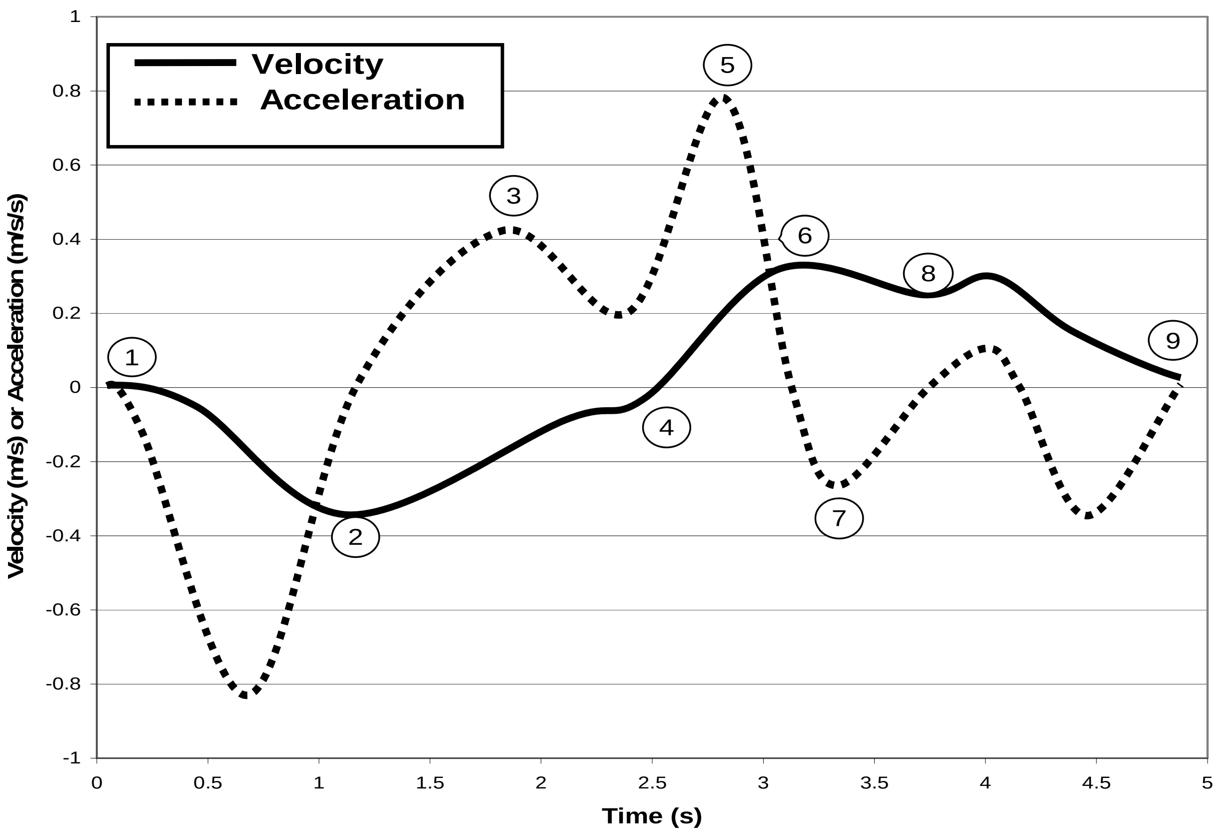

Figure 2.1: Typical vertical bar velocity and acceleration during the bench press. The nine point markers coincide with those described by Madsen and McLaughlin (1984) and discussed in the text.

2.2.4 Kinematic Variations With Lifting Skill

Before discussing the kinematic differences between the groups examined, it should be mentioned that there were significant differences in the amount of weight lifted by the two groups in Madsen and McLaughlin's 1984 study. The expert group lifted an average of 185 kg or 2.3 time body weight (BW), while the novice group lifted 101 kg or 1.3 BW, while the mean body masses of the two groups were similar (79 and 77 kg, respectively). They found differences in bar velocity and acceleration for recreational versus highly skilled lifters. Whether looking at downward velocity (0.17 $m.s^{-1}$ vs. 0.32 $m.s^{-1}$) or acceleration (3.3 $m.s^{-2}$ vs. 0.7 $m.s^{-2}$); the skilled lifters lowered the bar more slowly than the novice lifters. In fact, while the expert subjects lowered the bar at about half the velocity of the novice lifters, they took more time to lower the bar (1.723 s vs. 1.158 s) even though they were lowering it a shorter distance (0.30 m vs. 0.37 m). The authors suggest that lowering the bar more slowly reduces the acceleration required to stop the descent of the bar, therefore reducing the magnitude of the force applied during the descent phase. While they do not say this directly, it is assumed that the authors mean that the peak force required to stop the decent of the bar was lower relative to each individual lifter's force curve, not as an absolute lower force. This is unlikely since the novice lifters were moving much smaller weights and therefore likely exerted smaller forces throughout the lift.

2.3 Forces Applied to the Bar During the Bench Press

There is no description in the literature of the magnitude or direction of the resultant force applied to the bar during the bench press in the literature. The vertical forces applied to the bar have not been measured with force or strain transducers, but have been estimated from kinematic data.

2.3.1 Vertical Force Profile

The earliest detailed description of the vertical forces applied to the bar during the bench press appears to be 1985 (Lander, Bates, Sawhill and Hamill, 1985). The authors used "skilled lifters" who had a maximal single lift (1RM) of between 1333 and 1822 N (a relatively broad range of 1.27-2.16 BW). Only forces during the lift portion of the exercise were described. The typical vertical force pattern, for a lift at 90% 1RM includes four phases. The first phase, the acceleration phase, involves an early peak occurring at about 5% total lift time (LT) and lasts to about 16% LT. This phase is followed by a period where the force applied is less than the weight of the bar. This phase lasts from 16 to 42% LT and is termed the "sticking region." This phase corresponds well with the popular "sticking point" in the bench press where most failed lifts occur (Lander et al., 1985; Madsen and Mclaughlin, 1984). During the third phase of the lift, from 42 to 82% LT, the force applied to the bar is once again greater than the weight of the bar and is termed the maximum strength region. The rationale for the name of this phase is not provided. The final phase, occurring during the last 18% LT is the deceleration phase and once again, the force applied to the bar drops below the weight of the bar.

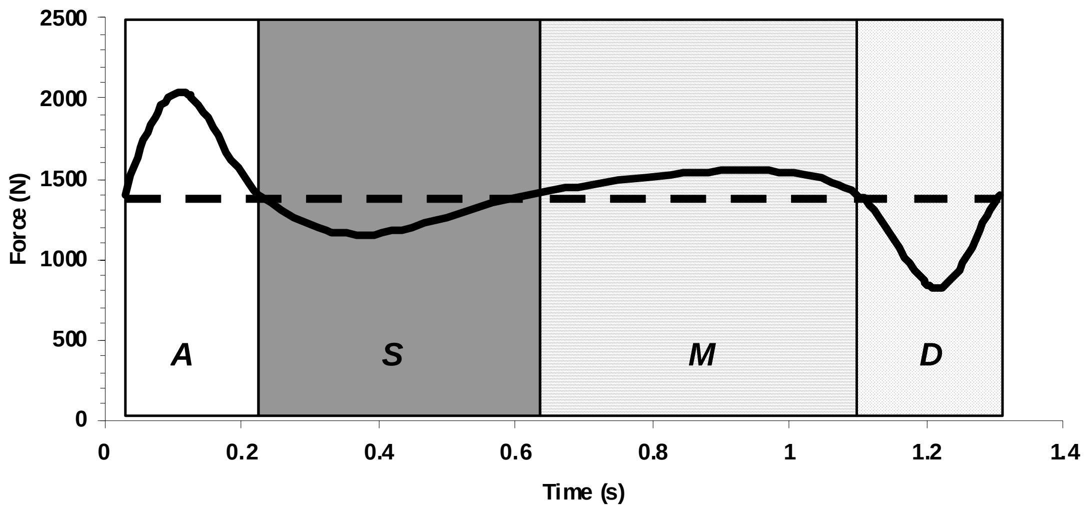

Figure 2.2: Typical vertical force curve during the bench press. *A*: Acceleration Phase, *S*: Sticking Region, *M*: Maximal Force Region, *D*: Deceleration Phase. From Lander, Bates, Sawhill and Hamill, 1985.

Madsen and McLaughlin (1984) studied a group of 19 national and world class competitive lifters and a group of 17 recreational lifters and determined that there are several differences in the force applied to the bar when lifting skill increases. The authors state that expert lifters exert greater peak forces during both the lower and the lift, even when normalized to body weight. These finding are not surprising given that the lifts of the expert group were ranked in the top three in the world.

2.3.2 Grip Width and Resultant Force

There is no description in the literature of how varying grip width affects the magnitude or direction of the resultant force applied to the bar, however, pilot testing with subjects performing push ups at various hand widths indicated a positive correlation between hand width (effectively grip width) and horizontal force (Duffey and Zatsiorsky, 2003). Therefore, it would be expected that as grip width in the bench press increases, the resultant force would be applied in a more outward (lateral) direction.

2.4 Isokinetic and Isotonic Bench Press

Studies of the kinetics of the bench press have especially focused on differences in free-weight and isokinetic lifting. Fundamental differences exist between isokinetic exercise and free-weight exercise. First, the load at the beginning and end of the range of motion of an exercise is typically zero for isokinetic exercise, while it remains effectively constant when using weights. This is because isokinetic machines typically are designed to reduce the load or resistance when the speed of the exercise drops below the desired or set speed. Another difference involves the possible direction of movement between the different categories of exercise. Free weights, by definition, are allowed to translate in all three directions whereas isokinetic machines typically allow movement only through a prescribed path, usually an arc. Studies can be designed to reduce the differences between the two types of exercise.

Lander et al. (1985) compared the vertical forces during free-weight and isokinetic bench press lifts. A "Cybex Power Bench Press" was used for the isokinetic trials. This device incorporated a transducer to record torque applied by the lifter which were later converted to vertical forces. They first examined subjects using free-weights, lifting loads equivalent to 90% and 75% of the maximal weight lifted in a single repetition (1RM). In these trials, subjects were asked to lift producing the greatest possible power without bouncing the bar on the chest. Since the load was constant, it is assumed that the lifters were instructed to lift as quickly as possible. The mean velocity for each lifter was determined for the two conditions, and these velocities were then employed for the two isokinetic conditions.

In general, the force patterns exhibited in both sets of trials (75% and 90% load or speed) in both conditions (free-weight and isokinetic) were similar, but not identical. Not surprisingly, the forces exerted during the 90% 1RM trials were greater, and were exerted for a longer period of time, than during the 75% trials. The time to the first maximum force was slower for the isokinetic trials at 90% 1RM. The design of the isokinetic system is the likely explanation for this. The force applied at the bottom of the lift (the bar on the chest) is zero when using the isokinetic system while in the free-weight condition, the force applied to the bar should be nearly the weight of the bar (approximately 1600N for the 90% condition). Therefore, more time will be required for the muscles to create the same maximal force.

Rosentswieg, Hinson and Ridgway (1975) examined muscle activity at the different speeds during an isokinetic bench press task. They employed "The Super Mini Gym, Model #130", which could be set at "Slow, Moderate and Fast" speeds, which were determined by the manufacturer and are apparently not quantified in the study. Their findings indicate increasing electrical activity in the involved muscles as speed of exercise decreased, which will be discussed further in the next section. No direct comparisons were made to free weight exercise.

2.5 Electromyography

In the following sub-sections, EMG concepts will be reviewed as they pertain to weight training exercise.

2.5.1 Definition and Practice

Electromyography is the study of the electrical activity in muscle. In humans, it is traditionally performed either by inserting a wire into the muscle (fine wire or indwelling EMG) or by placing electrodes on the skin superficial to the muscle (superficial or surface EMG). The electrodes or wires detect electric current, caused by motor unit action potentials, as it passes through the muscle. The electrical signal, through an electro-chemical pathway, initiates the contraction of the muscle. While it is possible to examine the electrical activity of a single motor unit when using indwelling electrodes, surface EMG will record the activity of multiple motor units. Thus the recording seen in surface EMG represents a sample of the summation of the nearby motor unit action potentials (MUAP).

In general, as the frequency of MUAPs increases and more motor units are recruited, the magnitude of the signal recorded will increase. Frequently, to analyze the magnitude of the signal, the raw EMG signal is full wave rectified, and then a low pass filter is employed to create a linear envelope. The area enclosed by this envelope can then be determined and used as a measure of EMG amplitude. Other options for assessment include taking a mean or a peak value over a period of time. Along with the amplitude, frequency content of the signal is often examined and used as an assessment of muscle contraction, particularly fatigue in muscles as well as the type of muscle fiber contracting. The rationale and the physiologic representation of both of these measures will be discussed in later sections.

2.5.2 Normalization

There are many factors that can alter the relationship between the EMG signal and the force production of a muscle. Some of these factors include: type of EMG electrode (surface versus indwelling), size of the muscle, distance from the electrodes to the muscle fibers, amount of tissue (especially fat) between electrodes and the muscle fibers, contact between the skin and the electrode, and position and orientation of the electrode on or in the muscle (De Luca, 1997). These factors further reinforce that, especially when performing in vivo, normalization of the EMG signal is imperative for deriving a result that has any physiological relevance.

There are options available for the method of normalization. Typically, however, the strength of the signal during the measured activity is normalized to, or divided by, a maximal signal that was recorded. This maximal value can be taken during the activity, or it may have been recorded during a separate activity, like a maximal isometric contraction.

Yang and Winter (1984) performed a study focusing on normalization methods as a way of improving the information gathered about muscle activity during gait. Their evaluation criterion was the reduction of variability. They found that normalization using a 50% isometric contraction was inferior to other available normalization methods and in fact, worse than non-normalized data. Normalization using either the peak or the mean of the "ensemble average" proved to be the best methods for reducing variability. Averaging the data presented for the rectus femoris, the vastus lateralis, the biceps femoris and the soleus, the coefficient of variability was 2.7 and 2.9 times greater when normailizing to 50% MVC versus normalizing to the peak and the average ensemble taken during walking, respectively. What is meant by "ensemble" is not clearly defined, however these two calculations appear to equate to the peak and the mean EMG level value for a given subject within a stride, which seems to make them similar to a dynamic maximum or a dynamic average taken within a single movement cycle.

Burden and Bartlett (1999) compared four methods of normalizing an EMG signal from the biceps of five subjects during an elbow flexion task. The four methods were normalization with respect to (1) peak and (2) mean EMG value during dynamic contraction (Dynamic Peak Method and Dynamic Mean Method, respectively), (3) EMG value during a maximal voluntary isometric contraction (MVIC) and, (4) EMG value during an maximal voluntary isokinetic contraction performed at a similar isokinetic speed and angular position as the activity of interest. The mean EMG value was obtained for each subject during each phase (concentric and eccentric). As there is no "gold standard" for comparison, the authors used a root mean square difference method for evaluation of the difference between each of the first three methods and the fourth normalization method. Their results indicated that either isometric or isokinetic MVC data should be used for normalization.

2.5.3 Electromyography-Force Relationship in Muscle

The ability to use EMG as a method of assessing muscle force is a topic of much debate in the literature. It seems clear that there is some relationship; in general, as the intensity of the motor neuron signal to a muscle increases, the electrical activity in the muscle increases, and the force produced increases as well (Lippold, 1952). Because it is much easier, at least in living humans, to asses the electrical activity of a muscle than it is to measure the force output of a muscle, the EMG-recorded signal has been used to estimate force output of the muscle. Laboratory experiments have done this with reasonable success. In vivo, the relationship is less strong, and holds up better with isometric contractions than dynamic ones. Early research seemed to indicate a nearly linear relationship between force and EMG signal (Lippold, 1952; Bigland and Lippold, 1954) especially in isometric conditions, while later publications provide evidence for a more curvilinear relationship (Clamann and Broecker, 1979; Komi and Buskirk, 1972) especially in dynamic conditions. Bigland-Ritchie suggests that the relationship may be either, and partially depends on the muscle being investigated (Bigland-Ritchie, Kukulka and Woods, 1980) and may actually be a result of the fiber type within the muscle.

To further complicate the matter, many factors affect the maximal force output of a muscle in vivo, including: cross sectional area of the muscle, the ratio of fiber types, muscle velocity, and muscle length, among others. Furthermore, many factors can affect the EMG signal recorded on a given muscle, including: electrode attachment and impedance, size of muscle, distance from muscle to the electrode, fatty tissue, muscle velocity, and electrode movement (De Luca, 1997). Finally, in vivo it is very difficult to measure the force output of a single muscle. More often a torque produced by a group of muscles working together, as well as the contribution of antagonist muscles, is recorded.

There are so many factors that can alter the absolute force output of a muscle and also the signal recorded, that estimation of absolute muscle force from EMG signal can be problematic. As a result, the relative level of contraction of a muscle rather than its absolute force output is more often assessed.

2.5.4 Fatigue Relationship

The first description of the relationship between EMG signal and muscle fatigue was in 1912. Specifically, Piper described that muscle fatigue can be observed in surface EMG signal as a reduction in EMG signal frequency (Piper, 1912). In addition, Cobb and Forbes (1923) found that muscular fatigue was indicated by an increase in the amplitude of surface EMG signal without a concurrent increase in force. Since that time, research on the topic has progressed to establish two general relationships between EMG signal and fatigue: as fatigue occurs, force output decreases but EMG amplitude remains the same or increases, and there is a shift in the EMG signal toward a lower mean and median frequency (De Luca, 1997). The underlying physiologic reason for this shift is that fatigue creates a change in the muscle fiber membrane permeability, thereby decreasing the conduction velocity of the fiber (Kamen and Caldwell, 1996). Commonly, in sustained submaximal activity, there will also be an increase in the amplitude of the signal without an increase in force production. This is likely caused by an increase in the number of recruited muscle fibers (Kamen and Caldwell, 1996) or an increase in the time duration of the MUAP, which at least in part is due to a decrease in conduction velocity of the action potential, which may be the result of a pH change in the muscle (De Luca, 1997).

2.6 Electromyography and Bench Press

In the following subsections, the literature that addresses EMG analysis and muscular activity during the bench press will be discussed.

2.6.1 Electromyography and Isokinetic Bench Press

The earliest article in the literature describing EMG activity during the bench press, and the only one that explored EMG during and isokinetic bench press, is the 1975 Research Quarterly article by Rosentswieg, Hinson and Ridgway. The authors studied 11 college age women performing the bench press on an isokinetic device called the Super Mini Gym, Model #130. The purpose of the study was to determine how the speed of the bench press influenced muscle activation. The Super Mini Gym utilizes a system of pulleys that allows for "slow, moderate and fast" contraction periods. Subjects were instructed to give maximal effort at each speed, while the "Muscle Action Potential" (MAP) was measured using surface EMG for the anterior deltoid, the pectoralis major, the biceps brachii, and the triceps. Further details of the EMG collection process are vague, describing only that the collection unit was able to measure "below the µV/sec level" and that the unit output is an average, absolute voltage. The authors found that the selected muscles did seem to be active during the exercise and for the pectoralis major, MAP decreased as speed increased through all three conditions. For the other muscles analyzed, there was only a significant difference as speed progressed from the moderate to the fast setting.

There are a few problems with this particular study. First, speed was not controlled in a systematic and quantitative fashion. The authors used the "slow, moderate and fast" settings of the unit, but it is not clear how much the speed of the exercise changed when increasing the speed setting, or whether the increase from slow to moderate was the same interval as moderate to fast. Furthermore, EMG data were not normalized in terms of signal strength (i.e. normalized using any of the previously discussed methods). While the authors did not make comparisons across muscle groups, they did combine subjects into groups. Combining subjects into groups using raw EMG signal will likely increase the within group variability due to some of the factors that influence EMG data collection, also discussed previously. Finally, the authors converted the units of their analysis into millivolts/sec, however, they do not describe this process. It is unclear whether the average value across the length of the trial was selected or a maximal value within the trial (either instantaneous or for a given period of time) was determined, or if "counts" were used.

2.6.2 Electromyography and the "Sticking Point"

Elliott, Wilson and Kerr published a paper in 1989 exploring the "sticking region" in the bench press. This term has been used two ways: one is to describe the location within the lift that most failures occur (Madsen and McLaughlin, 1984) the other is to describe the portion of the lift where the vertical force applied to the bar is less than the weight of the bar (Elliott, Wilson, and Kerr, 1989). Both of these tend to occur roughly in between 20% and 40% of the lift phase of a successful lift.

The authors collected kinematic and EMG data on 10 elite male lifters performing the bench press under a variety of loads. The authors used the kinematic data to calculate vertical force exerted on the bar. The subjects were state up through national record holders in Australia and were described as having maximal lifts between 150 and 245kg. The authors looked at maximal lifts, lifts at 80% of maximal, and failed lifts. While their results were useful as a general description of muscle activity during the bench press, they are not particularly helpful in their exploration of the sticking point.

Regarding the EMG results, it is important to note that the authors gave subjective descriptions of the EMG data only; no quantitative results to support their findings are given anywhere. The authors state that MVIC data from each muscle was used to provide the authors with a "reference" level for subjective analysis, but there is no mention of MVIC data collection in their methods.

The authors state that EMG activity in the pectoralis major, the anterior deltoid and the triceps was "moderate and occasionally maximal" throughout of the descent phase. Strangely, the representative EMG time curve included in the article seems to indicate that there was no maximal activity during the descent phase. During the ascent phase, the authors report that the primary movers contracted maximally at the start of the lift and maintained this level of contraction with little variation until the end of the lift.

2.6.3 Electromyography and Grip Width

It has been suggested that grip width plays a role in the relative muscular contribution during the exercise as well as the maximal weight that can be lifted (Lehman, 1995; Barnett, Kippers, and Turner, 1984). Several studies have shown that a relatively wide grip width, between 180 and 200% of biacromial width, is optimal for maximal bench press performance (Clemons and Aaron, 1997; Gilbert and Lees, 2003; Madsen and McLaughlin, 1984). As grip width on the bar widens, both the range of motion of the lifter and the final height of the bar are reduced. Especially this second factor has been discussed as one of the possible explanations for increased bench press performance with an increased grip width (Madsen and McLaughlin, 1984; McLaughlin, 1985).

It is generally accepted that increasing the grip width on the bar will increase the contribution of the pectoralis muscles, especially the pectoralis major, to the exercise (McLaughlin, 1985). There have been a few studies that have examined this theory and they have shown conflicting results. Barnett, Kippers and Turner (1995) looked at electromyographic activity in the anterior deltoid, the triceps, the latissimus dorsi (the authors stated this muscle was chosen because some lifters mention it as a contributor or stabilizer in the bench press) and two portions of the pectoralis major: the "clavicular head" which the authors consider the more proximal fibers; and the "sternocostal head", which the authors consider the more distal fibers. They had six experienced but non-competitive male lifters complete a submaximal lift at 100% and 200% of biacromial width. A unique aspect of this study was the selection of weight to be used for each lift condition. Prior to data collection, each subject completed a test of 1RM strength at both the wide and the narrow grip positions in the protocol. The lifts for this study were then performed using 80% of each position-specific 1RM load. The results were based on a comparison of integrated EMG signal.

The authors found the EMG activity in the triceps decreased with the wider grip width, but so did activity in the clavicular head of the pectoralis major. No consistent change was seen in the sternocostal head. As the authors expected, the latissimus dorsi was shown to be relatively inactive during the bench press.

In 1997, Clemons and Aaron examined the relationship between grip width and EMG, comparing relative muscular activity, based on a percent of maximum voluntary isometric contraction (%MVIC), as the primary variable. Grips widths of 100, 130, 165, and 190% of biacromial width were chosen for this study. Unlike the previous study, the subjects in this study lifted the same load in each condition. The load chosen was the greatest weight each subject could lift in the narrowest grip width condition. Increasing grip width increased the activity of all of the muscles analyzed (biceps, triceps, pectoralis major, and anterior deltoid), with no apparent differences between any of the muscles in the amount of increase. More specifically, for the widest condition (190%), EMG activity was significantly different from both the 100% and the 135% conditions. For all conditions, the authors chose the weight the subject could lift at 100% BAB assuming that this was the weakest position. The increase in EMG activity with the wider grips suggests that the muscles had to increase the intensity of their contractions to lift the weight in the wide grip condition. This might suggest that the widest grip condition was the weakest condition, exactly the opposite of the assumption the authors made while designing the study. The authors do not comment on this possibility. They also found that, at least in recreational lifters, the triceps were loaded the most of all the muscles (approximately 110% of MVIC) and there was no difference between the relative loading of the pectoralis major and the anterior deltoid during the lifts (approximately 75% and 95% MVIC). The biceps, which are not considered to be primary contributors to the bench press, were only loaded at approximately 22% of MVIC. The authors' methodological choice to use the same load at each grip width limits their ability to discuss EMG activity during maximal efforts at each grip width, which may be very important for overall performance. It is entirely possible that the relative activity between the different muscles may have been different if maximal weights had been used for the wider grip width conditions.

So it is interesting to note that not only did both studies have at least some findings that contradicted commonplace theory on how to alter muscular activity in the bench press, at times also contradict each other. A third study was performed in 2005, this time comparing narrow, mid and wide grip widths (Lehman, 2005). The wide grip equaled 200% biacromial width, the mid grip was 100%. The narrow grip was defined as having a space equal to the width of one hand between the hands. The average root mean square, using a 164 ms window, of an isometric contraction performed at the wide grip was used for normalized comparison for the different grip widths in the following muscle groups: the clavicular portion of the pectoralis major, the sternoclavicular portion of the pectoralis major, the triceps, and the biceps. Twelve experienced but non-competitive lifters completed this study. No differences were seen in the upper (clavicular) portion of the pectoralis major as the grips width changed. Activity in the lower portion of the pectoralis major (sternoclavicular) was statistically different only when the wide and narrow grips were compared. Activity dropped 27% in the narrow condition as compared to the wide grip. Mean activity level dropped 18% for the mid grip, but this was not statistically different. Activity in the triceps increased to 157 and 210% of that in the wide grip as the subjects shifted to the mid and then narrow grips. So this study showed further support for the theory that the triceps are more active when employing a narrower grip, but the results for the pectoralis major remain mixed.

2.7 Lifting Changes Associated with Load Variation

Most of the literature available examining the mechanics of the bench press has looked at maximal, single lift efforts. It is evident, however, that the mechanics of a lift change with the relative demand of the load. Early work by Hay et al. (1982) examining the effects of varying the load in the squat found changes in the kinematics that effectively amounted to a technique change. Their study involved subjects performing the squat at 40, 60, and 80% of 1-RM and found that, as the load increased, trunk inclination increased. At lower loads, the greatest demand, or largest moment production, was required by the knee extensors; however, at higher loads, this demand shifted to the hip extensors.

In their examination of the sticking point in the bench press, Elliott et al. (1989) analyzed their subjects' lift mechanics at both 80% and 100% 1-RM load and found changes in the mechanics of the lift that they describe as "radical." The force pattern of seven of the ten subjects in the study changed so that there was only an acceleration and a deceleration phase. The subjects had eliminated the "maximum strength region" and most importantly, the sticking region. Since this is the phase where the force applied is less than the weight of the load and most failures occur, it is extremely unlikely that these lifts will result in failure.

These authors revisited the topic in a publication later that year (Wilson, Elliott, and Kerr, 1989). This time, their specific aim was to examine differences in single lifts using maximal and submaximal load. They again studied 10 elite lifters, comparing bar path and force applied to the bar at 80% and 100% of 1-RM load. The differences in bar path during descent and lift described by Madsen and McLaughlin were observed in the 100% lift, but for most subjects, greatly diminished in the 80% lift. In particular, the pattern of keeping the bar more directly over the shoulder during the lift phase was no longer observable in the 80% lift. Also confirming previous results, the sticking phase and maximum strength phase disappeared in the force profile. Instead, there was a single maximum force applied during a longer acceleration phase, and a single minimum force during a longer deceleration phase. Again the absence of a sticking phase suggests that lift failure is highly unlikely.

2.8 Mechanics of Other Strength Training Exercises

The literature describing the mechanics of other strength training exercises is limited in a similar way to the literature on the bench press. The most commonly studied exercise other than the bench press is the squat. There are some similarities between the two exercises, i.e. bilateral movement which involve large muscle groups, and therefore, it warrants discussion here.

2.8.1 Analysis of the Squat

McLaughlin, Dillman and Lardner published a study in 1977 discussing some of the kinematics involved in the parallel squat. Their primary goal was to find a way to differentiate elite lifters from those with less skill. Their study included video analysis of 24 competitors at the U.S. National A.A.U. Powerlifting championships. The subjects were divided into two groups based on performance. The "elite" group were ranked in the top 7 in the world in their respective weight classes at the time of the competition whereas the "less-skilled" group did not have world ranking at the time. The variable chosen as the primary discriminator between the two groups was the vertical velocity of the bar. The graph of bar velocity was first divide in two parts, with the divisor chosen as the time when the thigh segment reached its most horizontal position. The time before this, titled the "descent" phase, was divided evenly into thirds, as was the time following this point, titled the "ascent" phase. Similarly to previous findings in the bench press (e.g. Madsen and McLaughlin, 1984), the less skilled lifters were found to lower the bar more rapidly as reflected by a greater peak downward velocity (-54.8 ± 6.1 cm/sec vs. -5.7 $\pm$ 3.0 cm/sec) and a greater average downward velocity (discussed but data not presented). Regarding body kinematics, the less-skilled lifters also had greater trunk lean, greater backward displacement of the hips and greater forward displacement of the knees and the bar. Again, these findings are discussed but actual data was not presented. The primary finding in the ascent phase was the less-skilled group leaned forward at the beginning of the ascent phase more than the elite group. This occurred even though they already had greater trunk lean that had carried over from the descent phase.

The authors include a discussion about the applicability of their research, primarily focusing on the homogeneity of the group. They suggest that the differences they found could be important for performance evaluation at the highest level of competition and also hypothesize that the trends they found would likely increase when looking at non-competitive lifters.

Those same authors also published a paper describing the kinetics of performing a squat. In this study, they analyzed film from 12 of the competitors at the 1974 US Senior National A.A.U. Powerlifting championships described in the previous study. No force data (i.e. ground reaction force, etc.) was available for this study. The authors used Dempster's anthropometric data and Plagenhoef's data on moments of inertia for their calculations. They did mention that the population in the study most likely displayed different physical characteristics from those used to establish those data sets, however, it appeared that the errors in moment of inertia estimates at least were negligible relative to the total magnitude of the muscular torques. The 12 subjects were divided into two categories: world champions, high-skilled (top 10 ranking in the world), and less skilled (ranked below 10 in the world).

Both resultant joint torques and joint forces were calculated and they found general trends of differences between the two groups. Both groups showed sizable trunk extension moments, suggesting that this exercise is accomplished by more than the knee and hip extensors, and the less skilled group showed greater trunk extension moments than did the higher skilled groups. This finding is a logical extension of their report on kinematics during the squat which showed greater trunk lean in the less skilled group. Thus both reports suggest that reducing trunk lean and therefore the torque required by the back extensors is an important element at least in high level squat technique.

2.8.2 Isolating Muscles in the Squat

Similarly to altering the grip width in the bench press to change the relative contribution of the muscles involved, it has been suggested that varying foot width will change what muscles are more involved (e.g. Schwartzenegger and Dobbins, 1985). McCaw and Melrose (1999) examined the interaction between stance width and the relative load on the bar, and surface EMG activity in the Rectus Femoris, Vastus Medialis, Vastus Lateralis, Adductor Longus, Gluteus Maximus, and the Biceps Femoris muscles. EMG data was sampled and then integrated in nine male recreational lifters as they performed five trials at each of three stance widths (narrow, shoulder width, wide) and two different bar loads (60% 1RM, 75% 1RM). The 1RM load had been previously determined using a shoulder width stance.

McCaw and Melrose (1999) found that increasing the load increased the EMG activity in the three analyzed Quadriceps muscles, but that stance width did not seem to have an effect. The integrated signal increase by approximately 20% as the load increased from 60% to 75% of 1RM. For the Adductor Longus, increasing the load increased the integrated EMG value, as did increasing the stance width. This supported the popular hypothesis that increasing stance width increases the involvement of the muscles of the inner thigh. The Gluteus Maximus displayed a similar pattern of change as the adductor muscle, but only at the high load. The Biceps Femoris was seemingly unaffected by the load or stance width.

2.8.3 Tibial Shear During Leg Exercise

An interesting topic of discussion is the use of open or closed chain exercise in both sport performance as well as injury rehabilitation (Escamilla, 2001). Open chain suggests the distal portion of the limb, the foot in this case, is free to move, whereas in a closed chain exercise, the foot remains nearly fixed. One of the primary topics of discussion is the use of the squat as a closed chain exercise in rehabilitation following ACL repair. While this concept does not have a parallel for upper body exercise, it does warrant discussion. It had been proposed that closed chain exercise, like the squat, is more protective than open chain exercise, like the knee extension or even the leg press, because it reduces shear forces across the knee. In 1991, Palmitier, An , Scott and Chao showed that the squat did indeed reduce shear forces as compared to the seated knee extension. It was not clear at the time whether the improved force pattern at the knee was a result of the different motion, a single joint knee extension versus a multi-joint squat, or because one was an open chain exercise while the latter is a closed chain exercise. In 1998, Escamilla, Fleisig, Zheng, Barrantine, Wilk and Andrews addressed this question. They recruited 10 male subjects who were "experienced in weight training" to perform a free weight squat, a seated leg press, and a seated knee extension exercise. EMG, video and force data were recorded during the movements and were used to calculate muscle activity and ligament forces.

They found that calculated ACL forces remained zero for both the squat and leg press throughout the exercise. Tensile forces in the ACL were present only near full extension during the knee extension, but averaged approximately 150N (peak force during extension, 158±258N; peak force during flexion 142±258N). Thus it appears the theory that closed chain exercise puts less load on the ACL is correct whether it is performed in the seated or standing position.

2.9 Specificity of Training

It is commonly reported that a rapid increase in maximal single lift performance is often seen following the initiation of a strength training program. Furthermore, this rapid increase has been attributed more to an improvement in neural firing pattern than an actual increase in muscular force output (Moritani and deVries, 1979). This would suggest that the training pattern, plays a role in improving lifting performance. Investigations into the relationship between specificity of movement and increase in performance have focused on training volume (specifically number of sets performed), training velocity, and movement pattern. Each of these will be reviewed in the following sections.

2.9.1 Training Volume

Many training texts and manuals suggest that greater training volume will result in greater strength improvements (e.g., Carpinelli and Otto, 1998). Studies of the effect of training volume often compare single set to three set routines, with peak strength, measured either as a 1RM weight or peak isokinetic torque, as the primary outcome measure. Berger (1962) showed significant improvement in training with three sets over a single set in the bench press, while Kramer, Stone, and Bryant (1997) showed similar results in the squat. Both studies examined men and lasted 12 and 14 weeks, respectively. Kraemer, Newton, and Bush (1995) later studied women performing multiple exercises in a 24 week study. In this case, they found that single and three set training groups improved through the first four months, but only the three set training group continued to improve after. These findings are not consistent throughout the literature, however. Starkey et al. (1996) compared peak isometric torque and muscle thickness in men and women following a 14 week program of strength training and found no significant differences between single and three set training groups. A similar lack of difference in strength improvement has also been reported by several others (Terbizan and Bartels, 1985; Reid et al., 1987; Stowers et al., 1983).

In 2002, a meta analysis was conducted by Rhea, Alvar and Burkett to examine the relative benefits of single-set versus three-set training studies. They explored all English language publications between the years 1962-2000 and found 16 articles that matched their criteria. Their analysis revealed that three-set training did indeed result in a greater strength gains. Furthermore, the effect was greater in the less trained subjects. The authors hypothesized that as the subjects became better trained, a greater volume, i.e. more sets would be necessary to continue a similar rate of strength improvement. The question of volume is important however; typically, multiple-set training programs will have a greater training volume than similar single-set programs. In the analysis by Rhea et al. (2002), when training volume was not controlled, the added improvement of three-set training was decreased, as evidenced by the decrease in effect size from 0.70 to 0.25. Thus from a research standpoint, controlling the volume of training is important for comparison. Without this control, it can not be clearly stated whether any changes were due to the training style, in this case the number of sets, or simply the increase in workload.

2.9.2 Training Velocity

The velocity of movement in training also seems to affect the performance gain. Publication of research in the area begins in the early 1970's and seems to coincide with the introduction and then increase in popularity of isokinetic testing and training devices. The reason for this seems to be that isokinetic devices offered a method of controlling movement velocity, something that is difficult in free weight and other isotonic type exercise. A common theory suggests that improvements in sport performance will be greater when training velocity is similar to sport performance velocity (Periera and Gomes, 2003).

Several studies have been conducted to examine strength or peak torque gains at different velocities after training at either high or low velocity. The results have been mixed. Reports have suggested that slow speed and high speed training will improve strength. Seaborne and Taylor (1984) compared groups that trained isokinetically at slow (36° /s) and high (108° /s) speeds. They found that they higher speed training group had greater improvements in strength, as indicated by peak isometric torque. The speeds chosen for this study were low compared to many other studies, which often employ speeds up to 300° /s (e.g., Coyle, et al., 1981; Smith and Melton, 1981; Kanehisa and Miyashita, 1983).

A recent study compared the effects of both training volume and velocity in a free weight exercise program for 115 untrained subjects (Munn, Herbert, Hancock, and Gandevia, 2005). For this study, the subjects performed either one or three sets of elbow flexion at a slow speed (approximately 50° /s) or fast speed (approximately 140° /s) for six weeks. A seated, isotonic elbow flexion test (1RM) was used to determine peak strength. The authors do not mention controlling or recording the speed of the 1RM lifts. Higher training volume resulted in nearly double the strength increase that was seen in the single set training group. Higher movement velocity also increased strength gains, though to a lesser degree (11% greater increase compared to slow training). There was not, however, an additional effect seen by combining high velocity and high volume training for the subjects in this study. The authors suggest that either program would provide the needed stimulus for strength gains in an untrained population, but cautioned that more experienced weight lifters may benefit from a combination of higher volume and higher velocity training.

2.9.3 Movement Pattern

There was no report evident in the literature that directly states that training with a movement pattern that is very similar to the desired movement will maximize strength gains for that movement. This seems logical, as it is clear that weight lifting performance improvement is not only due to increase in muscle size and force production, especially in new weight lifters (Moritani and deVries, 1979). There are numerous reports that show that training in a partial range of motion will result in position-specific strength gains. Kitai and Sale (1989) isometrically trained six female subjects in ankle plantarflexion three times per week for a period of six weeks. At the end of the training program, they found a slight (35.1±0.9 to 35.5±0.8cm) increase in calf circumference, which they assumed was due to muscle hypertrophy. Voluntary force output, which was tested in nine positions, increased only in positions that were ±5 degrees from the training position. Interestingly, they also tested maximal evoked plantarflexion twitch force; this force, despite the calf circumference increase, did not increase at any position. They suggested, because the amount of circumference change was so small (about 1%), that the force output increase was primarily due to a neural adaptation, not muscular hypertrophy. The lack of difference in evoked twitch force raises the question of where these neural adaptations might have occurred, but is not answered in this paper. This study, like several others, employed isometric exercise in the training program, whereas most people train using dynamic exercise.

Graves and colleagues (1989) examined position-specific strength gains that result from dynamic exercise. They trained 28 men and 31 women who had not participated in an exercise program within the previous year. They divided their subjects into four groups, three of which trained on a Nautilus knee extension machine through a full or partial range of motion (ROM), while the fourth group was a control. The three training groups performed one set of 7-10 repetitions of the exercise in the full ROM (Full Group, 0-120° flexion), a more extended ROM (Extended Group, 0-60° flexion) or a more flexed ROM (Flexed Group, 60-120° flexion). In this study, the improvements were still somewhat position-specific, but much less so than those seen in isometric training studies. The Extended Group improved force production, which was tested isometrically, at all positions except 95° flexion and the Flexed Group improved at all but the most extended (9° and 20°) test positions. Thus it seems that while dynamic exercise improves force production across a larger portion of the range of motion than does isometric training, it seems to be important to train through the full range of motion. This suggests that it is better to train with a movement that best mimics the movement and positions that will either be tested or be important for performance.

2.10 Summary

The popularity of the bench press as a weight training exercise combined with the relatively simple motion involved should make it a good candidate for biomechanical analysis. This chapter shows, however, that there has not to date been a thorough biomechanical analysis of the exercise. The most successful research attempts have been directed toward vertical plane kinematic, and kinetic analysis of the bar only; and those studies that did examine kinetics estimated forces based on kinematic data. Furthermore, the vast majority of data available thus far has been collected using male subjects, even though it is possible that there may be mechanical differences in the way men and women perform this exercise. Finally, most of the analysis of muscle activity seems to have either been done before the current EMG analysis standards were developed, or have inherent problems within the study design. It seems clear that this is a topic that needs further analysis.

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CHAPTER 3

Fatigue effects on bar kinematics during the bench press

3.1 Abstract

The bench press is one of the most popular weight training exercises. While most training regimens incorporate multiple repetition sets, there is little data describing how the kinematics of a lift change during a set to failure. To examine these changes, 10 male and 8 female recreational lifters were recruited. The maximum weight each subject could bench press (1-RM) was determined. Subjects then performed as many repetitions as possible at 75% of the 1-RM load. Three dimensional kinematic data were recorded and analyzed for all lifts. Statistical analysis revealed that differences between maximal and submaximal lifts, and the kinematics of a submaximal lift change as a subject approaches failure in a set. The time to lift the bar more than doubled from the first to the last repetition, causing a decrease in both mean and peak upward velocity. Furthermore, the peak upward velocity occurred much earlier in the lift phase in these later repetitions. The path the bar followed also changed, with subjects keeping the bar more directly over the shoulder during the lift. In general, most of the kinematic variables analyzed became more similar to those of the maximal lift as the subjects progressed through the set, but there was considerable variation between subjects as to which repetition was most like the maximal lift. This study shows that there are definite changes in the lifting kinematics in recreational lifters during a set to failure and suggests it may be particularly important for coaches and less skilled lifters to focus on developing the proper bar path, rather than reaching momentary muscular failure, in the early part of a training program.

Key Words: weightlifting, bench press, training, technique, fatigue

3.2 Introduction

The bench press is one of the events in competitive powerlifting, as well as one of the most popular exercises among athletes and recreational weight trainers. A large portion of the literature available discussing the mechanics of the bench press has focused on single maximal lifts. Madsen and McLaughlin (1984) described in detail the kinematics of the bar in single maximal lifts for world class power lifters; and then compared these data with the kinematics observed for a group of recreational lifters. They found that the best performers moved the bar more slowly throughout the exercise and kept the bar more directly over the shoulder during the lift phase. Other studies have focused on specific questions about single lift performance, including the optimum grip width (Clemmons and Aaron, 1997), and reasons for lift failure (Elliott, Wilson, and Kerr, 1989). Fewer studies have examined the differences between maximal and submaximal bench presses. Wilson et al. (1989) compared a maximal lift with a single sub-maximal lift at 80% of maximum in elite lifters and found noticeable kinematic and kinetic differences. Most notably bar vertical acceleration profiles were very different between the maximum and sub-maximal lifts. Also, the lifters tended to keep the bar more directly over the shoulder during the lift phase at maximal load, showing a pattern similar to the elite lifters discussed in Madsen and McLaughlin (1984). There does not appear to be any examination of maximum versus sub-maximum bench presses in recreational lifters; yet analysis of the parallel squat has shown that differences do exist in maximal and submaximal parallel squat lifts (Hay, Andrews, and Vaughan, 1982).

Lifters seem to voluntarily modify lifting kinematics based on the intensity of the lift (Hay, Andrews, and Vaughan, 1982), this may play an important role in designing a training program. It has been shown that, especially early in a training program, performance improvement is not strictly caused by increased force production in the working muscle (Moritani and deVries, 1979). It appears there is a neuromotor adaptation to the specific motion of the exercise that leads to greater performance than can solely be attributed to muscular hypertrophy and increased muscular strength (Komi, 1986). This suggests that training with a kinematic pattern most similar to that desired in a maximal effort will improve performance gains. However, differences may exist between maximal and submaximal lift patterns, but there is no report in the literature of how bar path movement changes throughout a multiple repetition set of the bench press. Since most programs utilize multiple repetition training, the importance of these difference warrants attention.

Frykman et al. (1988) examined the leg extension exercise and showed significant changes in performance across repetitions. For their subjects, torque production decreased, as did power, angular velocity, and total range of motion. If the mechanics change in a simple single joint exercise like a leg extension, greater changes may well be seen in a free weight multi-joint exercise like the bench press. If this is indeed the case and the kinematics of the task change with increasing number of repetitions, the specificity of the training must be questioned, as can its training effect on a particular muscle group. More specifically, assuming that development of a consistent movement pattern is important in training, it becomes important to know how the kinematics of a multiple repetition set vary from those of a maximal lift, and when in the set the kinematics are most similar to those of a maximal lift. The purpose of this study was to examine the effects of fatigue on the movement of the bar during a free weight bench press, and to determine when in a multiple repetition set the kinematics most resemble those of a single maximal lift.

3.2 Methods

Subjects for this study were recruited from an introductory weight training course. Subjects were tested to determine the maximal load they could lift in a single repetition bench press. Following this, subjects were asked to perform as many repetitions as possible at a submaximal load.

Approach to the problem

Previous research has examined the kinematics of a single repetition bench press, but most weight training programs involve multiple repetitions for a set. Subjects in this study performed both a single maximal lift as well as a multiple repetition set to failure. The kinematics of the first and last repetition in a multiple repetition set were compared to assess how the kinematics of the bar path change as the subject approaches failure. Comparisons were also made with the maximal lift to determine when in a multiple repetition set the kinematics are most similar to those of a single, maximal lift.

Subjects

Eighteen subjects (ten male and eight female) between the ages of 19 and 23 (mean height 1.71 m ± 0.08; mass 73.7 kg ± 13.6) were recruited at the conclusion of a 14-week introductory weight training class at The Pennsylvania State University. The subjects all had no previous formal weight training experience, but had during the course of the class assessed their one repetition maximum test (1-RM) free weight bench press. Those volunteers who had had no history of injury or illness that might affect lifting performance were recruited for the study.

Procedures

Potential subjects attended an orientation session during which time the test protocol was explained, and questions were encouraged. A signed informed consent was obtained from all subjects; all protocols had been approved by the institutional review board. Subjects were then given time to practice lifting in the experimental set-up, and once they reported being comfortable with the protocol a return visit was scheduled for data collection.

Upon arrival for the data collection session, subjects were provided time for a warm-up consisting of both light cardiovascular exercise and the opportunity to perform bench press repetitions with a bar of submaximal load. Following the warm-up period, testing began. The subjects performed a maximum bench press, and as many repetitions as possible at 75% of this maximum. For all of the lifts the subjects were handed the bar by the spotters. After accepting the bar, subjects were required to hold the bar still with the elbows extended for 2-3 seconds. Once instructed to start, the subjects lowered the bar until it touched the chest. Following a momentary pause the bar was raised until the elbows were extended once again. The execution of the lift conformed with the regulations of the International Powerlifting Federation**.** Speed of lifting was not controlled, but as part of their instructions in the weight training course, students were taught to lift in a “slow and controlled manner”. The two spotters were present at all times during data collection.

The starting weight for the maximum load testing was equivalent to 85% of the subject's reported 1-RM. After each successful lift a rest period of at least 3 minutes was provided, and the weight was increased by approximately 5% of the reported 1-RM. Then the subject attempted to lift the new weight. This continued until the subject was no longer able to lift the load. The greatest load lifted was considered the 1-RM.

Following the 1-RM testing, subjects rested for at least 5 minutes. During this time, a load equivalent to 75% of the 1-RM was placed on the bar. At the conclusion of the rest period, subjects were asked to perform as many repetitions as they could with the 75% load. The set was finished once the subjects reached volitional failure.

Data Collection and Analysis

A two camera Qualysis Pro-Reflex system was used to record the motion of retro-reflective markers that were placed on the bar and subject. These data was sampled at 240 Hz and later filtered with an 8 Hz low-pass Butterworth filter (Challis, 1999); derivative data were computed using first order finite difference equations. The markers were used to define bar motion in a sagittal plane. The motion of the bar for each repetition was separated into two phases: descent and lift. The start of the descent phase was defined as the point where continuous downward (negative) velocity began. The end of the descent phase was defined as the point at which the velocity of the bar returned to zero. The start of the lift phase was defined as the point at which upward velocity began, and the end of the lift phase was defined as the time when the velocity of the bar once again returned to zero (see Figure 3.1). Markers placed on the subject permitted determination of bar position relative to the shoulders.

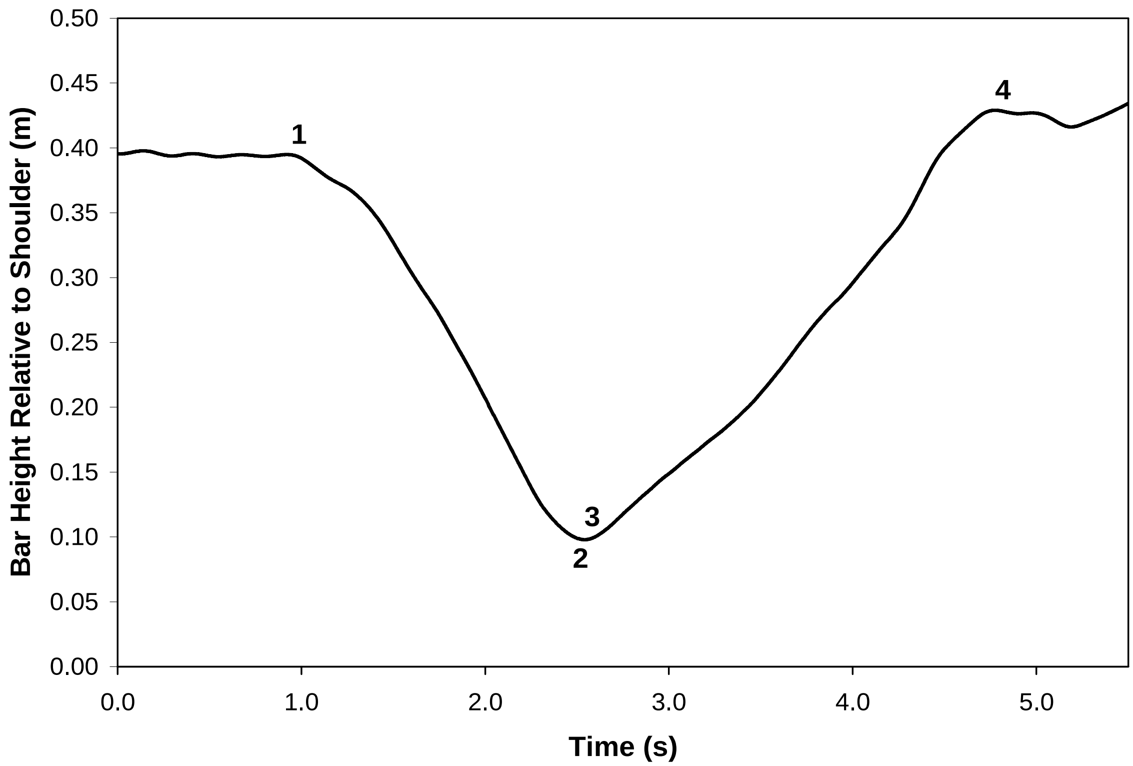

Figure 3.1. Phases of a single repetition. 1 - Start of the down phase, 2 - End of the down phase, 3 - Beginning of the lift phase, and 4 - End of lift phase. Note that in this subject, the end of the down phase and beginning of the lift phase (2 and 3) are nearly simultaneous.

From the data describing bar kinematics the following variables were computed to quantify bar motion: time to lower the bar, time to lift the bar, mean and peak velocity during the lift phase, timing of peak velocity, and mean bar position relative to the shoulder. The time to lower the bar was calculated as the time from point 1 to point 2 in Figure 3.1. The time to lift the bar was calculated as the time from point 3 to point 4 in Figure 3.1.

Two measures of the path of the bar during the lift phase were also analyzed. The first measure, the path length ratio (PLR) was an indicator of the straightness of the path that the bar followed. The length of actual path the bar traveled (*A*) was compared to the length of a theoretical straight line connecting the start and end points of the lift phase (*S*). The equation used was,

$$PLR = \left(\frac{A}{S}\right) \quad [1]$$

A value of 1.0 would indicate that bar had followed a straight line. The second measure, bar path deviation (BPD) compared the maximum perpendicular distance the bar deviated from a straight line (*D*) with the same theoretical straight line (see Figure 3.2**)** in the following equation,

$$BPD = \left(\frac{D}{S}\right) \quad [2]$$

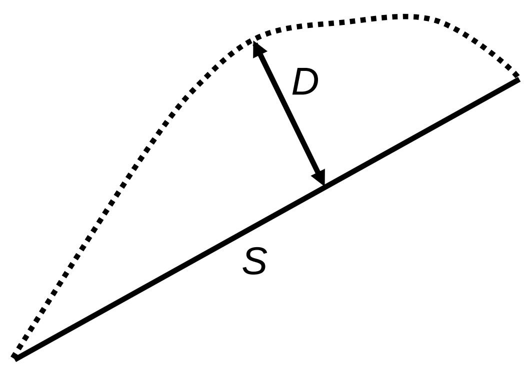

Figure 3.2. Illustration of measures required for equation 2, where *D* is the maximum perpendicular distance the bar deviated from a straight line, and *S* is the theoretical straight line connecting the start and end points of the lift phase.

Comparisons to Maximal Lift

To evaluate when in a multiple repetition set the kinematics are most similar to those of a maximal lift, the variables described above were also calculated for each subject's maximal lift trail. Data from the maximal lift was compared with the same measure for each of the repetitions of the sub-maximal test. The repetition with the least difference was selected. Because the subjects performed different numbers of repetitions, absolute repetition number was not particularly meaningful. To normalize this, the repetition number was expressed as a percentage of total lift time,

$$normalized = \left(100 \frac{lift\#}{\#repetitions}\right) \qquad [3]$$

Thus, if the 5th repetition in a set of 10 was the most similar to the maximal lift, it was said to occur at 50% of the total time for the set for that subject.

Statistical Analysis

One-way repeated measure analysis of variance was used to compare metrics of bar path trajectory across repetitions. Alpha was set at ≤ 0.05.

3.4 Results

The means and standard deviations are presented unless otherwise noted. The male subjects were able to lift a significantly greater absolute (89.5 kg ±17.0 versus 40.2 kg ± 9.5, $p \leq 0.01$) and relative (110 ± 26 % BW versus 63 % BW ± 11, $p \leq 0.01$) maximal load. For the remainder of the comparisons made there were no significant differences between the male and female subjects, so only results for the whole group will be presented. The number of repetitions completed with 75% of their 1-RM load was 10 ± 3 repetitions (range 4 to16). All repetitions were analyzed, however, because the subjects performed different numbers of repetitions, the first and last repetitions were selected for statistical comparison. Table 3.1 presents the data for the first and last repetitions of the set to failure.

3.4.1 Kinematic Changes in a Set to Failure

Several changes were observed in the bar velocity pattern as subjects progressed from the first to last repetition. With the exception of the time to lower the bar (Descent Time), all of the variables examined showed significant differences from first to last repetition (Table 3.1). The time to lift the bar (Lift Time) more than doubled from the first to last repetition, concurrent to a decrease in both mean (Mean Up Velocity) and peak vertical velocity (Peak Up Velocity).

Table 3.1. Comparisons of kinematic variables for first, last, and 1-RM repetitions (mean ± standard deviation). In the last column, actual p values are presented for each of the comparisons: FL - First to Last repetition, FM - First to Maximal (1-RM) repetition, LM - Last to Maximal repetition. P values ≤0.05 are in **bold**.

Variable	First Rep Mean±S.D.	Last Rep Mean±S.D.	Max Rep Mean±S.D.	p value
Descent Time (s)	1.40 ± 0.65	1.47 ± 0.71	1.65 ± 0.51	FL .711 **FM .001** LM .199
Lift Time (s)	1.08 ± 0.26	2.38 ± 0.66	2.33 ± 0.77	**FL .001** **FM .001** LM .828
Peak Up Velocity (m/s)	0.46 ± 0.11	0.25 ± 0.08	0.31 ± 0.12	**FL .001** **FM .001** LM .054
Time of Peak Up Velocity (% lift time)	65 ± 15	18 ± 21	75 ± 27	**FL .001** FM .140 **LM .001**
Mean Up Velocity (m/s)	0.33 ± 0.07	0.15 ± 0.04	0.15 ± 0.06	**FL .001** **FM .001** LM .565
Mean Bar Position (m)	0.11 ± 0.03	0.07 ± 0.04	0.08 ± 0.03	**FL .003** **FM .001** LM .321
Path Length Ratio	1.01 ± 0.02	1.08 ± 0.08	1.05 ± 0.03	**FL .003** **FM .001** LM .101
Bar Path Deviation	0.21 ± 0.18	0.48 ± 0.39	0.40 ± 0.18	**FL .049** **FM .005** LM .620

The path that the bar traveled changed from the first to last repetition. Analysis of the bar path in the horizontal plane showed that subjects kept the bar more directly over the shoulder as the number of repetitions increased (Mean Bar Position). The horizontal position of the bar at the start of the lift phase change did not change (0.13 m ± 0.02 away from the shoulder), showing that the change in the bar path occurred after the start of the lift phase. Further analysis showed that the bar path taken in the last repetition deviated more from a straight line (Path Length Ratio, Bar Path Deviation) than in the first repetition and is likely a result of the subjects' pattern of keeping the bar more directly over the shoulder in the later repetitions.

3.4.2 Maximal Lift Kinematics

Table 3.1 also presents data for the single repetition maximal lift (1-RM). It appears that, in general, as the subjects progressed from first to last repetition, the lifting kinematics became more like those of a maximal effort lift. For Lift Time, Peak Up Velocity, Mean Up Velocity, Path Length Ratio, and Bar Path Deviation, the first repetition was statistically different from the maximal lift while the last repetition was not. The timing of the maximal vertical velocity in particular did not follow this pattern and will be discussed in more detail later.

To further explore when the kinematics in a multiple repetition set most resemble those of a maximal effort single lift, the 1-RM data was compared to each of the repetitions. The repetition that was most similar was selected and then converted to a percentage. This number was averaged for all subjects. Table 3.2 shows that the repetitions do become more similar to a maximal effort as the lifter progresses though a set, but there is considerable variation depending on both the subject and the measure.

Table 3.2. This table demonstrates when in a multiple repetition set to failure the lift kinematics most resemble those of a maximal lift.

Variable	Mean ± Standard Deviation (%)	Earliest Occurrence (%)	Latest Occurrence (%)
Lift Time (s)	86 ± 16	50	100
Peak Up Velocity (m/s)	86 ± 21	33	100
Time of Peak Up Velocity (% lift time)	63 ± 23	18	100
Mean Up Velocity (m/s)	89 ± 20	18	100
Mean Bar Position (m)	69 ± 31	6	100
Path Length Ratio	79 ± 24	17	100
Bar Path Deviation	85 ± 17	38	100

3.5 Discussion

The two main purposes of this study were to determine how the bar kinematics of the bench press change during a set to failure, and to determine when in a multiple repetition set to failure the bar kinematics most resemble those of a maximal lift. It was expected that the kinematics of at least the lift phase of the bench press would change as the subjects progressed through a set to failure; in general this was supported. Most notably, the time to lift the bar more than doubled. With this dramatic increase there were concurrent decreases in the peak and mean upward velocity; however, the changes seen in both the position and velocity profiles of the bar suggest that last repetition was not merely a slow version of the first repetition. Two of the changes in particular suggest that there is a strategy change in these lifters as they approach failure.

The first component of the strategy is the development of a vertical velocity curve with two peaks, an early maximum and a delayed minor peak, in the lift phase. This two-peak pattern is also present in a maximal effort single lift. Figure 3.3 shows the velocity curve for a typical subject's first, last, and 1-RM repetitions. This two-peak pattern has been described by Madsen and McLaughlin (1984) in their analysis of world class competitive lifters, and later by Elliott et al. (1989) in their analysis of the sticking region in skilled lifters (those with maximal lifts of 1.27 to 2.16BW). They describe the sticking region, the time when most lift failures occur, as being between 25 and 42% of lift time. The shift to an early peak in vertical velocity seen in our subjects may reflect an attempt to enter the sticking region with the greatest possible vertical velocity, thereby increasing the likelihood of completing the lift.

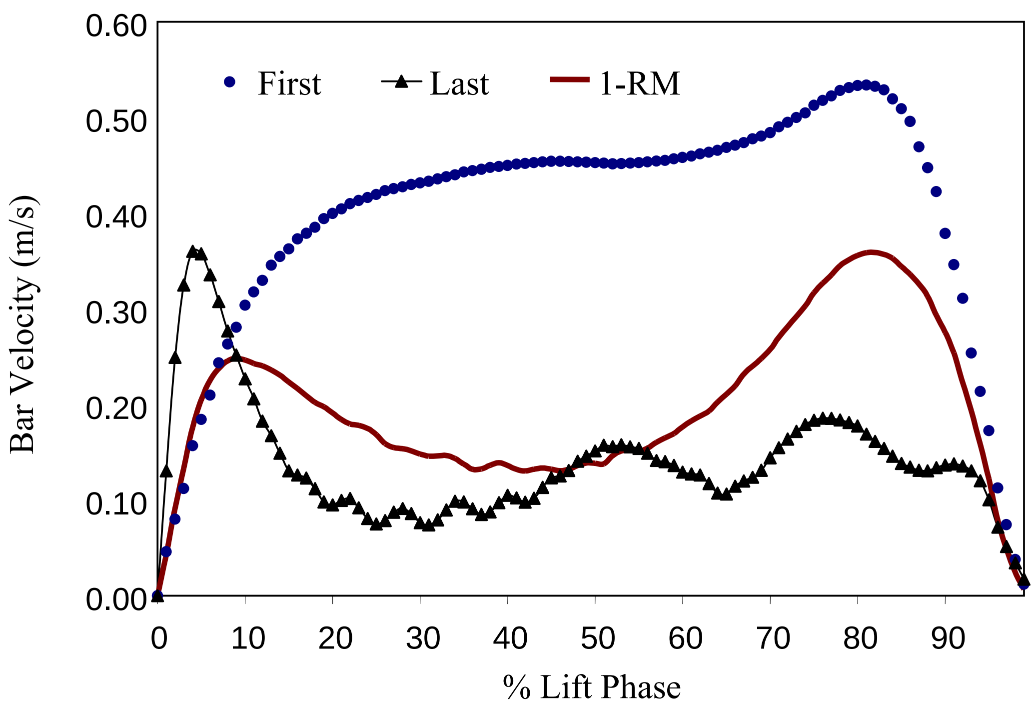

Figure 3.3. Bar vertical velocity for the lift phase of the 1-RM, the first, and the last repetitions of a representative subject.

The second component of the strategy was a tendency to keep the bar closer to the shoulder during the lift. It is possible that as the subjects began to experience fatigue, they might attempt to make their movements more efficient. Since the bar needed to be raised to the same height (elbows straight) for each lift, the first apparent option for increasing efficiency would be to reduce excess movement and move the bar in as straight a line as possible from the bottom to the top of the lift. The data indicate that this strategy was not adopted. Both of the measures of bar path straightness, the length of the path the bar traveled and the maximal deviation from a straight line, increased as the subjects progressed through the trial. The second option, as suggested by Madsen and McLaughlin (1984), was to reduce the moment the bar created at the shoulder joint by keeping the bar more directly over the shoulder; this was observed. It should be noted that their study involved the comparison of single lifts in world-class competitive lifters. They were in fact, able to use this metric as a performance discriminator in maximal lifts in athletes who were at the top of national and world rankings. The population in the current study was not of such a high performance level, and they tended to develop this pattern only as they progressed through the multiple repetition trial. Assuming this pattern makes the lift easier, it raises the questions of why the subjects did not utilize this pattern for every repetition, and how many repetitions they might have performed if they had used this lifting pattern throughout the trial.

Interestingly, there was a trend to decrease the height of completion of the lift. This was not a variable originally intended for analysis. The instructions for the subjects were to ensure that the elbows were straight at the end of every repetition, and thus a nearly identical finish height for each lift was expected. The researchers were careful to observe that the lifters touched the bar to the chest and then fully extended the elbows for each lift. Despite this vigilance the trend occurred. While the change was not found to be significant for the entire group (mean change ~1cm, p=0.06), it was strongly visible in many of the subjects. The authors hypothesize that this may be a change in the amount of scapular protraction that occurs during the movement. This type of scapular movement is discussed in studies analyzing the push-up exercise, especially when performing a "push-up plus", which has been reported as a beneficial rehabilitation exercise for the shoulder in general and the scapular muscles in particular (Decker, et al., 2003). Unfortunately, the kinematics of the upper extremity including the scapula were not available for this study, so it could not be confirmed whether this is indeed what occurred.

The last repetition had many similar qualities to the maximum repetition lift, for example statistically similar bar position, velocity, and path curvature. Given similar velocity profiles, the saggital plane acceleration profiles should also be similar. Despite these similarities the forces exerted to move the bar for the last repetition compared with the maximum lift were less, because the bar had less mass. This reduction in force indicates different muscular involvement in the last repetitions, indicating important neuromuscular differences between the maximum repetition and the sub-maximum repetitions. These differences do not support the concept that near maximum effort last repetitions in a set are necessarily similar muscularly to maximum effort single repetitions.

There are a number of potential limitations for this study. The results may be specific to the subject pool used; further study with both more and less experienced subjects would be useful. It is possible that the subjects did not actually produce a maximum effort on either task. The subjects all exceeded their previous maximums during the testing which suggests these were at least close to maximum efforts. Fatigue from the 1-RM test may have influenced the second part of the test (maximum repetitions at 75% of 1-RM), although none of the subjects reported they felt this was the case, and the number of repetitions performed was within the previously observed range (Zatsiorsky, 1995).

It is commonly reported that an early increase in maximal single lift performance is often seen following the initiation of a strength training program. Furthermore, this rapid increase has been attributed more to an improvement in neural firing pattern than an actual increase in muscular force output (Moritani and deVries, 1979). This would suggest that the training pattern, or more specifically learning the proper kinematics of the movement, plays a role in improving lifting performance, especially early on. If this is true, then training with an incorrect pattern might slow progress. Since most strength improvement programs involve multiple repetition training, it becomes important to know if the kinematics of the exercise change during a set to failure, and if they do change, when in the set the kinematics deviate away from the desired pattern. If the kinematics of the lift at the end of a set are dramatically different from the desired pattern, it may be beneficial to not train to muscular failure, at least in novice lifters who are still developing the proper lifting pattern. The data illustrate definite changes in the movement pattern throughout a set to failure, and that in general the kinematics of the later repetitions more resembled those of a maximal effort. However, that finding may be specific to the population of subjects in this study. The results of this study indicate that movement patterns vary between single maximum repetitions and repetitions in a multiple set, which highlights that specificity of training relates not only to exercise selection but also to the same exercise performed under different conditions.

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CHAPTER 4

Vertical and lateral forces applied to the bar during the bench press

4.1 Abstract

The purpose of this study was to determine the vertical and lateral forces applied along the bar during a maximal and a submaximal effort bench press lift. For this study, 10 male and 8 female recreational lifters were recruited and asked to perform a maximal and submaximal (80% of maximal lift) bench press. These lifts were performed with a bar instrumented to record forces applied to it in the vertical direction as well as along the long axis of the bar. To determine position of the bar and timing of events, three dimensional kinematic data were also recorded and analyzed for both lifts. Statistical analysis revealed the average force applied along the bar to be between 22 and 29% of the applied vertical force. The profile of the lateral force tended to be similar to the profile of the vertical force in both lifts. The absolute vertical and lateral forces were greater for the maximal lift than for the submaximal lift, but were not different when compared as a percentage of the load lifted. Thus, it is clear that a substantial portion of the force generated by the lifter is applied along the long axis of the bar. It is not certain if this force is necessary to generate vertical forces or if, with training, lifters could improve performance by decreasing the amount of force applied in the lateral direction.

4.2 Introduction

Millions of people, ranging from competitive weight lifters to senior citizens, include weight training as part of an exercise program. Reasons for training include improving sport performance, muscular strength, endurance, physique, self image, and delaying the decline in ability to perform normal daily activities that often accompanies advanced age. The bench press, while enormously popular, is relatively simple to perform and involves a large portion of the major muscles of the upper body. Therefore, it is included in programs designed for both competitive and recreational lifters alike.

The fundamental concept in weight lifting is to apply a force against a resistance which, with repetition, evokes a training response that develops and maintains skeletal muscle. Madsen and McLaughlin (1984), and Lander et al. (1985) have described the vertical forces applied to the bar during the bench press in elite and skilled lifters, respectively. According to Lander et al. (1985), the typical vertical force pattern during the lift phase, that is raising the bar from the chest, of a bench press repetition can be divided into four phases (Figure 4.1). The first, the acceleration phase, involves an early peak occurring at about 5% total lift time (LT) and lasts to about 16% LT. This phase is followed by a period where the force applied is less than the weight of the bar. This phase lasts from 16 to 42% LT and is termed the "sticking region." Because the force is less than the weight being lifted, the bar tends to lose upward velocity. Should the velocity go to zero before the lifter is able to once again apply a force greater than the weight of the bar, the lift will fail. Therefore this phase corresponds with the popular concept of a "sticking point" in the bench press where lifts fail. Elliott et al. (1989) however, showed that a failed lift still displays all four phases of the lift. Thus, it seems, the sticking region is not necessarily where the lift fails. During the third phase of the lift, from 42 to 82% LT, the force applied to the bar is once again greater than the weight of the bar and is termed the maximum strength region, though the rationale for the name of this phase was not provided. The final phase, occurring during the last 18% LT is the deceleration phase and once again, the force applied to the bar drops below the weight of the bar. This continues until the force returns to 100% of the bar weight and the movement ends.

The force applied to the bar by the lifter is not likely to be a purely vertical force. It is more likely that there is also a lateral force applied along the long axis of the bar. There is no report in the literature of the magnitude of the lateral force applied during the bench press. Previous research has shown that there is a lateral component to the force applied

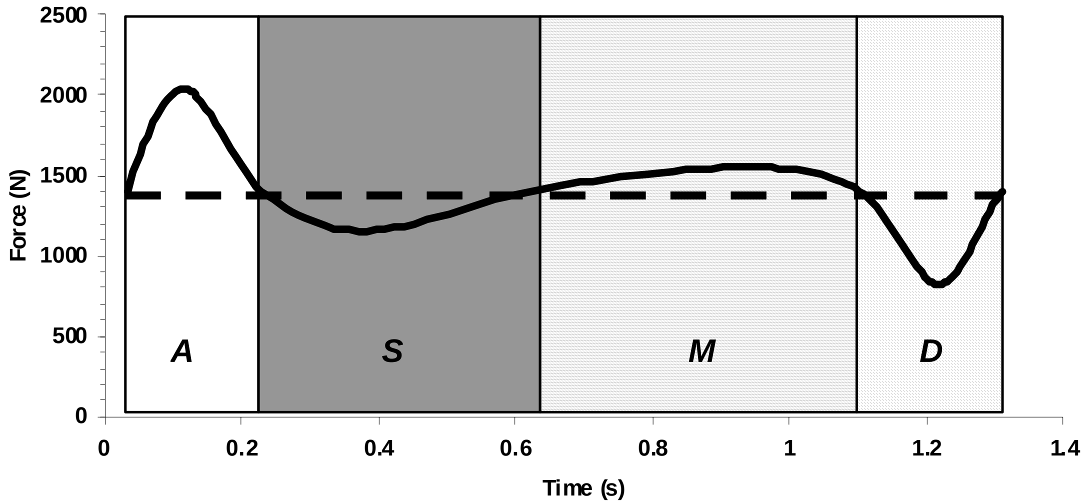

Figure **4.1**: Typical vertical force curve during the lift phase of the bench press. Here, *A*: Acceleration Phase, *S*: Sticking Region, *M*: Maximal Strength Region, *D*: Deceleration Phase. The dotted line represents the weight of the bar. Adapted from Lander, et al. (1985).

to the floor during a push-up (Duffey and Zatsiorsky, 2003). Given the similarities in the two exercises, it is hypothesized that there is a lateral component to the resultant force applied by the lifter to the bar in the bench press. While it would be presumably more efficient to exert a purely vertical force on the bar, maybe it is not possible to generate a large vertical force without a lateral component. This may be expected due to the musculoskeletal architecture of the torso and upper extremity. Therefore, the purpose of this study was to determine the vertical force and the force applied by the lifter along the long axis of the bar during a maximal and a submaximal effort bench press. Since most weight training is performed with multiple repetitions, a lift performed at submaximal load was examined to explore variations between maximal and submaximal lifts.

4.3 Methods

Subjects in this study performed a maximal and a submaximal single repetition bench press (1-RM) on a standard flat weight bench. The resistance selected for the submaximal effort was approximately 80% of maximal effort. Vertical and lateral forces were recorded and analyzed for both lifting conditions.

Equipment Design

To record the vertical forces as well as the forces applied along the long axis of the bar during the lifting tasks a steel sleeve was mounted along the grip portion of a standard, 20kg Olympic-style weight lifting bar. The sleeve was instrumented with five uni-axial force transducers (PCB 208B03). Three transducers were mounted horizontally at the middle of the sleeve and were use to record lateral forces. Two transducers were mounted vertically, one at each end of the sleeve, and were used to record vertical forces. This design necessitated a sleeve with a 1.75 inch outside diameter that was larger than the typical standard 1.1 inch (28mm) lifting bar but is similar to that seen in "fat bar" training equipment that is often seen today. A schematic of the bar can be seen in Figure 4.2. For more detailed information on the bar, see Appendix A.

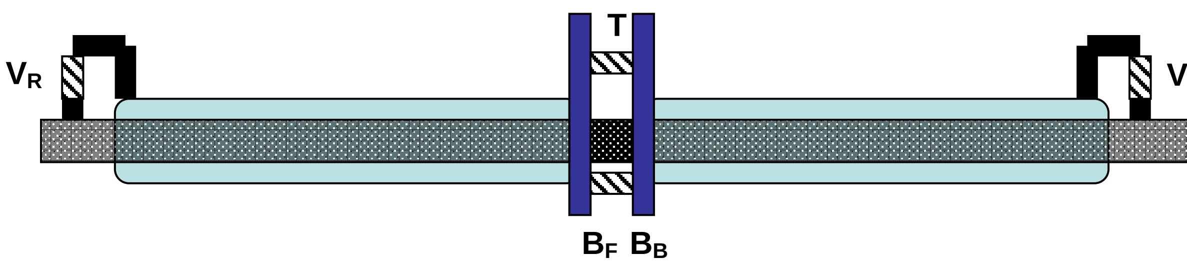

Figure 4.2. A schematic of the instrumented bar designed for this study. The two vertical plates are connected via three horizontally-mounted force transducers. The grip portion of the regular bar runs through the two sleeves and is suspended in place by a vertically-mounted force transducer at each end. A small "bridge" was built that extended up and past the end of the sleeve so that the transducer could be mounted in a straight, vertical line. VL and VR are the right and left transducers. T, BF, and BB are horizontal transducers. The figure is not to scale.

To assess the accuracy and validity of the instrumented bar, testing was performed prior to subject recruitment. Known loads up to 400N were added to the bar in approximately 100N increments, the bar was suspended so that the loads were supported through the vertically mounted transducers, and force recording were compared to expected values based on the mass of the system. Errors were less than ± 2N across all applied loads. Then, drift in the transducers was tested during a 5 minute data collection period. During this period, no additional load was applied. Force readings at the end of the 5 minute period remained within ± 2N of the original values. This amount of time was chosen because it well exceeded the time any single experimental trial would take. This amount of drift was considered negligible for this study. Nonlinearity in the transducers, as provided by the manufacturer, was less than 1% full scale.

Subjects

Eighteen subjects (ten male and eight female) between the ages of 19 and 23 (mean height 1.71 m ± 0.08; mass 73.7 kg ± 13.6) were recruited at the conclusion of a 14-week introductory weight training class at The Pennsylvania State University. The subjects all had no previous formal weight training experience, but had during the course of the class assessed their one repetition maximum test (1-RM) free weight bench press. Those volunteers who had had no history of injury or illness that might affect lifting performance were recruited for the study.

Procedures

Potential subjects attended an orientation session during which time the test protocol was explained, and questions were encouraged. Signed informed consent was obtained from all subjects; all protocols had been approved by the institutional review board. Subjects were then given time to practice lifting in the experimental set-up, and once they reported being comfortable with the protocol a return visit was scheduled for data collection.

Upon arrival for the data collection session, subjects were provided time for a warm-up consisting of both light cardiovascular exercise and the opportunity to perform bench press repetitions with a bar at submaximal load. Following the warm-up period, testing began. The bar was loaded to 80% of the subject’s reported 1-RM. The subjects were handed the bar by the spotters. After accepting the bar, subjects were required to hold the bar still with the elbows extended for 2-3 seconds to establish a static baseline for data collection. Once instructed to start, the subjects lowered the bar until it touched the chest.

Following a momentary pause the bar was raised until the elbows were fully extended once again. After a successful lift a rest period of at least 3 minutes was provided, and the mass was increased by approximately 5% of the reported 1-RM. Then the subject attempted to lift the new mass. This continued until the subject was no longer able to lift the load. The greatest load lifted was considered the 1-RM. The execution of the lift conformed with the regulations of the International Powerlifting Federation. Speed of lifting was not controlled, but as part of their instructions in the weight training course, students were taught to lift in a "slow and controlled manner". The two spotters were present at all times during data collection. Any lift performed with noticeable bar tilt was rejected and performed again by the subject.

Data Collection and Processing

Data from the force transducers was sampled at 2400Hz. A custom LabView program was used to collect data from the transducers. Data were passed through a low pass filter with a cut-off frequency of 5Hz. This cut-off frequency was selected given the movement the bench press is a relatively low frequency movement, and it has been successfully used in previous research (Wilson et al. 1989; Wilson et al. 1991). The signal was converted to Newtons using the conversion factor provided for each transducer by the manufacturer. Total vertical force was then calculated by summing the value of the two vertical force transducers. Positive vertical forces indicate an upward force exerted by the lifter. To eliminate any contribution of a bending moment to the recorded lateral force, the lateral force was calculated using the following equation:

$$\text{Lateral force} = 1.5 \bullet (T + (0.5 \bullet (B_F + B_B))) \qquad [4.1]$$

T = value of top horizontal transducer, B_F = value of bottom front horizontal transducer, and B_B = value of bottom back horizontal transducer. Positive lateral forces indicate an outward force exerted by the lifter.

Kinematic data for the bar was collected with the use of retroreflective markers that were placed on the bar and a two-camera (Qualysis, ProReflex) motion analysis system, sampling at 240Hz. Data collection from the motion analysis system and the load cells were synchronized. Position data from the bar was used to determine position and velocity of the bar, as well as start and finish times for each portion of the lift. The start of the descent phase was defined as the point where continuous downward (negative) velocity began. The end of the descent phase was defined as the point at which the velocity of the bar returned to zero. The start of the lift phase was defined as the point at which upward velocity began, and the end of the lift phase was defined as the time when the velocity of the bar once again returned to zero.

Statistical Analysis

Variables analyzed included the minimum and maximum force as well as the relative magnitude of forces during the descent and ascent phases. The timing of the minimum and maximum vertical and lateral forces, expressed as percent of lift time, were also analyzed. The first lift, performed at 80% reported 1RM was compared to the maximal lift. One-way repeated measure analysis of variance was used to compare metrics. Alpha was set at ≤ 0.05.

4.4 Results

The subjects in this study averaged a maximal lift of 63 ± 11 kg (90 ± 31% BW). The average load lifted in the submaximal condition, which was set at 80% of each subject's reported maximal lift was 52 ± 9 kg (75 ± 22% BW) which averaged 83% of the actual maximal lift performed in this study. A representative subject's vertical and lateral force profiles during one complete maximal effort bench press cycle are displayed in Figure 4.3.

Vertical Force

The vertical force profile for the subjects in this study resembled those reported previously by Madsen and McLaughlin (1984) and Lander et al. (1985), with most subjects displaying the four phases in both the maximal and submaximal lift. Table 4.1 shows the mean and standard deviation of the variables analyzed for the lower and lift phases of both the maximal and submaximal trials.

The magnitude of the vertical force during the submaximal trial was statistically significantly less than that in the maximal trial ($p < 0.01$); however, the difference between the vertical forces was not statistically significant when the two trials were expressed as a percent of the load lifted. For example, the absolute maximum vertical force applied during the lift phase was about 22% lower for the submaximal trial ($p \leq 0.01$), but when compared as a percentage of the load lifted, they were nearly identical (115 and 113%, respectively). The timing of the events during the lifts were also similar between the maximal and submaximal trials with one exception: the time at which the minimum vertical force occurred during the lift phase was significantly later in the submaximal lift ($p \leq 0.01$). The two times during the lift that this is likely to occur are during the "sticking region" relatively early in the lift, or during the "deceleration phase" at the end of the lift. During the maximal lift, the minimum vertical force was relatively evenly distributed between the two phases, with 11 of 18 subjects showing the minimum vertical force during the sticking region. For the submaximal lift, the minimum vertical force occurred during the deceleration phase for all but one subject.

Table 4.1 Group means and standard deviations for the analyzed variables for the descent and lift phases of both the maximal lift and the submaximal lift.

	Maximal		Submaximal	
Variable	Descent	Lift	Descent	Lift
Maximum Vertical Force (N)	772.5 ± 348.7*	832.8 ± 397.1*	607.6 ± 264.7	651.6 ± 289.1
Maximum Vertical Force (% load)	107 ± 18	115 ± 22	105 ± 16	113 ± 20
Time to Maximum Vertical Force (%)	82.4 ± 29.0	4.5 ± 3.2	91.6 ± 15.4	8.7 ± 4.5
Maximum Lateral Force (N)	208.2 ± 91.0*	235.0 ± 108.6*	152.8 ± 70.2	167.3 ± 78.0
Time to Maximum Lateral Force (%)	42.7 ± 46.7	20.2 ± 34.8	63.8 ± 46.8	17.4 ± 30.3
Minimum Vertical Force (N)	616.4 ± 264.5*	631.2 ± 261.4*	475.6 ± 192.8	457.4 ± 206.5
Time to Minimum Vertical Force (%)	31.0 ± 21.2	56.3 ± 36.0*	22.6 ± 14.7	93.8 ± 14.4
Minimum Lateral Force (N)	159.2 ± 63.3*	163.3 ± 64.9*	116.0 ± 50.0	106.9 ± 48.8
Time to Minimum Lateral Force (%)	58.5 ± 31.8*	42.2 ± 30.7*	40.2 ± 25.3	87.6 ± 22.8
Average Ratio	26.2 ± 4.9	26.3 ± 3.9*	24.1 ± 3.7	23.7 ± 3.9
Ratio Range	4.1 ± 1.5	5.2 ± 2.0*	4.0 ± 1.4	3.8 ± 1.9
Peak Ratio	28.7 ± 5.1	29.5 ± 4.4*	26.7 ± 3.9	26.1 ± 4.0
Time to Peak Ratio (%)	28.2 ± 40.1	50.6 ± 45.7	22.0 ± 36.5	37.0 ± 41.5
Minimum Ratio	24.6 ± 4.6	24.2 ± 3.8	22.6 ± 3.9	22.3 ± 3.7
Time to Minimum Ratio (%)	76.1 ± 17.2	35.6 ± 18.9	74.5 ± 14.5	56.5 ± 33.5
Phase Time (s)	1.7 ± 0.5*	2.2 ± 0.8*	1.5 ± 0.6	1.8 ± 0.3
* Indicates statistical difference between maximal and submaximal conditions ($p \leq 0.05$).				

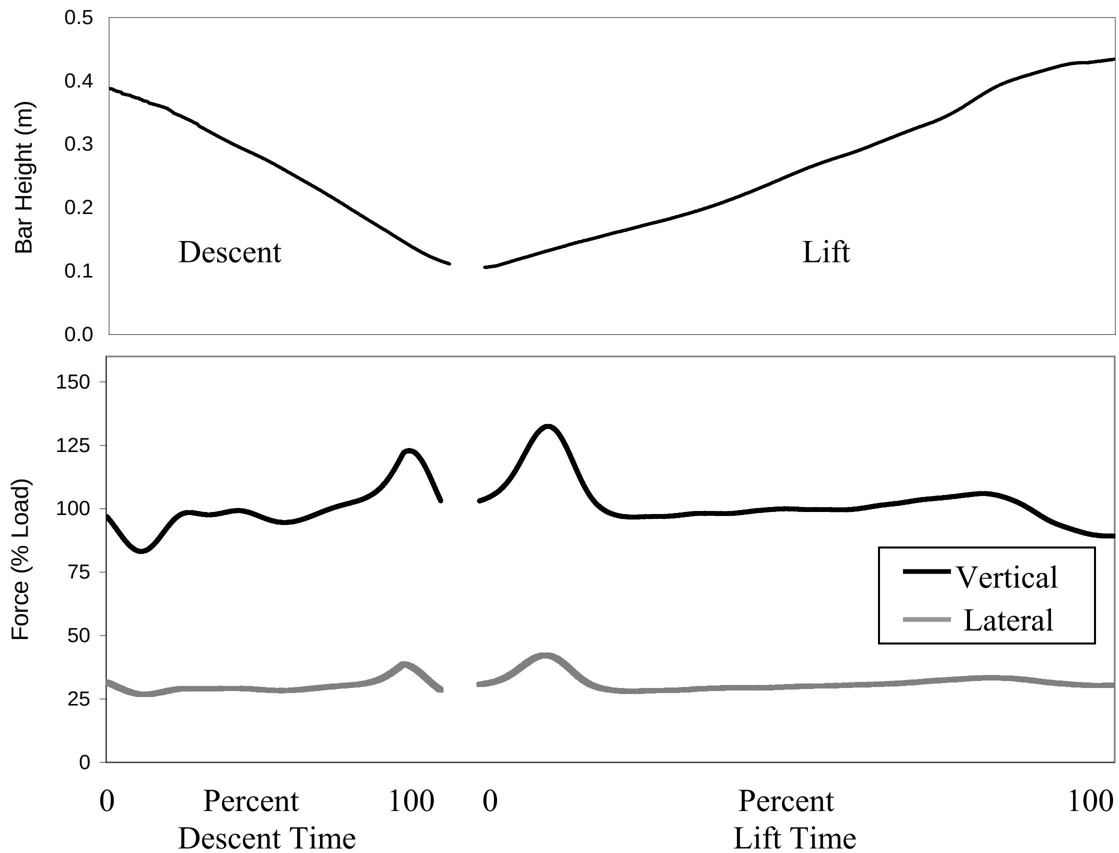

Figure 4.3 This figure shows the bar height (top) vertical and lateral forces (bottom) for the descent and lift phases during a maximal lift. Force values are expressed as a percentage of the load lifted. A break has been added to clarify when the descent phase ended and the lift phase began.

Lateral Forces

The lateral force profile in most subjects was similar to that of the vertical force, albeit at a lesser magnitude. As Figure 4.3 and Table 4.1 indicate, the timing of the maximum and minimum lateral forces were similar to that of the vertical force. Figure 4.4 shows the relative magnitude of the lateral and vertical force profiles with the lateral force presented as a percent of the vertical force for a representative subject. The lateral force magnitude was typically about one quarter that of the vertical force (Average Ratio in Table 4.1). Figure 4.4 also shows that the magnitude of the lateral force tended to increase relative to the vertical force at the beginning and end of both the descent and lift phases. However, this pattern was only clearly evident in about half of the subjects, and even in those subjects the change in relative magnitude of the two forces (Ratio Range) was only about ±2%.

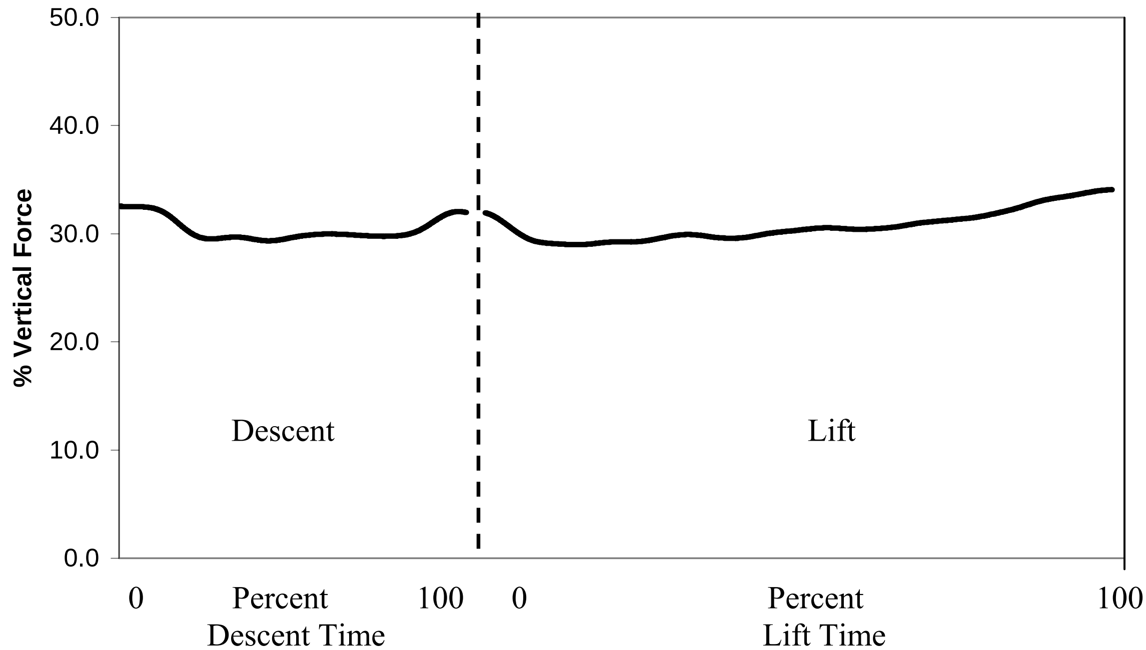

Figure 4.4 The ratio of lateral to vertical force, expressed as a percentage of the vertical force, for a representative subject's maximal lift. This subject's ratio was slightly higher than the average. A break has been added to clarify when the descent phase ended and the lift phase began.

4.5 Discussion

During the maximal lift, the lifters in this study typically displayed a profile pattern which was very similar to the force profile measured for competitive lifters (Madsen and McLaughlin, 1984). Previous research suggests that the force profile of competitive lifters changes when performing a submaximal lift (Elliott et al., 1989). Seven of the ten subjects in that study displayed only two discernable phases, acceleration and deceleration, during a submaximal lift. The results of this study, which followed a virtually identical protocol with novice male and females rather than elite competitive male lifters, did not necessarily agree with the earlier findings. Most of our subjects (14 out of 18) displayed a similar vertical force profile during the maximal and submaximal lifts. If the vertical forces for the two lifts are compared as a percent of the load lifted, they are nearly identical. However, it should be mentioned that, like the earlier study, these trends were not consistent across all of the subjects; three of the subjects did change to the two-phase pattern described by Elliott et al. (1989), and one subject displayed a pattern with three distinct maxima and minima. While the intensity of the submaximal lifts were similar in both studies, with the subjects performing a lift at 80% of self-reported maximum, clearly the skill level of the subjects was not. While the mass of each subject is not provided, the weight class for competition and maximum load lifted are. In that study, the subjects lifted 190% of their reported weight class. If we presume their lifters' body weights are close to their weight classes, those subjects were almost twice as strong as the male, and three times as strong as the female subjects in this study, who lifted an average of 110% and 65% BW, respectively.

The variability between the subjects in this study may be related to differences in their lifting ability. To explore whether skill had an influence on the ratio between the vertical and later force, lifting level (using percent body weight lifted as our indicator of lifting level) was correlated with the average and range for the vertical and lateral force ratio. There were no significant correlations between lifting ability and any of the variables compared. The r^2 values ranged from 0.05 to < 0.01, suggesting that the variability seen in our population was due to something other than lifting ability. It would be interesting in future studies to record multiple lifts in both experienced and novice lifters to determine if there is more variability in the performance of the less experienced lifters.

The lateral force profile followed that of the vertical force quite closely in most subjects. Correlation of the lateral and vertical forces during the lift phase resulted in a r^2 of 0.7 or greater for 11 of 18 subjects. The magnitude of the lateral force averaged about one quarter that of the vertical force (26% for the maximal lift, 24% for the submaximal lift). The position of the hands relative to the shoulder could influence the relative magnitude of the lateral force. More specifically, it was expected that there would be a greater lateral force when the bar was low because the hands are more lateral to the shoulders, and there would be less lateral force at the top of the lift when the hands are more vertical to the shoulders. This was not typically the case. There was a tendency for a greater relative lateral force at the beginning of the lift phase, followed by a rapid decrease lasting through the first 15% of the lift, but then the lateral force tended to increase relative to the vertical throughout the rest of the lift. Therefore, linear correlation between the ratio of force magnitude and lift height showed virtually no relationship ($r^2 \leq 0.05$).

Given that about 25% of the force recorded is applied in the lateral direction raises questions about the importance of efficiency in performing a bench press. It would seem logical that the greatest load could be lifted when all of the force is applied vertically. Any force applied along the bar will not directly contribute to moving the weight in a vertical direction. This would suggest that teaching lifters to apply a more vertical force would improve bench press performance. A simple option for this would be training with dumbbells. A straight bar will resist and therefore mask any lateral forces as long as they are equal in each direction along the bar. Since dumbbells have no fixed attachment, a lateral force would result in the dumbbells moving away from each other. Thus, this would seem like a good training feedback system.

Immediately, there appear to be two potential difficulties in training lifters to push more vertically. First, lifters are able to lift a smaller weight using dumbbells compared with a straight bar. Therefore, training with dumbbells only might result in a reduced training effect. Second, better efficiency may not necessarily result in better performance. It may be the case, because of the musculoskeletal architecture of the upper limb, that greater total vertical force can only be generated when the force is applied in an upward and outward direction. At the beginning of the lift phase, when the upper arm is below horizontal (elbow below shoulder) adduction of the shoulder would create a force both upward and outward. Also, throughout the lift, but especially later in the phase, extension of the elbow would also tend to create an outward force. Indeed, this seems to explain the pattern seen in the ratio between the vertical and lateral forces as well. If this is the case, then the only way to apply a purely vertical force may be to change the position of the hands relative to the shoulders by reducing grip width. Narrower grip width, however, has previously been reported to result in a decrease in maximum lifting ability (McLaughlin, 1985), so this may also be an inadequate solution.

Clearly additional research is necessary to understand the relationship between the vertical and lateral force applied to the bar. The next study will look at the effect of grip width on the vertical and lateral forces. Also, upper body kinematics and muscle electrical activity will be examined to try to determine what role they may play in the generation and application of force in the bench press. Understanding the relationship between grip width, arm position and force application on the bar may help explain what role lateral forces play when subjects perform a maximal vertical lift.

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CHAPTER 5

Electromyographic, kinematic, and kinetic changes with grip width in the bench press

5.1 Abstract

The purpose of this study was to determine how electromyographic (EMG) activity, bar and upper limb kinematics, and vertical and lateral forces applied to the bar are affected when performing the bench press at different grip widths. For this study, eight male and three female recreational lifters were recruited and asked to perform a maximal bench press at self-selected grip width, and five submaximal (75% of maximal lift) lifts at predetermined grip widths. These lifts were performed with a bar instrumented to record forces applied to it in the vertical direction as well as along the long axis of the bar. To determine position of the bar and timing of events, three-dimensional kinematic data were also recorded and analyzed for both lifts. EMG data were recorded for the pectoralis, the triceps, the biceps and the anterior deltoid. Statistical analysis revealed that vertical force and lateral forces decreased as grip width increased. Higher forces and EMG recordings were observed in the descent rather than the lift phase. Neither peak nor mean EMG levels were systematically affected by grip width. While the narrow grip position resulted in higher vertical and lateral forces, these novice lifters did not display different muscle activation levels when performing the bench press with a wider or narrower grip.

5.2 Introduction

There are several reports in the literature discussing how variations in performance of the bench press alter muscle activity. These studies have typically addressed one of two hypotheses: that a wider grip width allows for greater weight to be lifted, and that increasing grip width places more emphasis on the pectoralis muscles and less on the triceps. Several studies have addressed, and have generally supported the concept that, in the bench press, lifting performance increases as grip width is increased up to approximately twice the distance between the acromion processes, or twice the shoulder width, of the lifter (Madsen and McLaughlin, 1984; Wagner, Evans, Weir, Housh, and Johnson, 1992; Clemmons and Aaron, 1997; Gilbert and Lees, 2003). Wagner et al. (1992), for example, showed that the greatest single lift performance was achieved at a relatively wide 200% biacromial breadth, and decreased when grip width increased or decreased from that width. The explanations given for this suggest that performance is improved because the range of motion of the lifter and the final height of the bar were reduced with a wider grip, thereby reducing the total work that had to be performed to reach a fully extended arm position. Additionally, this improvement in performance may be a result of a change in the relative activity, and therefore relative contribution, of the muscles involved in the lift (McLaughlin, 1984).

The data addressing the effect of increasing grip width on relative muscle activity is less clear. Barnett, Kippers, and Turner (1995) attempted to differentiate between activity in the upper and lower heads of the pectoralis major and examine relative tricep activity across conditions using electromyography (EMG), while subjects performed lifts at 100 and 200% acromial width using incline, flat and decline bench positions. As they predicted, the wider grip position elicited less activity in the triceps and greater activity in the pectoralis but only in the upper portion of the pectoralis, and only when performing an incline bench press. Activity in the lower portion of the pectoralis decreased with the wider grip. Clemmons and Aaron (1997) found higher electrical activity in the pectoralis when the grip width was 190% of acromial width compared with 130% acromial or narrower grip width; however, this increase was observed in all of the primary movers (anterior deltoid and triceps). Most recently, Lehman (2005) found that the wider grip width reduced triceps activity and pectoralis activity, at least in the upper portion of the latter muscle.

What has not been addressed is the change in force production in the bench press as grip width is changed. Chapter 4 examined typical vertical and lateral force profiles during a bench press performed at a freely chosen grip width. The goal of this study was to examine if the muscular activity and force profiles change as grip width is varied. It is anticipated, based on earlier literature, as grip width increases, the activity of the pectoralis will increase, the relative activity of the triceps will decrease, and the magnitude of the lateral force will increase.

5.3 Methods

For this study, subjects were first asked to perform a maximal, single repetition (1-RM) bench press. Following this, the lifting load was reduced to 75% 1-RM. Subjects then performed single lifts at five different grip widths. Kinematic data were collected for the bar and the upper extremity of the lifter. EMG data were collected for the pectoralis major, triceps, anterior deltoid and biceps. The forces applied by the lifter to the bar were recorded using a specially designed instrumented bar.

Subjects

Eleven subjects (eight male and three female) between the ages of 19 and 23 (mean height 1.73 m ± 0.08; mass 77.2 kg ± 14.5) were recruited at the conclusion of a 14-week introductory weight training class at The Pennsylvania State University. None of the subjects had formal weight training experience prior to taking the class, but during the course of the class had assessed their one repetition maximum test (1-RM) free weight bench press. Those volunteers who had had no history of injury or illness that might affect lifting performance were recruited for the study.

Procedures

Potential subjects attended an orientation session during which time the test protocol was explained and questions were encouraged. Signed informed consent was obtained from all subjects; all protocols had been approved by the institutional review board. Subjects were then given time to practice lifting in the experimental set-up, and once they reported being comfortable with the protocol a return visit was scheduled for data collection.

Upon arrival for the data collection session, subjects were provided time for a warm-up consisting of both light cardiovascular exercise and bench press repetitions with a bar at submaximal load. Following the warm-up period, the skin was prepared for EMG electrode placement. The skin was shaved where necessary and rubbed with an alcohol swab. Disposable, bipole Ag-AgCl electrodes with an inter-polar distance of 2cm were placed superficially above the following muscles: the upper third of the Pectoralis Major, the anterior portion of the Deltoid, the lateral head of the Triceps Brachii, and the Biceps Brachii. A reference electrode was placed above the bony portion of the medial humeral condyle. The specific location for each electrode placement was chosen following the guidelines suggested by Cram and Kasman (1998).

A high impedance, differential preamplifier with a standard gain of 500 was located near each electrode. Final amplification of the EMG signal was set independently for each muscle and each subject to maximize signal output without clipping.

To provide reference data for relative magnitude of muscular contraction activity during the bench press tasks, subjects were asked to produce three, five-second maximum voluntary isometric contractions (MVIC) for each of the muscles analyzed (a total of 12 contractions). Positions for the MVIC testing were as follows: for the biceps, the upper arm was kept adjacent to the torso and the elbow was flexed to 90° with the hand supinated; for the triceps, the upper arm was again kept adjacent to the torso and the elbow was flexed to 90° with the hand pronated; for the anterior deltoid, the shoulder was flexed to 45° with the thumb pointing up (hands partially pronated); finally, for the pectoralis major, the shoulder was abducted to 90°, then horizontally adducted to 45°.

For this data collection protocol, a single repetition maximum bench press (1-RM) was first determined. Following this, the bar load was reduced to 75% of the subject's 1-RM, subjects then performed a single bench press repetition at the following grip widths: 100%, 125%, 150%, 175% and 200% of biacromial breadth. Marks had been placed on the grip portion of the bar in 1cm increments. Subjects were asked to place the forefinger over the correct width mark for each lift. For all of the lifts the subject was handed the bar by two spotters. After accepting the bar, the subject was required to hold the bar still with the elbows extended for 2-3 seconds. Once instructed to start, the subject lowered the bar until it touched the chest and then raised it until the elbows were once again fully extended. If, in any lift, the bar did not touch the chest or appeared to have bounced off the chest, that lift was not accepted, and subjects were asked to repeat the condition.

Speed of lifting was not controlled, but as part of their instructions in the weight training course, students were taught to lift in a "slow and controlled manner". The two spotters were present at all times during data collection. All lifting was performed with an instrumented bar which permitted measurement of applied forces. To prevent an order effect, the sequence of the submaximal lifts was randomized for each subject.

Data Collection and Processing

Force Data

Kinetic, EMG, and kinematic data were synchronously collected and processed. A custom LabView program was used to collect data from the transducers. The electrical signals from the load cells in the instrumented bar were converted from millivolts to Newtons using the conversion factor provided for each transducer by the manufacturer. Data were sampled at 2400Hz and passed through a low pass filter with a cut off frequency of 5Hz to reduce the influence of noise in the data. This cut-off frequency was selected given the bench press is a relatively low frequency movement, and it has been successfully used in previous research (e.g., Wilson, Elliott, and Kerr, 1989; Wilson, Elliott, and Wood, 1991). Total vertical force was then calculated by summing the value of the two vertical force transducers. To eliminate any contribution of a bending moment to the recorded lateral force, total lateral force was calculated using the following equation:

$$\text{Total lateral force} = 1.5 \bullet (T + (0.5 \bullet (B_F + B_B))) \qquad \textbf{[5.1]}$$

T = value of top horizontal transducer, B_F = value of bottom front horizontal transducer, and B_B = value of bottom back horizontal transducer. Positive lateral forces indicate a force applied outward along the bar. For an illustration of the locations of the transducers on the bar, see Figure 5.1.

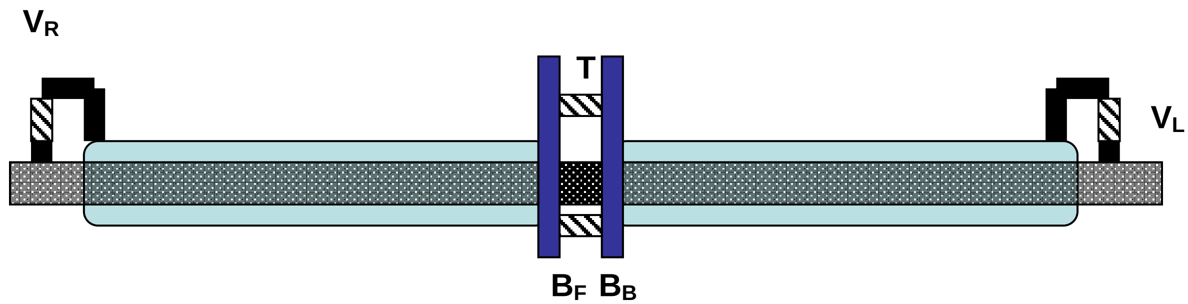

Figure 5.1. A schematic of the instrumented bar designed for this study. The two vertical plates are connected via three horizontally-mounted force transducers. The grip portion of the regular bar runs through the two sleeves and is suspended in place by a vertically-mounted force transducer at each end. A small "bridge" was built that extended up and past the end of the sleeve so that the transducer could be mounted in a straight, vertical line. VL and VR are the right and left transducers. T, BF, and BB are horizontal transducers. The figure is not to scale.

Electromyography Data

A Bortec electromyography system (Bortec AMT-8) was used to collect muscle activity data. The differential signal from the surface electrodes was sampled at 2400Hz. To reduce noise, data were first band pass filtered with cut off frequencies of 20 and 500Hz, then full-wave rectified, and finally passed through a low pass filter with a cut off frequency of 5Hz to create a linear envelope. EMG activity in each muscle was normalized to the peak EMG signal in the MVIC trials, then compared across each grip width condition, as well as with the maximal bench press condition.

Kinematic Data

A two-camera (Qualysis, ProReflex) motion analysis system, sampling at 240Hz was used to record the three-dimensional position of the retroreflective markers that had been placed on the bar, the bench, and the right upper extremity of the subject. Specifically, these markers were placed on the subject in the following locations: 1) acromion process, 2) biceps brachii immediately distal to the insertion of the deltoid, 3) lateral condyle of the humerus, 4) mid-forearm between the radius and the ulna, and 5) head of the ulna. The first three markers were used to define the upper arm, while the last three were used to define the forearm. The middle marker on each segment (on the bicep or the mid-forearm) was placed so that it would remain in a non-colinear position with respect to the other two markers defining that segment. Three markers were placed on the end of the bench to establish an inertial reference frame.

The kinematic data were passed through a Butterworth low pass filter with a cut off frequency of 5Hz. This frequency was again chosen based on previous research (Wilson, Elliott, and Kerr, 1989; Wilson, Elliott, and Wood, 1991). First order finite difference equations were used to determine vertical velocity of the bar, which in turn was used to determine the start and finish times for each portion of the lift. The start of the descent phase was defined as the point where continuous downward (negative) velocity began. The end of the descent phase was defined as the point at which the velocity of the bar returned to zero. The start of the lift phase was defined as the point at which upward velocity began, and the end of the lift phase was defined as the time when the velocity of the bar once again returned to zero. Joint angle positions were then calculated for the descent and ascent phases of each lift.

For kinematic analysis, the rotation axes were defined to conform with the guidelines set forth by the International Society of Biomechanics (ISB) (Wu et al., 2005). The bench was chosen as the reference frame for relative motion and the following axes definitions were used: the X axis was vertical, the Y axis was along the length of the bench and the Z axis was across the bench (Figure 5.2). For the humerus the following axes definitions were used (assuming anatomical position): the X axis was anterior-posterior, the Y axis was the long axis of the bone, and the Z axis ran in a mediolateral direction. For the forearm the definitions were the same as the upper arm (again assuming anatomical position).

Rotation sequences were also chosen to conform with ISB guidelines, though with one exception. Shoulder rotations were calculated as position of the upper arm (humerus) relative to the bench rather than relative to the torso. Because of the position of the subject, the presence of the bench and two spotters, and the number of cameras available for analysis, it was not practical to place markers to develop a torso segment. Instead, the position of the bench was used and assumed to be parallel to the position of the torso.

The order of rotations, as per ISB guidelines for the shoulder was (with the positive rotation as an example in parentheses): 1) rotation about the Z axis of the bench (forward flexion of the shoulder), 2) rotation about the X axis of the upper arm (abduction of the shoulder), 3) rotation about the Y axis of the upper arm (internal rotation of the upper arm). The order of rotations, as per ISB guidelines for the elbow was (with the positive rotation as an example in parentheses): 1) rotation about the Z axis of the upper arm (flexion of the elbow), 2) rotation about the X axis of the forearm (referred to as the "carrying angle", this will not be reported), 3) rotation about the Y axis of the forearm (external rotation of the forearm). Two angular position measures were made for the forearm segment. The "forearm angle" was determined by the position of the hand relative to the elbow in a vertical plane passing through the long axis of the bar. A negative angle indicated that the hand was inside the elbow (hands closer to each other than the elbows). The "forearm tilt" was perpendicular to the previous angle, so that a negative angle indicated that the bar was above but between the elbow and the shoulder.

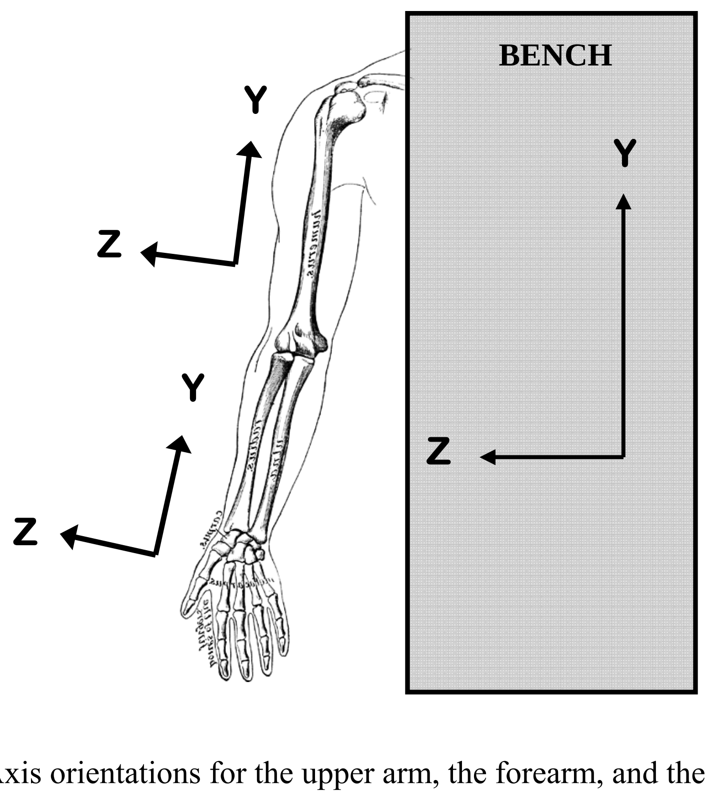

Figure 5.2 Axis orientations for the upper arm, the forearm, and the bench. The view is from above looking down at the bench and the right arm of the subject as if the subject were laying on the bench. For each, the X axis is directed up toward the reader. The origin of each segment is located at the proximal end of the segment. The figure is not to scale.

Statistical Analysis

One-way repeated measure analysis of variance was used to compare kinematic, EMG, and kinetic data across grip width and maximal lift conditions. Kinematic data of the subject analyzed included shoulder abduction, elbow flexion, and orientation of the forearm relative to vertical. Specific variables analyzed included shoulder abduction (rotation away from the trunk) and flexion (rotation away from vertical), elbow flexion, forearm orientation at the start and finish of each lift phase, as well as total range of motion (ROM) for each lift. Muscular activity variables analyzed included peak and mean EMG activity (expressed as a percent of the maximal value during MVIC contraction and/or the maximal lift) as well as timing of peak EMG in each of the muscles during the descent and ascent phase of each lift. Force variables analyzed included peak and mean vertical and lateral force, and the timing of the peak vertical and lateral forces, expressed as percent of lift time and percent of lift height. Alpha was set at $\leq$0.05.

5.4 Results

The subjects in this study averaged a maximal lift of 63 ± 11 kg (98 ± 33% BW). The grip width, which was self-selected for the maximal condition, averaged 169 ± 28% BAB (range 117-214%). Group means and standard deviations for the metrics of the maximal and five submaximal lifts, performed at grip widths of 100, 125, 150, 175, and 200% BAB are presented in the Tables 5.1 through 5.8.

5.4.1 Kinematic Data

Bar Kinematics

The vertical distance that the bar was lifted increased significantly as grip width narrowed. Subjects lifted the bar 7 ± 2cm higher in the narrowest condition than in the widest condition, representing a 24 ± 8% increase in the distance the bar had to travel (Table 5.1). Furthermore, the distance the bar traveled was greater in the lift phase than in the descent phase.

Lift time tended to be shorter as grip widened, at least when comparing with the narrowest condition, but this change was not consistent across all grip widths. During the descent phase, the mean velocity of the bar tended to decrease as grip widened, but again this change was not consistent across all conditions. During the lift phase, there were no consistent changes in bar velocity across grip width conditions, but was much lower in the maximal lift than any of the submaximal lifts.

The mean grip width chosen by these subjects for the maximal condition was a relatively wide grip (168 ± 28% BAB); however, the range of grips chosen varied from the narrowest grip at 117% BAB to the widest at 217% BAB.

Table 5.1 Group means and standard deviations for kinematics of the bar. The five grip width conditions are designated 1-5. Statistical differences ($p \leq 0.05$) between conditions are listed in the row above each variable while statistical differences between grip width conditions and the maximal attempt are listed above the maximal attempt value.

	100 (1)	**125 (2)**	**150 (3)**	**175 (4)**	**200 (5)**	**MAX**
	2,3,4,5	1,4,5	1,4,5	1,2,3,5	1,2,3,4	1,2,3,5
Bar Displacement – Descent Phase (cm)	35.4 ± 3.9	33.7 ± 4.3	33.4 ± 3.6	31.2 ± 4.5	28.8 ± 3.8	30.8 ± 4.5
Lift Time – Descent Phase (s)	2.19 ± 0.44	2.12 ± 0.44	1.93 ± 0.40	2.04 ± 0.38	2.02 ± 0.29	2.05 ±0.35
Mean Bar Velocity – Descent Phase (cm/s)	16.8 ± 3.7	16.6 ± 4.3	18.1 ± 4.3	16.0 ± 4.3	14.6 ± 3.0	15.4 ± 3.4
	2,3,4,5	1,4,5	1,4,5	1,2,3,5	1,2,3,4	1,2,3,5
Bar Displacement – Lift Phase (cm)	38.1 ± 3.2	36.1 ± 3.9	35.1 ± 3.5	33.3 ± 4.3	30.9 ± 3.5	32.9 ± 5.6
	5		5		1,3	1,2,3,4,5
Lift Time – Lift Phase (s)	1.92 ± 0.60	1.78 ± 0.39	1.92 ± 0.67	1.77 ± 0.57	1.44 ± 0.31	2.93 ± 0.88
						1,2,3,4,5
Mean Bar Velocity – Lift Phase (cm/s)	21.4 ± 6.6	22.5 ± 5.7	20.1 ± 7.0	20.8 ± 7.5	22.3 ± 4.8	11.7 ± 0.4

5.4.2 Lifter Kinematics

To achieve the wider grip position at the bottom of the lift, subjects increased shoulder abduction and reduced elbow flexion, while shoulder flexion did not vary significantly. At the top of the lift, shoulder flexion and abduction angles were greater (upper arm was farther from vertical and farther away from the torso) in the wider conditions. Since subjects were instructed to raise the bar until the elbows were fully extended, the decreased elbow flexion at the bottom of the wider grip widths also represents an decrease in total ROM at the elbow. Shoulder flexion ROM also decreased as grip width increased (Table 5.2).

Forearm angle changed from -24.7° (hands inside elbows) in the narrowest condition to 9.8° (hands outside elbows) in the widest condition at the bottom of the lift and from 0.3° to 20.2° at the top of the lift. Forearm tilt also showed small yet significant differences between grip width conditions. In general, the subjects kept the bar between the elbows and the shoulders. Though the mean tilt angle during the lift phase was smaller than 5° for all conditions, as the grip width narrowed, the subjects tended to keep the bar more directly above the elbows (Table 5.3).

Table 5.2 Group means and standard deviations for kinematics of the shoulder and elbow. The five grip width conditions are designated 1-5. Statistical differences ($p \leq 0.05$) between conditions are listed in the row above each variable while statistical differences between grip width conditions and the maximal attempt are listed above the maximal attempt value.

	100 (1)	**125 (2)**	**150 (3)**	**175 (4)**	**200 (5)**	**MAX**
Shoulder Flexion Angle – Bottom	101.5 ± 6.8º	101.7 ± 9.4º	102.3 ± 11.4º	102.7 ± 10.8º	100.7 ± 13.8º	98.7 ± 17.8º
	2,3,4,5	1,3,4,5	1,2,4,5	1,2,5	1,2,3,4	1,2
Shoulder Flexion Angle – Finish	27.0 ± 10.4º	33.3 ± 11.5º	38.9 ± 8.5º	40.0 ± 9.3º	46.4 ± 8.2º	43.3 ± 16.2º
	2,3,4,5	1,3,4,5	1,2,4,5	1,2,5	1,2,3,4	1,2,3
Shoulder Flexion Angle – ROM	74.5 ± 9.3º	68.4 ± 10.1º	64.4 ± 9.7º	62.7 ± 7.9º	54.3 ± 11.7º	55.4 ± 14.9º
	3,4,5	4,5	1,4,5	1,2,3	1,2,3	1,2,3
Shoulder Abduction Angle – Bottom	45.7 ± 13.8º	50.3 ± 9.3º	52.0 ± 11.9º	58.9 ± 10.6º	60.6 ± 8.8º	59.3 ± 9.3º
			4,5	3	3	2,3,5
Shoulder Abduction Angle – Finish	81.7 ± 33.6º	83.0 ± 28.7º	80.6 ± 21.8º	89.3 ± 20.8º	85.6 ± 19.6º	90.9 ± 19.0º
	4,5	4,5	4,5	1,2,3	1,2,3	1,2,3
Shoulder Abduction Angle – Mean	65.4 ± 17.4º	67.1 ± 13.2º	67.2 ± 13.8º	73.5 ± 13.1º	74.1 ± 11.9º	76.8 ± 12.1º
	2,3,4,5	1,3,4,5	1,2,5	1,2,5	1,2,3,4	1
Elbow Flexion Angle – Bottom	88.0 ± 7.9º	81.9 ± 9.4º	76.1 ± 8.9º	73.3 ± 6.8º	63.3 ± 8.5º	66.3 ± 12.8º

Table 5.3 Group means and standard deviations for kinematics of the forearm segment. The five grip width conditions are designated 1-5. Statistical differences ($p \leq 0.05$) between conditions are listed in the row above each variable while statistical differences between grip width conditions and the maximal attempt are listed above the maximal attempt value.

Variable	100 (1)	125 (2)	150 (3)	175 (4)	200 (5)	MAX
	2,3,4,5	1,3,4,5	1,2,4,5	1,2,3,5	1,2,3,4	1,2,5
Forearm Angle – Bottom	-24.7 ± 7.0°	-16.3 ± 5.4°	-5.9 ± 5.0°	1.4 ± 4.6°	9.8 ± 3.7°	-1.0 ± 10.0°
	2,3,4,5	1,3,4,5	1,2,4,5	1,2,3,5	1,2,3,4	1,2,5
Forearm Angle – Finish	0.3 ± 4.1°	4.7 ± 3.9°	10.0 ± 4.3°	15.7 ± 3.5°	20.2 ± 3.0°	13.4 ± 7.3°
	2,3,4,5	1,3,4,5	1,2,4,5	1,2,3,5	1,2,3,4	1,2,5
Forearm Angle – Mean	-16.2 ± 4.6°	-10.7 ± 3.8°	-2.6 ± 3.9°	3.0 ± 2.4°	11.0 ± 2.9°	0.4 ± 7.8°
	3	3	1,2			1,2
Forearm Tilt – Bottom	-1.3 ± 6.0°	-2.9 ± 5.2°	-6.5 ± 4.8°	-4.7 ± 6.0°	-3.4 ± 9.6°	-6.9 ± 6.2°
	3		1			
Forearm Tilt – Finish	-3.1 ± 3.7°	-3.3 ± 5.2°	-5.7 ± 4.7°	-3.0 ± 5.6°	-0.4 ± 10.1°	-1.7 ± 5.5°
	2,3,4,5	1,3,5	1,2	1	1,2	1
Forearm Tilt – Mean	-0.7 ± 5.3°	-2.2 ± 5.4°	-4.3 ± 5.1°	-3.2 ± 5.3°	-4.7 ± 4.4°	-4.3 ± 5.4

5.4.3 Kinetic Data Results

Tables 5.4 and 5.5 show the group means and standard deviations for the analyzed variables for the descent and lift phases respectively for all lifting conditions. Both tables show that the vertical and lateral forces tended to decrease as the grip width increased. Comparison between the two tables shows that the maximal vertical and lateral forces were greater in the descent phase than in the lift phase. This was also true for the mean vertical force, but the mean lateral forces were not significantly different between the two phases of the lift. Throughout all phases of all lifts, the lateral force was applied outward along the bar.

The maximal vertical force tended to occur between 75 and 85% of the total decent phase time and did not change significantly across the any of the conditions. During the lift phase, there tended to be two peaks in vertical force, one occurring in the first 20% of the lift, and one occurring in the last 35% of the lift. For the narrower grip widths, about half of the subjects had a greater first vertical peak and a similar number had a greater late vertical peak force. Therefore, the mean time for the vertical force was close to the midpoint of the lift phase in the narrowest grip. As grip width increased, the early peak became more dominant, to the point where the early peak force was greater in all subjects at the widest grip condition.

The maximum lateral force profile tended to have two peaks during the descent phase, one occurring in the first 25% and the second one in the last 25% of the phase. For most subjects, the later peak was greater than the earlier in the submaximal lifts; however, this was not always the case, and therefore, there is a substantial standard deviation for this measure. During the descent phase of the maximal attempt, the earlier lateral force maximum tended to be greater. During the lift phase, the maximum lateral force occurs at approximately 75% of the lift time and does not significantly vary across grip conditions; however, in the maximal lift, the timing of the maximum lateral force tended to coincide with the maximum vertical force, at about 30% lift time.

The ratio of lateral to vertical force showed small yet significant changes as grip widened. In general, as grip width increased, the magnitude of the lateral force decreased relative to the vertical force. There were no significant differences when comparing the ratio of the applied forces between the descent and lift phases.

Table 5.4 Group mean and standard deviations for the descent phase kinetic variables. Force values are normalized to the weight of the bar lifted in that condition. Timing of peak events is normalized and presented as a percentage of the descent phase. Statistical differences ($p \leq 0.05$) between conditions are listed in the row above each variable while statistical differences between grip width conditions and the maximal attempt are listed above the maximal attempt value.

	100 (1)	**125 (2)**	**150 (3)**	**175 (4)**	**200 (5)**	**MAX**
	3,4,5	5	1	1,5	1,2,4	5
Max Vertical Force Descent	1.33 ± 0.12	1.31 ± 0.14	1.25 ± 0.11	1.24 ± 0.10	1.21 ± 0.09	1.17 ± 0.11
Time of Max Vert Force Descent (%)	84.6 ± 19.3	84.5 ± 21.7	82.8 ± 17.8	83.2 ± 15.7	81.1 ± 19.3	76.9 ± 33.7
	4,5	5	5	1	1,2,3	1
Mean Vertical Force Descent	1.14 ± 0.07	1.12 ± 0.09	1.11 ± 0.09	1.08 ± 0.07	1.03 ± 0.02	1.05 ± 0.06
	2,3,4,5	1,3,4,5	1,2,4,5	1,2,3	1,2,3	1,2,3
Max Lateral Force Descent	0.42 ± 0.08	0.38 ± 0.07	0.36 ± 0.06	0.33 ± 0.07	0.29 ± 0.11	0.29 ± 0.04
	3		1			1,2,3,4,5
Time of Max Lateral Force Descent (%)	68.3 ± 34.2	71.8 ± 23.1	65.1 ± 32.2	67.3 ± 34.1	65.6 ± 34.6	36.0 ± 44.8
	2,3,4,5	1,3,4,5	1,2,4,5	1,2,3,5	1,2,3,4	1,2,3,5
Mean Lateral Force Descent	0.33 ± 0.02	0.30 ± 0.02	0.28 ± 0.02	0.25 ± 0.02	0.21 ± 0.06	0.26 ± 0.03
	4,5	5		1	1,2	1,2,3,4,5
Max Ratio Descent	37.1 ± 6.8	35.8 ± 7.3	35.4 ± 7.6	35.0 ± 7.9	34.0 ± 8.0	27.2 ± 4.0
	3,4,5	3,4,5	1,2,4,5	1,2,3	1,2,3	1,2
Mean Ratio Descent	28.5 ± 2.0	27.3 ± 2.2	25.9 ± 2.3	24.4 ± 2.0	23.6 ± 1.8	24.5 ± 3.9

Table 5.5 Group mean and standard deviations for the lift phase kinetic variables. Force values are normalized to the weight of the bar lifted in that condition. Timing of peak events is normalized and presented as a percentage of the lift phase. The five grip width conditions are designated 1-5. Statistical differences (p≤0.05) between conditions are listed in the row above each variable while statistical differences between grip width conditions and the maximal attempt are listed above the maximal attempt value.

	100 (1)	**125 (2)**	**150 (3)**	**175 (4)**	**200 (5)**	**MAX**
	4,5	5	5	1,5	1,2,3,4	3,4,5
Max Vertical Force Lift	1.25 ± 0.08	1.24 ± 0.13	1.19 ± 0.12	1.18 ± 0.09	1.02 ± 0.26	1.27 ± 0.14
	5	5	5		1,2,3	
Time of Max Vert Force Lift (%)	53.0 ± 21.9	49.0 ± 27.2	45.2 ± 26.3	42.7 ± 35.7	16.1 ± 16.9	30.2 ± 40.6
	5	5	5	5	1,2,3,4	5
Mean Vertical Force Lift	1.10 ± 0.09	1.08 ± 0.10	1.07 ± 0.09	1.04 ± 0.06	0.99 ± 0.09	1.06 ± 0.08
	2,3,4,5	1,3,4,5	1,2,4,5	1,2,3	1,2,3	4,5
Max Lateral Force Lift	0.38 ± 0.05	0.35 ± 0.04	0.31 ± 0.03	0.29 ± 0.04	0.24 ± 0.07	0.35 ± 0.06
						1,2,3,4,5
Time of Max Lateral Force Lift (%)	74.6 ± 8.0	74.2 ± 6.2	74.7 ± 6.6	77.5 ± 7.1	73.8 ± 5.3	23.6 ± 37.1
	3,4,5	3,4,5	1,2,4,5	1,2,3,5	1,2,3,4	1,2,5
Mean Lateral Force Lift	0.31 ± 0.03	0.29 ± 0.03	0.28 ± 0.02	0.25 ± 0.02	0.23 ± 0.03	0.26 ± 0.04
	3,4,5	5	1	1	1,2	1,2,3,4,5
Max Ratio Lift	37.5 ± 6.7	36.2 ± 6.0	35.0 ± 6.2	34.9 ± 6.2	34.0 ± 8.0	28.1 ± 3.3
	3,4,5	4,5	1,4,5	1,2,3	1,2,3	1,2,3
Mean Ratio Lift	29.9 ± 1.6	29.1 ± 1.8	28.2 ± 1.8	27.3 ± 1.9	27.1 ± 1.7	25.0 ± 2.2

5.4.4 EMG Data Results

EMG data for the lift phase of the maximal condition were normalized to the maximum activity level recorded for each muscle during the MVIC trials. Table 5.6 shows the mean and maximum EMG value for the lift phase of the maximal trial. The pectoralis was the most highly active muscle, followed by the deltoid, the triceps, and finally the biceps. For the remainder of the EMG analysis, the data were normalized to the maximum EMG recording during the lift phase of the maximal trial for each respective muscle and are presented in Tables 5.7 and 5.8. Figure 5.3 shows the EMG patterns for a subject under the 150% BAB condition.

Deltoid

The EMG activity in the deltoid tended to be very consistent across conditions in both the descent and lift phases. Deltoid peak activity ranged between 80 and 95% of that in the maximal lift phase, and tended to happen at roughly the midpoint in both the descent and lift phase. The mean activity level was also consistent at about 45% of maximal activity, though the mean activity level in the lift phase of the maximal condition was significantly higher than that in the lift phase of the two narrowest grip width conditions. There were no significant differences in deltoid EMG activity measures between the descent and lift phases.

Pectoralis

The highest relative EMG activity in the pectoralis occurred late in the descent phase. The peak activity in the lift phase occurred early (less that 35% lift time) and was significantly lower than that of the descent phase; however, there was no difference in mean activity between phases. Grip width had no significant effect on any of the variables analyzed, though the mean activity in the pectoralis was greater in the lift phase of the maximal attempts than in the same phase of the submaximal lifts.

Triceps

Peak and mean tricep EMG activity were significantly greater in the lift phase than the descent phase across all conditions. Grip width did not have a significant effect on tricep activity, though the maximal attempt showed greater peak and mean activity than some of the submaximal conditions. Like the pectoralis, the maximal activity of the tricep occurred late in the descent phase and early in the lift phase.

Biceps

The peak activity in the biceps muscles during the lift phase was about 25% of the peak seen in the MVIC trial. Throughout the submaximal trials, the peak activity in the biceps did not exceeded 45% of the peak seen in maximal lift. Because of the very low relative activity level throughout all of the submaximal trials, the biceps was not analyzed further.

Table 5.6 Group means and standard deviations for the lift phase of the maximal lift. EMG values are normalized and presented as a percentage of the maximal value observed maximal voluntary isometric contraction.

	Bicep	**Deltoid**	**Pectoralis**	**Tricep**
Mean Value (% MVIC)	12 ± 7	44 ± 18	54 ± 13	38 ± 16
Maximum Value (% MVIC)	23 ± 23	82 ± 33	109 ± 41	72 ± 31

Table 5.7 Group means and standard deviations for the descent phase of the maximal and submaximal lifts. EMG values are normalized and presented as a percentage of the maximal value observed during the lift phase of the maximal attempt. Timing of peak events is normalized and presented as a percentage of the descent phase. The five grip width conditions are designated 1-5. Statistical differences ($p \leq 0.05$) between conditions are listed in the row above each variable while statistical differences between grip width conditions and the maximal attempt are listed above the maximal attempt value.

	100 (1)	125 (2)	150 (3)	175 (4)	200 (5)	MAX
Deltoid Maximum Descent	83 ± 27	82 ± 28	84 ± 22	80 ± 32	88 ± 33	82 ± 13
Deltoid Mean Descent	43 ± 15	44 ± 15	44 ± 13	41 ± 15	45 ± 14	46 ± 11
Deltoid Max Time Descent	48.2 ± 15.6	52.4 ± 23.8	50.1 ± 20.1	42.4 ± 17.7	48.6 ± 18.0	55.9 ± 14.9
Pectoralis Maximum Descent	136.5 ± 26.1	137.5 ± 33.9	129.1 ± 54.5	143.0 ± 45.6	158.5 ± 52.0	163.9 ± 40.9
Pectoralis Mean Descent	35 ± 10	35 ± 9	34 ± 15	33 ± 14	37 ± 12	39 ± 7
Pectoralis Max Time Descent	78 ± 18	75 ± 16	72 ± 29	73 ± 38	84 ± 37	84 ± 14
						5
Tricep Maximum Descent	57 ± 13	52 ± 14	60 ± 23	61 ± 17	48 ± 9	64 ± 13
						2,5
Tricep Mean Descent	29 ± 8	28 ± 7	29 ± 8	32 ± 9	26 ± 5	34 ± 7
Tricep Max Time Descent	79.5 ± 17.0	69.7 ± 18.5	70.6 ± 13.1	69.1 ± 17.3	72.7 ± 17.1	78.2 ± 14.3

Table 5.8 Group means and standard deviations for the lift phase of the maximal and submaximal lifts. EMG values are normalized and presented as a percentage of the maximal value observed during the lift phase of the maximal attempt. Timing of peak events is normalized and presented as a percentage of the lift phase. The five grip width conditions are designated 1-5. Statistical differences ($p \leq 0.05$) between conditions are listed in the row above each variable while statistical differences between grip width conditions and the maximal attempt are listed above the maximal attempt value.

	100 (1)	**125 (2)**	**150 (3)**	**175 (4)**	**200 (5)**	**MAX**
Deltoid Maximum Lift	94 ± 33	95 ± 46	90 ± 33	87 ± 35	84 ± 25	100 ± 0
						1,2,4
Deltoid Mean Lift	49 ± 11	47 ± 15	52 ± 19	45 ± 17	51 ± 16	57 ± 4
Deltoid Max Time Lift	46.8 ± 15.9	48.2 ± 17.2	51.0 ± 21.6	45.2 ± 24.3	48.7 ± 19.6	54.8 ± 17.1
						3,4,5
Pectoralis Maximum Lift	83 ± 14	82 ± 16	78 ± 19	74 ± 24	76 ± 30	100 ± 0
						1,2,3,4,5
Pectoralis Mean Lift	37 ± 9	39 ± 8	38 ± 11	38 ± 15	40 ± 9	55 ± 8
	2,3	1	1			1
Pectoralis Max Time Lift	12.7 ± 8.8	24.9 ± 13.8	27.9 ± 17.9	30.8 ± 25.9	23.2 ± 15.4	34.0 ± 18.4
						1,2,5
Tricep Maximum Lift	70 ± 16	73 ± 26	81 ± 36	81 ± 38	63 ± 14	100 ± 0
						1,2,5
Tricep Mean Lift	42 ± 10	42 ± 14	49 ± 18	48 ± 16	39 ± 10	57 ± 6
	5	5			1,2	1,2
Tricep Max Time Lift	7.4 ± 3.6	8.9 ± 4.8	14.7 ± 15.1	10.1 ± 7.5	14.3 ± 8.0	13.3 ± 7.0

5.4.5 Change in Relative Muscle Contribution During the Lift Phase

To explore whether there was a shift in the relative contribution of the muscles examined as the lift progressed, the lift portion of each repetition was divided into two halves. The bottom half was defined as the initiation of vertical movement during the lift phase through the midpoint, defined as the point at which the bar had reached ½ of the total lift height. The top half continued from the point at which the bar had reached ½ of the total lift height to the completion of the lift. Lift height rather than lift time was chosen because it was believed that any change in relative contribution would be the result of a change in upper extremity position rather than the amount of time of the lift. The movement of a joint or the mean activity in a muscle in the top half of the lift was divided by the same in the bottom half of the lift. Therefore, a movement ratio less than one (1.00) indicated greater ROM during the first half of the lift while a value greater than one indicated greater ROM at the joint in the top half of the lift. Likewise, a ratio less than one indicated greater mean EMG activity in the bottom half of the lift phase and a ratio greater than one indicated greater mean EMG activity in the muscle during the top half of the lift. The ratio of shoulder flexion ROM was 1.01 ± 0.02, indicating that the angular distance the shoulder traveled in the bottom half and in the top half of the lift were nearly identical, yet the ratio of mean activity of the two shoulder flexors was substantially higher during the first half of the lift (pectoralis = 0.63 ± 0.14 and deltoid =0.75 ± 0.13). The ratio of elbow extension ROM and mean tricep EMG activity were 1.30 ± 0.02 and 1.17 ± 0.02 respectively, indicating that there was more elbow extension and muscle activity during the second half of the lift.

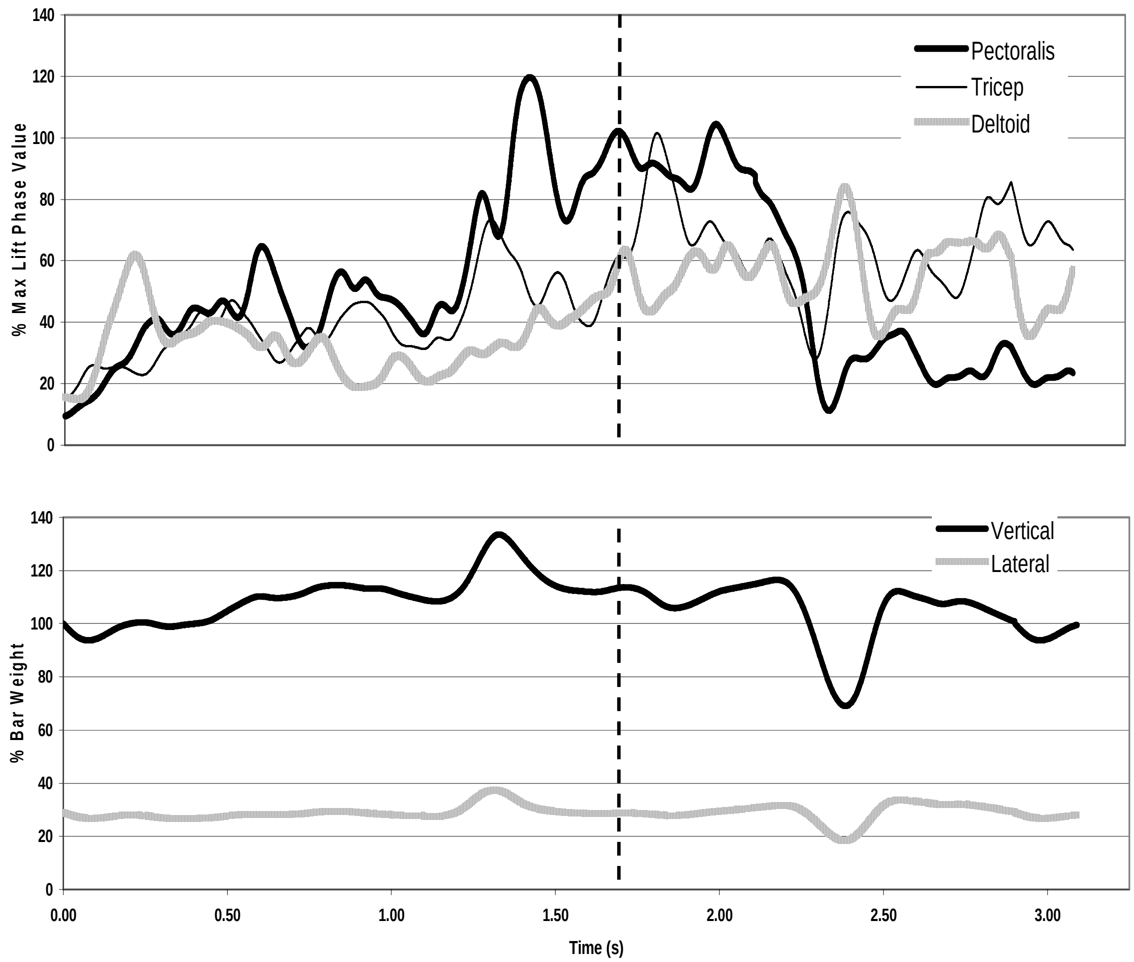

Figure 5.3 This figure shows representative EMG and force profiles for a submaximal repetition at the middle (150% BAB) grip width. The top graph shows the EMG activity for the pectoralis, tricep and deltoid normalized to their respective peak recordings in the lift phase of the maximal attempt. The bottom graph shows the vertical and lateral force profiles, normalized to the load lifted, for the same lift. A dashed vertical line has been added to indicate the transition from descent to lift phase.

5.5 Discussion

Previous research has suggested that a wider grip width during a bench press increases pectoralis and decreases triceps activity (McLaughlin, 1985; Wagner, Evans, Weir, Housh, and Johnson, 1992; Barnett, Kippers and Turner, 1995; Lehman, 2005), and leads to a greater maximal single lift (Madsen and McLaughlin, 1984; Clemons and Aaron, 1997; Gilbert and Lees, 2003). In the following section, the effects of changes in grip width on the kinematic, the kinetic, and finally the EMG data will be examined. It was anticipated an increase in grip width would result in an increase in lateral forces and pectoralis activation and a decrease in triceps activity. In fact, wider grip widths resulted in smaller vertical and lateral forces and little change in muscle activation levels.

Effects of grip width on kinematic data.

One of the reasons given for the decrease in performance with a narrower grip in the bench press is that more work must be done with a narrower grip because the bar has to travel a greater vertical distance; the data in this study seemed to support this. The bar traveled almost 25% further in the narrowest condition than in the widest condition. The increase in lift height required an additional 20° of shoulder flexion and 25° of elbow extension. Position of the forearm was also affected by the width of the grip. Throughout all conditions, it appeared that the subjects tried to keep the elbows almost directly below the bar with only a slight tilt, less than 5°. The narrow grip resulted in the hands being closer together or “inside” the elbows. This relatively steep forearm angle, as high as 25° in the narrowest condition, seems disadvantageous for applying a vertical force to the bar. This position, as will be discussed in more detail later, was associated with an increase in both the vertical and lateral forces that were applied to the bar.

There was however, only a moderate correlation between grip width (expressed as %BAB) and maximal lift normalized to body weight ($r^2 = 0.37$). While most of the subjects in this study adopted a relatively wide grip position when attempting a maximal lift, the mean grip width was 170% BAB, this was not always the case. The subject who had the highest normalized maximal lift had the second-narrowest grip width (144% BAB).

Effects of grip width on kinetic data

The peak force applied during the lift phase of the maximal lift was about 8% greater than in the descent phase. This is larger than the 1.5% difference previously reported (Madsen and McLaughlin, 1984) however, this may be a result of a difference in lifting style or in method of determining force. Earlier studies have determined forces from kinematic data rather than using force transducers. Across all submaximal conditions in this study however, greater peak vertical forces were applied during the descent phase rather than the lift phase. There are two explanations for the discrepancy between the two studies. First, it may be due to a difference in methodology: their lifters were required to perform a competition-style lift which required a pause on the chest, whereas the subjects in this study were instructed to perform each lift as they would in training, and were not required to pause at the bottom of each repetition.

The second explanation is that these novice lifters lowered the bar too quickly and have to apply a relatively large force to stop the descent. In the same paper, Madsen and McLaughlin (1984) report that the speed of the lift is predictive of relative performance in elite, competitive lifters. Specifically, the better lifters lowered the bar more slowly. Calculating mean descent velocity based on their reported time and distance of descent showed their expert group lowered the bar at a mean velocity of 9.6cm/s while their novice group had a mean velocity of 19.1cm/s. Comparing those results with the data in this study shows their novice lifters lowered the bar at a very similar velocity as our subjects; however, there were still some substantial differences between the two groups. Their lifters were all males and had an average maximal lift of 1.3BW compared with 0.97BW in the mixed gender group in the current study. In addition to the gender differences in the two studies, it seems likely that their lifters may have been more experienced, or at least more accomplished recreational lifters, compared with the current cohort. Because their lifters were substantially better performers yet still had not adopted the slower lowering technique suggests this technique may not be developed without specific instruction.

Previous research examining the forces applied to the floor when performing pushups at various hand width positions showed that lateral forces increased when the hands were placed farther apart (Duffey and Zatsiorsky, 2003). The data in Chapter Four showed a strong relationship between the vertical and lateral forces. This relationship was present once again in this study and was largely unaffected by a change in grip width. The magnitude of the vertical and lateral forces changed similarly across grip widths and the timings of the peak vertical and lateral forces also tended to occur at similar times. Surprisingly, as grip width increased in this study, both the mean and maximum vertical and lateral forces decreased. Instead of showing a strong positive relationship with grip width, the lateral force appeared to be much more strongly related to the magnitude of the vertical force regardless of hand position. Therefore, if lifting efficiency is defined as lifting a given load while exerting the least force, it appears that wider grip widths produce more efficient lifts.

Effects of grip width on muscle activation

Previous research has suggested that a wider grip width tends to result in increased pectoralis and decreased triceps activation (McLaughlin, 1985; Lehman, 2005), while others have suggested that such changes do not occur (Barnett, Kippers, and Turner 1995; Clemmons and Aaron, 1997). Analysis of the data in this study showed that EMG activity was not systematically affected by grip width. There were no significant changes in mean or peak activation level in any of the muscles across any grip width condition.

The lack of statistical difference in muscle activation between grip width conditions in these novice lifters has several possible explanations. The first option is that the superficial EMG data collection methods used in this study were not sensitive enough to show differences in muscle activation in this population. The second option is that these subjects are not able to immediately change muscle activation patterns to accommodate the different grip width positions introduced in this study. The third option is that muscle activation does not need to change across grip widths when lifting a constant load. The lack of consistent changes associated with a wider grip width points to this as the most likely explanation. Previous studies have shown both a statistically significant decrease (Barnett, Kippers, and Turner, 1995; Lehman, 2005) and increase (Clemmons and Aaron, 1997) in triceps activity when grip width increases. Furthermore, the study by Barnett, Kippers and Turner (1995) showed that activation of the upper fibers of the pectoralis increased while activation in the lower fibers decreased, whereas Lehman (2005) found virtually the opposite: no change in the upper fibers and an increase in activation of the lower fibers.

While joint moments were not calculated in this study, some inferences regarding them can be drawn. The moment about the elbow would be the result of the mass lifted and the moment arm about the elbow. That moment arm would be related to the two forearm angles measured in this study. As seen in Table 5.3, forearm tilt, which was measured as the forearm angle perpendicular to the long axis of the bar, was relatively small and only varied a few degrees throughout the lift across all grip width conditions. Thus the contribution of forearm tilt to the moment arm about the elbow was small. The forearm angle, which was the angle formed between the forearm and the long axis of the bar, varied greatly across grip widths. At the bottom of the lift, the forearm was nearly vertical (1.4°) at the second widest (175% BAB) condition; while at the narrowest condition, the forearm angle is almost 25°. This increase in forearm angle would require a substantially greater extension moment to be generated by the lifter to extend the elbows at least through the lower portion of the lift phase. This increase in required elbow extension moment, plus the previously discussed increase in the height the bar has to be lifted, helps explain why narrow grip widths tend to result in smaller maximal lifts (Madsen and McLaughlin, 1984; Clemons and Aaron, 1997; Gilbert and Lees, 2003).

Comparison of Maximal and Submaximal Lifts

It is also interesting to note the lack of difference in muscle activation between the maximal and submaximal conditions, even though the weight lifted in the submaximal trials was 25% less than the maximal lift. Figure 5.3 shows the EMG and force profiles for a representative subject performing a submaximal lift at the middle (150% BAB) grip width. It is readily apparent that the activation of the triceps and pectoralis is close to or greater than that seen in the maximal activation for those muscles during the lift phase of this subject's maximal attempt. During the descent phase, only the triceps showed any statistically significant reduction in the peak or mean activation level between the maximal lift and any of the grip width conditions, and even those differences were small and limited to the comparison with one narrow (125% BAB) and one wide (200% BAB) position. For the lift phase, there were few statistical differences between the maximal and submaximal trials. The peak and mean EMG signal in the triceps was not different in two of three of the conditions (125%, 150%, 200% BAB) and the peak pectoralis activity in the two narrowest conditions were not significantly different from that of the maximal lift. There were no differences in peak deltoid activity between the maximal lift and any of the submaximal lifts.

It is possible that this lack of change in muscle activation is due to the increase in lifting velocity observed in the submaximal lifts. The submaximal trials were performed at roughly double the velocity of the maximal trial (22 cm/s and 11 cm/s, respectively). This increase in lift velocity would necessitate an increase in contraction velocity of the muscles involved. For example, the shoulder flexion range of motion for the 200% BAB lift (54.3°) was similar to that of the maximal lift (55.4°), but was completed in half the time; therefore, the average contraction velocities for the pectoralis and the anterior deltoid should have roughly doubled when the subjects performed the faster lift. This change in contraction velocity causes a reduction in force production capability of the muscles (Hill, 1938). Therefore, because less force can be generated at higher muscle contraction velocities, the lack of change in muscle activation between the maximal and submaximal trials may indicate that the "submaximal" grip width lifts may have resulted in near-maximal muscle contractions.

Differences in Phases of the Lift

EMG activity was different, however, when lowering and lifting the bar. The peak activation level during the descent phase was almost double that during the lift phase for the pectoralis. The triceps showed opposite results; with significantly higher peak and mean activity during the lift phase. Therefore, it seems that in these subjects, the pectoralis was most highly activated when slowing the descent of the bar while the triceps was more active when lifting the bar. Interestingly, EMG activity in the deltoid showed no significant differences in mean, peak, or timing of peak activity, between phases. This suggests that the deltoid is equally active when lowering and lifting the bar, and its peak activity occurs very close to the middle of the movement, regardless of which direction the bar is moving. These trends are evident in Tables 5.7 and 5.8 but were not consistent across all subjects, including the representative subject whose data are shown in Figure 5.3.

Comparison of both relative joint movement and EMG activity between the bottom and top halves of the lift phases revealed interesting information regarding what is being done throughout the lift. The shoulder flexion ROM was nearly equal in the first and second halves of the lift. For the pectoralis, the peak activity occurred in and the mean EMG level was higher in, the bottom half of the lift phase. For the deltoid, the mean EMG level was higher in the bottom half of the lift, while the peak activity level occurred very near the midpoint of the lift. More elbow extension occurred in the top half of the lift, which was also the time when the triceps were more active. Thus, is seems that the two muscles acting at the shoulder are more active when moving the bar through the bottom half of the lift, while the tricep muscle, acting to extend the elbow, is more important for completing the top half of the lift.

Conclusions

The narrower grips produced both greater vertical and lateral forces. It had been anticipated that there would be a strong direct relationship between the grip width and lateral forces. Instead, the increases in lateral forces were more strongly associated with changes in the vertical force which increased with a narrower grip. The narrower grip positions put the lifter at a performance disadvantage, which required greater vertical and lateral forces for the subjects to lift the same bar mass. More specifically, moving the hands closer together increased elbow flexion which increased the moment the bar created about the elbow, thereby requiring a greater extension moment to be generated by the triceps in the bench press. Because the subjects were able to lift the same weight while applying lower vertical and lateral forces in the wider grip conditions, it seems that the wider grip widths are more efficient for performing a maximal lift bench press. Furthermore, contrary to evidence in the literature, the novice lifters in this study did not alter muscle activation levels when performing the bench press with a wide versus a narrow grip position.

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CHAPTER 6

Summary and Conclusions

6.1 Introduction

This chapter will summarize the main findings of this research project. It will first review the goals of the research project, then summarize the main findings, and finally conclude with a discussion of the implications of the findings and possible directions for future research.

6.2 Summary

This study had three specific aims. Each of these aims will be re-stated and then addressed.

Aim 1: To compare the kinematics of the bar of a single, maximal effort lift with those of a multiple repetition set performed at 75% of the maximum load.

There were statistically significant differences between the kinematics of the maximal single lift and submaximal multiple repetition lifts. Furthermore, the kinematics of the submaximal lifts changed as a subject approached failure in a set. The time to lift the bar increased from the first to the last repetition, this resulted in a decrease in bar velocity. The peak upward velocity occurred much earlier in the lift phase in the later repetitions. The path the bar followed also changed while lifting 75% of maximum, with subjects keeping the bar more directly over the shoulder during the lift. In general, most of the kinematic variables analyzed became more similar to those of the maximal lift as the subjects progressed through the set with 75% of maximum.

Aim 2: To examine the vertical and lateral forces exerted by the lifter on an instrumented bar while performing a bench press.

In both the maximal and submaximal lifts, lateral force was applied to the bar and it averaged between 22 and 29% of the vertical force. The profile of the lateral force tended to be similar to the profile of the vertical force. The absolute vertical and lateral forces were greater for the maximal lift than for the submaximal lift, but were not different when compared as a percentage of the load lifted. Thus, a substantial portion of the force generated by the lifter is applied along the long axis of the bar.

Aim 3: To determine how an increase in grip width alters the relative muscular activity and the forces, both vertical and along the bar, during the bench press.

Both the vertical and lateral forces applied to the bar decreased as grip width increased. Neither peak nor mean electromyography (EMG) levels were systematically affected by grip width. Higher forces and EMG recordings were observed in the descent rather than the lift phase. Both vertical and lateral force increased as grip width narrowed. Since subjects could lift the same load while applying smaller forces to the bar, it appears that wider grip width is more efficient for performing the bench press.

6.3 Discussion

Performance of the bench press was analyzed under several different conditions. Novice lifters were recruited and asked to perform a maximal single lift, submaximal lifts performed in a set to failure, and submaximal single lifts at different grip widths.

Multiple Repetition Sets

After examining the kinematic profile of the bar as subjects progressed through a set to failure, it became apparent that novice lifters moved the bar differently at the beginning of a set than they do at the end. The time to lift the bar more than doubled, and there were concurrent decreases in the peak and mean bar upward velocity. Furthermore, the lifters tended to have two peaks in the vertical velocity curve in the later repetitions in the set. This two-peak pattern was similar to what was seen in the maximal effort single lifts. The shift to an early peak in vertical velocity seen in these subjects seems to reflect an attempt to enter the “sticking region” with the greatest possible vertical velocity, thereby increasing the likelihood of completing the lift. In an apparent effort to reduce the moment the bar created at the shoulder joint, the subjects also kept the bar more directly over the shoulder joint in the later repetitions.

Maximal and Submaximal Lifts

During the maximal lift, the lifters in this study typically displayed a force profile pattern which was very similar to that reported for competitive lifters (Madsen and McLaughlin, 1984). The lateral force profile followed that of the vertical force quite closely in most subjects. The magnitude of the lateral force averaged 26% of the vertical force for the maximal lift while the lateral force applied during the submaximal lift was slightly less, averaging 24% of the vertical force; there were no differences in the lateral force profiles between the two conditions. In both maximal and submaximal lifts, there was a tendency for a greater relative lateral force at the beginning of the lift phase, followed by a rapid decrease lasting through the first 15% of the lift. From that point on, the lateral force tended to increase slightly, about 2% relative to the vertical force, throughout the remainder of the lift.

There was no statistically significant difference in muscle activation between the maximal and submaximal conditions, even though the weight lifted and the vertical force applied to the bar in the submaximal trials were 25% less than their counterparts in the maximal lift. While it may be that novice lifters were not able to readily modify their muscle activation patterns to a level that could be detected by the surface EMG methods used in this study when encountering different loads, it is more likely an artifact of the increase in lifting velocity observed throughout the submaximal lifts.

Effects of Grip Width

When lifting the same load at different grip widths, the vertical and lateral force increased significantly as grip width narrowed. There was also a substantial increase in the amount of elbow flexion in the narrower grip width conditions. Moving the hands closer together, or further inside the elbows, acts to increase the moment the load lifted creates about the elbow. It appears that a byproduct of the lifters' efforts to overcome this increased moment is an increase in both vertical and lateral force. The increase in force required to lift the load, as well as a 25% increase in distance the bar has to be lifted, clarifies why maximal lift performance decreases when grip narrows.

Within repetitions, there were differences in muscular activation level between the descent and lift phases; the pectoralis is highly activated when slowing the descent of the bar, and the triceps is most active during the lifting phase. There was little or no statistically significant change in muscle activation across grip widths. This contradicts the theory that pectoralis involvement tends to decrease and triceps involvement increases with a narrower grip (Madsen and McLaughlin, 1984).

Training Applications

The subjects in this research project have displayed some definite trends that have practical implications for the development of training programs for novice lifters. Looking at their lifting kinematics, it is immediately apparent that, not only do novice lifters move the bar with a different kinematic pattern than expert lifters, they do not maintain the same movement pattern throughout a set to failure. It has been established that strength gains are influenced by the position used in training in isometric (Kitai and Sale, 1989) and or range of motion used in training isokinetic exercise (Graves, Pollock, Jones, Colvin, and Leggett, 1989). More recently, Massey, Vincent, Maneval, and Johnson (2005) found that the range of motion used in training also influences strength gains in the bench press. More specifically, their novice subjects who trained with a partial range of motion showed significantly less strength gain than those who trained with a full range of motion. Therefore, novice lifters may benefit (i.e. improve more rapidly) by performing their training lifts at a similar velocity and with a similar kinematic pattern as their 1-RM lifts.

6.4 Study Limitations

The first main limitation of this study was the number of subjects used throughout this research project. The number of subjects who completed each proportion of data collection did not always allow for analysis of sub-groups based upon different characteristics like sex or lifting ability.

Secondly, the design of the bar may have influenced some of the results of the study. To allow for recording of both vertical and lateral forces, the sleeve that was built around the bar and housed the force transducers altered the height of the hands at the bottom of the lift. When the plates that held the horizontal transducers touched the chest, the bar and the subjects' hands were about 2cm above the chest. In the future, lateral forces could be determined using strain gages mounted on a standard bar.

Finally, joint kinetics were not examined in this research project. Determining joint moments in particular would provide better insight into the relative contributions of different muscles toward completing the bench press under different lifting conditions.

6.5 Directions for Future Research

This research project has shown the kinematic, kinetic, and EMG patterns in novice lifters performing the bench press in several different conditions. Three promising directions for future research are apparent. First, a larger novice population should be recruited. This would provide an opportunity to examine joint kinetics as well as allow for subgroup analyses based on sex or lifting ability throughout all lifting conditions. Second, a study should be performed to simultaneously examine the kinetics, kinematics, and muscle activation patterns of elite lifters performing both maximal and submaximal lifts. There is currently no description of the lateral forces that elite lifters apply to the bar and it is possible that competitive lifting technique has evolved in the two decades since most of the existing data were recorded. Establishing (or re-establishing) this information for elite lifters would create a better standard for comparison and reveal how today's novice lifters differ from today's elite lifters. Once this is accomplished, longitudinal studies could then be performed to determine what training strategies result in the most rapid improvement in novice lifters.

6.6 Conclusions

There has been a lack of research describing how novice lifters perform the bench press. This research project has clarified the kinetics, kinematics, and EMG patterns of novice lifters as they perform the bench press under different conditions. The key findings of this project show that novice lifters lift the bar more rapidly and through a different path in submaximal lifts than in maximal lifts; they alter the path of the lift as they progress through a set to failure and do not modify muscle activation levels in response to different grip widths. This project has also shown that novice lifters apply force both vertically and outward along the bar when performing the bench press. The profile of the lateral force is similar to, and averages about 25% of, the vertical force. Finally, novice lifters reduce the vertical and lateral forces applied to the bar when lifting with wider grip positions, indicating that a wider grip width is more efficient for performing the bench press.

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APPENDIX A

A.1 Design of the instrumented bar

One of the goals of this research project was to determine the vertical and horizontal forces applied by the lifter to the bar during the execution of the bench press. To accomplish this, an instrumented bar was designed. The key components of the bar included three horizontal and two vertical force transducers that were mounted to a sleeve that the lifters would grip during the exercise.

Two, 1.75 inch (4.45cm) outside diameter, steel sleeves were cut to slightly less than one half of the length of the grip portion of a standard weight lifting straight bar. A hole, equal in diameter to the opening of these steel sleeves, was cut into each of two, 3/8 inch thick steel plates. One of the steel plates was welded onto one end of each of the sleeves so that the opening in the sleeve was aligned with the hole in the plate. This was done so that the bar could be placed inside the sleeve and plate. Three force transducers (PCB 208B03, range ± 2200N) were mounted onto the face of one of the plates and then the other, so that the transducers connected to two plates. Effectively, the plates created a sandwich around the three force transducers (Figure A.1)

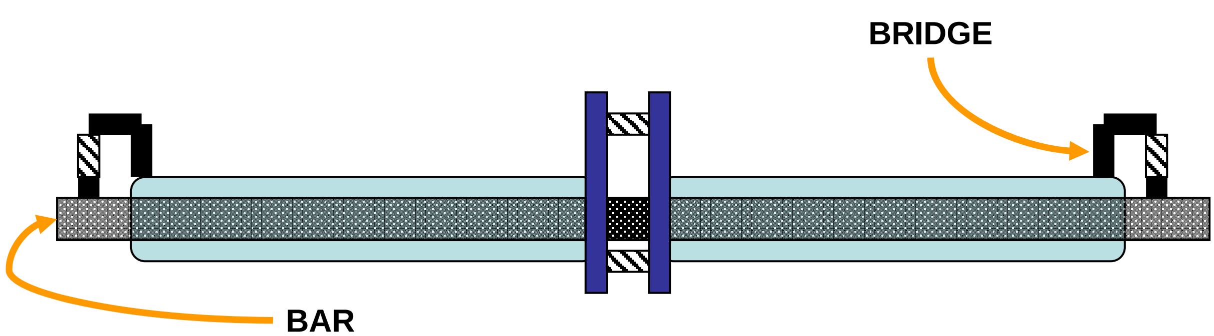

Figure A.1. A schematic of the instrumented bar designed for this study. The two vertical plates are connected via three horizontally-mounted force transducers. The grip portion of the regular bar runs through the two sleeves and is suspended in place by a vertically-mounted force transducer at each end. A small "bridge" was built that extended up and past the end of the sleeve so that the transducer could be mounted in a straight, vertical line. The figure is not to scale.

A bridge was designed and attached to the other end of the each sleeve. To the end of the bridge, a transducer was suspended. The lifting bar was slid through the sleeves and then attached to the free end of each force transducer, thereby suspending the lifting bar inside the sleeve.

The only physical attachment between sleeve and bar was through the vertical force transducers at either ends of the sleeves. When used, the lifter would grip and push on the sleeve and the bar and weights would be lifted via its suspended connections to the two vertical transducers. Because the bar and weights were suspended only by the connection at the transducers, all of the vertical force (F_V) used to lift the bar would be applied through the transducers and could be recorded. The horizontal force applied in tension and compression along the long axis of the bar (F_H) resulting from the force applied by the lifter to the sleeve or the bending moment created by the mass of the bar and added weights (F_L) were registered by the force transducers mounted between the two steel plates. See Figure A.2.

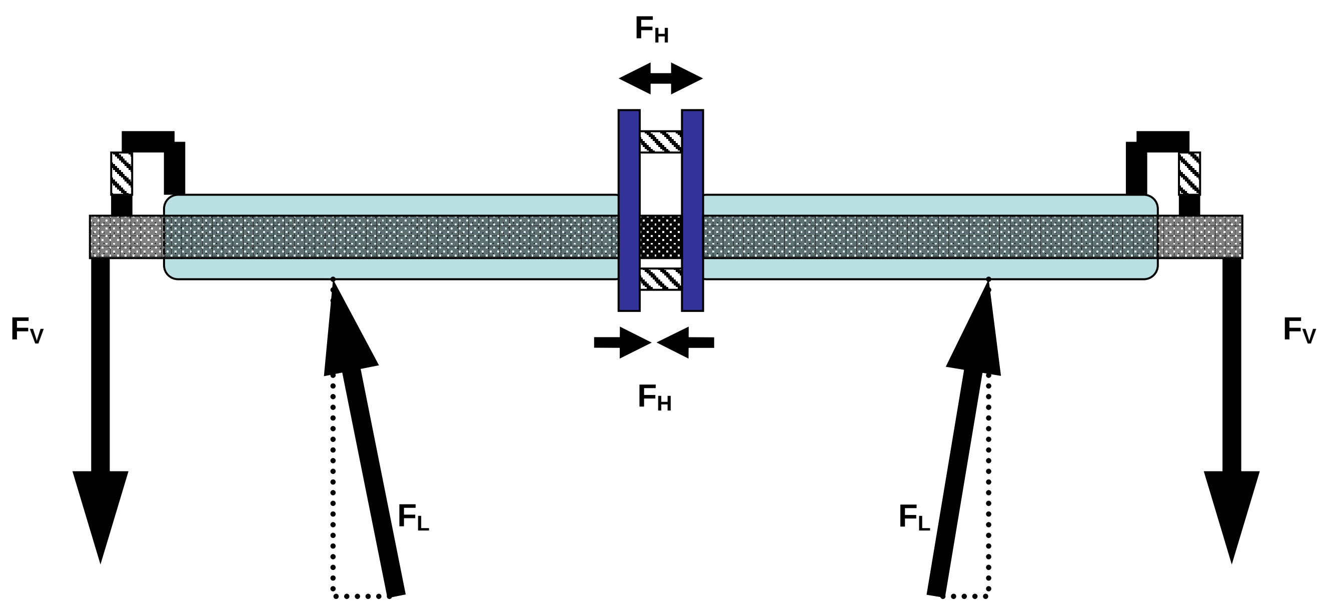

Figure A.2. A representative free body diagram of the bar and the forces acting on and across it. F_L is the force applied by the lifter (one for each arm), F_V is the force of the bar and the weights loaded onto each end, and F_H is the horizontal force acting along the long axis of the bar.

A.2 Calculating forces

The following names were assigned to the force transducers (See figure A.3)

V_L = Left vertical transducer

V_R = Right vertical transducer

T = Top horizontal force transducer

B_F = Front bottom horizontal force transducer

B_B = Back bottom horizontal force transducer

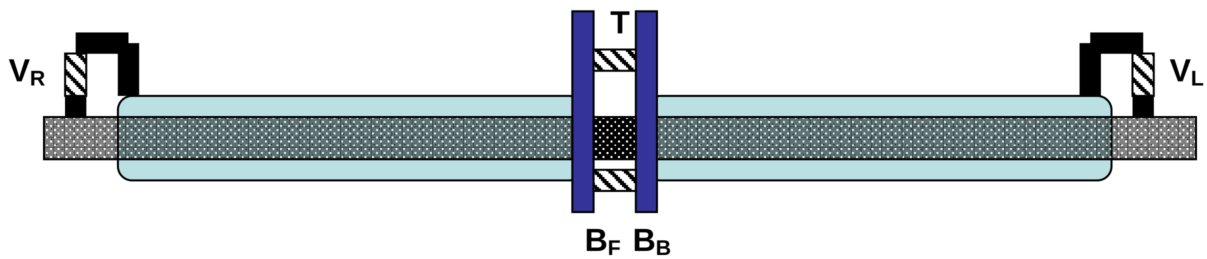

Figure A.3. Illustration of the locations of the various transducers. In this view the two bottom transducers are located immediately in front and back of each other. While the illustration is not to scale, the distance from the center of the bar to T was double that of vertical distance to B_F and B_B.

To determine vertical force and horizontal force applied along the bar, the following equations were used:

$$\text{Vertical force} = V_L + V_R$$

$$\text{Horizontal force} = 1.5 \bullet (T + (0.5 \bullet (B_F + B_B)))$$

A.3 System Calibration

Prior to use in this study, calibration data was taken for the force transducers. The manufacturer included values for converting voltage into Newtons. To determine the accuracy of these conversion values, each transducer was subjected to several static forces applied by a known mass. The manufacturer supplied conversion for each transducer proved to be highly accurate, within ±1N of expected value. Later, once the transducers were mounted within the modified lifting bar, loads with known mass up to 400N were added to the bar, the bar was suspended so that the loads were supported through the vertically mounted transducers, and force recording were compared to expected values based on the mass of the system. Errors were less than ± 2N. Then, drift in the transducers was tested during a 5 minute data collection period. During this period, the same 400N load was applied. Force readings at the end of the 5 minute period remained within ± 2N of the original values. This amount of time was chosen because it well exceeded the time any single lifting trial would take. This amount of drift was considered negligible for this study. Nonlinearity of the transducers, as provided by the manufacturer, was less than 1% full scale. Following these calibration efforts, data collection with human subjects commenced.

APPENDIX B

INFORMED CONSENT FORM FOR CLINICAL RESEARCH STUDY
The Pennsylvania State University

Title of Project: Force control in varied muscular tasks

Principal Investigators: Vladimir M. Zatsiorsky, John H. Challis, Michael J. Duffey

Contact: John H. Challis
30 Recreation Building
University Park, PA 16802
(814) 865-3445

This is to certify that I, ______________________________, have been given the following information with respect to my participation as a volunteer in a program of investigation under the supervision of Michael Duffey, M.S. & Drs. Vladimir M. Zatsiorsky and John H. Challis.

1. **Purpose of the study:**

   Appropriate control of muscles and their force production is essential for any human movement. In this project, we will compare the magnitude and direction of force produced with the desired magnitude and direction. Performance may be related to skeletal architecture, experience, strength, and age. We will explore the role of all of these.

2. **Procedures to be followed:**

   Subjects will be asked to perform certain muscular tasks. They include:
   1. Submaximal body-weight push ups
   2. Submaximal and maximal free-weight bench press
   3. Submaximal and maximal hand and finger gripping
   4. Maximal gripping combined with elbow flexion or extension
   5. Submaximal and maximal isokinetic knee flexion and extension

   The forces produced in each of the tasks will be recorded through force plates or force transducers.

3. **Discomforts and risks:**

    There are minimal risks associated with participation in this experiment for healthy people (those people with no history of traumas to, or neuropathies of the upper limbs). Force generation above a certain level can be painful for patients with hand disorders. Patients will be asked to generate forces below this level. Some muscle soreness may be experienced following this type of testing.

4. a. **Benefits to me:**

    Subjects will have the opportunity to learn about various experimental techniques and methods used in biomechanics and motor control research. In addition, patients will gain a greater understanding of their performance in various strength training tasks.

    b. **Potential benefits to society:**

    The methods developed have potential use as diagnostic tools in clinical and practical settings. They will enable clinicians to test muscle function and task performance to identify existing muscular weaknesses, imbalances, and control deficits and instruct on improved technique.

5. **Alternative procedures which could be utilized:**

    N/A

6. **Time duration for the procedures and study:**

    Each session will last between one and two hours. Subjects will participate in one to three sessions.

7. **Statement of Confidentiality:**

    All records associated with my participation in this study will be subject to the usual confidentiality standards. In the event of any publication resulting from the research, no personally identifiable information will be disclosed.

8. **Right to ask questions:**

    I have been given an opportunity to ask any questions I may have, and all such questions or inquiries have been answered to my satisfaction.

9. **Compensation:**

    I understand that medical care is available in the event of injury resulting from research but that neither financial compensation nor free medical treatment is provided. I also understand that I am not waiving any rights that I may have against the University for injury resulting from negligence of the University or investigators. Questions regarding this statement of your rights as a subject of this research should be directed to the Office for Regulatory Compliance, The Pennsylvania State University, 212 Kern Graduate Building, University Park, PA 16802-3301 (814-865-1775).

10. <u>Voluntary participation:</u>

I understand that my participation in this study is voluntary, and that I may withdraw from this study at any time by notifying the investigator. My withdrawal from this study or my refusal to participate will in no way affect my care or access to medical services.

11. In the event that abnormal test results are revealed, you will be appraised of the results and recommended to contact your private medical care provider for follow-up.

This is to certify that I give consent to and give permission for my participation as a volunteer in this program of investigation. I understand that I will receive a signed copy of this consent form. I have read this form, and understand the content of this consent form.

____

Volunteer Date

I, the undersigned have defined and explained the studies involved to the above volunteer.

____

Investigator Date

Michael J. Duffey

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Education

Doctor of Philosophy in Kinesiology — December 2008
The Pennsylvania State University
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Master of Science in Health and Sport Science — May 1996
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Bachelor of Science in Physical Education — May 1994
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Employment History

Instructor, Department of Kinesiology — 2006-Present
The Pennsylvania State University, University Park, PA

Instructor, Department of Physical Education — 2003-2006
Researcher, Center for Physical Development Excellence
United States Military Academy, West Point, New York

Instructor, Department of Kinesiology — 2001-2003
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Research Assistant & Lab Coordinator — 1996-1998
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Professional Memberships and Certifications

Member, American College of Sports Medicine (ACSM)
Member, American Society of Biomechanics (ASB)
CPR and AED certified, American Heart Association
Coach, NAIA Champions of Character